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

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D2.6 Handbook with guidelines for fire fighters to face to extreme fires, fires in WUI and fires in high latitudes/ altitudes

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Executive Summary

The risk of wildfire has rapidly evolved in Europe in the recent years, causing new challenges for responders:

- Extreme fires and extreme fire behaviours;
- Fires in the wildland-urban interfaces;
- Fires in higher altitudes and higher latitudes which were not so impacted before.

Observing and anticipating such developments, scientists are constantly producing knowledge about the risk. However, the transfer of this knowledge to responders and the transformation into guidelines is insufficient because of the gap between the research and the operational communities. Additionally, the firefighting community is very fragmented in Europe – with local / departmental / regional / national authorities – which makes the levels of training very disparate. As a result, responders are insufficiently informed and prepared to face the new challenges associated with wildfires. This hamper both their efficiency and their safety.

This deliverable compiles the outputs of the research on fire behaviour done by FirEUrisk partners. This research is presented in a simplified form, so that it is accessible to practitioners. The first chapters detail the fundamental of fire behaviour and then the extreme fire behaviours. The following chapters describe fires in specific areas – WUI, high altitude and high latitude; and the mechanism of smoke emission and dispersion.
The final chapters analyse firefighting methodologies in different contexts and then provide safety recommendations and study cases.

To maximise the achievement after delivering this document, the FirEUrisk consortium will explore how to translate and transfer it into national handbooks and trainings.

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Table of abbreviations

Abbreviation	Definition
ABC	Airway, Breathing, Circulation
ATSDR	Agency for Toxic Substances and Disease Registry
BMI	Body Mass Index
BUFE	Blow-Up Fire Event
CDC	Centers for Disease Control and Prevention
CFWIS	Canadian Fire Weather Index System
DC	Drought Code
DMC	Duff Moisture Code
EFB	Extreme Fire Behaviour
EFB	Eruptive Fire Behaviour
EFFIS	European Forest Fire Information System
EMC	Equilibrium Moisture Content
EPA	Environmental Protection Agency
EWE	Extreme Wildfire Event
FDI	Fire Danger Index
FFDI	Forest Fire Danger Index
FFMC	Fine Fuel Moisture Code
FWI	Fire Weather Index
GFDI	Grassland and Forest Fire Danger Index
HR	Heart Rate
IAP	Incident Action Plan
ISI	Initial Spread Index
LCES	Lookouts, Communications, Escape routes, and Safety zones
MSDS	Material Safety Data Sheet
NFDRS	National Fire Danger Rating System
NFFL	Northern Forest Fire Laboratory
NIH	National Institute of Standards and Technology
NIOSH	National Institute for Occupational Safety and Health
NPR	National Public Radio
NWCG	National Wildfire Coordination Group
OSHA	Occupational Safety and Health Administration
PM	Particulate Matter
ROS	Rate of Spread
SAV	Surface Area to Volume
SDS	Safety Data Sheet
SSD	Safe Separation Distance
TOS	Time of Spread
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	United States Department of Agriculture
US	United States
UFI	Urban forest interface
UTC	Coordinated Universal Time
WUI	Wildland Urban Interface

1. Introduction

1.1. Future trends of fire risk in Europe

In recent years, the frequency and severity of wildfires have increased, leading to devastating consequences for communities and ecosystems.

This trend will continue and worsen in the following years with a trajectory that would be clarified in the frame of the activities realised by the work package 3 of FirEUrisk project (FIREURISK, 2024).

Recent research has already demonstrated that:

- The risk will expand over the European territory and affect wider areas (Jones et al., 2022)
- the most exposed area, i.e. the Mediterranean region, will face more and more extreme fires (Turco et al., 2018).

Simultaneously, increasingly vulnerable Wildland-Urban Interface (WUI) are exposed to the risk (Almeida et al., 2023; Zikeloglou et al., 2023).

At the European level, all these trends converge towards exposing firefighters to new challenges. They may not have the proper knowledge, adequate strategies and tactics to face fires in new fire-prone areas, extreme fire behaviours and fires in the WUI. More importantly, those lack of knowledge and inappropriate strategies and tactics could jeopardize their safety and expose their lives.

1.2. Need for firefighting guidelines

From an operational perspective, the agencies in charge of response to face wildfires constitute a fragmented ecosystem in Europe and beyond (Lahaye et al., 2018a). Depending on the states, national, regional or subregional forest and fire services manage their resources according to their own procedures. These procedures may be aligned with national standards, but they are also generally based on local context and experience of fires. That experience is very variable from one region to another. Economic and human resources are also variable, so the level of knowledge and formalism differs from one service to another.

From a research perspective, several teams are already working in Europe and beyond to develop the best knowledge and understanding of fire behaviour and the whole cycle of fire risk management. The strength of FirEUrisk project is to gather many of these research teams and to provide a bridge with operational responders.

The purpose of this Document is to collect a set of concepts and guidelines that should be part of the curriculum of training of firefighters and other agents that must deal with the problem of forest fires (also referred as wildfires) to manage the risk of wildfire in all its components. Given the urgency and relevance of providing training to firefighters in this spectrum of forest fires occurrence, particular emphasis will be given to the fire suppression in the case of extreme wildfires. Improved training and better situation awareness are key aspects regarding fire safety, significantly contributing to decreased fire-related deaths and human losses from wildfires.

Fighting extreme fires induces exceptional dangers to firefighters. These situations are often characterized by high heat, intense flames, massive spotting and rapidly changing, unexpected fire behavior, creating hazardous conditions for firefighting personnel. Fires in the WUI also generate challenging situations. The firefighters have to deploy to protect lives, regardless of the level of risk and the behaviour of fire which is often erratic. That behaviour is indeed driven by the arrangement of vegetation and human settlements, including gas tankers, cars and other very flammable or explosive materials.

The concept of fire impacting Wildland-Urban Interface (WUI) has been widely investigated by FirEUrisk project: dissecting past occurrences, assessing the exposure of population and assets, quoting the vulnerability of communities, houses, and infrastructure. Therefore, the deliverable also extracts the outputs of this research to guide operational procedures in the WUI.

Finally, the authors have contacted their network of responders to investigate which specific technics of response could fit the best in different situations, including in the context of the extension of the risk toward higher latitudes in Europe and higher altitudes.

The contents of this document are based on the curriculum used by some of its authors in training firefighters and other operational agents on these topics of fighting fires under extreme fire behaviour conditions to achieve improved safety.

The main contributions of the present deliverable would be extracted to build a "European handbook for Firefighters". This handbook could be essential to raise awareness, using a simplified approach but exploring key aspects of wildfires. All civil protection agents would benefit from these quick concepts and topics. That is true especially from a safety perspective as most research that produced the innovative perspectives presented here on extreme fire behaviour were inspired and motivated in the analysis of actual accidents and some large fires that caused significant loss of lives.

1.3. Contributions

This deliverable capitalises contributions from several teams of the project.

The work firstly builds upon the extensive experience of ADAI Team in the investigation of fire related accidents involving both civilians and operational agents (cf. Viegas et al., 2001; Viegas et al., 2005; Viegas et al., 2008; Viegas, 2004, 2009, 2013, 2017; Ribeiro et al., 2020) and on the study of large fires that was developed by request from national authorities (cf. Viegas et al., 2012; Viegas et al., 2013; Viegas et al., 2017; Viegas et al., 2019)). The derived research on extreme fire behaviour includes some innovative concepts on fire behaviour that are presented and referred below but are summarised here for consistency: (i) Concept of dynamic fire behaviour (cf. Viegas, 2004; Viegas & Pita, 2004); (ii) Concept of eruptive fire (cf. Viegas, 2006; Viegas & Simeoni, 2011); (iii) Concept of junction fire (cf. Raposo et al., 2018); (iv) oscilatory fire behaviour (cf. Viegas et al., 2021).

No details on the different matters are given here, especially if they correspond to standard material that can be found in well-known documents.

The first author of the deliverable has also reproduced here materials extracted from his studies on firefighters' safety (Lahaye et al., 2018b; Lahaye et al. 2018b; lahaye et al. 2018c) and from current trainings to build fire behaviour analyst capabilities in France.

The chapter on firefighting methodologies is founded on the results of interviews and inquiries to European responders realised by SAFE Cluster junior researchers.

Finally, senior researchers from, RISE Institute (Sweden), the University of Aveiro (Portugal) and the University of New South Wales (Australia) have provided specific contributions within the document.

2. Fundamentals of Fire Behaviour

2.1. Factors affecting fire spread

The propagation of a fire depends on various factors that can be grouped, to simplify, according to Viegas (2004), in the following four set of factors: 1) Topography, 2) Vegetation, 3) Meteorology and 4) Time.

Although the above factors are not independent of each other, it is possible to analyse each one of them separately to understand their role in fire spread better. The role of topography, fuels and meteorology will have dedicated treatment below. The factor “time” corresponds to the chronological time and enhances the dynamic character of fire spread processes in the general case, but also considering extreme fires.

In chapters 3 to 6, these factors will be analysed to provide a common background of concepts and ideas to better understand Extreme Fire Behaviour (EFB).

In the above approach, fire suppression is not considered but as we shall see, the more the conditions are favourable for the response, the higher the chances that firefighting limits the fire spread.

2.2. Fire meteorology

2.2.1. Meteorological factors

The meteorology is the state of the atmosphere surrounding the Earth which is described by a series of parameters or properties that are constantly changing in both time and space. These properties, when described in ways related to their influences on wildland fire, constitute fire meteorology. Meteorological factors that directly or indirectly affect the fire behaviour can be divided into two groups: i) Conditioning factors and ii) determining factors.

i) **Conditioning factors** - favourable to ignition by conditioning the load and moisture content of fine fuels. This group includes the following factors: precipitation, air temperature and relative humidity.

Precipitation, expressed in millimetres (litres of rainfall that fall on the ground per square meter), affects the water content of the soil and also the moisture content of forest fuels (live and dead). The persistence of precipitation at the beginning of the hydrological year (October in the Northern Hemisphere) favours the growth of fine vegetation, which may be available to support the fire spread in the summer. However, the absence of precipitation during the months leading up to summer, with values much lower than the climate normal (average precipitation values that characterize a region over a period of 30 years), can lead to a situation of drought or water deficit that favours the general dryness of forest fuels, which are available to support the fire spread and contribute to larger burned areas by summer fires (Viegas & Viegas, 1994).

The air temperature changes in a diurnal cycle due to the effect of solar radiation, but it can also change due to the entry of warmer or colder air masses. Typically, the temperature increases during the day and decreases at the end of the day. This diurnal cycle is of great importance in wildfires as it directly affects the flammability of forest fuels since the amount of heat required to raise the temperature of the fuels to the ignition point depends on their initial temperature and that of the surrounding air and on the fuel moisture content that is greatly dependent on the air temperature (Schroeder & Buck, 1970).

Relative humidity of the air (*RH*) is the percentage of the mass of water vapor in the air in relation to the mass of vapor necessary to saturate the environment. A *RH* value equal to 100% corresponds to a saturated atmosphere, in which there is condensation, while a value of 30% or less corresponds to very dry air, which also favours the drying of fuels. *RH* also has a diurnal cycle but tends to decrease throughout the day and increase at the end of the day – basically, it changes inversely to the temperature cycle.

ii) **Determining factors** - those that affect directly the fire spread. This group includes wind and atmospheric stability.

Wind is generally defined as the horizontal movement of atmospheric air (atmospheric wind) characterized by the following components: windspeed (or intensity) in m/s, and direction (from where the wind comes) referred to the North in *degrees*. Windspeed and direction change from one point to another, and at a given point it changes continuously over time (slow variation). There is another variation due to the turbulence of the wind flow, which is manifested by sudden variations in windspeed in a short period of time (gusts). These variations have a direct influence on fire propagation conditions.

The windspeed profile increases with altitude (it is zero near the ground and increases until it reaches a maximum value at the top of this layer). However, in a wildfire, this profile can be changed due to the wind induced by the fire, which can lead to the fast fire development even if the atmospheric wind is low. Therefore, in a wildfire the wind can be defined as the sum of the *atmospheric wind* and the *wind induced by the fire*.

Atmospheric stability is characterized by the air temperature variation in the vertical direction, measured by its gradient of temperature or rate of variation, *dT/dz*, [ºC/m], which determines whether the atmosphere is stable, neutral or unstable. Atmospheric stability may either encourage or suppress vertical air movement. The heat of fire generates vertical movement, at least near the surface, but the convective circulation thus established is affected directly by the stability of the air (Schroeder & Buck, 1970). In turn, the indraft into the fire at low levels is affected, and this has a marked effect on fire intensity. Also, in many indirect ways, atmospheric stability will affect fire behaviour, for examplewinds tend to be turbulent and gusty when the atmosphere is unstable, and this type of airflow causes fires to behave erratically (Schroeder & Buck, 1970). Thunderstorms with strong updrafts and downdrafts develop when the atmosphere is unstable and contains sufficient moisture (Schroeder & Buck, 1970). Their lightning may set wildfires, and their distinctive winds can have adverse effects on fire behaviour (Schroeder & Buck, 1970); more information in chapter 3.

2.2.2. Fire danger

Fire danger indicates the physical probability that a fire starts and propagates (UNISDR, 2009). The fire danger is expressed as fire danger indices that are estimated in fire weather systems, or fire danger systems. Those systems are based on meteorological factors and their effect on the moisture content of forest fuels.

A variety of fire danger systems are used in many parts of the world to integrate meteorological and fuel information into a single or small number of measures (Dowdy et al., 2009). These measures can then be applied to regions to issue warnings, or more locally to estimate the suppression difficulty of a single fire or fire complex (Dowdy et al., 2009).

The primary fire danger systems, usually used in fire prevention and assessment plans around the world, are:

- the Australian **McArthur Forest Fire Danger Index (FFDI)** (McArthur, 1967); in Australia FFDI is widely used to forecast the influence of weather on fire behaviour, and the Australian Bureau of Meteorology routinely issues forecasts of Grassland and Forest Fire Danger Index (GFDI and FFDI) for use by fire authorities (Dowdy et al., 2009);
- the United States **National Fire Danger Rating System** (NFDRS) (Deeming et al., 1978; Bradshaw et al., 1984); first introduced in 1964, it has been updated in 1972, 1978, 1988, and in 2016 to integrate newer science and improved processing (NWCG, 2021a); it combines the effects of existing and expected states of selected fire danger factors into one or more qualitative or numeric indices that reflect an area's fire protection needs (USDA/Forest Service, 2023).
- the **Canadian Fire Weather Index System** (CFWIS) (Van Wagner, 1987); it is the result of years of applied research carried out in Canada, developed in 1970 with revised versions issued in 1976, 1984 and 1987 (Dowdy et al., 2009). CFWIS is a comprehensive system of tools designed to evaluate environmental factors that influence the ignition, spread, and behaviour of wildland fire (NWCG, 2021a), and it is adaptable enough to have been implemented in countries with very different climates to Canada (Dowdy et al., 2009).

We will succinctly present the CFWIS since it constitutes a common language for the European operational community to approach the fire danger.

The CFWIS based on 1987 version (Van Wagner, 1987) estimates the moisture content of dead fuels using a combination of daily meteorological data at 12h in local hour (temperature, relative humidity, precipitation and wind). The system computes three fuel moisture codes each with different drying rates, nominal fuel depth and nominal fuel loads: i) FFMC - Fine Fuel Moisture Code (represents the moisture content of fine fuels and litter on the forest floor), ii) DMC - Duff Moisture Code (represents the moisture content of loosely compacted decomposing organic matter) and, iii) DC - Drought Code (represents the moisture content of deep compact organic matter of moderate depth). These codes are each calculated with a daily time-step and include their previous day's value as an input to the current day's value (Dowdy et al., 2009).

The combination of these codes will produce the fire behaviour indices: iv) ISI - Initial Spread Index (estimates the combined influence of wind speed and the FFMC on fire spread), v) BUI - Build-Up Index (it is a combination of DMC and DC, representing the availability of the deeper or larger-sized fuel) and, vi) **FWI - Fire Weather Index** which is the main output of the system; FWI is a combination of ISI and BUI, representing the peak daily intensity of the spreading fire as the energy output rate per unit length of fire front (Van Wagner, 1987). The increase of FWI corresponds to an increase of fire danger, and it is usually classified according with five classes: Low, Moderate, High, Very High, and Extreme.

In many European countries FWI has been adopted since it shown a good performance as representative of fire danger conditions when compared with other fire danger systems (Viegas et al., 1999). However, adoption of the FWI by foreign countries occasionally calls for modifications to existing practices (e.g. Alexander, 2008,) and therefore need to be calibrated with local data, usually accomplished through an analysis of historical fire weather data and historical fire records (e.g. De Groot et al., 2005; Viegas et al., 2004; Alves et al., 2018).

Table 1 presents the FWI classes defined by the EFFIS (European Forest Fire Information System) network as the method to assess the fire danger level in a harmonized way throughout Europe (EFFIS/JRC, 2023). However, given the different climatic conditions in Europe, EFFIS publishes two indicators that provide information on the local/temporal variability of the FWI compared to a historical series of approximately 30 years (EFFIS/JRC, 2023).

Table 1. Fire Danger Classes for FWI in Europe defined by EFFIS. Source: EFFIS/JRC (2023).

Fire Danger Classes	FWI
Low	<11.2
Moderate	11.2 - 21.3
High	21.3 – 38.0
Very High	38.0 – 50.0
Extreme	>50.0

A "Very Extreme" Fire Danger Class was introduced in June 2021 to provide discrimination about the level of fire danger in extensive areas that were initially classified at "Extreme" Fire Danger in the Mediterranean region during the summer months. The "Very Extreme" class include areas with FWI values above 70 (EFFIS/JRC, 2023).

2.2.3. Fire danger and moisture content of dead fuels

Weather changes strongly affects the moisture content of dead fuels (the materials lying on the forest floor) since they change their water content in parallel to atmospheric conditions (Chuvieco et al., 2010). Consequently, the dead fuels are drier and more prone to ignite. The fuel moisture content of dead fuels is a critical element of fire behaviour and one of the most used and oldest indicators in predicting fire danger (Carmo et al., 2022). The fuel moisture content of live species is not commonly included in fire danger system, as it is more difficult to estimate from meteorological data than is dead fuels moisture (Chuvieco et al., 2014).The rising relevance of shorter-term water balance in the development of severe fire can be observed on the Fine Fuel Moisture (FFMC, the fastest drying component of the FWI System) (Carmo et al., 2022). This moisture code is an indicator of the relative ease of ignition and the incidence for spot fires since it is directly related with the moisture content of fine dead fuels (m_f) according with Equation 1 defined by Van Wagner (1987).

$$FFMC = 59.5 \times \frac{250.0 - m_f}{147.2 + m_f} \qquad \text{Equation 1}$$

The moisture content of dead fine fuels (e.g. leaves of *Pinus pinaster*) changes inversely to the FFMC. These FFMC changes are incorporated into ISI and, consequently, on FWI that is the final output parameter of the system related with the fire danger potential. When moisture content of dead fuels is low (and the FFMC is high) the fires start easily, and wind and other driving forces may cause rapid and intense fire spread (corresponding to a high FWI). The moisture content of dead fuels usually change between 3% and 30% (Ribeiro, 2011). Recent work has found that low fine fuel moisture content may determine when large fires can occur, advocating close relationships between moisture thresholds and fire behaviour transitions (Carmo et al., 2022). When its value is lower than 5%, there is a strong possibility that a wildfire will present extreme characteristics of fire behaviour (Viegas et al., 2017). The m_f variation during large wildfires is fundamental to understanding the extreme events (Viegas et al., 2017). Even in the night period, where the effectiveness of firefighting is traditionally favoured by the increasing of relative humidity and decreasing of air temperature, it helps to know whether the moisture content is rising or falling. The growing trend of drier and hotter nights (driven by heatwaves for example), and consequently the lack of recovery of m_f, can lead to more intense wildfires at night, whose behaviour may be underestimated during this period.

The moisture content of dead fuels can be measured in the field (e.g. MCFIRE/ADAI, 2022; NWCG, 2021b), can estimated by fuel moisture indicator sticks (e.g. van der Kamp et al., 2017) and can be estimated indirectly by several models (Viney, 1991). Fine dead fuels may be in approximate equilibrium with their immediate environments (e.g. Lopes et al., 2014). The equilibrium moisture content (EMC) of a fuel element under given environmental constant conditions is the moisture content that the element will attain if left for sufficient time in those conditions (Viney, 1991). Except after rain, a reasonably accurate estimate of their moisture content and, therefore, their flammability may be obtained from the EMC corresponding to the immediate surrounding air temperature and humidity (Schroeder & Buck, 1970).

We present in Figure 1 the variation of fine dead fuels in a Lousã – a Central region in Portugal – for July 2022. This period was marked by an extensive heatwave that hit the country (2/Jul - 18/Jul), and the western European countries and an extreme wildfire season. As an example of *mf* variation for the different methods, the figure presents: m_f of *Pinus pinaster* leaves measured in the field through the gravimetric method, m_f measured in a fuel stick moisture sensor (CS506 10-hour) and, m_f estimated for *Pinus pinaster* leaves according with the modelling followed by Lopes et al. (2014) through meteorological data (temperature and relative humidity of the air).

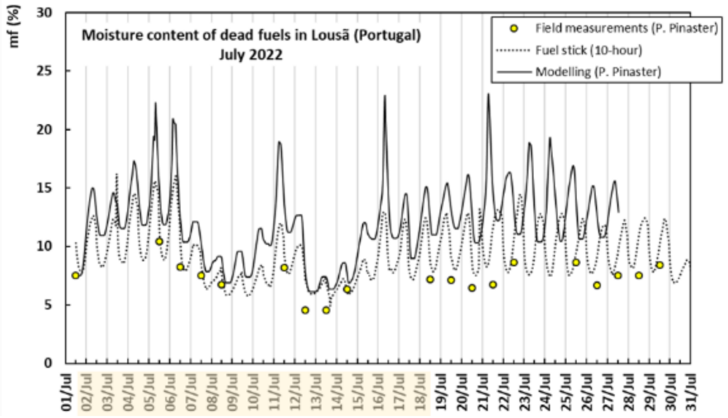

Figure 1. Moisture content of dead fuels (m_f) in Lousã during July 2022. Legend: Field measurements: m_f of Pinus pinaster needles in the field; Fuel stick: m_f measured by a fuel moisture sensor (CS506 10-hour); Modelling: m_f estimated for of Pinus pinaster needles according with Lopes, 2014. Highlighted period (2/Jul-18/Jul): heatwave. (Authors illustration)

2.3. Fuel properties

When addressing wildfires, natural vegetation is usually considered as the "fuel" necessary for the combustion processes. The physical and chemical properties of any specific fuel determine its ease of ignition and sustaining combustion. This section describes the main properties that characterize the fuel particles and the fuel complexes.

The specificities of the fuels that can be found in the Wildland Urban Interface will be described in the correspondent section (4.1).

In a more generic approach, fuels are usually classified according to 2 parameters:

i. <u>Vegetative state</u>, dividing them into live fuels (herbs, shrubs, trees) and dead fuels (dry or fallen leaves, herbs, fallen branches, etc.). Dead fuels are considered to have a greater influence on the spread of surface fires.
ii. <u>Stratum</u>, considering their vertical distribution. i.e., ground fuels, surface fuels and aerial fuels. The type of fire propagation is related to the stratum, or layer, in which the fuels are:

ground, surface and crown fires. The fuel particles in the three layers can be similar or equivalent in properties.

When there is the need to quantify fuels for fire behaviour modelling and assessment, a more detailed description is needed. This description is done primarily at two levels: the particles and the fuelbed.

2.3.1. Fuel particles

The individual fuel particles, that form any kind of fuel type, have several distinct characteristics that contribute differently to the processes of ignition and combustion. At a particle level, the most important properties of the forest fuels are:

i. Particle size class

This is one of the fuel properties that most affects combustion and fire behaviour (Byram, 1959), as smaller particles require a smaller amount of energy or time to ignite. The relation between the particles size and fuel moisture content is very marked. Following the original unpublished classification from George Byram in 1963 (Byram & Nelson, 2015), later adopted for the US National Fire-Danger Rating System (Bradshaw et al., 1984), fuels are divided according to their “timelag interval”. This is defined as “the time required for fuels to lose approximately two-thirds of their initial moisture content”. In simple terms, if the moisture of a fuel particle is in equilibrium with the environment (EMC, already referred in section 0), i.e., no gains or losses, the timelag of that particle corresponds to the average time it would take it to reach again that equilibrium in case there was a change in the environment conditions.

The classes considered are named after the average time interval needed: 1 hour, 10 hours, 100 hours and 1000 hours. The reasoning behind the concept is that, under constant ambient conditions, the fuel drying rate depends on particle thickness (Byram & Nelson, 2015): thinner particles lose moisture faster than thicker particles. These classes represent the following fuel dimensions, respectively: 1Hr) thin or light, with a diameter less than 6 mm (needles, leaves, herbs); 10Hr) regular, with a diameter between 6 and 25 mm (thin branches and shrub stems); 100Hr) medium, with diameter between 25 and 75 mm (branches); 1000Hr) thick or heavy, with a diameter greater than 75 mm (thick branches and trunks).

ii. Shape

This property is expressed as the surface area-to-volume (SAV) ratio, i.e., the ratio between the exterior surface of a particle and its volume, usually in cm^2/cm^3 (cm^{-1}) or in m^2/m^3 (m^{-1}). It translates the suitability of a particle for combustion, as the amount of energy it can receive per unit time increases with the exposed surface (Rothermel, 1972).

Fuel particles with large SAV will ignite more readily than those with relatively small SAV. For instance, large logs have low SAV values, and pine needles or grasses have high SAV values.

iii. Chemical composition

The combustion process can be influenced by the chemical composition of fuels, to a greater or lesser extent, speeding up or slowing down combustion. Bradshaw et al. (1984) consider three important chemical properties: a) heat content, or the energy available per unit mass of fuel through combustion; b) total mineral content, the fraction of a fuel mass composed of inorganic minerals (only organic minerals can sustain combustion); and c) effective mineral content, or the active mineral content in a fuel particle that interferes with the chemical processes of combustion, namely the release of volatile gases.

iv. Density

Density affects ignition and the rate of spread (Countryman, 1982). Together with moisture content it strongly impacts on the thermal conductivity of a fuel (Chandler et al., 1983). Fuels with a lower density ignite in less time for the same amount of heat or require less heat for the same amount of time.

v. Moisture content

Represents the amount of water per dry mass of the fuel and directly influences the possibility of a fuel igniting and combusting. In terms of fire behaviour assessment, live and dead fuel moisture must be distinguished.

Dead fuel moisture essentially depends on the environmental conditions (Bradshaw et al., 1984), and different size classes may have different moisture content in the same instant. As is expected, the fire rate of spread (Viegas et al., 2013) and the probability of ignition (Viegas et al., 2014) increase as fuel moisture decreases. Very low dead fine fuels moisture content (below 5-7%) indicates a high probability of having extreme fire behaviour (crown fires, spotting, very high rate of spread and fireline intensity). More information on this parameter can be found in section 0.

Live fuels have moisture contents that result from the interaction of physical and physiological processes (Pyne et al., 1996), hence their temporal variability is very different from dead fuels (Rego et al., 2021). Live fuel moisture content is generally greater than the dead fuel moisture content, for the same environmental conditions, often going above 100%.

2.3.2. Fuelbeds and fuel types

When describing wildland fuels in a certain area, the arrangement of all the fuel particles in the different vertical layers (ground, surface and aerial fuels), is called a fuelbed. Each layer, or *stratum*, may have different types of natural fuels. A fuelbed may have one, two or all three *strata*. For instance, a grassland usually has only one (grasses and/or herbs), shrublands may have two (grass, litter and shrubs) and a mature forest may have the three (duff layer, litter, grass, shrubs and trees).

The delimitation of each stratum in the vertical profile is somehow subjective but usually follows the schematic representation of Figure 2.

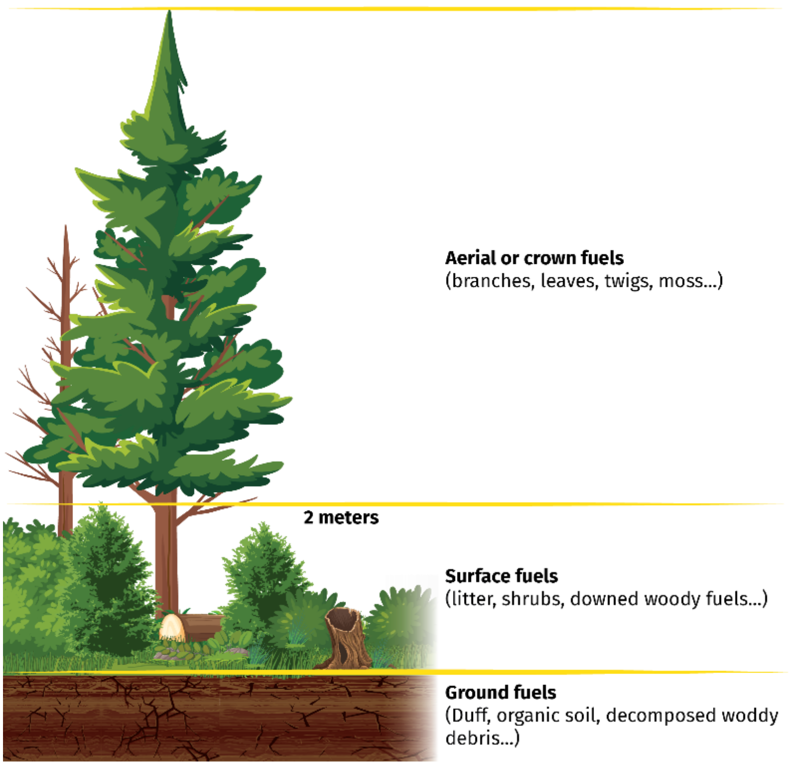

Figure 2. Schematic representation of the fuelbed strata (image credits: ADAI)

This characterization is directly related the needs of the fire behaviour models, and each one may support a specific fire propagation: ground fire, surface fire and crown fire. More details can be found in the fire propagation section.

In the 1930's, Hornby (1936) introduced the term "fuel type", based on qualitative criteria, that established four types based on their potential for fire spread and resistance to control. Nowadays, the term is applied to generically describe the predominant vegetation in the fuelbed or even in each layer. For example, a fuelbed may be a pine stand, if pine trees are predominant overall, but the surface layer may be considered shrubs or litter, if one prevails in that specific layer. When selecting the layer responsible for fire propagation, this is important for fire behavior modeling.

Regarding fire management, vegetation species are not very relevant, as the same species can present very different fire behaviour when its fuelbed and particles' characteristics are different (Anderson, 1982; Riaño et al., 2002).

The most important fuelbed characteristics to be considered in fire behaviour assessment are:

i. <u>Fuel load</u>

The fuel load expresses the mass of combustible vegetation material per unit area and is usually expressed in kg/m^2 or t/ha. Depending on the fire behaviour modelling needs, this parameter can be presented as a total value or divided by stratum (ground, surface, canopy), size class (fine, regular, medium and heavy) or vegetative state (live and dead).

For a specific fuelbed, the fuel load and moisture content determine the amount of fuel consumed and heat released during combustion.

The amount of fuel that is consumed directly influences fire effects in vegetation and soils (Rego et al., 2021), fire spread and intensity Alexander & Cruz, 2020) and the potential fire emissions and smoke impacts (Miranda, 2004; Fernandes et al., 2022).

ii. Fuel height

Also called depth, this is an estimate of the vertical dimension of the combustion zone and is required to estimate the fuelbed compactness (Cruz & Viegas, 1995). Although it may require some training in defining the top of the fuelbed, this parameter can be measured easily and quickly and is therefore commonly used in double sampling techniques to estimate fuel load.

iii. Compactness

The compactness of a fuelbed refers to the available fuel per unit volume and is incorporated in fire behaviour prediction as the bulk density (kg/m^3).

The degree of compactness reflects the availability of air for individual particle combustion and the ease of heat transfer to the particles immediately in front of the fire (Chandler et al., 1983). In the ground fuels, compactness significantly influences the variation in moisture content since highly compacted fuels limit evaporation.

Less compactness means more oxygen is available for combustion. However, if the fuel particles are too far apart, there is no longer enough proximity for the necessary heat exchange and the consequent ignition of adjacent particles. All size classes have an ideal compactness point that maximizes heat transfer and the presence of oxygen and, therefore, combustion.

iv. Continuity

Fuel continuity expresses “the degree or extent of continuous or uninterrupted distribution of fuel particles in a fuel bed thus affecting a fire’s ability to sustain combustion and spread” (Drury, 2020). Continuity exists when fuels are within each other's combustion zone, i.e., when the combustion of one has a preheating effect on the other.

This term is used for surface fuels (horizontal continuity) and ladder fuels (horizontal continuity). Ladder fuels are the designation of the more or less continuous fuelbed that can support fire propagation from the surface fuels to the canopy or crown fuels.

v. Moisture of extinction

This property represents the fuel moisture content of a fuelbed at which a fire will not propagate. It is an essential parameter for applying Rothermel’s model, who initially considered it constant among all fuel types (30%). It was soon found that it could vary with fuel bed compactness, fuel particle size, windspeed, and slope (Bradshaw et al., 1984) or even the location on the fire perimeter (Fernandes et al., 2008).

Moisture of extinction values used in fire behaviour fuel models (see below) can go from 12% up to 40%, depending on the beforementioned conditions. On live fuels the values may be higher.

2.3.3. Fuel models

The publication of Rothermel's fire spread model (1972) came along with the need to quantitatively describe wildland fuels with a relatively small number of parameters that would allow for the prediction of surface fire behaviour. It is assumed that the vegetation is homogeneous in a given area, just as the weather and topography will be, allowing the fire to maintain constant characteristics, which can then be predicted (Ribeiro et al., 2021).

Rothermel defined the fuel model as “complete set of [fuel] inputs for the mathematical fire spread model” and listed parameters for 11 fuel models (Scott & Burgan, 2005). Albini (1976) further refined those fuel models and added two others, creating what is now called the original 13 fire behaviour fuel models, or the 13 NFFL (Northern Forest Fire Laboratory) fuel models. This set, widely used worldwide, groups fuels into 4 classes (herbaceous, shrubs, timber and slash), according to the primary fire propagation vector, and was thoroughly described in Anderson (1982). More recently, Scott & Burgan (2005) expanded this dataset to 40 to characterize a greater number of situations and better visualize the effect of fuel management by using tools to simulate fire behaviour.

In Europe there has been some attempts to create adapted fuel models, like the Prometheus system (PROMETHEUS, 2000), the FUELMAP project (FUELMAP, 2011) that developed the classification of European fuels used by the European Forest Fire Information System (EFFIS, 2017) or the FirEUrisk project, that developed a fuel type classification with a crosswalk to Scott & Burgan fuel models (Aragoneses et al., 2023).

Rothermel (1972) model predicts surface fire spread, hence the fuel models typicaly describe the surface fuels layer. The characteristics that are quantitatively described in a fuel model have already been described above and are:

- Fuel load by vegetative state (live or dead) and size class (1 hr, 10 hr, 100 hr).
- Fuelbed height.
- Surface-to-volume ratio of fuel particles by vegetative state (live or dead).
- Heat content.
- Dead fuels moisture of extinction.

Fire behaviour simulation tools, like BehavePlus (Andrews, 2014) or FlamMap (Finney, 2006), have the 13 and 40 sets of fuel models already incorporated, allowing the users to easily simulate fire behaviour. Figure 3 illustrates the results for the BehavePlus 6 calculation of fire rate of spread for different slopes, with the wind blowing upslope at 20 km/h in 3 different fuel models of the NFFL set.

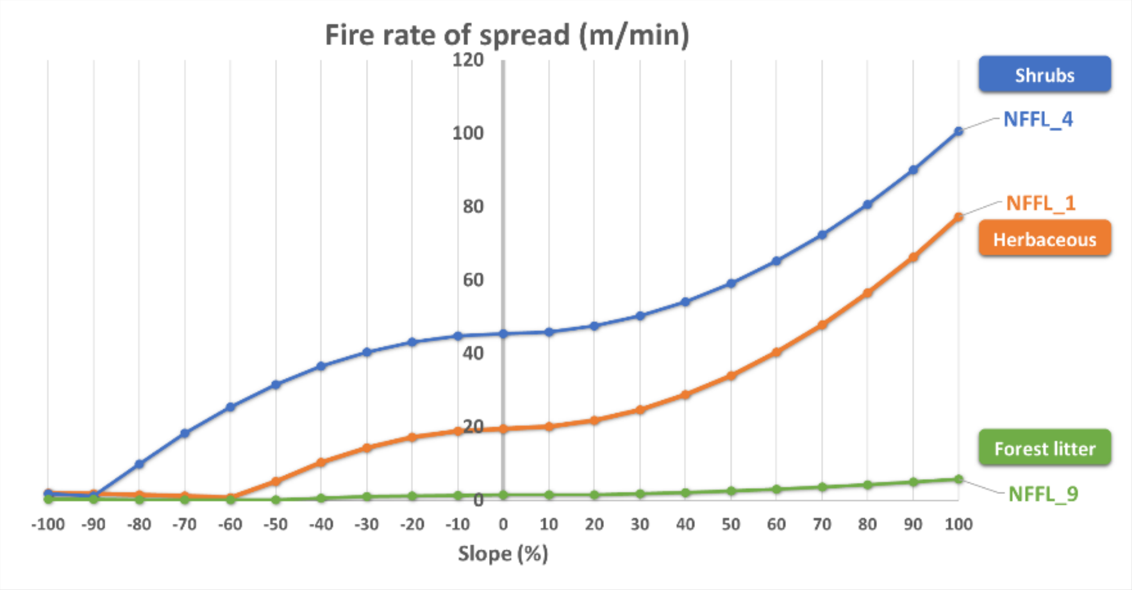

Figure 3. Example of fire behaviour simulations, using BehavePlus 6, for 3 different fuel models, in different slopes and with 20km/h upslope wind.

Custom fuel models are often needed for particular regions, for instance, the set of 14 fuel models developed for Central Portugal by Cruz (2005) or the set of 18 developed by Fernandes et al. (2009) for Continental Portugal. This development includes the quantification of the properties of the fuelbed and fuel particles identified earlier, but, more importantly, the calibration of the fuel models against observed fire behaviour (Rego et al., 2021)

In terms of practical application, other than the use of fire simulation tools, fuel models are usually accompanied by estimates of fire behaviour propagation for an easy evaluation in the field, many times with photo guides to allow for a visual correspondence of fuel models to observed fuel complexes (Anderson, 1982; Cruz, 2005; Patrick, 2009).

2.4. Role of topography

Topography is a key aspect on fire spread intensity and behaviour. Topography includes several aspects of the terrain, also described as the landscape. Here we introduce some general insights as well as dedicated sections on some aspects that significantly change fire behaviour. In certain conditions, fire spread might be dominated by the effect of topography, also involving specific convective patterns.

In brief, topography may influence several aspects important for fire behaviour, including:

- Wind patterns – channelled windy areas can be created by landscape features or specific locations, i.e., affected by the presence of canyons, mountain areas or the sea.
- Fuel accumulation and location – regions of the landscape having increased shade or moisture, i.e., canyons, may have increased fuel production and accumulation. On the other hand, drier areas as exposed slopes and ridges may lead to scarce fuel, but continuous and drier fuel that induces increased and faster fire spread.
- Natural and artificial fire breaks – Large bodies of water and large mountain ranges may act as landscape-embedded fire breaks due to lack of fuel. Man-made changes that impact slope or topography, which might be also considered, i.e., windmills for energy production in ridges or terraced slopes.

2.4.1. Terrain gradient

Terrain gradient in relation to the horizontal reference, or slope, is a major parameter characterizing topography. It can be measured as an angle or a percentage of inclination (indicating the number of metres that we climb when we travel horizontally for a given distance). The steeper slopes are well known as a key driver on fire spread and intensity. With slope the flames become closer to the fuel, which due to their smaller angle, favour significantly heat-transfer processes, leading to increased fire progression uphill. However, if the fire front is progressing downhill, these phenomena are not as effective and fire spread is decreased due to increased flame angle. Downslope spreading fires will propagate at a ROS close or smaller than that in horizontal ground. Knowing the role of topography and in particular of a certain landscape feature is crucial to understand fire spread behaviour, to model and better conduct fire suppression measures.

Slope angles above 20º (36%) to 25º (47%) can have an important effect on fire spread and on fire acceleration. This is particularly important for slope angles above 30º (58%) for which the displacement of the personnel on foot or even on vehicles becomes difficult and dangerous. Inclination angles above 40º (84%) are not common, as the soil does not remain stable at such angles, but it may occur in some regions like in volcanic hills.

2.4.2. Landscape direction: sunlight and wind exposure

South-facing landscapes in the northern hemisphere (and *vice versa*) are normally drier due to increased sunlight and wind exposure. These landscapes are known to have decreased fuel moisture content that leads to increased fire spread when compared to other landscape directions.

2.4.3. Elevation: temperature and wind patterns

In normal conditions, altitude may affect temperature and wind patterns. Also, vegetation typology and growth, and fuel moisture content may be changed accordingly. Overall, these aspects may change fire behaviour due to changes caused by elevation.

2.4.4. Terrain curvature

The terrain curvature may change fire spread, changing its speed due to flame angle and heat-transfer efficiency to the unburnt fuels. In brief, straight slopes have a more predictable fire behaviour, while concave or convex slopes are normally associated to increased fire spread, nearer to the top or the bottom following the location of the steeper slopes in the landscape, respectively. One relevant case is the canyon shaped terrain in which the concave shape of the terrain enhances the convective flow towards the combustion zone, causing a feedback effect that produces fire acceleration.

2.4.5. Ridges

The ridges are normally associated with complex wind patterns, namely direction changes due to flow separation and recirculation, and vortex formation. Wind may have additional features when flowing over or around ridges, creating complex fire behaviour patterns that can either accelerate or decelerate its spread. If the fire is wind-driven, it can quickly spread laterally along the ridge and widen its transverse dimension, therefore entering the downhill slope with a much wider front. These areas might be also associated with increased probability of fire whirls formation or horizontal extended fire spread, being both described below as specific features of fire behaviour. On the other hand, in particular conditions, ridges may act as natural barriers inducing the decrease of fire spread due to wind or slope-derived effects.

2.4.6. Complex topography

Complex topography is a term that integrates the presence of several landscape characteristics, which are normally associated with increased slopes and terrain particular features. The complex topography significantly affects fire behaviour and suppression activities since it is harder to predict fire behavior effectively and establish safe strategies. Complex slopes, terrain features and exposure will lead to multiple features of fuels and wind direction or airflow, resulting in alternative fire spread patterns that are difficult to anticipate and simulate. This increasingly difficult scenario is also generally associated with an increased probability of spotting behaviour.

Complex fire topography features are associated to complex interactions with wind flow and therefore with potentially difficult to predict fire behaviour. For example, in inclined ridges (cf. Abouali et al., 2021), fire can spread faster downhill than upslope in parts of the terrain.

The presence of canyons embedded in flat slopes must also be considered a factor of increased risk as fire behaviour is completely modified in the slope when it enters the nearby canyon if it is relatively shallow.

When fires are mainly affected by topography, fire spread and behaviour are increased by terrain-induced patterns, including higher intensity or direction caused by steeper slopes, sunlight exposure, or local wind patterns. Elevation may change local conditions, leading to a change in the spread of fires. Terrain curvatures and ridges may pose additional changes in fire progression associated with slopes, wind patterns, and specific fire behaviour modes, i.e., fire whirls and horizontal vorticity. Complex topography will add multiple features that are difficult to integrate, potentiating fire spread intensity and uncertainty.

2.5. Types and modes of fire propagation

2.5.1. Types of fires

According to the layers of the vegetation cover in which they spread, we can distinguish the following types of fires:

1. **Ground fires** - those that spread, usually with non-flaming combustion, under the surface of the soil, consuming the organic material that exists in the duff or in the peat layers.
2. **Surface fires** - those that spread, usually with a flaming fire front, consuming the fuels that are above the ground, like litter, grass, shrubs and small trees.
3. **Crown Fires** - those that spread consuming the foliage of the tree crowns, usually with the support of the surface fire below the canopies and propagating from one tree to another.
4. **Spot fires** – those that spread by burning particles or embers, released by some of the previous types of fire, that are carried out by the atmospheric or fire induced wind, when landing on burnable material may start new ignitions.

Most of the deliverable refers to **surface fires**, which are present in all major fires and are responsible for a major part of the burned areas. It is necessary to consider the specificities of ground fires when dealing with mop-up operation and in the specific case of **peat fires**. At this stage they are not considered in the work. **Crown fires** and **spot fires** are dealt as particular cases of Extreme Fire Behaviour in the corresponding sections.

2.5.2. Modes of surface fire propagation

According to their behaviour, we can consider the following modes of surface fire propagation:

1. **Marginal Behaviour** - It corresponds to the situations of an initiating fire or to a fire in the extinction phase, when the fire may or may not go.

It occurs when ignition or spreading conditions are not good, for example because the fuels have a large moisture content or are very sparsely distributed in space.

This mode is important to analyse the efficiency of extinction agents like water or retardants and the eventual rekindling process. The fire suppression requirements (minimum amount of water or a fire retardant to suppress a fire) fall in this type of fire behaviour.

Some fuel treatment techniques (modifying the fuel bed compactness or creating fire breaks) also fall into this type of fire behaviour.

The conditions required for a prescribed fire to ignite and run demand for specific research.

The conditions for rekindling of a nominally extinct fire correspond to Marginal FB.

Peat fires that burn with smouldering combustion – without flame – can be considered in this mode of Marginal FB.

2. **Static Behaviour_**– It corresponds to fire spread regime in which the properties of propagation are assumed to be constant over time. If the boundary conditions do not change during a period of time the fire spread properties, namely the rate of spread, remain constant.

In this case, the usual procedure of estimating average properties of fire spread in each period of time is acceptable, as they correspond to the actual values of that property over the entire period. In this approach, we assume that the fire behaviour depends on the three common factors described below (topography, vegetation, and meteorology) or more common mode of fire behaviour.

As we shall see this mode of fire behaviour is very particular and it occurs only in very restricted conditions. Despite that, this is the usual or more common mode of fire behaviour considered in most studies.

3. **Dynamic Behaviour** – In the general case, the interaction of the fire with its surrounding environment, modifies the fire spread properties over time, even if the boundary conditions (topography, vegetation, and meteorology) remain constant or uniform.

The description of fire properties explicitly involves the variable time, and the process of taking average values of the fire spread properties may not be valid.

This mode of fire behaviour is the most common, particularly relevant in large fires and the analysis of accidents. As described in the following chapters, extreme fire behaviour is important for these matters.

3. Extreme fire behaviour

3.1. Characterisation of extreme fire behaviour (EFB)

In Tedim et al (2018) the concept of "Extreme Wildfire Event (EWE)" was defined using various criteria as one in which several parameters characterizing fire spread, size or impact exceeded certain thresholds. It must be noticed that an EWE and "Extreme Fire Behaviour (EFB)" are not the same thing. An EWE will certainly have one or more episodes of EFB, but we may observe EFB even in relatively small fires that are not classified as EWE.

For safety in fire suppression we use the following definition of EFB (Viegas, 2012): *Extreme Fire Behaviour is the set of forest fire spread characteristics and properties that preclude the possibility of controlling it safely using available present-day technical resources and knowledge*.

3.1.1. Dynamic Fire behaviour

Traditionally it is considered that the fire behaviour at a given point is affected by the three following factors. (i) Topography, (ii) Vegetation and (iii) Meteorology, that compose the well-known "triangle of fire factors". Each one of the above factors and its respective role was described above. Extensive research and observation of fire spread showed that in many cases even when those three sets of actors remain constant, the behaviour of the fire changes, due to its interaction with the environment and the ROS does not remain constant. This prompted us (Viegas 2005) to propose the concept of "square of fire factors", adding the factor "chronological time" to the set of factors.

It is important to recognise the dynamic character of fire spread, in the sense that the convective processes created by the interaction between the fire and its surrounding (also designated as "fire-atmosphere coupling") induces changes on the behaviour of the fire, namely its ROS becomes explicitly depend on time. There are particular cases in which this variation of ROS with time may have grave consequences for fire safety.

Only in the cases of back and flank fires, in the absence of slope or wind, the ROS is practically constant and equal to the designated "basic rate of spread" Ro. In all other cases the TOS will vary with time, even if the other factors (fuel, slope or wind) remain constant.

As the behaviour of a fire varies with time, for the sake of fire safety, it is important to recall the following rule:

"**What the fire is doing now may be very different from what it will do in the next minutes**".

3.1.2. Fire intensity

It must be noted that in the definition of EFB given by Viegas (2012) no quantitative factors are given as the concept of "extreme" has a relative character as it depends on the conditions and the circumstances of a person that is facing a fire. The safety of the agent is judged in terms of the properties of the fire spread – namely its fireline intensity – and the resources and knowledge available to the agent. It is assumed that the better the training of the agent the better he is prepared to fight more intense fires.

It is implicitly recognized that with present-day technology direct attack of a fire front exceeding 10 MW/m is not feasible. However, depending on the resources available, the limits of response are even much lower (Table 2).

Table 2. Limits of firefighting depending on the fire intensity.

Firefighting resources	Maximum fire intensity (kW/m)
Hand tools	350
Water and fire trucks	1700

Light aerial means	3500
Heavy aerial means	10000

3.2. Adverse developments of EFB for responders

3.2.1. Spot fires

A spot fire consists of a new fire resulting from an original fire front that develops outside its perimeter. Among several classifications, the most common is the one that typifies spot fires based on their distance from the original fire front, namely:

Short-distance spotting at a few meters away; are normally quickly overtaken by the main fire front. They primarily contribute to increasing the rate of fire spread, often surprising those who expected the main fire front to arrive later.

Medium-distance spotting at a few tens of meters away triggers the advance of the original fire front to occur intermittently as it interacts with the new ignition. Besides contributing to increasing the fire spread, they are extremely dangerous as they can trap anyone caught between the two fire fronts/spots, especially during their interaction phase.

Long-distance spot fires occur at distances of a few hundred meters and are initially considered separate fires in the same fire scene. They may interact with the original fire front as the distance between them shortens and the fire intensity is sufficient to cause such interaction.

Very long-distance spotting can occur several kilometres away. Typically, these spot fires are considered new fire events that lead to the dispersion of firefighting resources in the same area. These spot fires may interact and merge with the original fire front in long-lasting and extensive wildfires.

The creation mechanism of a spot fire involves several phases, namely: 1) the release of firebrands; 2) the firebrand uplift in the convective smoke plume; 3) the downwind transport of the firebrand, after it leaves the updraft smoke plume; and 4) the firebrand landing on a flammable fuel bed recipient. While it is complicated to predict where a spot fire may occur, analysing the conditions under which the fire event is occurring, considering those four phases, can provide indications of when, how, and where spot fires may be created. For example, the fire front location may suggest the potential for firebrands production at a specific space and time – e.g., if the fire front reaches the edge of a mature water-stressed forest, the probability of firebrands production is very high; fire intensity is associated with the transport of firebrands in the convective column and together with strong local winds can indicate a long or very long spotting; and the type of fuel in the fire area can indicate where the likelihood of a spot fire is higher – e.g., dry grasslands or shrublands area more likely to ignite than an agricultural area.

Eucalyptus trees are commonly considered species with the greatest potential for spot fire formation. Indeed, the aerodynamic behaviour of their leaves and especially their bark, combined with their high flammability, make them highly capable of causing spot fires, especially over long distances. However, it is important to consider that some broadleaves species, even with lower flammability, have a great potential for causing spot fires, especially at medium distances. Almeida et al. (2021) highlighted the significant release of firebrands from burning cork oaks and oak tree canopies. These results are corroborated by some past wildfire incidents, such as the Cicouro accident (Portugal) in 2013, where two firefighters died after a firebrands showers from oak leaves that caused several spot fires in their surroundings (Viegas et al., 2013); or the Regadas Fire (Pedrógão Grande Fire, Portugal) in 2017, where the loss of fire control occurred when the canopy of a cork oak ignited, causing numerous spot fires nearby (Viegas, et al., 2017).

The difficulty in suppressing spot fires is exacerbated because they typically do not occur isolated. Since the source of firebrands releases several embers during the passage of the fire front, and due these embers face similar environmental conditions, it is common that spot fires appear in group, separated of several tens of meters from each other, promoting their interaction and potentially leading to the formation of a large new fire that, depending on the distance, may interact with the original fire front. As a result, the large number of spot fires and their intensity can hinder or even prevent fire suppression, associating this mechanism with extreme fire behaviour.

Spot fires are commonly associated with the wind transport of firebrands, so they are expected to occur leeward of the fire front. However, it should be noted that spot fires can also result from other mechanisms, such as a rolling pinecone down a slope or a burning animal that causes a new ignition when try escaping from the fire. Thus, the danger associated with spot fires arises not only from their effect on the original flame front, accelerating it, but also from the possibility of trapping people and/or animals and their capacity to occur unexpectedly, causing surprise. Spot fires can also render escape routes unviable, compromise anchor points, or even invalidate refuge locations at the fire scene.

3.2.2. Crown fires

In addition to being a type of fire, together with ground and surface fires, crown fires are also a manifestation of extreme fire behaviour. The high energy associated and the capability of crown fires to produce strong convective fire plumes and to generate firebrands with potential to spotting at different distances, makes this mechanism one of the most difficult to suppress.

Crown fires are subdivided into three types: 1) passive crown fire, in which a tree or a small group of trees ignite, causing a high intensity for a short period; 2) active crown fire, when the fire spreads sustainably between crowns supported by surface fire that propagates in the canopy under-story vegetation, releasing energy in a more lasting and intense way than in passive crown fire; 3) independent crown fire, which is characterized by a sustained fire spread between crowns (active fire) without being supported by surface fire under the crowns, i. e., the fire transits between canopies independently of the occurrence of surface fire in the understorey.

In contrast to a surface fire, in a crown fire the oxygen/comburent entrance also occurs from below, as the crowns are usually high – in a surface fire the airing only occurs from the sides because the fuels are limited below by the ground. In an active crown fire, the surface fire preheats the canopy, making it more susceptible to burn. Thus, the simultaneous availability of a lot of comburent and fuel leads to very intense combustions with high energy release. If a high availability of fuel does not match the high availability of comburent, the combustion reaction becomes unbalanced and consequently extinguishes. For this reason, independent crown fires are rare and occur mainly in conditions where crown moisture content is extremely low, with a favourable density for combustion. These episodes are so rare that they will not be further developed in this chapter.

The energy released is so high and frightening that accidents rarely happen in a crown fire that started some time ago, as human instinct encourages us to move away from such an impressive scene. However, the transition from a surface fire to a crown fire can be rapid, surprising those who approached it thinking they were fighting a fire of lesser intensity. It is, therefore, crucial to understand how the fire transitions from a surface fire to a crown fire, the so-called “vertical transition". According to Van Wagner (1977), the vertical transition depends on the intensity of the surface fire and the critical intensity[1], which is a function of the crown base height and the foliar moisture content. If the critical intensity is higher than the surface fire intensity the probability of crown fire, passive or active, is high. Suppose the critical intensity is lower than the surface fire intensity. In that case, the fire will most likely not pass to the canopy – the fire may also transit through fine fuels (e.g., lichens) that may exist on the tree trunk, which can lead to a canopy fire episode that is usually passive.

The horizontal transition of fire in the canopy, i.e., for fire to change from being passive to becoming active crown fire, requires a canopy density that ensures that the distance between fuels is favourable for fire spread. Furthermore, in this case, a threshold parameter is defined as the "critical after-crowning rate of spread"[2] which is inversely proportional to the canopy density (Van Wagner, 1977). If the rate of spread of the surface fire is higher than the critical rate of spread there may be a transition to an active crown fire, otherwise the fire may remain passive. According to (Rothermel, 1972) the canopy fire spread rate is 3.34 times higher than the rate of spread predicted for surface Fuel Model 10 (timber/litter and understory – Anderson, 1982) using a 0.4 wind reduction factor, regardless of the actual surface fuels or wind reduction factor.

In summary, for a crown fire to occur, the surface fuel load must be high, leading to a high surface fire intensity, and the distance between the crown base and the surface fire flames must be close enough for a vertical transition to occur. For this crown fire to be active, the proximity of the canopies must be such that the fire can pass from tree to tree. These definitions allow us to understand the importance of under storey management and tree pruning and thinning to reduce the likelihood of crown fire and to ensure safer firefighting within the forest. These will be the main factors that should be assessed before starting a firefight in the forest.

Wind intensity and slope are also factors to consider, especially for the increase in surface fire spread rate they provide. Naturally, the species in the forest also play an important role in the occurrence or non-occurrence of crown fires as their flammability[3] is highly determinant in the vertical and horizontal transition. In general, broadleaf species such as oak or chestnut trees lead to a lower probability of crown fire than pine or eucalyptus trees.

3.2.3. Eruptive fires

Eruptive fires are associated with a very high acceleration of the fire, which can be assimilated to an eruption. The destructive power of these eruptions is very high, and it can surprise the people. Most accidents in fires are associated to this type of FB. This type of behaviour is very much linked to canyons and to steep slopes but the physical processes that are involved happen even in more normal situations. In the literature they are also designated as "blow-up" or explosive fires, although there is nothing to relate them to an explosion, as the growth of the ROS is a continuous process.

This type of EFB was studied systematically for the first time by Viegas and Pita, 2002 who found that this behaviour was associated to the fire induced flow which is enhanced by the concave shape of the terrain of a canyon. In the laboratory experiments a canyon table composed by two inclinable plane surfaces was used to analyze systematically this type of fire

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[1] $I_c = (0.010 \times z \times 400 + 26 \times m)^{3/2}$, with I_c – Critical (minimum) fireline intensity, that will ignite foliage (kW/m); z – crown base height (m) and; m – foliar moisture content (%): 100% by simplification [Philpot and Mutch 1971].

[2] $R_c = 3.0/d$, with R_c – Critical after-crowning spread rate (m/min) and d – canopy bulk density (kg/m^3)

[3] According to Pausas et al. (2017) sociated with four components (Anderson, 1970; Martin et al., 1994): 1) ignitability, the facility to produce ignition; 2) sustainability, the ability of a material to maintain combustion and produce energy; 3) combustibility, velocity with which the combustion occurs; and 4) consumability, the proportion of biomass consumed during combustion.

behaviour. The shape of the canyon was determined by the slope angles of the two faces of combustion table and the overall angle of its base. Larger values of these angles induce higher values of the fire acceleration.

The increase of the ROS occurs by the dynamics of the fire, regardless of the ambient wind and even of the particular conditions of the fuel bed. The time required for the fire to reach very high values depends on the compactness of the fuel bed, being small for loose fuels like herbaceous and higher for heavier fuels like shrub and slash.

In the very common case of shrubland fuel the time required for full acceleration is of the order of twenty minutes and this time lapse is observed in many situations of real accidents and experimental fires.

3.2.4. Junction fires

In a wildfire, it sometimes happens that two or more fire fronts spreading in the same area interact with each other, possibly even creating an interaction and a larger fire with a rapid ROS. This is a situation that occurs quite frequently in firefighting and controlled fire operations. The interaction of two fire fronts is related to the convection currents they generate and can take on characteristics of extreme fire behaviour, which is important to know.

The simplest situation is the interaction of two identical and/or parallel fire fronts spreading on flat and horizontal terrain when there is no wind. In this case, the two fire fronts spread at the same speed. When they are far away, their propagation speed is equal to the basic ROS, but as they approach, the propagation speed gradually increases due to the intensification of the convection current generated by the two fire fronts. When they meet, the intensity of the propagation suddenly increases and reaches very high values.

The increase in intensity during the interaction of the fronts, even if it only lasts for a relatively short time, can lead to the development of a wildfire. For this reason, when planning the firefighting operation, care must be taken to ensure that the interaction of these two fire fronts takes place far enough away from the edges of the burnt area to avoid problems with possible spot fires.

In the case of wind or slope, the front running against the wind or down the slope will initially progress more slowly, but when it reaches the new fire front, the behaviour changes. In the final phase of the interaction, there is also an increase in the intensity of the spread. A similar process takes place in an interaction between a fire front and a wildfire when they form close to each other or near the main fire front. If the fires start a short distance from each other, they interact in their growth until they merge, and a new fire may start. If the fires start a short distance from the main fire front, they tend to be attracted to it. In strong winds or at greater distances, the. spot fires can spread independently and contribute to faster fire development.

A special situation of merging fronts occurs when two fire fronts form an angle between them and create a “V-shape”. The space between the two fronts is consumed after some time, but this process does not occur by the advance of one fire front towards the other, but by the advance of the apex of the “V-shape”, i.e. where the two fire fronts interact.

Viegas et al. (2012) investigated the interaction and merging of two oblique and symmetrical fire fronts that intersect at one point (forming a “V-shaped” fireline). Originally, Viegas et al. (2012) referred to this phenomenon as “Jump Fire" due to the sudden increase in ROS of the head fire, but after further analyses they changed this term to “Junction Fire”. In the last decade, several authors have analysed this phenomenon, and it has been called “Junction Fire" (Viegas et al., 2013; Sharples et al., 2013; Raposo et al., 2015; Hilton et al., 2016; Thomas et al., 2017; Sullivan and Gould, 2019; Filkov et al., 2020; Ribeiro et al., 2023). The results showed that the fronts and the ROS suddenly increased from zero to values in the order of a hundred times the basic ROS. Recently, Ribeiro et al. (2023) investigated the slope effect of Junction Fire with two non-symmetric fire fronts.

3.2.5. Conflagrations

Conflagrations are those fires that occur under strong meteorological wind conditions lasting for relatively long time – hours or days – in large areas, leading to widespread of fire propagation with high values of the ROS and other manifestations of EFB like crown fires, spot fires and other, even on relatively flat ground.

The fires that occurred in Portugal on the 15th of October of 2017 were an example of a conflagration. In this day there were more than 400 fire ignitions and from these we had nine major fires that burned a total of more than 200kHa and caused the death of 52 persons.

3.2.6. Fire Whirls

Another manifestation of Extreme Fire Behaviour are fire whirls or fire tornadoes. Fire whirls are structures with a vertical extent of several dozen to hundreds of metres, which are characterised by a very strong rotational movement and can carry flames column in their core.

Fire whirls are created by an upward flow generated by fire or heated areas of the ground and are generally associated with a rotational motion caused by asymmetries in the flow or in the surrounding land. The rotational motion takes place around a vertical axis and is like what occurs in cyclones, but on a smaller scale. In the core of the fire whirls, close to the axis of rotation, the air rotates and reaches the maximum wind speed at the edge of this core. The pressure is lowest in this area and therefore the suction effect of the fire whirl is greatest. This fact explains why a fire whirl produces flames or flame column of great height.

The fire whirl can remain relatively static, that is, its axis is practically fixed at any location, or it can move and carry the fire with it. The movement is difficult to predict and can have an unpredictable trajectory, i.e., its axis can change speed and direction, seemingly without any reason.

As you can understand, a fire whirl is very difficult to fight, which justifies its inclusion in cases of extreme fire behaviour. When fire whirls move from one burning area to another outside the fire perimeter, they can become extremely dangerous. Due to its unpredictable movement, the fire whirl can enter areas where it can promote a very dangerous spread of fire. In some cases, it can move in such a way that responders find themselves between the tornado and the main fire they would be fighting, creating a very dangerous situation.

Large wildfires can result in multiple fire whirls due to the strong convection currents that are created. The presence of atmospheric instability favours this formation. As already mentioned, fire whirls have very high wind speeds — which can reach 100 to 200 km/h — which gives them great destructive power. This effect manifests itself in the felling of trees or parts of buildings, which further increases the destructive power of the fire (Viegas et al, 2017).

Tornadoes are sometimes observed in burnt areas because the tornado sucks in dust and ash. The formation of these tornadoes results from the increased absorption rate of solar radiation by the ground (which is darkened in these burnt areas), creating the updrafts that lead to tornadoes.

3.2.7. Blow-up fire events

In certain situations, interactions of fire with the terrain and the atmosphere can cause a blow-up fire event (BUFE).

As described before, “normal” fire spreads by lines of fire, and by spotting. For these you need to know the terrain, the fuel, and the fire weather.

The dynamic fire behaviour behind a BUFE requires a prior uncontrolled fire and certain conditions of terrain and atmospheric profile, which all together allow feedback loops to form. Fuel loading has no explicit role.

The conditions required are:

1. An on-going fire in the right type of fuel. Flashy fuels, like most grasslands burn too quickly. Forests and shrublands are the main fuel involved.
2. Conditions that can cause deep flaming; there are 7 known causes:

- Strong winds (a headfire runs a long way during the burn-out time)
- A wind change, making a flank a new, larger headfire
- Eruptive growth
- Vorticity-driven lateral spread (VLS), the main cause of major fire damage
- Inappropriate use of a drip-torch
- Dense spotting
- Interior ignition, where unburnt islands later become flammable, and their heat adds to the main fire’s heat.

Some, such as VLS, require the fire to be in certain landforms at critical times (i.e. times of elevated winds and low fuel moisture).

Atmospheric conditions suitable to develop violent pyro-convection:

It is important to know what is happening above the fireground – observe clouds, fly weather balloons, use aviation sources.

The Convective Cap is critical. Inversions due to processes like subsidence can block convection. If the cap is under c.4°C a pyroCb might form, or if the cap is over c.8°C then a foehn wind driven fire might occur. BUFEs tend not to occur under intermediate values.

The daily weather cycle may no longer be dominant - 30% of BUFEs occur overnight. This often requires the mixing down of dry air aloft, and may be aided by rugged terrain.

There are predictive tools for BUFEs, based on studies of many events – see
http://www.highfirerisk.com.au/hpf/bufo_2.xlsx
or see:
http://www.highfirerisk.com.au/hpf/bufo.pptx

Potential consequences of BUFE:

A two- or three-hour long escalation of the fire on one or more sectors, that should be considered uncontrollable - if not unsurvivable. In that time, BUFEs typically burn 7,000ha, running for 16km with a width of 7km. They can be much larger. They cannot be suppressed. Often fire intensity will collapse afterwards, often allowing suppression to begin when conditions have become safe on the fireground (such as by removal of dangerous trees or powerlines). It is best to have no-one in proximity of a BUFE, if predictions can be made with enough lead-time.

For a small fire, the BUFE will involve all the fireground. Larger may have one or more sectors involved, while fire complexes may need involvement at the division level.

Safety concerns:

For the duration and extent of the BUFE(s), the Incident Action Plan (IAP) for affected sectors/divisions should have only one objective – save lives. *Will another BUFE develop somewhere on the fire?*

Safety issues include:

- No headfire, requiring new approaches to situational awareness.
- Dense spotting, allowing increased intensities in merger zones and rapid loss of situational awareness.
- Low oxygen combustion, leading to unusual fire phenomena.
- Eruptive growth, allowing extended fire acceleration up canyons and burnovers.
- It may be too dangerous to use drip-torches.
- Rapid loss of safe egress, leading to burnovers.
- Foehn winds eventually switch from laminar downslope flow to turbulent flow, changing fire behaviour.

Sectors without BUFEs should be continually re-assessed for safety.

Issues arise not from downbursts (as pyroCbs typically form downwind of the fire ground), but reflections off the convective cap, especially where terrain puts the fire close to the cap.

How to deal with BUFE?

Keep fire out of key landforms at critical times. Understand when fire might enter VLS or eruptive growth prone areas. Know when winds will pick up or fuel moisture fall below 5%. Planning Sections need particular skills to do this. *Can you burn-out such an area when conditions are more favourable?*

Lock up drip-torches at critical times. Certain ignition patterns can create BUFEs at such times. This needs to be in the Incident Action Plan.

Evacuate ahead of BUFE initiation if one is expected. When a BUFE initiates, fire crews can be at risk as much the public is.

Many members of the Incident Management Team have a role in keeping crews safe:

- Safety Officer: making sure everyone knows what to do.
- Fire Behaviour ANalyst or technical specialist: detailed predictions.
- Situation Officer / Planning Officer: Ensuring intelligence products are suitable.
- Operations Officer / Incident Controller: application of IAP.
- Field observers (ground & air – including senior Operations personnel): what to watch out for and how – covering BUFE lead-up; initiation; duration; decay.

Fire Service Trainers: need to provide training covering terminology & dynamic fire behaviour awareness. A safety message relating to unusual safety risks needs everyone in the loop to understand the terms used (e.g. VLS). The same applies to decision making.

4. Challenges caused by specific fires on response

4.1. Fires at the wildland-urban interface

The Wildland Urban Interface (WUI) consists of the area where vegetation and infrastructures are significantly present, with the temporary or permanent presence of people. Thus, in these areas, in addition to vegetation, various types of infrastructure are also present, typically occupied or used by people, which gives it distinct characteristics that require a specific approach. Due to the typical human activities in areas with human presence, the probability of ignitions in the WUI is higher than in wildland areas. Moreover, the value of exposed elements is also higher, highlighting the possible loss of human and animal lives, as well as the potential destruction of infrastructures with high economic, social, and/or cultural value.

There are several classifications of the WUI. One classification involves the coexistence between vegetation and infrastructures. The type “interface” includes a clear demarcation between the infrastructure area and the area occupied by vegetation. Typically, the "Interface " is associated with a built-up area surrounded by a forest – within this typology, there is a special situation of isolated buildings surrounded by vegetation. However, it may also happen that a forest patch appears surrounded by buildings, as in the case of city parks, and this is referred to as the "occluded WUI." There is also the possibility of a WUI scenario where vegetation and infrastructure are mixed in the same area, known as "intermix".

The type of present infrastructure defines another classification of WUI. A scenario where vegetation coexists with typically urban buildings (e.g., residential houses, commercial or service buildings, etc.) is referred to as "urban-forest interface (standard)." If the buildings are industrial, it is called "industrial-forest interface." There is also a particular type of WUI – the linear WUI – where the infrastructure elements extend along a line, such as railways, highways, or power distribution networks.

Given the unique characteristics, heterogeneity, and complexity of scenarios, the challenges associated with wildfires in the WUI are significantly different from those faced in wildland fire scenes. The main challenges associated with the three main components of the WUI are highlighted below.

4.1.1. Natural fuels - vegetation

The vegetation present in the WUI is typically divided into spontaneous and managed/ornamental vegetation. In the "Interface WUI," especially in areas farther from buildings, the vegetation is typically spontaneous and so similar to the vegetation found in wildlands. In the linear WUI, the vegetation is also spontaneous due to its extensive nature.

In occluded interface scenarios, the vegetation can be either spontaneous or ornamental (selected species), usually more carefully managed than in the "Interface WUI”.

In isolated buildings (specific case of “interface”” or in an intermix scenario, ornamental well-maintained vegetation is common. The maintenance of the vegetation usually involves watering, which is highly beneficial for fire risk reduction as it increases fuel moisture. The plant species in these scenarios also differ from spontaneous vegetation, with varying flammability. For example, while hydrangeas have highly favourable fire risk mitigation properties, other species like laurel trees have flammability values much higher than several spontaneous species (Almeida et al., 2022).

Vegetation hedges typical of gardens, and often close to buildings, can also trigger a significant fire danger if unproperly selected and maintained. Some species (e.g., *Cupressus* *arizonica*), especially when trimmed to keep a desired shape, accumulate a lot of dry fuel material inside, making them highly disposed to burning with great intensity. Other hedge species (e.g., *Prunus laurocerasus*) shed dead material, presenting a more favourable behaviour for fire risk management. Ribeiro & Almeida (2020) presented a study detailing the flammability characteristics of various species commonly used in vegetation hedges.

4.1.2. Man-made fuels

Man-made fuels comprise all fuels that are not vegetation, including infrastructure (or its most flammable components), equipment (e.g., vehicles, electrical cables, outdoor industrial machinery), and other fuels (e.g., firewood, gas cylinders).

These fuels are so diverse that they significantly complicate understanding, characterizing, and modelling fire behaviour in the WUI, as their flammability characteristics are highly heterogeneous. Moreover, these elements can represent a source of danger, leading to deflagrations or explosions (e.g., gas cylinders), collapses and crushing (e.g., structural fall), or electrocutions (e.g., electrical cables), among other hazards.

4.1.3. People

The presence of civilians at the fire scene adds several difficulties, not only due to the increased responsibility for protecting these individuals but also because people are often under stress, exhibiting behaviour driven by panic. Additionally, among population, there may be individuals with special needs, such as children, elderly, or people with health (e.g., cardiorespiratory problems), physical, or psychological limitations, among others. Therefore, the decision to evacuate or shelter in place, which will be addressed in Section 6.2, requires a balanced consideration that takes various factors into account.

Despite of fire risk in the WUI being often associated with the arrival of flames, the mechanism of spotting (which will be described in Section 0) is what brings the most difficulties. In studies conducted by Ribeiro et al.(2020) on 963 buildings affected by the Pedrógão Grande wildfires in Portugal in 2017, 61% were ignited by spotting, while 21% started burning due to direct flame contact. It is worth noting that roofs (62% of cases) and windows (16%) were the structural components that showed the highest vulnerability to wildfire.

In the report on the wildfires of October 15th, 2017, in Portugal, Viegas et al. (2019) described that out of 140 industrial facilities damaged by the set of fires of that day, 53% ignited due to spotting, as opposed to 27% that were ignited by the direct impact of flames. In this case, openings (29%), walls (19%), and roofs (17%) were the structural components that first compromised the integrity of the structure.

In conclusion, the WUI presents a dynamic and intricate setting that introduces distinct challenges in wildfire management. The coexistence of natural fuels and man-made fuels, including various infrastructures and equipment, creates a complex fire behaviour that is difficult to predict and model. The presence of people further complicates as the instinct reactions of panic, safeguarding goods at all costs or even an irrational willingness to help complicates fire response operations. Spotting emerges as a critical mechanism in the WUI fires, significantly contributing to fire spread and presenting a major threat to structures. Studies reveal that spotting is a significant cause of building ignitions during wildfires, underscoring the propensity of roofs and windows to fire ignitions. The heterogeneity and unique characteristics of the WUI demand comprehensive approaches for effective fire prevention and mitigation.

4.2. Fires at high altitude areas

Fires at high altitude, i.e. in mountainous area, are characterised by specific behaviour, which can be very different from the normal behaviour in flatter area. The issue and the impact of these fires at high altitude, on both population and ecosystems, meet also very specific characteristics (Mayer et al. 2020).

4.2.1. Topography-driven behaviour

The first specificity is the way of propagation of the fires. The strong declivity along the slopes and the presence of valleys both induce breezes, i.e. local winds, which greatly influence the way fires propagate. These breezes are induced by thermal radiation which varies from ridges to gullies. It is a diurnal phenomenon, therefore the fire behaviour, and even the direction of propagation, changes along the diurnal cycle (Figure 4).

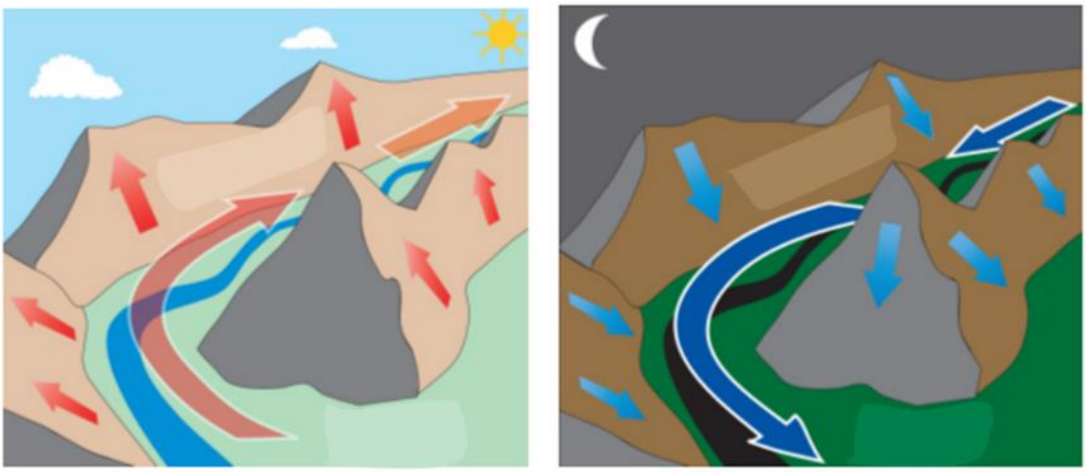


Figure 4: Slope and valley breezes during day (left) and night (right) (source: Meteo France)

When the slope breeze is rising, along afternoons, fire is moving upward very rapidly, with a narrow shape. Once on the top of the ridge, the frontal propagation stops, then fire slowly enlarges. This enlargement increases along the night.

4.2.2. Safety issue

When slope is steeper than a threshold, approximately 20°, flame may "attach" the slope (Edgar et al. 2016). This results in a dramatic escalation of the fire propagation speed, so that the whole slope could be ignited within few minutes, sometimes tens of seconds. This phenomenon has led to several entrapments of firefighters, as reported in the following chapters.

4.2.3. Access and response challenges

Because of the topography, accessing to fires at high altitude is generally challenging. Roads and paths are narrow; they cannot be used by heavy fire trucks with water. For terrestrial resources, there is sometimes a several hours walk to access the fire line from the closest motorable way.

As a result, these territories cannot be covered by squads of trucks, like in flat areas. Responders must rather invest in:

- Aerial resources, especially helicopters with flexible capability to drop water and to embark teams of firefighters with their equipment.

- Light four-wheel drive vehicles.
- dedicated teams of firefighters with:
    - Strong training (including safety issues) and experience of fire,
    - Good Fitness to evolve in mountainous terrain,
    - Ability to use hand tools,
    - Ability to collect water from remote sources,
    - Ability to use backburning options (refer to Deliverable 2.2 *Report on training session for prescribed burnings*),
    - Autonomy and flexibility to adapt to the changes in fire behaviour.

The dedicated teams described above could walk to the fire line or they could be transported by helicopters when available.

4.2.4 Impact of fires in high altitude

In mountainous areas, even small fires can have devastating consequences. Burning the vegetation that stabilizes the ground induces cascading effects:

- Rockfall
- Mudslides
- Avalanche-prone slopes
- Soil erosion

Due to the long cycle of forest in altitude, stand replacing crown fires also alter for a long time the protection function of the forest on soil (Mayer et al. 2020)

4.3. Fires at high latitude regions

The high latitude region of Europe (British islands, Norway, Sweden, Finland and the Baltic states) usually does not raise much attention in relation to wildfires. Years with extensive droughts are regularly occurring but sometimes with several wet seasons between them (Sjöström & Granström 2024). Most of Sweden, Finland, and the Baltic states belong to the boreal or hemiboreal, where heavily managed conifers with small inclusions of deciduous trees dominate. Norway and the northern UK have plenty of high mountains in addition to coastal heather and coastal coniferous type forests, while the rest of the UK is dominated by arable land and grasslands (Morton et al. 2020).

4.3.1 Fuels and landscapes

If dry enough, the boreal forests have very flammable fuelbeds. The mix of predominantly Scots pine and Norway spruce favours a deep layer of mosses, often penetrated by dwarf shrubs constituting an excellent fuel during dry weather. Non-vascular plants like mosses exchange moisture directly with the air and become as dry as fine litter during a dry summer day. Before the onset of industrial forestry (mid 19th century), the boreal parts exhibited 100 times larger bunt area than modern fire regimes (Niklasson & Granström 2000). A well-established infrastructure for forestry accessibility and high incentives for suppressing productive forests leads to a remarkable reduction in burnt areas. In contrast, in remote areas of North America and Siberia, where fires often burn in exclusively wildland areas with poor accessibility and limited human assets in terms of buildings or infrastructure.

For UK and Norway, fires mostly burn open landscapes dominated by heather and grasslands Davies et al. 2013). Fires in those regions are mostly concentrated in spring, before traditional fire danger indices become high. The reason is that the dormant phenological phase of northern shrub- and grasslands provide ample amounts of dead light fuel which quickly becomes flammable with low humidity, despite a water saturated soil. That can cause fast-moving fires in occasional dry periods during snow-free parts of winter, such as the Norwegian Lærdal and Frøya fires of January 2014 (Log 2016) and several Island fires off the Scottish coast (Fulton 2024). During the greenery period (concurrent with chances of high forest fire danger), these landscapes are less fire prone due to the green vascular vegetation keeping a high moisture content in the fuelbed.

4.3.2 Demographics

As with most regions, fire ignition follows population density, but Northern Europe's largest and most intense fires occur in sparsely populated areas (Figure 5). While sufficient cover of conifer forests occurs throughout the boreal areas, the more rural areas suffer from (i) a long time to detect fires, (ii) a long time to find and reach the fire, and (iii) fiscal restraints resulting in resource and personnel scarcity (Sjöström & Granström 2023a).

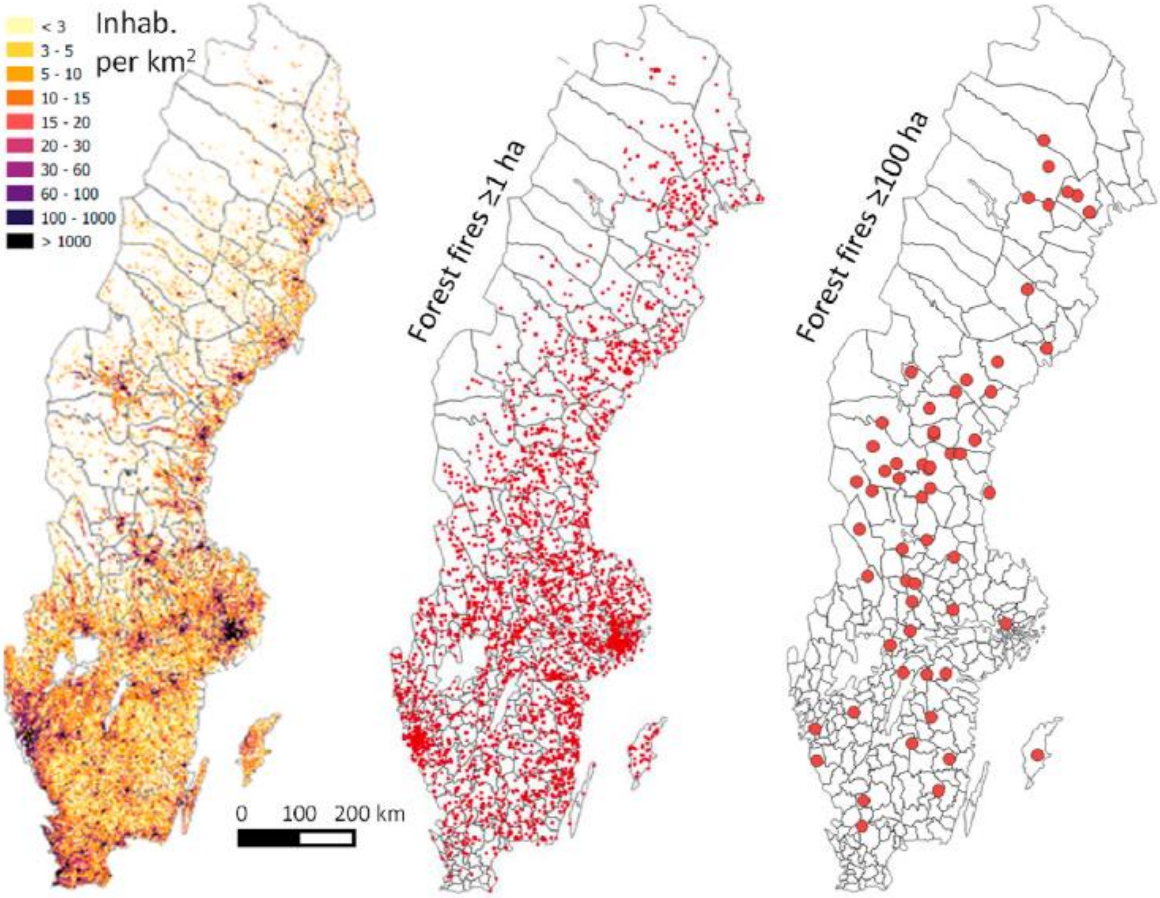


Figure 5. Example from Sweden 1996-2020. Population density (left), forest fires occurrence (≥1 ha), (middle), forest fires occurrence (≥100 ha), (right) (Sjöström & Granström 2023a).

Since the likelihood of the fire escaping the initial attack increases exponentially with the time to start the attack, the long distances in the north are a challenge, reinforced by a decreasing population since the 1970s. This has resulted in longer distances between fire stations and longer response times for the (primarily part-time employed or volunteering) firefighters. Fifty years ago, wildfire fighting knowledge was spread among the population, but it is now a skill known by a few, leading to difficulties during peak seasons.

4.3.3 Challenges and improvements observed during the last decades

- During the 1990s and beginning of 2000s the resource availability in boreal Europe decreased with a consequent increase in response time to wildfires.
- The flame spread potential of the commercial production forest is very large but often underestimated during initial attack.
- Resource scarcity and insufficient mop-up (which is the landowner's responsibility) were two major factors for the large fires across all Scandinavia during 2018.
- Fire fighting in cold, dark, and windy conditions requires more preparedness than during the Norwegian winter fires of 2014, where close to 100 buildings (some belonging to the UNESCO World heritage list) were destroyed. Weather prohibited helicopter use and ice clogged hoses in the cold temperatures (Log 2016).
- The UK fire management system does not consider the phenological aspect and cannot give proper prognosis for most of the fires.

The last five years have come with some improvements.

- State- and EU-sponsored programs for aerial firefighting (Sweden and Norway) have increased the utilisation of fixed wing or helicopters in the early stages of the fire, unlike previous decades when aerial resources were deployed only after the failure of the initial attack.
- A reorganization of fire services to more central command and control enables easier access to resources in highly rural areas.
- Larger deployments on alarm increases the success rate of early suppression.
- Most buildings burn in spring fires in very small fires, often starting directly outside (or within) gardens. The potential for improvement using risk awareness and simple cleaning methods is high.
- A warning model for spring grassfires has been operational in Sweden since 2021 (Sjöström & Granström 2023b).

4.3.4 Factors for the future

- Continued depopulation of rural areas will aggravate recruitment difficulties.
- Simple land management tools. These include (i) limiting the plantation of *Pinus contorta*, which is more flammable than the native *P Sylvestris* and (ii) limiting the aggressive pre-commercial thinning of deciduous trees (predominantly birch or aspen). Deciduous tree inclusion reduces the flammability of the moss layer (Vermina Plathner et al 2022).
- Training of firefighters after several seasons of poor fire weather. Firefighting must be coordinated and finished from the ground and not from the air. Knowledge of tactics and methods fades quickly without practice.
- Simple garden practices significantly increase likelihood of building survival in northern wildfires: (1) A managed lawn around the building, (2) reducing stacks of fuel close to the facades and (3) deciduous trees around the garden (Vermina Plathner *et al*. 2023).

5. Smoke emission and dispersion

5.1. Smoke emission

The smoke released by forest fires contains significant amounts of carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), nitrogen oxides (NOx), ammonia (NH3), particulate matter (PM) (commonly referred to as particles with an equivalent aerodynamic diameter less than 2.5 µm, or PM2.5, and particles with an equivalent aerodynamic diameter less than 10 µm, or PM10), non-methane hydrocarbons (NMHC) and other chemical compounds. Figure 6 illustrates different compounds that compose smoke. These compounds can have severe consequences regarding local and regional air quality (e.g. Valente et al., 2007; Miranda et al., 2009; Carvalho et al., 2011; Martins et al., 2012; Keywood et al., 2015; Osswald et al., 2023), reducing visibility, contributing to photochemical smog and deteriorating air quality in general, thus affecting human health (e.g. Miranda et al., 2010, 2012; Johnston et al., 2012; Dennekamp et al., 2015; Reid et al., 2016; Haikerwal et al., 2016, Sebastião et al., 2019).

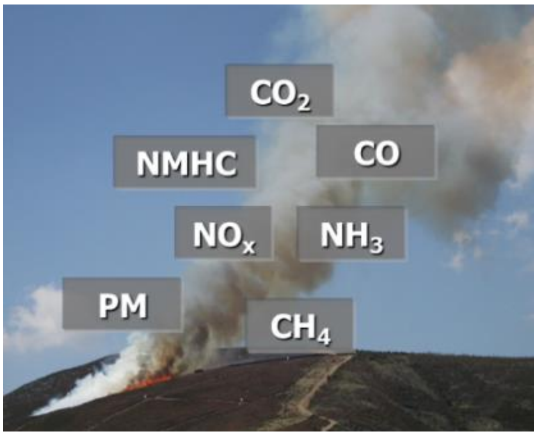


Figure 6 Some of the smoke compounds emitted during a forest fire.(Authors illustration)

It is possible to estimate forest fire atmospheric emissions by considering the various interrelated factors on which they depend: fuel characteristics, burning efficiency, phase of combustion, type of fire, meteorology, and geographic location. The estimation of forest fire emissions also implies knowing the burned area and the duration of the fire.

The type of vegetation and its fuel load (or biomass load) are two of the most important factors for estimating emissions from forest fires. Variations in the characteristics of the fuel can contribute 80% to the uncertainties in estimating emissions from forest fires (Ottmar et al., 2009).

When estimating emissions, the different phases of combustion, namely pre-ignition, flame or flaming, smouldering, and glowing, should be considered. The duration or predominance of different phases depends on the type/mixture of fuel, its humidity, and atmosphere conditions. According to Lobert and Warnatz (1993), during flaming combustion, the most emitted compounds are CO2 and water vapour, and in minor quantity, NOx, sulphur dioxide (SO2), nitrogen (N2) and particles with high carbon content. The most oxidized emissions are predominant due to the high efficiency of burning. In the smouldering phase, emissions of compounds that are partially oxidized or reduced are dominant, namely CO and others, such as CH4, NMHC and polycyclic aromatic hydrocarbons (PAH), NH3, sulphur compounds, and particulates with low carbon content. CO is, however, the main compound associated with this phase.

Burning efficiency is also relevant when calculating emissions from fires. It is usually defined as the ratio between the carbon released in the form of CO2 and the total carbon in the fuel. It is also common to resort to modified efficiency, which consists of the ratio between the carbon released in the form of CO2 and the sum of CO2 and CO. In experimental, field, or laboratory settings, burning efficiency is expressed as the fraction of available fuel that is consumed, and it is directly dependent on the type of vegetation and its moisture content.

Finally, the emission factor consists of the mass of pollutant emitted per mass of fuel consumed or area burned. Emission factors vary depending on the pollutant, the fuel, and the burning efficiency (and combustion phase). For example, fires that mainly occur in smouldering combustion can emit a mass of pollutants (excluding carbon dioxide) several times higher than a fire in which the fuel is consumed during the flame phase (Peterson, 1987).

Emission factors for Southern-European conditions were chosen (Fernandes et al., 2022) based on a bibliographic review taking into consideration land-use types, as well as considering values selected by previous studies (Miranda 2004; Alves et al. 2011; Martins et al. 2012, Van Der Werf et al. 2017; Vicente et al. 2017, 2012). Table 3 lists the averaged emission factors (in g.kg-1 fuel burned, dry basis) for relevant air pollutants. All reported values were obtained from experimental forest fires.

Table 3. Averaged emission factors (g.kg-1 fuel burned, dry basis) of the main smoke pollutants, per vegetation type (Fernandes et al., 2002)

Species	Eucalyptus [c, d, e]	Other resinous[b]	Oak, Chestnut, Cork Oak[b]	Acacia[c, d, e]	Other hardwoods[a]	Pinus pinaster[c, d, e]	Stone pine[b]
PM10	21	10	13	11	8.3	13	10
PM2.5	19	9	11	10	6.3	11	9
NOx	5	3	3	5	3.11	3	5
CO	170	100	128	232	102	204	91
SO_2	0.8	0.8	0.8	0.8	0.4	0.8	0.8
NH_3	0.6	0.6	0.6	0.6	2.17	0.6	0.6
CO_2	1408	1497	1393	1561	1585	1398	1487
CH_4	6	6	6	4.7	5.82	6	5

a Van Der Werf et al. (2017)
b Miranda (2004)
c Vicente et al. (2012)
d Vicente et al. (2017)
e Alves et al. (2011)

Nowadays, the scientific community is putting considerable effort into quantifying the impact of wildland fires by remote-sensing approaches to improve emissions estimates (e.g. Monteiro et al., 2013; Ichoku and Ellison, 2014; Darmenov and da Silva, 2015; Chuvieco et al., 2016; Van Der Werf et al., 2017). Furthermore, the instantaneous fire radiative power (FRP) is used as a measure of the rate of radiant energy emission from the fire, to derive directly the amount of fuel burned, in particular, to facilitate real-time applications (Sofiev et al., 2009; Kaiser et al., 2012; Nguyen et al., 2023).

5.2. Smoke dispersion

The emitted gases and particles undergo dispersion and chemical transformations in the atmosphere as they are transported, and their effects can be felt long distances from the source, that is, from the fire. Although most fires are limited to some hundred hectares, their impacts, without natural or political boundaries, can be felt and reported at considerable distances from the physical limits of the progression of the fire; depending on the weather conditions, the plumes of smoke can remain in the atmosphere for long periods, changing its physicochemical characteristics.

The air quality of a given region, often expressed in terms of concentration of pollutants, depends, in addition to their emissions, on the physical phenomena that regulate the dynamics of the atmosphere, namely transport or advection, and dispersion; the chemical transformations undergone by pollutants (e.g. photochemical processes); the mechanisms for removing these pollutants from the atmosphere (dry and wet deposition).

The assessment of the effects of forest fires on air quality can be based on measurements and/or results from numerical models. Notwithstanding some particular monitoring campaigns (e.g. Miranda et al., 2005; Valente et al., 2007; Miranda et al., 2010), air quality measurements are usually not specifically carried out for situations involving forest fires, and the monitored data mainly comes from available air quality data from existing monitoring networks. The application of air quality models for assessing the contribution of forest fires to air pollution episodes is a technique that is becoming more frequent (e.g. Rea et al., 2016; Turquety et al., 2020; Osswald et al., 2023).

A numerical air quality model aims to estimate the concentration C(x,y,z,t) fields of a specific atmospheric pollutant caused by its emission into the atmosphere. Figure 7 presents an air quality model scheme in relation to what it intends to simulate. The model simulates the interactions of pollutants in the atmosphere and the resulting impact on air quality, using as information emissions and meteorological values, among other data.

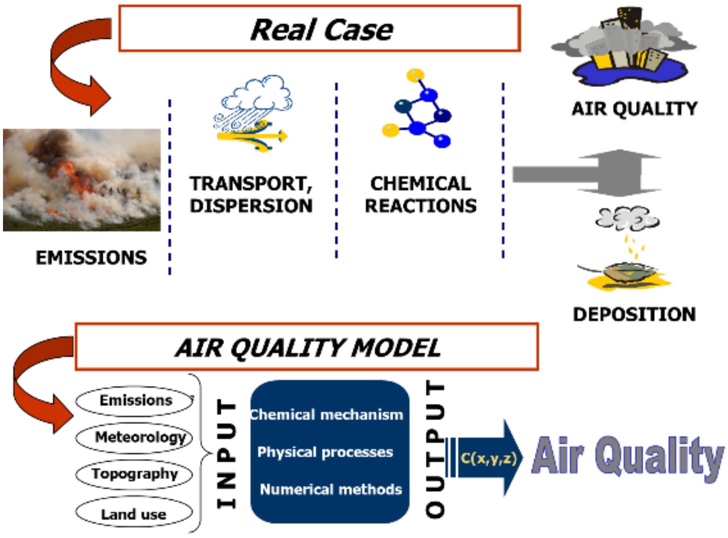


Figure 7 Scheme of an air quality modelling approach (Authors illustration).

There are several numerical air quality models, depending on the scale of the process to be analyzed and the type of approach or formulation to be used. Considering the spatial scale, global or planetary models are distinguished from macroscale, mesoscale, and local or microscale. In temporal terms, the models can be classified as short-term or long-term. The spatial and temporal scales are closely related; for example, a local scale model is generally short-term.

One example of a local scale dispersion model is DISPERFIRE (Miranda et al., 1994; Valente et al., 2007), which is based on a Lagrangean approach for dispersion modeling. It was applied to an experimental field fire and validated with monitored data that was acquired explicitly during the experiments. Figure 8 shows the PM10 concentration field estimated by DISPERFIRE for the burning of experimental plots.

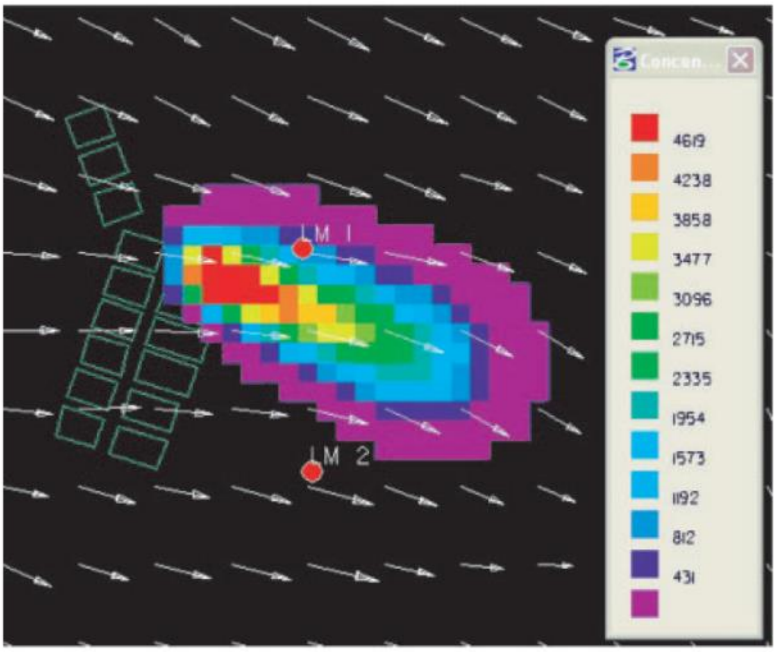


Figure 8. Concentration field (µg.m-3) of PM10 simulated by a local dispersion model (Valente et al., 2007).

Simulated values were compared to measurements taken by equipment in a mobile laboratory van (LM1 in Figure 8), and the range of estimated values (431-812 µg.m-3) agreed reasonably well with the monitored value for the same period of time (486 µg.m-3).

In summary, understanding smoke production and dispersion is crucial for preventing people, particularly firefighters and populations, from its impacts on human health. Nowadays, solid knowledge, data, and tools can help train stakeholders to forecast and react to smoke.

6. Firefighting methodologies

A survey completed by interviews regarding wildfire suppression strategy and techniques were conducted by SAFE in April-May 2023 to develop this chapter. The survey and the interviews focussed on the following:

- Initial attack to keep starting fires as small as possible
- Fighting extreme fires
- Fighting fires in the WUI

The survey received responses from 27 firefighters across ten countries: Spain, Portugal, Italy, Croatia, France, Greece, Ireland, Russia, Germany, and South Africa. The interviews were conducted with four experts: two from Portugal's National Authority for Emergency and Civil Protection (informants 1 and 2), one from the Fire and Rescue of the Bouches du Rhone Department in France (informant 3), and one from the Forest Fire service of Castilla La Mancha in Spain (informant 4).

6.1. Fire suppression strategies and techniques

According to the survey, a significant majority of 89% of firefighters stated that the strategy and techniques they have been employing have proven effective in combating fires during the initial response phase or initial attack. The techniques and strategies employed are summarized in Figure 9, with the aerial strategy being the most commonly mentioned approach in surveys. That suggests that most European countries utilize this strategy for wildfire management.

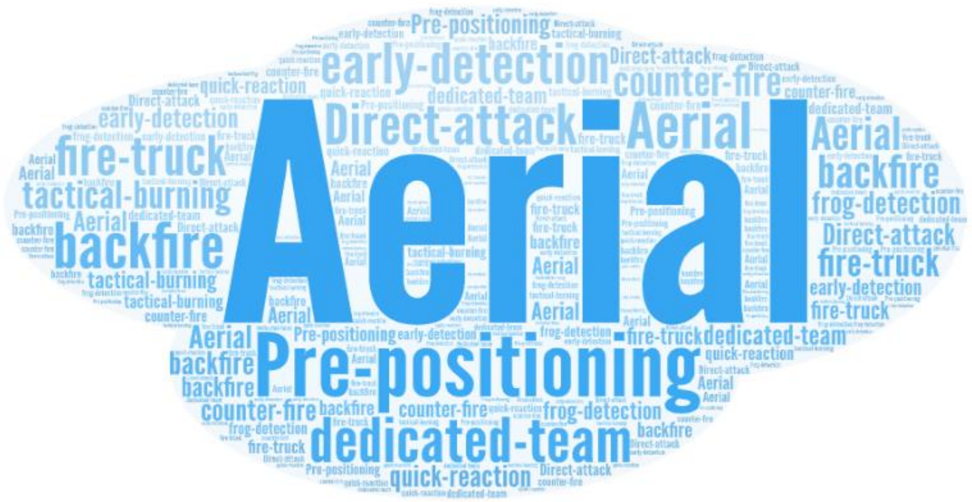


Figure 9. collection of words related to fire suppression strategy and techniques used in Europe (authors illustration)

This chapter aims to differentiate between fire suppression strategy and fire suppression technique. A fire suppression strategy refers to a broad approach or plan developed to combat and control fires. In contrast, fire suppression technique refers to a specific method or approach used to extinguish or control a fire.

6.1.1 fire suppression strategy

a. Aerial strategy

Aerial strategies in fire suppression involve the use of aircraft to combat and control wildfires. These strategies leverage the capabilities of aircraft to deliver various fire suppression techniques from the air, conducting reconnaissance, and supporting ground-based firefighting operations.

b. Pre-positioning strategy

Prepositioning strategy in wildfire management involves strategically positioning resources and personnel in high-risk areas to enhance response capabilities and improve wildfire suppression efforts. The objective is to minimize response time and increase effectiveness in containing and extinguishing wildfires.

This strategy is employed in several countries, including France, as shared in an interview with a firefighter in the Bouches du Rhone Department.

"We use prepositioning ground forces in the special points that are close to the main roads and close to the access to the forest. If we have a detection of fire somewhere, we just send a lot of people and trucks" (Informant-3)

c. Utilization of helitack crews/ dedicated team strategy

A helitack crew is a specialized firefighting team that is transported by helicopter to remote areas to combat wildfires. They are highly trained and skilled in firefighting techniques, including rappelling from helicopters, constructing fire lines, and using hand tools to extinguish flames. Helitack crews are often the first responders to wildfires in difficult-to-reach areas and play a crucial role in containing and suppressing fires before they can spread further. They work in coordination with other firefighting teams on the ground and in the air to ensure the safety of both the crew and the public, as well as to protect property and natural resources.

6.1.2. Fire suppression technique

a. **Direct attack**

Direct attack is a firefighting approach that involves personnel aggressively combating the fire close to the fire line. This method can be carried out by crews utilizing hand tools, or by crews equipped with a water delivery system, or a combination of both. The objective of direct attack is to directly extinguish the fire by applying water or physically removing fuel through the use of tools, with the aim of quickly gaining control and preventing further fire spread.

- Direct head attack: involves firefighting efforts directly face to the head, i.e. the most active fire front;
- Direct tail attack: involves attacking the fire from the rear and working along the flanks towards the head fire
- Direct flank attack: involves attacking the side of the fire and working around the head and tail.

b. **Indirect attack**

This method involves applying suppression tactics that take place away from the burning edge of the fire, either by using control lines to contain fire spread, or the proactive use of fire as a suppression tool.

- The use of control lines: Control lines are constructed or natural barriers, including treated fire edges, which are used to control a fire. They can be constructed manually, mechanically or by applying water or retardants (which are called wet lines).

- Parallel Attack: Parallel attack is a specific type of indirect attack where control lines are created along the flanks of the fire towards and around the head of the fire. This suppression method is usually most effective when using appropriate vehicles, such as tractors pulling swipes or flails, or bulldozers.
- Controlled burning /Backfiring
    - Defensive burning - lighting a controlled fire to remove fuel in front of an advancing fire, and extinguishing the controlled fire before the wildfire arrives; this method is commonly applied some distance from the fire front and should be planned in good time
    - Offensive burning - lighting a controlled fire and allowing it to burn towards the approaching fire front; this technique combines the advantage of removing the fuel and creating a thermal flux that faces the fire front; however, it requires careful assessment and trained operators.

c. **Aerial attack**

Aircraft may be deployed at wildfire incidents to use direct and indirect attack methods.

- Direct aerial attack involves aircraft dropping water or fire retardants onto the burning area
- Indirect aerial attack involves aircraft dropping water or fire retardants in front of the burning area to form control lines or to strengthen existing control line.

6.2. Fighting Fires at the WUI

As described in chapter 4, Wildland-urban interface (WUI) fires are a complex type of fire that occurs at the interface between wildland areas and human communities. These types of fires are particularly dangerous and challenging to fight because they often involve a mix of vegetation, structures, and human lives. Southern Europe is a highly fire-prone region where extreme fires often have disastrous consequences on both structures and people. Facing fires in the WUI is highly difficult, as affirmed by a firefighter from France:

“In our region, the difficulty is that we have a lot of houses in different areas and we cannot defend each House. We cannot put one truck in front of each house because they're too many houses, so it's difficult if the forest is very close to the house” (Informant-3).

The point of fighting fires in WUI is to cut off the fire before it reaches the building, essentially at the outer edge of the yard or where wildland fuels begin (Ganteaume et al., 2021)

6.2.1. Fire suppression at the WUI

Table 4 discuss how the fire suppression techniques described above can be used to combat fires in the WUI:

Table 4: potential and limits of the fire suppression techniques in the WUI

No	Technique	Action
1	Aerial Attack	Fire retardant and water cannot be dropped directly within the area due to safety concerns and the presence of people, property, and power lines. Instead, aerial attacks are conducted outside the WUI to create a barrier or containment line before the fire reaches populated areas. This proactive approach maximizes safety while effectively suppressing the fire and protecting the WUI.

2	Direct attack	To protect structures in the WUI, firefighters use structure defense tactics, which are offensive when resources steer the head of the fire to a desirable endpoint. If firefighters can safely attack a fire directly, they may be sent into action with hand tools to remove fuels and smother burning fuels, handlines to knock down flames, and other firefighting equipment. Direct attack can be inherently dangerous due to the dynamic nature of WUI fires. Direct attack should also be conducted immediately when firefighters find spot fire.
3	Indirect attack	Creating a firebreak and conducting a backfire along the road ahead of the fire can be an effective tactic to protect the WUI; however, before initiating such backfire, special attention is required to ensure that conducting a backfire is safe and feasible given the circumstances.

Most of the time, using heavy equipment for firefighting or other purposes is not feasible or practical. This could be due to various reasons, such as limited space, rugged terrain, or concerns about damaging infrastructure or property. As a result, responders have to use alternative equipment suitable for the WUI. These specialized tools and vehicles are designed to be agile, maneuverable, and effective in combating wildfires in WUI areas. Here are some of the mobile and tactical firefighting equipment that can be used to fight fires in WUI:

- **Portable Pumps**: These lightweight pumps are designed to be easily transported and operated in remote locations. They can be used to draw water from nearby water sources such as swimming pools, ponds, lakes, or portable tanks, and supply water to firefighting crews.
- **Backpack Sprayers**: Backpack sprayers are handheld devices that firefighters can wear on their backs, allowing them to move quickly through rugged terrain while applying water or fire retardant to suppress flames. They are particularly useful for accessing areas where larger equipment cannot reach.
- **Light specialized Vehicles**: Specialized vehicles, such as brush trucks or off-road vehicles, potentially equipped with firefighting apparatus, are designed to navigate through narrow roads, rough terrains, and WUI areas. These vehicles carry small water tanks, pumps, hoses, and other firefighting tools, allowing crews to respond and suppress wildfires in challenging environments quickly.

6.2.2. Protection of population and buildings

This major concern is fully investigated in the frame of another task of the project. The outputs will be documented in Deliverable 2.8 “Guidelines to reduce communities’ vulnerability to extreme fires and fires in the WUI.

Basically, there are 2 main options:

- **Evacuation.** It is sometimes the best option, especially in case of vulnerable kinds of WUI, e.g. campsites or light housing made of combustible materials. However, it has to be planned and organised sufficiently early before the fire get close to the WUI since it may take a long time. The number, the availability and the safety of egress routes, are also crucial to consider before deciding on evacuation.

- **Shelter in place.** In most European contexts, buildings are made of non-flammable materials which provide the best protection, compared to evacuation. However, preparation may be required to ensure there is no fragility in the shelter, and people can stay inside without panicking.

6.3. Fighting Extreme Fires

As detailed in chapter 3, Fighting extreme fires is very challenging compared to combating regular wildfires. Extreme fires are characterized by intense heat, rapid spread, and unpredictable behaviour, which significantly increase risks to firefighter safety and make it difficult to predict fire dynamics. Traditional firefighting methods that primarily involve directly attacking the flames may not be as effective due to the intense heat and erratic behaviour of the fire, making containment and control more challenging.

The firefighters we interviewed emphasized that:

a) combination of tactics, including combining heavy machinery with tactical firefighting, is crucial in combating extreme fires.

b) it is necessary to shift the mentality from direct attack methods to indirect attack.

In our survey, it was revealed that the majority of respondents (89%) found their current strategies effective during initial attacks, but this effectiveness did not extend to strategies used in extreme fires. A significant portion (26%) deemed them ineffective or very ineffective, while only 30% considered them effective. Furthermore, a majority of respondents (40%) remained neutral on the effectiveness of these strategies. These findings underscore the necessity of compiling recommendations based on scientifically-grounded strategies that firefighters can employ to effectively combat extreme fires.

Drawing insights from the survey, interviews, and literature review, Table 5 summarizes the techniques that can be used to address extreme fires behaviours described above.

Table 5: Strengths and limitations of the different techniques face to extreme fire behaviours

Extreme fire behaviour	**Fire Suppression Technique**			**Notes**
	Direct attack	**Indirect Attack**	**Aerial Attack**	
Spot fires	Very recommended Suppress spotting as soon as possible	Conduct indirect attack when initial attack is failed and fire escapes.	When the aerial team see the spot fire, direct attack from above is very recommended	Prioritize the initial attack
Crown Fires	Not recommended Direct attack of the fire front is impossible and dangerous	Creating firebreaks and backfiring are recommended	Direct and indirect aerial attack is recommended	Focus on controlling the flanks of the fire, rather than directly attacking the fire front
Eruptive fires	Not recommended	Controlled or tactical burning is recommended	Aerial attacks may be used, but it is challenging to manoeuvre in	

			landscapes such as canyons.	
Junction fires	Recommended before junction, with caution	Construct firebreaks or control lines around the junction area	Very recommended to support ground operations and protect the junction.	
Conflagrations	Recommended before the intensity of fire is too high, keep stand in safe zone	Controlled burning is recommended	Direct and indirect aerial attack with water and retardant are recommended	Preventive evacuation may be required
Fire whirls	Not recommended	Not recommended	Not recommended	Just wait and see until the phenomenon stops, because fire whirls mostly occur for a short period.

The following chapter provides detailed information justifying the options listed in Table 5

7. Fire Safety

7.1. Health status and multifaceted performance

Now firefighters are responding to increasingly worse and dangerous forest fires that are increasingly more intense and dangerous due to climatic change. Through their big efforts, they prevent massive damages and dramatic human losses. However, they are also exposed to increasingly difficult weather and supraphysiologic conditions when combating extreme fires, which may hamper their overall performance, health status and well-being. In fact, a good health status and physical capability may improve their overall firefighting capacity and safety, especially during the worst conditions. Consequently, it is important to integrate health-focused training strategies and insights into firefighter training programs and exercise routines. Some of these key aspects that should be added to firefighting training programs that will face extreme fires are briefly introduced below:

- Comprehensive health status and improved physiology to foster performance:
    - Cardiovascular health:

Cardiovascular system and fitness are of utmost importance for firefighters, considering the ability to perform strenuous tasks when exposed to harsh environments. Improved cardiovascular physiology and endurance capacity should be introduced and highlighted. The increased cardiovascular capacity and endurance might be achieved through aerobic exercises, including cycling, running, and swimming. In addition, heart-healthy habits should be highlighted, which may focus on nutrition, exposure to smoke and tobacco, stress and increased adipose tissue accumulation.

- Physical assessment:

To ensure firefighters' efficiency and well-being, it is crucial to establish personalized improvement of firefighter physical capabilities that will improve overall output, but most importantly, also prevent injuries or the increased risk of cardiovascular-related events. Firstly, a comprehensive physical assessment should be done to understand the baseline health and physical capabilities, for instance, following standard parameters of cardiovascular status and endurance as well as muscular strength and body composition.

- Physical conditioning:

After assessing individual status, personalized training programs and exercise sessions must be implemented, aiming for regular physical conditioning to better frame individual capabilities and special needs. The type of aerobic exercise, which might consider running, weightlifting, circuit training, and functional movements, might be integrated to achieve the required needs. The main firefighting functions and tasks when performing labour should be also considered, for instance, mimicking real-life situations to potentiate muscle coordination and overall task-related performance.

In sum, firefighting trainings must have dedicated training sessions and programs introducing and exploring these physical aspects to foster improved physical outcomes in firefighter forces. Better-prepared firefighters will be exposed to less accumulation of lactate within their muscles, avoiding muscle failure and, ultimately, exhaustion or even collapse.

- Mental health and resilience, sleep quality and stress management

Firefighters are usually exposed to threatening and stressful situations that can significantly impact their mental well-being, decision-making processes, and overall performance. These aspects are of upmost importance to safety aspects and safety-related awareness and actions. In this sense, firefighter trainings must include the potentiation of better leadership skills, mental resilience, and stress management. Sleep quality is also an impacting factor in these aspects, and it is of utmost importance to highlight and reinforce strategies and practices for optimizing sleep hygiene and health. Managing shift work-related sleep disruptions should also be considered within teams and forces to be deployed.

- Nutrition and hydration:

Adjusted nutrition and proper hydration are key aspects to keep an optimal performance and physiologic homeostasis. Training programs should also foresee insights into planning balanced diets and meals before, during and after big workloads. Healthy diets, enriched in antioxidants and other detoxifying components, might be of great importance to mitigate and recover from the increased exposure to smoke. The same applies regarding hydration, that should be also favoured before and during hard workouts, especially to keep osmoregulation and essential electrolytes, but also after the workload to restore proper levels and potentiating a faster recover. Training on this topic also should include hydration concepts, types and the periodicity of water or specific hydrating fluids consumption.

When promoted effectively, these healthy habits will mitigate unfortunate events and excessive fatigue, potentiating resilience and better performance during larger activity periods.

7.2. Smoke impacts on visibility and health

Acute smoke inhalation is a complex and potentially fatal syndrome involving a multisystemic response (not just respiratory) related to the exposure to an extensive family of chemical agents and particles resulting from the combustion of several materials. It can occur in open or closed environments and may or may not be associated with coexisting skin burns (Gill et al., 2015; Walker et al., 2015; Herndon, 2018).

7.2.1. Etiopathogeny

The toxic risks associated with fire and the inability of victims to leave hazardous atmospheres can be considered under three main aspects: (1) exposure to heat, (2) smoke and (3) combustion products. The specific toxicology of the main fire effluents has been exhaustively studied, depend on the environment of the fire (outdoors, indoors), where we highlight numerous substances with asphyxiating action (e.g. carbon monoxide, hydrocyanic acid), irritant (e.g. bromidric acid, hydrochloric acid, hydrofluoric acid, sulphur dioxide and organo-irritant substances, such as acetaldehyde, acrolein, benzene, crotonaldehyde, formaldehyde, phenol, toluene), greenhouse gases (e.g. carbon dioxide, methane) but also the very low levels of oxygen present in fire zones may be of concern (Gill et al., 2015; Herndon, 2018).

Thermal damage from heat exposure is mainly localised to the upper respiratory tract and potentially induces edema, with its associated risks, namely for the glottis and vocal cords (Walker et al., 2015).

The more water-soluble chemicals (e.g. ammonia, sulphur dioxide) quickly affect the upper airways. The less water-soluble agents (e.g. phosgene, nitrogen dioxide) do not produce immediate irritation, being inhaled more deeply, because they do not produce as much coughing, resulting in alveolar lesions, namely in non-cardiogenic pulmonary edema, which may appear late, requiring longer vigilance (Stec, 2010, Demling, 2008).

Carbon dioxide and carbon monoxide, among the main components of smoke, are responsible for a drop in the ambient oxygen concentration between 5% and 10%. Carbon monoxide and hydrocyanic acid block the alveolar-capillary transfer of oxygen, leading to severe and potentially fatal hypoxaemia and are considered as asphyxiating gases with systemic effect. Carbon monoxide is a colourless, odourless, non-irritating gas produced by incomplete combustions, mainly of hydrocarbons, fire-heating sources and petroleum distillates. Its affinity for haemoglobin is more than 200 times higher than for oxygen, inducing a shift of the haemoglobin dissociation curve to the left, formation of oxygen free radicals, lipid peroxidation and disruption of cellular respiration and mitochondrial metabolism. The brain and myocardium are among the most affected structures (Walker et al., 2015; Dries et al., 2013, Stec, 2010, Demling, 2008; Haponik, 1990; Lafferty KA, 2018).

Carbon monoxide has been implicated in more smoke inhalation deaths than any other single compound. Methemoglobinemia can also arise in the acute smoke inhalation environment (mainly due to inhalation of smoke from the burn of plastics and other synthetic materials). This oxidised form of haemoglobin has no oxygen-carrying potential, causing cyanosis; levels above 70% are usually fatal. Inhalation of soot can also act as a vehicle for transporting gases and various toxins into the lower respiratory tract, where they can dissolve and form acidic and alkaline substances with significant damage to bronchial and alveolar structures (Lafferty, 2018).

7.2.2. Diagnostics

The clinical pictures associated with acute smoke inhalation occur essentially by exposure to direct or convection heat, inhalation of asphyxiating gases and exposure to neurological and respiratory irritants (ISBI Practice Guidelines for Burn Care, 2016). Four phases are generally recognised following acute smoke inhalation:

(1) Acute respiratory distress - occurs 1 to 12 hours after exposure and is due to bronchospasm, laryngeal edema and bronchorrhea.

(2) Non-cardiogenic pulmonary edema (acute respiratory distress syndrome) - 6 to 72 hours after exposure and results from increased capillary permeability, sometimes simulating acute cardiogenic edema of the lung.

(3) Cervical space conflict - 60 to 120 hours after exposure, associated with cervical eschar formation in burn patients with circumferential neck burns.

(4) Potential onset of pneumonia - 72 hours after exposure, mainly involving Staphylococcus aureus, Pseudomonas aeruginosa or gram-negatives.

Clinical history and objective examination

The clinical presentation and potential risks of smoke inhalation are highly dependent on the duration of inhalation, type and environment of exposure, the substances burnt (namely whether the fire occurred indoors or outdoors), the concomitant skin burn and the general condition and previous health of the victim.

The victim presents various degrees of dyspnea, which may be associated with dysphonia, hoarseness, stridor and/or bronchospasm (Walker et al., 2015). Coughing is a very frequent symptom of the inhalation of irritant substances. There may also be carbonaceous expectoration.

The alteration of the mental state can occur with several of the substances mentioned above, which contributes to the severity of the clinical pictures and to the progressive incapacity of the victims to escape. In some circumstances convulsive episodes may occur. Other symptoms, with minor inhalations, include headache, anxiety, agitation, convulsions, diaphoresis and vertigo.

Hypotension may arise from peripheral vasodilatation, myocardial depression, arrhythmia, or changes in body water components.

In situations where carboxyhemoglobin (inhalation of carbon monoxide) and/or methemoglobin are formed, pulse oximetry may give erroneous readings. For example, the colorimetric absorption of carboxyhemoglobin is identical to that of oxyhemoglobin, and oximeters do not detect the differences between these two forms accurately (Rehberg et al., 2009).

The clinical manifestations corresponding to carboxyhemoglobin levels in the blood are as follows (Lafferty, 2018; Rorison & McPherson, 1992):

0-10% - usually no symptoms;
10-20% - mild headache, dyspnea;
20-30% - throbbing headache, impaired concentration;
30-40% - severe headache, confused thinking;
40-50% - confusion, lethargy, syncope;
50-60% - respiratory failure, convulsions;
> 70% - coma, death.

Analytical assessment

The assessment of arterial blood gasses can give very useful indications, but their values are very dependent on the substances inhaled. Thus, in the case of poisoning by fumes containing systemic asphyxiants such as hydrocyanic acid and cyanide, metabolic acidosis may appear, with high lactates - in this specific case the hypoxaemia is paradoxically later. In laboratories with the appropriate technology, carboxyhaemoglobin and methemoglobin can be measured (Dries et al., 2013).

Chromatographic or spectrophotometric techniques may carry out the quantification of carbon monoxide in blood. However, portable equipment allows the monitoring of its level in exhaled air, as well as the corresponding estimated evaluation of the percentage of carboxyhaemoglobin (Rehberg et al., 2009).

Other examinations

Chest radiology may be useful in assessing later pulmonary changes such as non-cardiogenic pulmonary edema, atelectasis, or pulmonary infiltrates. However, it should be noted that in the early stages, post-acute smoke inhalation may be totally normal on the chest X ray (Adams, 2013).

In circumstances to be assessed individually, direct visualisation of the airways, such as by laryngoscopy or flexible bronchoscopy, is sometimes necessary: in several instances, rapid progression to complete airway obstruction may occur, even in initially mildly symptomatic patients. These situations may require early tracheal intubation and close monitoring is recommended for a period of time that should not be short, as the associated edema sometimes appears several hours after exposure. Flexible bronchoscopy can corroborate the presence and extent of inhalation injury. The most frequent findings are the presence of soot in the airways, edema and erythema of the mucosa, haemorrhage and ulceration.

Endorf and Gamelli (2007), proposed the bronchoscopic criteria used to grade inhalation injury (Abbreviated Injury Score), that we usually use:

- Grade 0 (no injury): absence of carbonaceous deposits, erythema, edema, bronchorrhea, or obstruction.
- Grade 1 (mild injury): minor or patchy areas of erythema, carbonaceous deposits in proximal or distal bronchi (any or combination).
- Grade 2 (moderate injury): moderate degree of erythema, carbonaceous deposits, bronchorrhea, with or without compromise of the bronchi (any or combination).
- Grade 3 (severe injury): severe inflammation with friability, copious carbonaceous deposits, bronchorrhea, bronchial obstruction (any or combination).
- Grade 4 (massive injury): evidence of mucosal sloughing, necrosis, endoluminal obliteration (any or combination).

7.2.3. Treatment

The victim should be quickly removed from the hazardous atmosphere. The immediate priority is to secure the airway, breathing and circulation (ABC- airway, breathing, circulation). Early tracheal intubation and even mechanical ventilation may be necessary in more severe cases. Note that the progressive increase in upper airway edema may make later intubation difficult. A high flow of oxygen through a high output mask should usually be given (Toon et al., 2010; Sheridan, 2016; Herndon, 2018).

In specific circumstances, in the case of carbon monoxide and cyanide poisoning, hyperbaric oxygen therapy may be used. This method of administration, available in only a few centres, significantly reduces the half-life of carbon monoxide as well as pulmonary interstitial edema (Herndon, 2018; Spinou & Koulouris, 2018).

Clinical and vital surveillance and monitoring measures, hydro-electrolytic, acid-base and pharmacological support (namely the correction of metabolic acidosis) as well as respiratory kinesiotherapy are fundamental. Thus, the vast majority of these situations require referral to a more differentiated medical centre, which can address the various possible therapeutic aspects in a detailed and global manner.

7.2.4. Conclusions

Smoke inhalation accounts for up to 80% of fire-related deaths. This inhalation can significantly increase the risk of death in other specific situations, such as skin burns. Timely diagnosis and correct initial treatment are crucial. In some severe cases, respiratory sequelae may persist (e.g. tracheal stenosis, tracheomalacia, bronchiectasis, bronchial hyperreactivity, bronchiolitis obliterans), so there is an indication for subsequent outpatient reassessment.

7.3. Safety rules

Very often forest fires' related accidents are due to insufficient knowledge of fire behaviour. This document is intended to close that gap and help fire managers understand fundamental concepts that often translate into standards or basic rules that should be a consistent part of personal training for all actors involved in any phase of fire management. This section will describe some of the most widely used rules and guidelines currently used worldwide.

7.3.1. Standard FF orders and Watch Out Situations

The United States has pioneered modern wildland fire science in the same way they have pioneered the development of fire safety protocols and procedures. In the mid-20th century, several fatal accidents took the life of large groups of firefighters in some infamous wildfires in the US. Some of them are still studied and presented in training sessions nowadays: the Blackwater fire in Wyoming (1937), with 15 deaths; the Bryant Canyon fire in California (1947), with 11 deaths; the Man Gulch fire in Montana (1949), with 13 deaths; the Rattlesnake fire in California (1953), with 15 deaths or the Inaja fire in California (1956), with 11 deaths. This sequence of events, in particular the last one, triggered a response from the US Forest Service, and a Task Force was created to analyse the events and to "*Recommend Action to Reduce the Chances of Firefighters Being Killed by Burning While Fighting Fire*" (USDA Forest Service, 1957). The task force report originated the 10 Standard Fire Fighting Orders, first published by R.E. McArdle, (1957) and the 13 (now 18) Watch Out Situations. These two groups of rules consist of a set of lessons that the task force learned from analysing what went wrong in the fatal accidents. The report states that the number of casualties could probably be reduced, and fire suppression could be improved if good firefighting practices, closer supervision, and improved organizational functioning were used in all situations (Zimmerman & Parkinson, 2020). The task force also looked at near misses that had a positive outcome and emphasized the need to include the prediction of fire behaviour and weather forecasts in the strategy.

The "10 Standard Fire Fighting Orders" have been widely adopted, not only in the US, and are currently organized as a sequence of steps that firefighters must take to ensure safety during operations. They are grouped by three main topics – fire behaviour, fire safety, and organization – that aim to create the necessary conditions for the 10th rule to be applied. The 10 orders, or rules, are listed in Table 6.

Table 6. 10 Standard Fire Fighting Orders (NWCG, 2022)

Topic	Nbr	Order
Fire Behaviour	1	Keep informed on fire weather conditions and forecasts.
	2	Know what your fire is doing at all times.
	3	Base all actions on current and expected behaviour of the fire.
Fire Safety	4	Identify escape routes and safety zones, and make them known.
	5	Post lookouts when there is possible danger.
	6	Be alert. Keep calm. Think clearly. Act decisively.
Organizational Control	7	Maintain prompt communications with your forces, your supervisor, and adjoining forces.
	8	Give clear instructions and be sure they are understood.
	9	Maintain control of your forces at all times.
	10	**Fight fire aggressively, having provided for safety first.**

This set of orders was written in a way that they would be self-explicative, but more detailed information can be found at the National Wildfire Coordinating Group website (https://www.nwcg.gov/publications/pms110, visited on 17/11/2023).

The 18 Watch Out Situations (NWCG, 2022) were listed to describe particular situations that must be an alert trigger to all firefighters, in case they face any of them during any firefighting operation (hence the name "watch out"). These situations, listed in Table , are a sort of an expansion from the 10 Standard Firefighting Orders.

Table 7. 18 Watch Out Situations (NWCG, 2022)

Nbr	Watch out situation
1	Fire not scouted and sized up
2	In country not seen in daylight
3	Safety zones and escape routes not identified

4	Unfamiliar with weather and local factors influencing fire behaviour
5	Uninformed on strategy, tactics, and hazards
6	Instructions and assignments not clear
7	No communication link with crew members/supervisor
8	Constructing fireline without safe anchor point
9	Building fireline downhill with fire below
10	Attempting frontal assault on fire
11	Unburned fuel between you and fire
12	Cannot see main fire; not in contact with someone who can
13	On a hillside where rolling material can ignite fuel below
14	Weather is getting hotter and drier
15	Wind increases and/or changes direction
16	Getting frequent spot fires across line
17	Terrain and fuels make escape to safety zones difficult
18	Taking nap near fireline

Similar to the 10 Fire Fighting Orders, these watch out situations were written to be self-explicative, and further explanations can be found at the National Wildfire Coordinating Group website (https://www.nwcg.gov/publications/pms118, visited on 17/11/2023).

One of the intentions of these two tools is to be interiorized by all individuals that may work in fire management actions, particularly in firefighting, and to “place emphasis on the identification of trigger points that remind firefighters to reanalyse LCES concepts” (Zimmerman, 2020).

7.3.2. LCES - LACES

The LCES system was developed by Paul Gleason (1991), an experienced Hotshot Crew Supervisor from the USDA Forest Service, in the aftermath of the Dude Fire in 1990, in Arizona. Despite all the effort put into the adoption of the 10 rules and 18 situations, well established by then, this fire took the life of 6 firefighters. Gleason was asked to investigate the accident and extract some lessons. He stated in his report, *“Throughout my career I have dealt with wildland fire suppression, as a Hotshot Crew Supervisor, with only minor injuries occurring to those I have directly supervised. That is primarily because of two reasons: luck (which cannot be ignored) and basic lessons which I learned from the exceptional firefighters I have had the opportunity to work with*”. It was precisely those “basic lessons” that he managed to incorporate in the acronym LCES, which correspond to **L**ookouts, **C**ommunications, **E**scape routes, and **S**afety zones. The underlying idea was that everyone on a fire front would constantly observe this set of safety-related items. All firefighters should establish LCES before starting any activity on a fire. The NWCG Incident Response Pocket Guide (NWCG, 2022) lists the items that should be observed in each topic, and we transcribe them here:

1) Lookout(s):
    a. Experienced, competent, trusted
    b. Enough lookouts at good vantage points
    c. Knowledge of crew locations
    d. Knowledge of escape and safety locations
    e. Knowledge of trigger points
    f. Map, weather kit, watch, Incident Action Plan (IAP)
2) Communication(s)
    a. Radio frequencies confirmed

    b. Backup procedures and check-in times established
    c. Provide updates on any situation change
    d. Sound alarm early, not late

3) Escape Route(s)
    a. More than one escape route
    b. Avoid steep, uphill escape routes
    c. Scouted for loose soils, rocks, vegetation
    d. Timed considering slowest person, fatigue, and temperature factors
    e. Marked for day or night
    f. Evaluate escape time vs. rate of spread
    g. Vehicles parked for escape

4) Safety Zone(s)
    a. Survivable without a fire shelter
    b. Back into clean burn
    c. Natural features (rock areas, water, meadows)
    d. Constructed sites (clear-cuts, roads, helispots)
    e. Scouted for size and hazards
    f. Upslope? Downwind? Heavy fuels? Each means more heat impact meaning larger safety zone.

With more or less adaptations, the LCES system is nowadays the basic safety protocol used worldwide and is viewed as a simplification of the 10 Fire Fighting orders into its essential elements, keeping the focus on safety.

In 2001, Thorburn & Alexander proposed the inclusion of an "A" for Anchor Points, again in the aftermath of a fatal accident, this time in Alberta, Canada, in 1995. The authors define "anchor point" as a barrier to fire spread, designed to be employed as a starting point to begin fire suppression work in order to minimize the chance of being outflanked by a fire.

This new protocol, LACES, was adopted by the Alberta Fire Protection Agency and by many other fire services outside of US, namely in the Mediterranean countries.

LACES has a sequential implementation: **L**ookouts observe the fire being fought from an **A**nchor point, and **C**ommunicate all important observations to the crews, who, in case of danger may use the **E**scape routes to reach a **S**afety zone. This last point, the safety zone, is of the utmost importance to safeguard the possible retreat in case of danger. In theory, a safety zone is a pre-planned area of refuge that can be utilised without the use of fire shelters in case of entrapment (Page & Butler, 2017). Choosing a safety zone is not always easy, and several models (e.g. Butler & Cohen, 1998; Butler, 2014) and guidelines (e.g. Green & Schimke, 1971; Butler & Cohen, 1998b) have been produced to help in the task. We retain here one of the latest suggestions by Butler (2018), in which he combines slope, wind speed and fuel height, to assess the Safe Separation Distance (SSD) that must be observed to consider a safety area effective. The SSD is calculated using Equation 2, where Δ is the slope-wind factor, according to Table .

SSD (*Safe Separation Distance*) = 8 x fuel heigh x Δ   Equation 2

Figure exemplifies the variation of the SSD with slope and wind, according to the above formulation.

Table 8. Slope-wind factor (Δ) to calculate SSD in different vegetation heights (Butler, 2018).

Slope-Wind factor (Δ)	**Terrain slope (%)**		
Wind speed (km/h)	Flat (<15%)	15-30%	>35%
Weak (0-10)	**1/0.7/0.7**	**1/1/1**	**4/2/2**
Moderate (10-25)	**2/1/1**	**4/2/1**	**6/3/2**
Strong (>30)	**4/2/2**	**6/3/2**	**8/3/2**

Fuel < 3m / 3m > Fuel > 15m / Fuel > 15m

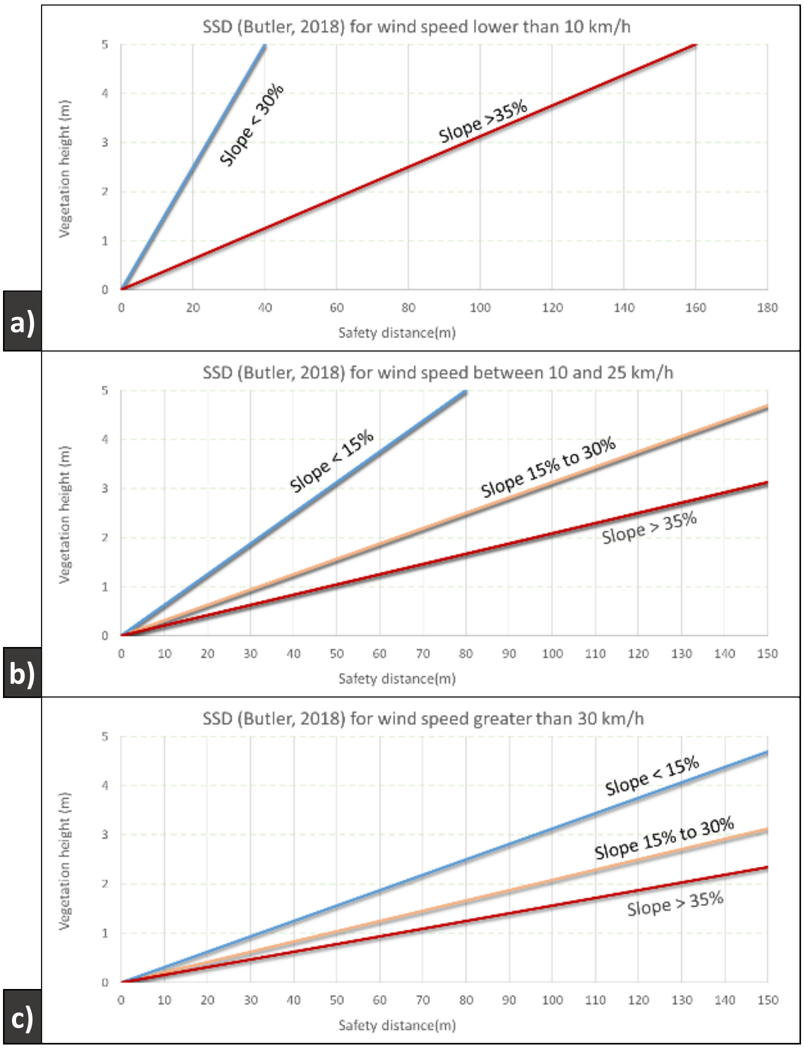


Figure 10. SSD for a) weak wind, b) moderate wind and c) strong wind, for the 3 classes of slope in the formulation. (Butler, 2018)

7.3.3. Additional recommendations for fires on slopes

Lahaye et al. (2018b) investigated 103 entrapments across the world, most of them in Southern Europe (Lahaye et al., 2018c) and in Australia (Lahaye et al., 2018d). They highlighted that 40% of them happened while the entrapped teams were on slope steeper than 20°, above the position of the fire line. The same study found that 30% of the entrapments they studied happened on slope prone to vorticity-driven lateral spread, i.e. lee-facing slopes steeper than 20° with wind speed over 20 km /h (J. J. Sharples et al., 2012).

As a result, those two critical watch-out situations are now considered with care in the fire behaviour analyst trainings provided in New South Wales (Australia) and in France since 2023.

In the same way, we can also mention the US NWCG "Downhill fireline construction checklist" (NWCG, 2022). Fighting a fire or building a fireline downhill, with the fire below, is something to avoid at all costs unless it is absolutely necessary. If it needs to be done, then several extra steps should be considered. The checklist refers to LCES protocol but includes the anchor points in two items. For this reason, we opted to merge them adapting the original NWCG (2022) checklist to present here:

1) Discuss assignments with supervisor(s) and team leaders before starting downhill work. The persons in charge should stay with job until completed.
2) Only begin working after the work location is thoroughly scouted and the feasibility of the work assessed by the supervisor(s) or team leaders.
3) Coordinate LACES for all personnel involved.
    - Crew supervisor(s) is in direct contact with lookout who can see the fire.
    - Establish communication between all crews.
    - Rapid access to safety zone(s) in case fire crosses below crew(s).
    - Starting point will be anchored for crew(s) building fireline down from the top.
4) Use direct attack whenever possible. If not possible, the fireline should be completed between anchor points before being fired out.
5) Fireline will not lie in or adjacent to a chute or chimney.
6) Monitor bottom of fire; if potential exists for the fire to spread, take action to secure the fire edge.

To wrap up this section, and despite all the rules, check-lists, or tools that were presented here, or others that most certainly may exist elsewhere, we highlight here 3 of the most important "Rules of Engagement for Firefighter Survival" from the International Association of Fire Chiefs of the United States Safety, Health and Survival Section (IAFC, 2016), related to structural firefighting, and perfectly applicable to wildland firefighting:

> (…)
> 3) DO NOT risk your life for lives or property that cannot be saved.
> 4) Extend LIMITED risk to protect SAVABLE property.
> 5) Extend VIGILANT and MEASURED risk to protect and rescue SAVABLE lives.
> (…)

This sums up what should be the priority in wildland firefighting: individual and collective safety.

8. Case Studies

8.1. Large fires

8.1.1. Pedrógão Grande Fire

The fires that started in the early afternoon of 17 June 2017 near Pedrógão Grande (PG) will be remembered as the worst on record in Portugal as they destroyed around 45 000 ha of vegetation and forestry land but above all because they caused the death of 66 persons. This description is based on Viegas *et al.* (2017) and on Viegas *et al.* (2023).

The fire was initiated by a 15 kV electrical power line at two locations separated by 3 km (Fig. 11). The interaction between a thunderstorm, and the two fires was extensively analysed in Pinto et al. (2022) using weather station, satellite and radar observation data. As a result of this interaction, the two insufficiently manned fires began to spread out of control. The very unusual conditions that resulted from that interaction produced the merging of the two fires during the late evening of that day, which are described here. This process is designated a Junction Fire (Viegas et al., 2012; Raposo et al., 2018) and is accompanied by powerful convective processes resulting in very fast fire spread, which in this case caused the death of 66 persons in a period of 2 h. The spread of the fire was accompanied by the development of the very tall smoke column and the violent convective processes that were reported in Viegas *et al.* (2017), showing the relevance of the merging processes of the two separate ignitions on the PG fire development, namely, to show that the fire development would have been quite different if only one of the fire ignitions had occurred.

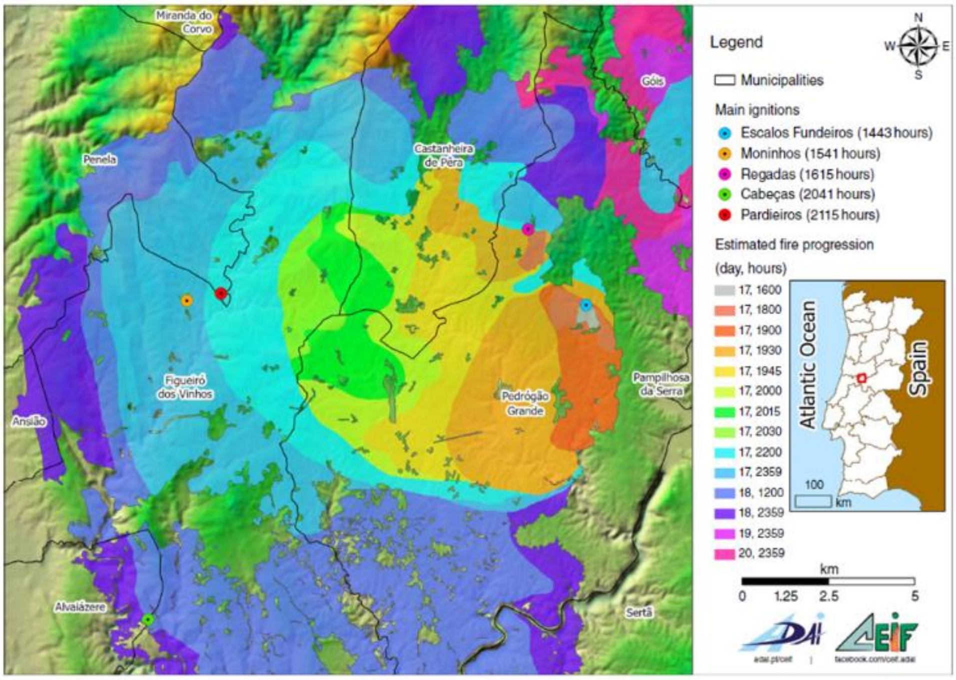


Figure 11. Map of Portugal and of the area of the fire of Pedrógão Grande with fire ignition points and the fire spread shown. (authors illustration)

1800 hours

1815 hours

Figure 12. Views of the column of the fire of Escalos Fundeiros at 1800 hours and at 1815 hours, showing the interaction with the downflow produced by the mesoscale convective flow.

Fire ignition and spread The PG fire occurred in the district of Leiria, in central Portugal (Fig. 11), in a period of drought with air temperatures above 40°C and very low relative humidity. The wind flow in the region was from the NW and not very strong. A large meso scale convective system developed over the central-western Iberian Peninsula and moved W-NW, causing several fires due to lightning, but at 1430 hours (all indicated times are local time, which is UTC (Coordinated Universal Time) plus 1 h), when the PG fire started, the most active part of this system was still nearly 100 km away and electrical strikes were not registered in the area of the fire until 1800 hours (Pinto et al., 2022). The PG fire was caused by two ignitions that occurred near Escalos Fundeiros (EF) at 1430 hours and near Regadas (RE) at 1540 hours. Both ignitions were caused by an electrical power line touched by the foliage of trees below and very close to the lines. The two places are 3.2 km apart but the road from EF to RE was not very accessible to heavy vehicles. As there were other fire ignitions in the area, firefighting resources were dispersed and there were not sufficient ground and aerial means capable of coping with the very difficult spread of the EF fire, which at 1530 hours started to spot and threaten houses in the village of EF. When the RE fire was detected, there also were no resources to deploy there, and the fire was left spreading practically on its own. Between 1800 and 1815 hours, a downflow from the MSC, which was not yet over the region of the fire, forced the fire column to tilt towards the SW, spreading flames over a wide area and making control of the fire virtually impossible from that time. This process was recorded continuously by video cameras installed in the Fire Brigade of PG Station. Two frames recorded at 1800 and 1815 hours by the north-facing camera are shown in Fig. 2. The process of this downflow was carefully studied using various methods, namely radar and ground sensors, to analyse the very complex flow produced by the thunderstorm and by the fire in Pinto et al. (2022). The EF fire started to spread towards the town of Pedrógão Grande, sweeping through a large number of villages. At the same time, the RE fire, which was smaller, also spread completely out of control, towards the NW, forming the right side of a large pincer that was now advancing like a curved fire front more than 20 km long, threatening an approximately circular area of 10-km diameter where hundreds of people lived, who felt their life threatened by this very violent and roaring fire (cf. Fig. 11).

Merging of the two fires There is evidence that after 1930 hours, both fires had their inner flanks very close to each other, making a small angle between them, therefore with the ideal conditions to merge as a junction fire, studied by Viegas et al. (2012), Raposo et al. (2018) and Ribeiro et al. (2023). Between 1930 and 2030 hours, the process of merging induced very strong winds in the area ahead of the fire. The rate of spread (ROS) of the head fire was of the order of 14 km h^{-1}. The quick combustion of a very large amount of vegetation produced a convection column that reached 12 000 m at 2010 hours and remained at that height for several hours. Flames of the order of 50–100 m long separated from the vegetation were recorded, creating an environment near the ground like the inside of a furnace. There are reports of tree stands starting to burn from their tops to the ground, persons in the area of the fire were in pitch dark and reported that the air was full of fireballs. Besides this, pieces of wood, branches and bark flew all around, sometimes igniting new fires. In at least two very localized areas, wind tornadoes twisted and broke many trees more than 20 cm in diameter, breaking them like toothpicks. The wind velocity required to cause this is estimated to be of the order of 200 km h^{-1}. Similar phenomena were observed in the merging process of the McIntyre and Bendora fires near Canberra on 18 January 2003, with a very fast spreading fire (27 km h^{-1}) and a tornado that broke tree trunks larger than 30 cm in diameter (Doogen, 2006). The perception of the violence of the fire caused by the noise produced by its very tall and roaring flames that threatened to destroy everything in their path caused many citizens to decide to flee from their houses. Some of them took this decision despite knowing that their houses would usually sustain the passage of a fire, which most of them did. While escaping in their cars, many persons, sometimes entire families, were caught by the smoke, loss of visibility and flames and lost their lives. Particularly dramatic was the situation of a stretch of 200 m of Road N326-1, between Figueiró dos Vinhos and Castanheira de Pêra, in which 30 persons were killed inside or near their cars. The lack of maintenance of vegetation – including trees – in the vicinity of the main roads contributed to the lack of survival conditions for the citizens. We identified one particular pine tree that was very close to the road edge and fell over the road with the very strong fire-induced wind, crossing it from one side to the other. This tree and a group of cars that crashed into each other created a trap from which the cars could not drive out. Based on the testimony of survivors and of persons who passed by that road before or during the accident, we were able to identify at least 16 persons whose deaths can be directly attributed to this tree. The main fire was controlled on 22 June by 2350 hours with the effort of more than 1400 firefighters and other agents after burning a total area of 45 328 ha.

8.1.2. Garrocho (Serra da Estrela) Fire

The Garrocho/Serra da Estrela fire in Portugal is noteworthy for the operational lessons it offers. This wildfire stands out for its size, covering approximately 25 thousand hectares, and its duration, remaining active for 12 days, from 06 Aug 23 to 17 Aug 23, being extinguished on 03 Sep 23. Fortunately, there were no casualties, but the main impacts included damage to several buildings and the affecting of a large protected natural area.

The fire alert was given at 01:18 on 06 Aug 23, and since the beginning, the firefighting endeavours encountered significant challenges attributable to restricted terrain access, particularly exacerbated during the nocturnal period. Despite apparent nearly contained in various occasions, unforeseen incidents disrupted the implemented strategy. Two of these incidents will be described shortly, with valuable lessons to learn.

Eruptive fire in a gorge, triggered by a helicopter operation

Around 10:23 on the first day, a firefighting helicopter entered in the fire scene, deploying its team of eight members. Supported by aerial water discharges from the helicopter, the team started the ground firefighting, descending the slope with the intention to close this flank at the base of the gorge (Figure).

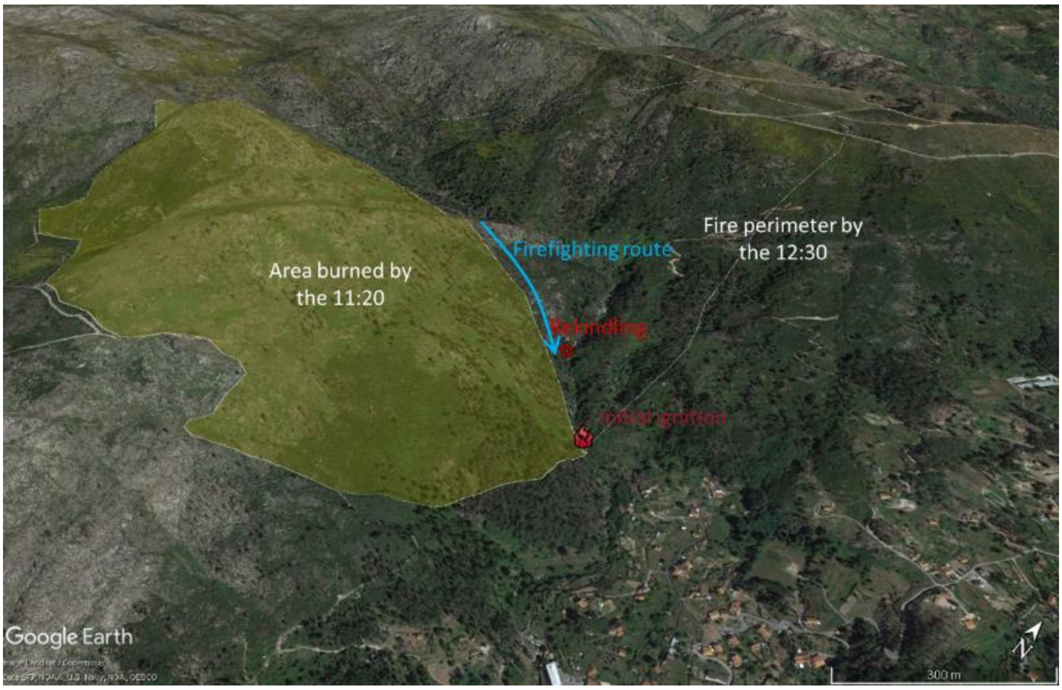


Figure 13. Operational situation at 11:30 on 6Aug23. (authors illustration)

The helicopter's water supply reservoir was only 5 km away from the discharge location, but it was about 600 m higher in altitude, significantly reducing the helicopter's autonomy and operational time. After about an hour, the ground combat team, supported by the helicopter, had nearly reached the bottom of the flank. The rest of the fire perimeter was almost resolved, with only a small section near the base of the gorge remaining. However, the helicopter needed refuelling before completing the mission.

Following operational doctrine, the helicopter had to retrieve its team before leaving the fire scene for refuelling. This retrieval occurred near the waterline at the base of the gorge, where the ground team was stationed, avoiding the need for them to climb the slope. Testimonies indicated that the turbulence caused by the helicopter when retrieving its team reignited the fire in this area, carrying the flame front to the opposite slope of the gorge. At this point, an eruptive fire behaviour episode was occurred (Figure), leading to the loss of control over the situation that was almost contained.

This incident provided two main lessons. The first relates to the determination of the autonomy of aerial means, which should consider not only the distance between water supply points and fire intervention zone but also the difference in elevation between these sites. The second lesson emphasizes the caution that operators of aerial means should exercise in their operations to prevent atmospheric turbulence, naturally generated by the aircraft, especially helicopters, near the fire front and sensitive/critical points.

Rekindling in Vale da Amoreira

Between 12Aug23 and 14Aug23, with a significantly expanded fire perimeter, surrounding a burned area of 9 thousand hectares, the fire was spreading slowly being nearly under control. All fronts were under “active surveillance and residual extinguishing maintenance", except for a hot spot to the northeast, where firefighting was progressing favourably. On 15Aug23, at 15:44, the fire was classified as "under resolution."

The Vale da Amoreira village was one of the critical areas due to several rekindlings recorded in this area and the potential opening of the associated fire front. On the northwest slope of this village, where a later and abrupt rekindling occurred, the fire had reached a few days earlier, being stopped halfway up the slope, leaving its lower part unburned. To consolidate the burned perimeter, a firebreak was opened halfway up the slope using a bulldozer. There was also a firefighters’ concentration point in Vale da Amoreira, leading to increased resources in this area.

At 15:47 of 15Aug23, just three minutes after considering the incident resolved, a strong rekindling occurred in Vale da Amoreira (Figure), quickly opening three fire fronts progressing in divergent directions, primarily due to the heterogeneous local winds caused by the rugged topography of that area. According to a citizen's testimony who observed the development of this episode from the opposite slope, the rekindling occurred in an area with a significant accumulation of dry vegetation. In response to this rekindling, a helicopter hovered near that location, resulting in the sudden widening of the flame front and the emergence of sparks projecting down the slope after the firebreak opened by the bulldozers, which had not yet burned. We did not obtain details to analyse the helicopter's manoeuvre in detail, but other citizens of Vale da Amoreira corroborated this testimony. From this moment until 17Aug23, the situation again spiralled out of control, causing the fire to spread with great intensity to the east, adding another 6 thousand hectares to the previously burned area.

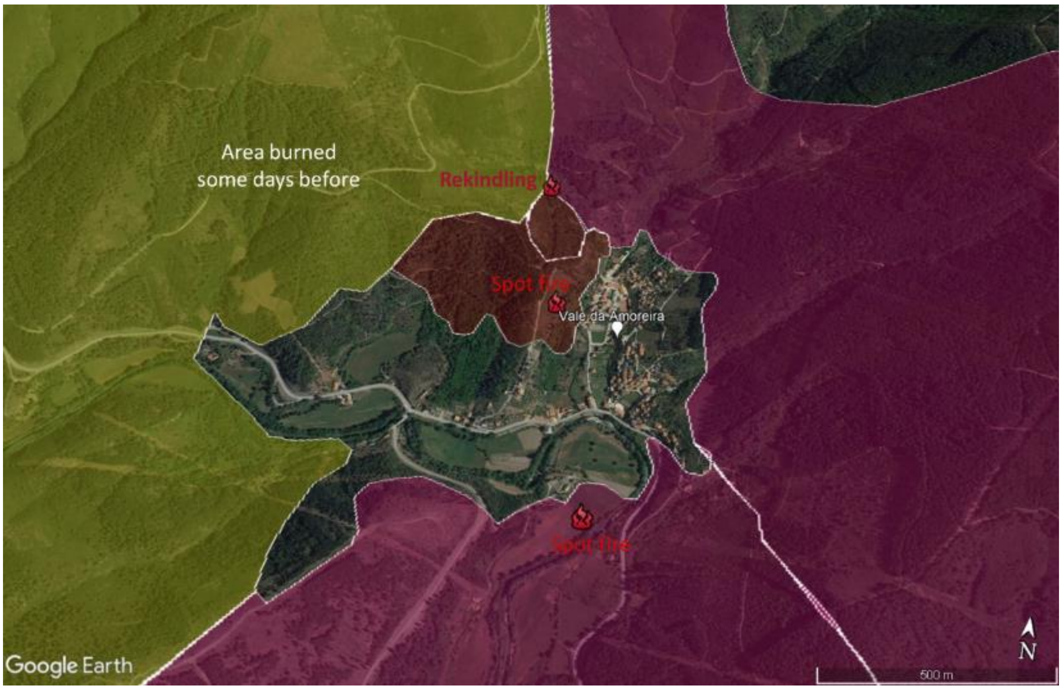


Figure 14. Operational situation on 15Aug23. (authors illustration)

Several lessons can be drawn from this episode. The first follows the reinforces the lessons from the previous incident, serving as a warning about the danger posed by helicopter-induced turbulence, requiring operational considerations of these potential effects. The second lesson pertains to the posture of operational means, which were very close to the rekindling site but might have been more relaxed due to the favourable evolution of the firefighting and its entry into the resolution phase. Finally, operations to consolidate halfway up the slope should be avoided because incandescent fuels, pushed by the wind, may roll down the slope, causing new ignitions in the unburned part. In this case, a tactical fire operation to bring the burned area to the bottom of the slope or continuous and effective surveillance of that slope for immediate action would be necessary, which did not occur.

8.2. Accidents

8.2.1 - Accident of Freixo de Espada a Cinta

During the summer of 2003, among the various fatal accidents that occurred in Portugal, there is one that occurred at Freixo de Espada-à-Cinta on August 5 (cf. Viegas, 2004a) in which two persons lost their life due to a sudden fire blowup on the wide slope in which the fire developed in the bank of the River Douro in the northeast of Portugal just inside the border between Portugal and Spain (Figure 15). The area of interest for the present study was covered by surface vegetation that was a mixture of herbaceous-type vegetation with shrubs and some agricultural fields. The origin of the fire that occurred at 14:30 h is marked in the map as point A. The fire fighters tried to maintain the fire in the lower part of the slope and let it burn in the direction of the riverbank. When it reached the point marked B, the fire was practically controlled; only a small section of less than 50m of fire line remained to be extinguished. At this stage, the fire boss, who was at point C with a machine that was creating a fire break, informed his superiors that the fire was under control. Then suddenly the fire started to spread very quickly up the slope of a canyon above point B (cf. Figure 15) and blew up along the entire slope, reaching its top in a matter of minutes.

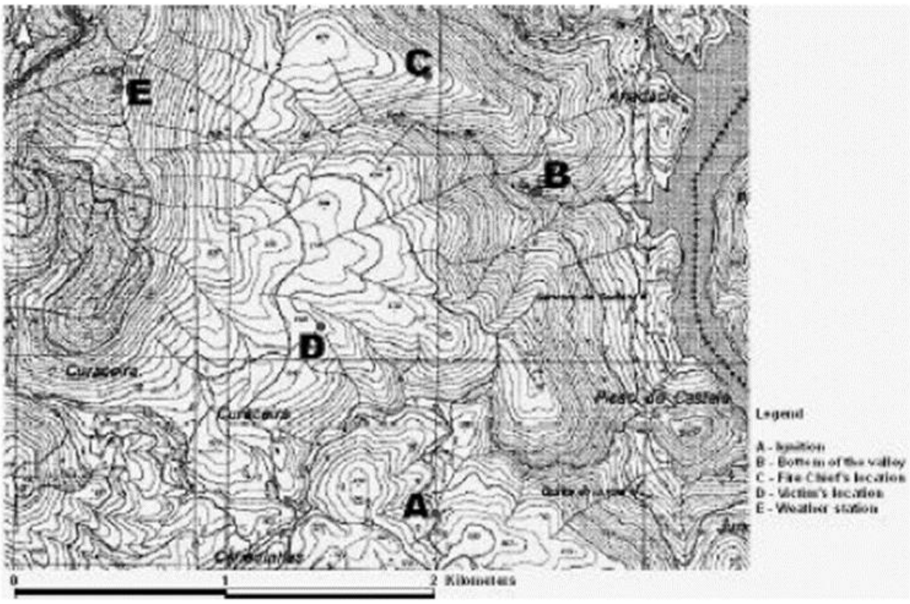
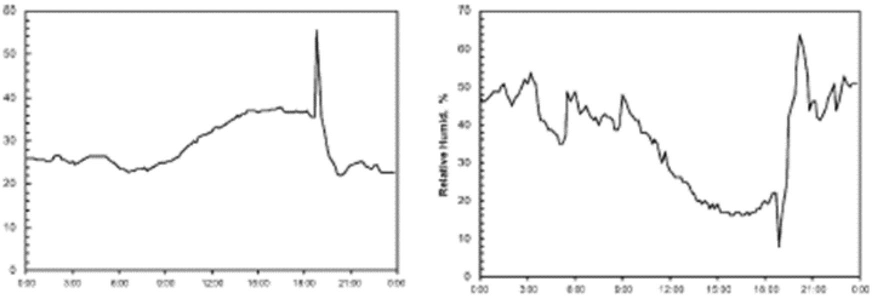


Figure 15 Topographic map of the area of the Freixo fire. North is indicated by the white arrow in the top-left corner of the figure

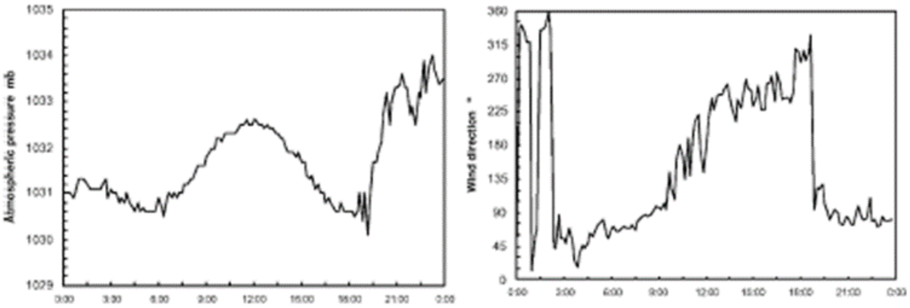
A couple that was checking the security of their property situated at D quite far from the fire and in principle not endangered by it were caught by the blowup and were both killed. More details about this accident can be found in the literature (Viegas, 2004a). At the top of the slope, at point E, a meteorological station was in the way of the fire front. Due to a fire break that existed on the top of the ridge, its sensors were not destroyed—although the heat damaged their protections—and the recorded data recorded every 10min were retrieved.

A trace of the air temperature, relative humidity, atmospheric pressure, wind direction, and wind velocity on the August 5 is shown in Figures 16–18. As can be seen in those figures, at about 18:30 h, all the records show very abnormal behavior: the temperature (10-min averages) went up to 55.5°C, the relative humidity dropped to 8%, the average wind velocity rose to 63.8km/h while the maximum (in 10-min periods) reached 96km/h.



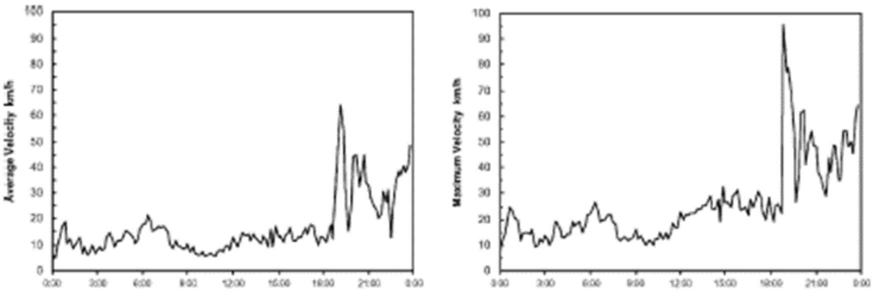
(a) (b)

Figure 16 (a) Air temperature and (b) relative humidity at Freixo during August 5, 2003.



(a) (b)

Figure 17 - (a) Atmospheric pressure and (b) wind direction at Freixo during August 5, 2003.



(a) (b)

Figure 18 - (a) Ten-minute average wind velocity and (b) maximum wind velocity at Freixo during August 5, 2003.

One particularly noteworthy feature of these records is the sudden change of wind direction that occurred at 18:40 h, as shown in Figure 3b. The wind that was blowing from the northwest (327º) in a downslope direction with an average velocity of the order of 12.2km/h, turned suddenly to south-southwest (95 to 120º), which is approximately the direction up slope from the bottom of the river valley, and increased to about 64 km/h 30 min later, with gusts of 96km/h.

This record is clear proof that the blowup that occurred in that fire produced wind velocities on the order of 100km/h that cannot be explained by any other atmospheric phenomenon other than the interaction between the fire and the overall flow induced by the slope. Although there is no image record of the accident, the descriptions given by all persons interviewed are consistent with a sudden fire acceleration of the fire from the bottom of the canyon to the ridge top and beyond it. The already mentioned loss of two lives is also a sad testimony of this surprising fire behaviour.

The mathematical model proposed by Viegas (2005) was used to predict the time evolution of the fire and the wind velocity induced during the blowup, and values of the order of 113km/h were obtained very much in line with the observations.

It must be remarked that this is one of the very few examples of real cases of accidents associated with a canyon in which detailed meteorological records very close to the fire exist and document and confirm the assumptions that are made in the development of the model to predict the behaviour of a fire in canyons.

8.2.2 - Accident of Famalicão da Serra (Portugal) 2006

This report is based on Viegas et al. (2009).

Introduction

In this accident, six firefighters lost their lives while attempting to suppress a large fire on the outskirts of the small village of Famalicão da Serra in the District of Guarda in the Centre of Portugal in the early afternoon of the 9th July 2006. Five of them were Chilean citizens that worked in Portugal as professional firefighters for Afocelca, a private company especially dedicated to protecting tree plantations belonging to a group of Portuguese cellulose plant companies. The sixth victim was a Portuguese volunteer firefighter of the local fire brigade of Gonçalo that was working with this team.

This accident had a tremendous impact not only due to the number of victims and the circumstances of the accident but also because a whole team of foreign professional firefighters had perished due to fire.

Description of the accident

Ambient conditions

The fire developed in a slope of Serra da Estrela overlooking a valley in which the small village of Famalicão is situated. The initial part of the slope was covered by agricultural land with some herbaceous and other light fuel vegetation; the upper part was covered by a mature pine stand that was clean and protected by a wide fire break.

Fire weather conditions were extreme that day, with temperatures of 35ºC and relative humidity of 15% with light wind blowing from East- Southeast, as can be seen in the data from the meteorological station of Meimoa.

Figure 19. General view of the area of the fire of Famalicão. The origin of the fire was near the bottom centre of the picture. The accident occurred in the canyon at the centre of the photo.(Viegas et al. 2009)

Fire origin and initial attack

The fire was started by accident at 12.30h in a farm due to sparks released by the blades of an herbaceous cutting machine when they touched some stones. Although two persons in the area tried to suppress the initiating fire using a car fire extinguisher, their efforts were unsuccessful, and the fire spread quickly through the farm and entered the slope.

A light vehicle of the local section of Volunteer Firefighters of Gonçalo was immediately dispatched and reached a rural road above the location of the fire origin. The fire extension overwhelmed their capacity and crossed that road. Helped by the slope and the wind the fire spread in the direction of the top of the mountain. This group left the place and headed for the top where another group of firefighters and several other forest owners and civilians were already working trying to protect the pine stand.

The alarm was given and, among other means, two heli brigades were dispatched to the fire. One of them was of the National Civil Protection and landed near the base of the fire at its right flank. Due to the ruggedness of the terrain in that area and the large quantity of fuel, the suppression of that flank was not achieved entirely. With the arrival of more fire trucks, this team left the area practically when the accident happened.

The other heli-transported brigade was that of Afocelca and was composed by five Chilean fire fighters. They landed on a road near the top of the slope in the pine stand border that they were required to protect.

The fire had already entered the pine stand as a flank fire backing against the wind and had burned the triangle seen in Figure 1, formed by the two fire breaks and the row of burned pines.

The team started to work with hand tools in a line down from the road along the row of burned pines and to its left. His Commander ordered a fire fighter of the local Brigade of Gonçalo to help the team of Chilean fire fighters to suppress the fire. Their position seemed to be safe and the group was advancing quickly down slope extinguishing the relatively short flames produced by pine litter that were spreading against wind.

Fire entrapment

After some minutes, at around 13.30 h there was a sudden sequence of fire eruptions below the position of the group and the fire started to burn the crowns, forming three strips that can be seen in Figure 19. There was a general alarm. Those that were placed above near the road escaped along the top of the ridge to the right side. There were spot fires, and some persons suffered slight burns while escaping.

The group of six firefighters that were at mid-slope decided to run away from the crown fire to the left side of the main fire. They went along the road towards the centre of the large canyon where they were.

Unknown to them the bottom of the fire was not being suppressed on the ground due to the difficulty of access. Only one helicopter was dropping water in the left flank of the fire near its bottom without support from the ground.

While the group was running away from the main fire the left flank entered the water line and the slope on the right side of the canyon. In few minutes the fire erupted along that slope cutting the escape route of the group. When the road reaches the water line there is an open area without vegetation. There the group split in two. The Portuguese fire fighter decided to stay in the same area ant took cover in a trench at the edge of the fire break.

The five Chilean dropped the material that they still carried with them and following the command of their boss departed uphill trying to escape to the two walls of fire that were approaching them. The terrain in that direction is quite rough, with terraces and barriers that are four to five meters in height. One of the firefighters could climb four of them and reach a distance of 60 meters from the starting point.

The strong convection induced by the erupting fire in the left slope forced the fire in the pine stand to converge over the group completely overwhelmed by smoke and fire.

The body of the Portuguese firefighter was found unburned due to the sheltering effect of the stone trench in which he took refuge. The five Chilean firefighters also died in the middle of the pine stand. Some of them had attempted to use a respiratory device but to no avail.

Fire Simulation

There was a general belief that the cause of the entrapment was a sudden change of wind direction. There was no evidence of this in the wind records.

A fire simulation in the Famalicão canyon was made in the Large Canyon Table DE4 of the Fire Research Laboratory (LEIF) of the University of Coimbra in Lousã. The basic canyon geometry was reproduced, and straw was used as fuel bed. A line fire was ignited to simulate the position of the left flank of the main fire when the Chilean Brigade moved in. The fire spread slowly widening its flanks until it reached the water line. When this happened, it erupted and burned the left side of the canyon in a few seconds.

This simulation showed that the fire-induced convection had produced the sudden change in behaviour that was interpreted as caused by a wind shift. The sequence of images of the tests shows the dramatic acceleration of the fire when it enters the left side slope of the canyon and there were no wind effects inside the Laboratory during the experiment.

Conclusions

The present case study involved the loss of six firefighters who were entrapped by a fire erupting in a canyon. What was apparently a safe situation and almost routine fire suppression became a death trap. Arguably, the use of fire shelters might have saved the lives of these men, but it cannot be assured.

The simulation of the accident in the Fire Laboratory produced convincing results of fire behaviour during the entrapment. It showed that no wind shift was required to explain the sudden acceleration of the fire on the left side of the canyon that caught the group of six firefighters by surprise.

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