State of the art of forest firefighting technologies and methodologies: fire behaviour, risk evaluation and countermeasures

Written by Elisa Guelpa and Vittorio Verda,
Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy

Edited by Michael Remes
EFPC Group

Abstract

Forest fire are significantly dangerous events, which frequently leads to hazards for human lives and losses in term of money and environmental aspects. Prevention and early detection are important operations for reducing wildfire frequencies and their effects. Wildfire propagation prediction and related risk are important issue for managing emergency events. In particular, risk evaluation is very important due to the large variability and unpredictability of fire driving forces, and the inaccuracy of fuel characteristic estimations. This paper aims to summarize the state of the art of wildfire behaviour, understanding, risk evaluation and countermeasures in relation to the AF3 research project.

Keywords
wildfire behaviour, risk, prevention, detection, extinction

Introduction

Forest fires, either from natural or human origin, are a growing source of destruction, for people, vegetation and for socio-economic aspects. This is particularly true in Mediterranean areas (Salis et al. 2013), as in many other areas where an increasing presence of severe fire seasons has been registered (Moreno et al. 1998; Viegas et al. 2006). Six million square kilometers of forest land have been lost around the world, in less than 200 years, mainly due to wildfires. (Dimopoulou and Giannikos I. 2004). It is estimated that 90% of fires between 2000 and 2009 in countries of south-western Europe were caused by human factors such as arson and negligence (Salis et al. 2013). Wildfire frequency and intensity is expected to increase in the future due to the temperature increase and changes in land use (Fernandes 2013, Moriondo et al. 2006).
In this framework, wildfires are receiving an increasing attention worldwide. It is important to possess a situational awareness in order to understand how information, events, and actions may affect the goals, both now and in the near future. In the context of planning, preparation and suppression of wildfires it is important to detect early the fire, know the fire locations, and understand its current and future growth and behaviour. Several strategies and technologies have been developed during decades for preventing, mitigating and suppressing wildfire. Fire propagation has been deeply analysed and several models have been proposed in literature, such as physical (Sullivan 2009a) and empirical models (Sullivan 2009b). Furthermore, several methods have been suggested with the aim of evaluating high risky areas in order to plan evacuations and extinction measures.
This article summarizes key information from the AF3 Project Summer School which was held in Rome on 20-22 September 2016. The main aim of the paper is give a state-of-the art of the understanding in fire management, technology and tool available for prevention and risk evaluation. This enables the work conducted within the AF3 project to be contextualized and compared with the knowledge developed in academies and companies, dealing with forest fire behaviour, prevention actions, detection and extinction technologies. The invited speakers were, D. Ascoli, A. Benali, P. Fernandes, M. Salis, L. Tonarelli.

1 Basics in fire behaviour

Fire behaviour can be defined as the way the fuel ignites, develops and propagates, when it interacts with vegetative fuels, weather, and topography (Pyne 1996). A wildfire is fundamentally defined through (Fernandes 2016):

- Movement of the fire front
- Vegetative fuel consumption
- Heat energy production through visible flaming combustion

The ignition is the starting point of each wildfire. It occurs as long as oxygen, fuel and a heat source are present, as indicated in the fire triangle (Fig. 1a). The ignition produces a chemical, exothermic reaction, which is the fire. The energy released during combustion is partially lost; the remaining quantity causes the ignition of other amount of fuel which makes the fire propagate.

About 30% or more, a fraction of the energy produced, is dispersed in the atmosphere by gases and particulates and about 5-15% of the heat released is absorbed and transmitted towards organic matter and mineral soil (Salis 2016). This last phenomenon may cause changes in the physical, chemical and biological properties of the soil.

The part of the heat that is not lost is transmitted to the surrounding fuel in the form of radiative and convective flux and as hot mass transfer. Radiation is the most relevant form of heat transfer occurring in the first phases of fire spread and when wildfires propagate in a stable atmosphere, i.e. in conditions of limited wind speed and slope (Salis 2016). Convection is due to transfer of heat through the movement of fluid masses (gases and smoke). In particular in forced convection the fluid masses movement is not free and is altered by external forces (e.g. wind) while in free convection the fluid masses movement is only related to the differences in density due to high temperature differences. As regards the heat that is transferred by the movement of burning firebrands it is commonly called spotting. To be effective, the firebrands must have enough heat to produce new ignitions when they touch the ground. Small and light firebrands can cover great distances, but usually they land completely extinguished or to too limited heat to initiate new ignitions (Salis 2016).

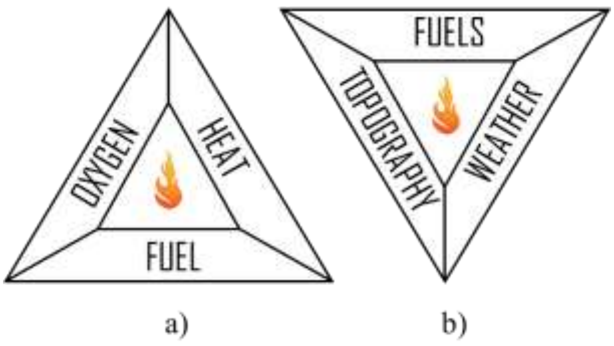


Fig. 1 a) Fire ignition triangle b) Fire behaviour triangle

The fire propagation is mainly driven by three factors, explained in the fire behaviour triangle (Fig. 1b). These are fuel type and characteristic, topography and weather.

As regards the topography, the first factor affecting fire behaviour is the presence of up-slope terrain. When fire propagates in up-slope terrain a fuel pre-heating occurs due to different phenomena, such as the smoke columns effects, the higher radiation contribution, the upslope winds and the upcoming tilted flames. Furthermore, regarding the terrain aspect, it affects the fuel moisture and temperatures.

Different types of fuel may produce very different types of fire, for example surface fuels (e.g. grass or shrub) lead to a surface fire while aerial fuels (such as trees) produce crown fires, which propagate a few meters above the ground. In addition, there are several fuel characteristics affecting fire propagation; among them, the most important are:

- Load (live and dead)
- Heigth
- Size and compactness (surface over volume ratio)
- Heat content
- Moisture
- Moisture of extinction

The weather affects wildfire in different phases. At first, during the fire ignition, temperature, relative humidity, rain and solar radiation have an influence on fuel temperatures and moisture values, and on the energy needed to start the combustion process. Secondly, wind speed and wind direction significantly influence the flow of oxygen needed for the combustion and the heat transfer processes and therefore the fire spread.
Human factor also affects the fire behaviour; such issue will be handled in paragraph 3.3, related to the extinction.

(a) (b) (c)

Fig. 2 a) Terrain-driven fire b) Fuel-driven fire c) Weather-driven fire (Salis 2016)

Fire behaviour can be described by several indicators, which include:

- Spread rate and direction;
- Intensity (fireline intensity, flame length, heat per area);
- Type of fire (crown fire, surface fire, ground fire);
- Rates of perimeter and area increase;
- Spotting density and distance;
- Fire size and shape;
- Residence time and burn-out time;
- Extreme behaviours (e.g.: fire whirls, eruptive propagation, etc.).

In particular, the rate of spread indicates the velocity the fire propagates, while the fireline intensity measures the numerical product of a fire's rate of spread, fuel consumption, and heat yield on a fire’s perimeter.

The prediction of wildfire propagation is a very important aspect for managing resources for fire extinction. Different models are available in literature. They can be grouped into three classes: physical (Sullivan 2009a),

empirical and semi-empirical models (Sullivan 2009b) and mathematical and simulation models (Sullivan 2009c).
Physical models solve both chemical and physical governing equations dynamically. The high complexity of the mechanisms that occur in forest fire leads to the need of very high computational resources. It precludes their use as operationally oriented tools (Sullivan2009a). For this reason, there is currently high interest in creating a compact physical model (Guelpa et al 2016, Guelpa 2016). Empirical models are built as a correlation between data collected from experimental fires, while semi-empirical models, which also use experimental data, are based on a physical framework without a distinction among different modes of heat transfer (Mell et al. 2007). They provide an approximation of the rate of spread when the fuel load, fuel characteristic, wind intensity and terrain slope are known. Such kind of models represent a valuable operational tool because they are based on algebraic equations and therefore are fast and easy to manage. Among the most used are McArthur's (1966) and Rothermel's (1972) models.

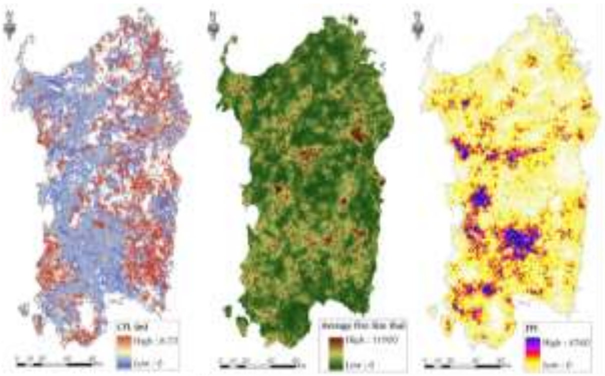
2 Risk

Risk is the possibility that something negative will happen. The risk can be obtained by combining the fire probability in a certain area and the effective damage the fire can cause on that area. In particular, wildfire risk is the probability that a fire of a specific intensity occurs, multiplied by the effects in terms of losses which can be obtained at that intensity (expected losses). The estimation of the expected losses (E) can be performed as indicated in Equation 1.

$$E = \sum_i p_i * d_i \quad [1]$$

where p is the probability of burning intensity level i, d is the damage that is obtain with an intensity i. Depending on the kind of damage considered, the expected risk changes its unit. It can be measured in terms of human lives if the risk on population is considered, in € if the economic risk is considered etc.
In case of wildfire there are two main risk maps which may help operators in fighting wildfire: preventive risk map and the real time risk map.
The preventive analysis provides the risk that a wildfire event occurs in a particular area, on a selected day. Preventive risk maps provide information about the potential ignition points and the prevalent propagation zones. It is called preventive because it is performed before a fire event occurs and therefore it potentially provides information for avoiding the fire ignition or preventively prepares operators for interventions.
The real time analysis enables evaluation of risks after a fire event has already started. It takes into account the current position and extension of the fire front and provides information about risk that can be obtained after a certain amount of time passes without using countermeasures. It can be very useful in order to manage resources for fire extinction and planning evacuation activities in the areas that most probably will be reached by fire.
Real time risk analysis requires for a fast calculation method, in order to be run various times for taking into account the input data variation (simulation in super real time). In both preventive and real time risk analysis, uncertainty of the various influencing variables, such as wind speed and direction, humidity and, fuel moisture must be taken into account. Also, preventive risk requires a fast calculation model, in particular if input data variability is taken into account.
For fast predicting burn probability and fire intensity, empirical and semi-empirical models or compact physical models can be used. For operational purposes, one of the most used models is the Rothermels'. Such a model receives as input data the topography, the weather conditions and the fuel characteristics (such as fuel loading, surface area to volume ratio, fuel depth, heat content of fuel, packing ratio, moisture of extinction, total mineral content, effective mineral content and ratio fuel moisture on oven-dry weight). In order to pass from the 1D rate of spread to the 2D propagation, fuel and terrain maps are necessary, in addition to a proper

model. Among them are methods based on cellular automata (Alexandridis et al. 2008), elliptical waves (Anderson et al 1982) and minimum travel time (Finney 2002).
Concerning preventive analysis, historical wildfire data are generally insufficient to map burn probability and intensity at fine scales, therefore recently in several studies landscape fire simulation models have been used. (Salis et al. 2013).
In Salis et al. 2013, the potential for losses related to different factors have been implemented. The approach has been applied in Sardinia for evaluating wildfire characteristics based on a historical grid for the definition of ignition points.



(a) *(b)* *(c)*

Fig. 3 Maps of simulation outputs for (a) flame length, (b) average fire size and (c) fire potential index (FPI), calculated by historical grid of ignitions. (Salis 2016)

In Vivalda et al 2017, the preventive tool is integrated with a Monte Carlo approach for considering the variability and unpredictability of wind direction and speed and the inaccuracy of the fuel parameter estimation.
As regards real time risk analysis in Vivalda et al. 2017, a real time tool is presented, based on a stochastic approach. A fire front propagation predictor based on the Rothermel model and a main propagation direction approach is used, obtaining a fast tool suitable for multi-scenario simulations. A Monte Carlo method is used for considering (through a stochastic distribution) the input quantities variability. A stochastic approach provides a more realistic view of the risks related to a wildfire event. The tool enables obtaining the risk distribution on the analysed areas, combining burn probability with different types of damage, such as population, vegetation and protected species, tourism and infrastructures. It is possible to observe some results when the model is applied to an area near Athens (Vivalda et al 2017).

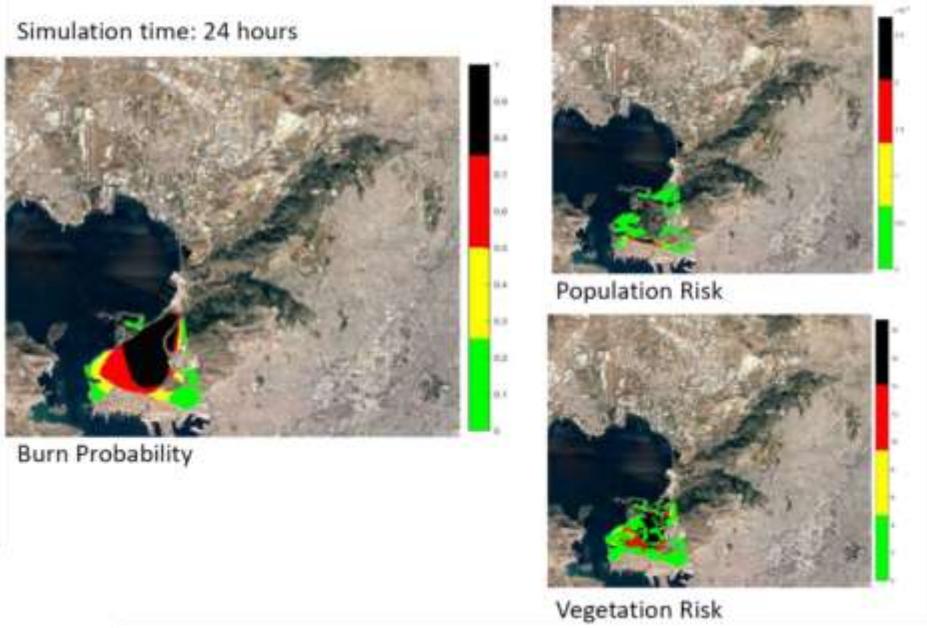


Fig. 4 Real Time risk analysis results. (Vivalda et al. 2017)

3 Countermeasures for firefighting

Several countermeasures can be used in order to avoid fire ignition, or for stopping and slowing down the front propagation. Prevention encompasses all the operations that can be performed before the fire event occurs in order to avoid the ignition or reduce the effect and the widening of wildfire. Detection concerns all the systems and the measures for understanding the position and the extension of wildfire in different conditions. Extinction encompasses all the means and operations which allow fire suppression. In the next sections, these three phases are deeply analysed in connection with the available devices resulting from research activities in firefighting.

3.1 Prevention

In general, firebreaks, i.e. areas that lack combustible fuels, help protect soil, water, air, plant, animal, and human resources by preventing the spread of wildfires or controlling prescribed fires. They consist of fire-resistant vegetation, non-flammable materials, bare ground, or a combination of these and allow slowing down fire (Demir et al 2009). Firebreak dimensions vary depending on fuel type, loads and position. They have always to be preserved through maintenance activity (Tonarelli 2016). The preventive silviculture allows obtaining firebreaks or decreasing the fuel load with a consequent reduction in potential wildfire intensity.

Prescribed fire has the aim of reducing fuel load and breaking fuel continuity in the litter layer as well as reducing ignition risk in particular in high-risk areas (Ascoli and Bovio 2009). According to Ascoli et al. (2012), prescribed fires allow a significant reduction of the potential fire intensity of 69%. Furthermore, they provide firebreaks, for hindering wildfire propagation.

Other several measures enable a better management of extinction operations (Tonarelli 2016). As regards the use of extinguishing means, it is important to utilize strategic point of water and helicopter bases (Tonarelli 2016). Furthermore, forest roads are an essential requisite for accessibility of fire-extinguishing appliances to the areas affected by fires. Observation towers are also strategic infrastructure for collecting information about the fire through a fast overview of the surrounding areas. (Tonarelli 2016)

3.2 Detection

Theoretically, detection should be performed by systems able to detect all fire events and that never detect non-fire events (low false-alarm rate). Actually, wildfire events occur in different conditions and in terms of extension and weather conditions. It is therefore impossible to possess an instrument for early detection and/or fire front evaluation that can be used in all the cases and which allows a perfect detection. It is necessary to consider all means that can be used and look for a trade-off between sensitivity and specificity. Fig. 5 show the importance of an early detection in wildfire management.

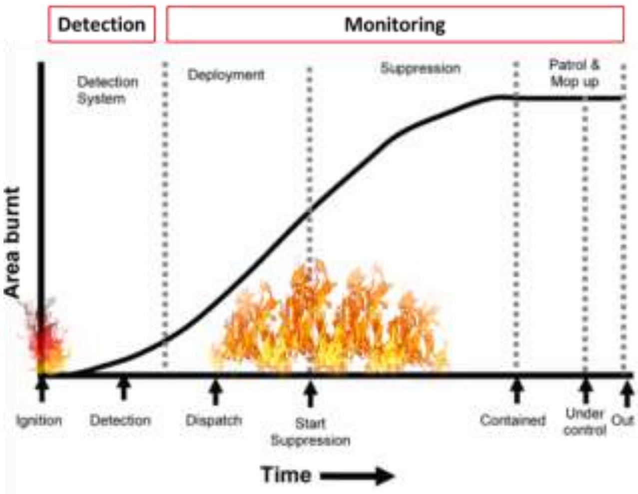


Fig. 5 Wildfire management phases (Benali 2016)

There are different ways of identifying a fire and its position, depending on the quantity detected. In particular the most used are:

1. Smoke, which is a very reliable signal during daytime, in particular when good weather conditions are prevalent; it can be affected by clouds, fog, haze, shadows. Smoke characteristics vary with different kinds of fuel, burning and combustion conditions. It can be detected through a spectral signature, which can be used to measure the variation of reflectance (or emittance) of a sensor with respect to wavelengths, or through motion capturing.
2. Heat, which allows fire detection also during night-time through the measure of the radiative fraction emitted by the fire, which follows Stefan-Boltzmann's law and Planck's law. In particular, short-wave to thermal infrared region are detected. (SWIR, MIR, TIR).
3. Temperature variation is another phenomenon which allows fire detection through proper sensor installation.
4. Flames and light produce visible effects and therefore it is possible to evaluate the presence and the position of a fire through the observation of the affected area.

Different means can be used for the detection of fire and the evaluation of its dimensions. They can be grouped into four families: human means, camera and sensors, airborne and spaceborne systems (Benali 2016):

- Humans (general public, operatives, ground staff, patrols) can directly observe the fire position and extension or its smoke from strategically placed monitoring towers. Clearly human fire detection is affected by a certain degree of uncertainty due to the probability that someone notices the smoke or the fire and also regarding the extension evaluation it has several limitations due to the area visibility. In particular, the factors that influence human detection are: the sensitivity, attention span and experience of the person involved; the fire size, position and distance; the plume shape characteristics and the atmospheric conditions. Other disadvantages of human detection are characterized by the high probability of faulty alarms and the presence of many remote areas less covered by humans and with limited telephone networks.

However over 95% of fires reported to the NSW Rural Fire Service between 2004 and 2009 were reported by the general public or authorities.

- Cameras and sensors can be useful for detecting and identifying the location of the fire and communicating the information. Sensors can be automatic, whereby an algorithm automatically detects fire and decides whether to send an alarm or not, or supervised, if there is a trained operator that sends the alarm. Different types of cameras that detect mostly smoke (visible and IR) and heat (thermal IR), are available commercially; they detect smoke and fire in a range of 15-80 km. Sensors detect parameters such as temperature, pressure and humidity, and gases; they may have high monitoring frequency and can be linked with cameras (Lloret et al.) to be used in inaccessible places. Such systems can also be affected by human errors in supervised systems. Their reliability also depends on fire size, topography, atmospheric conditions (visibility) and distance from the target.

  Some examples of detection systems are ForestWatch (http://evsusa.biz/productsservices/forestwatch/), which includes a semi-automatic smoke detection system that can be used during the day and FireWatch (http://www.fire-watch.de/) which automatically detects smoke and radiation and which can be also be used at night-time. Pilot scale systems are used in different countries around the world. Tests show that these systems allow a reliably detection of up to a 20-km range; some false alarms were also generated.

  Another detection system is Libellum (http://www.libelium.com/) which is able to measure temperature, humidity and several gas concentrations, analysing the information and sending an alarm; it also has an optional integrated camera. The information it sends includes accurate position and time information. Such systems can also be located in remote areas and have high monitoring frequencies, data recording and are also able to detect additional information (e.g. weather). The main drawbacks are the considerable detection times (10-220 min) and location errors (4-18 km), cost, lifespan and the possibility of omissions and false alarms, especially in the case of small fires. However future developments are likely to improve its performances.

- Airborne systems can be used in order to allows human to gain a better perspective of the fire location and extension. They can be used in combination with infrared imaging, that can be used during day and night, visible light, NIR cameras, UAV for visual flame detection and other kind of thermal cameras. The possibility of using airborne systems and the systems' potentials are affected by atmospheric conditions, altitude and fire intensity. The use of such kind of systems is quite expensive, requires planning aerial detection patrols and it is more suitable for monitoring than detection. However, they can be very manoeuvrable, deployable and flexible. The performances of such systems are influenced by camera and sensor characteristics. In particular, in addition to those indicated above, line scan systems, able to detect hotspots using MIR and TIR, red-eye systems for helicopter-based detection and monitoring and AMS-Wildfire on a UAV (unmanned aerial vehicle) are available commercially.

  In particular UAVs complement aircrafts and helicopters for detection when extreme conditions prevail at night-time with heavy smoke and low air traffic. The main drawbacks are related to problems of short endurance, stability and safety, on board processing and flight regulations. Spaceborne systems use sensors measuring reflectance in the visible and infrared (after an atmospheric correction), combined with algorithms that allow extracting specific information, such as active fire locations, burned areas etc. Clearly a good selection of sensors (with their characteristics) and algorithms is important for a correct fire detection. Fig 6 shows that that when higher spacial resolutions are required, the time frequency of the data signal is low; it rules out use of some types of sensors for wildfire detection applications. Weather conditions (e.g. fog, clouds), vegetation type and fire

dimension and intensity affect the outcomes of the system. However, such systems allow a large spatial coverage, low costs, and they are particularly suitable for monitoring medium-large fires.
Regarding existing systems, recent advances have improved early detection. The MODIS system (Zhang et al 2003, Hawbaker, et al. 2008) allows an automatic day and night-time detection using TIR, four times per day at a 1 km nominal resolution. It has been able to detect 50% for fires larger than 100 ha. With GOES-EFD (http://www.cstarsd3s.ucdavis.edu/systems/goes-efd/) it is possible to detect most fires within 30min (>2ha) and 31% before they are reported while the system RST-FIRES (Filizzola et al 2016) has provided the sole fire alert in 348 cases and in 227 warnings >1h out of any other source (N = 950).

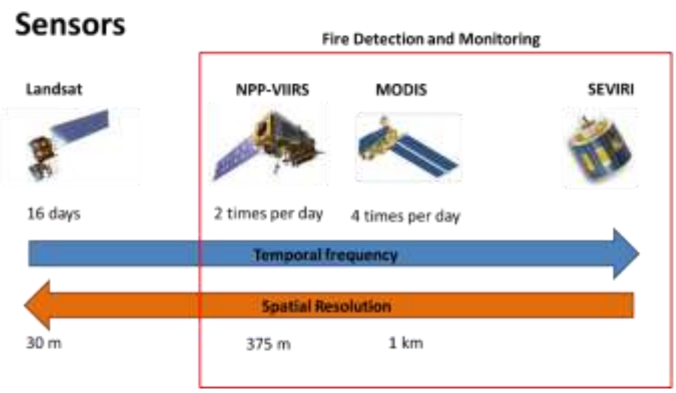


Fig. 6 Satellite based sensors (Benali 2016)

3.3 Extinction

The mitigation or stop of the fire front propagation has to be performed acting on one of the fire triangle sides: fuel, heat or oxygen (Morvan 2011). The oxygen reduction is a very complicated task in an unconfined environment, therefore the mitigation is usually conducted through reduction of fuel (which is often performed in the preventive phase) and the use of substances that reduce the quantity of heat released by fire, or increase the moisture of fuel content. Heat reduction is usually performed through the use of water directly on the flames. The most common kind of suppression strategies are direct attack through hand tools and the use of water tankers and aircraft.
In all these cases, firefighters have to be near to the fire front, running some danger, in order to get water to the flame and to the fuel. Firefighting can be a dangerous operation; the reduction of risk can be obtained through understanding fire behaviour and through a risk analysis. Among the most useful measurements for managing operations during fire extinction is the reaction intensity I, defined as per Eq. 1 and the flame length.
$I = H \cdot W \cdot R$
H is the heat of combustion, W is the fuel consumption rate and R is the rate of spread.
The knowledge of these measurements enables understanding of the fire type and the suppression difficulties (Fig 7). These quantities also enable evaluation of the type of suppression approach which is most useful in a particular set of circumstances.

Mature Jack or Lodgepole Pine*

Frontal fire intensity (kW/m)[a] [Btu/ft/s]	Flame length (m)[a] [ft]	Type of fire and fire suppression difficulty
<10 [<3]	<0.2 [<0.7]	Firebrands that cause an ignition to occur are self-extinguishing (i.e., fire fails to spread). Going fires remain of the smouldering ground or subsurface variety, provided there is a forest floor layer of significant depth and a general level of dryness*. Extensive mop-up is generally required. *Drought Code >300 and or Buildup Index >40.
10-500 [3-145]	0.2-1.4 [0.7-4.6]	Creeping or gentle surface fire. Direct manual attack at fire's head or flanks by firefighters with had tools and water is possible. Constructed fireguard should hold.
500-2000 [145-578]	1.4-2.6 [4.6-8.5]	Low vigor to moderately or highly vigorous surface fire. Hand-constructed fireguards likely to be challenged. Heavy equipment (bulldozers, pumpers, retardant aircraft, skimmers, helicopters with bucket) generally successful in controlling fire.
2000-4000 [578-1156]	2.6-3.5 [8.5-11.5]	Very vigorous or extremely intense surface fire. (torching common). Control efforts at fire's head may fail.
>4000 [>1156]	>3.5 [>11.5]	Intermittent crown fire to active crown fire development (at >10000kW/m)*. Very difficult to control. Suppression action must be restricted to fire's flanks. Indirect attack with aerial ignition (i.e., helitorch or A.I.D. dispenser) may be effective. *Violent physical behavior probable at frontal fire intensities greater than 30000 kW/m (i.e., blow-up or conflagration type fire run); suppression actions should not be attempted until burning conditions ameliorate.

Fig. 7 Reaction intensity and flame length related to fire suppression difficulties (Fernandes 2016)

Extreme fire behaviour is very dangerous for firefighters and usually impedes direct action on the fire, mainly for: fast fire spread, high fire intensity, crown fire activity, possibility of spotting and whirls and well-developed convection columns. In particular, drier fuels, presence of wind and up-slope terrain make fire behaviour more unstable and extreme. Most injuries and fatalities result from temporary and often sudden increases in fire behaviour activity. The main causes of tragedy and human life losses during extinction operations are due to the following reasons (Fernandes 2016):

- Underestimation of risk; in fact, small fires and isolated sections of large fires account for most incidents.
- Incorrect estimation of the fuel load, that appears lower than the actual.
- Sudden changes in wind speed and direction.
- Complacency; in fact, sometimes accidents happen in the mop-up stage.
- Alignment of driving forces.

More generally, all these aspects can be incorporated into three main aspects: deficiency in knowledge of fire behaviour, inaccuracy of weather data, lack of defined escape routes.

To achieve safety, it is highly important that all firefighters have a general knowledge and the leaders of the firefighting forces have a high degree of knowledge of fire behaviour (Barrows, 1951).

In order to reduce risk for firefighters, several provisions have been defined. Among them, the most widespread are (Fernandes 2016):

- Ten Standard Firefighting Orders, which are a set of systematically organized rules designed by USDA (USDA 2013) to reduce danger to personnel and increase firefighting efficiency
- Eighteen "Watch Out!" Situations, includes a series of dangerous situations to be careful of (USDA 2013)
- LACES Wildland Fire Safety System (Lookout, Anchor point, Communication, Escape routes, Safety zone) Fig. 8a, which is an acronym which should prompt firefighters to focus on the key factors. (Thorburn and Alexander 2001).

- Margin of Safety concept Fig 8b (Alexander at al 2005), where the safety margin is the difference between T1, which is the time for the fire to reach the safety zone (SZ), and T2 , which isthe time for the firefighter (FF) to reach the safety zone (SZ).
- Safety distances, Butler & Cohen (1998), which states the minimum distance that the operators have to keep from the fire, as a function of the flame length (Fig.8c).
- The Dead-Man Zone (Cheney et al 2000) which is a particularly dangerous event; it occurs when wind suddenly changes direction. Fig 8d depicts an example of a Dead-Man Zone situation, where a change in wind direction and speed make the flank fires become head fires. In this phenomenon, a change in wind direction may cause a change in the line of the fire such that the firefighters may have very small time to reach a safe area. This issue refers to firefighters working both in parallel attack or indirect attack.

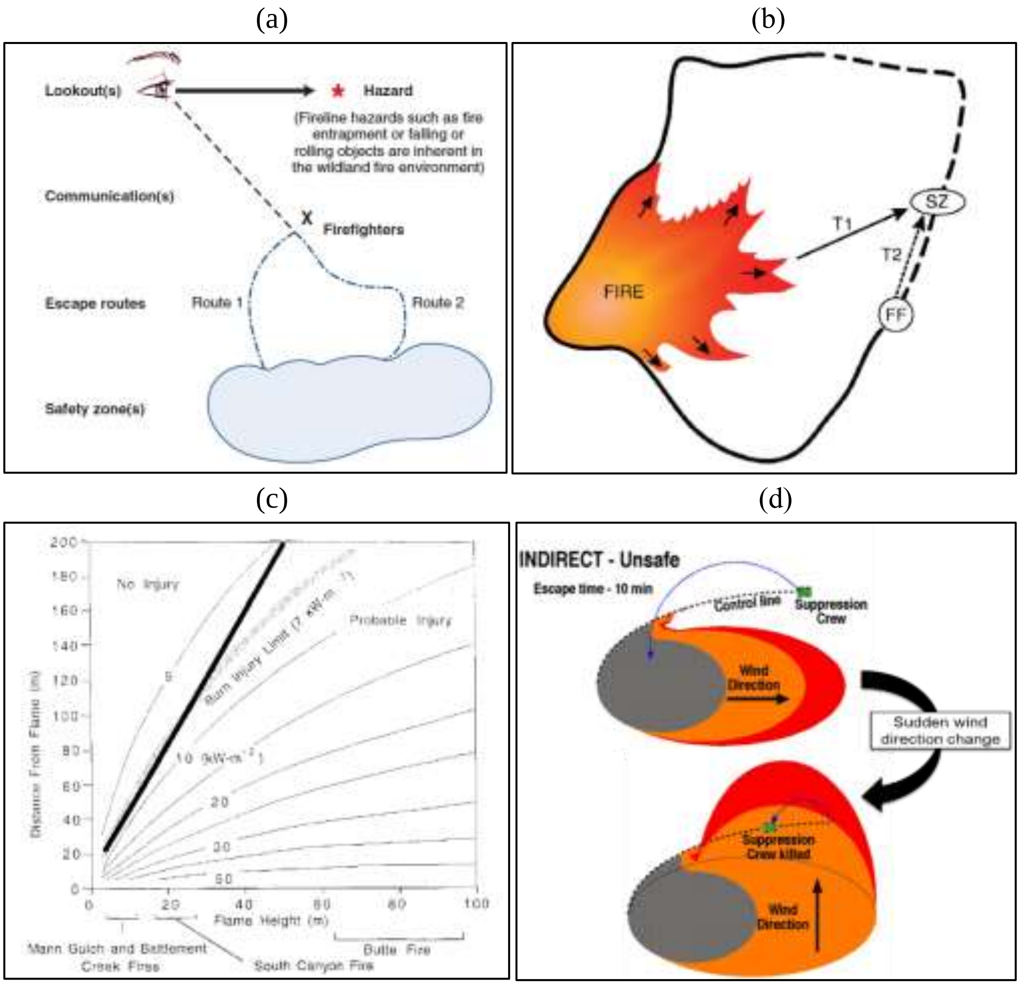


Fig. 8 provisions for firefighter safety a) LACES b) Margin of safety concept c)Safety distance d) Dead-Man Zone (Fernandes 2016)

Summary

In this paper, the current framework for forest firefighting approaches, methods and technologies has been presented. An introduction to fire behaviour have been given, including the main variables affecting wildfire ignition and behaviour. The various indicators used to describe the fire and the fire propagation models developed during last decades are also discussed.

Utility of risk maps has been discussed for both the prevention and extinction stages. Risk maps allow a better exploitation of fire suppression resources, planning of evacuation actions and reducing danger in firefighting activity. Risk can be evaluated for different parameters such as human, environmental, economic etc. In particular, recent works in wildfire safety field have been discussed, related to both preventive and real time analysis.
Furthermore, the countermeasures for slowing down and stopping fire propagation have been described. Prevention methods, techniques and systems have been analysed and technology for early fire detection, which is a crucial aspect in fire extinction, has been deeply discussed. The extinction stage has then been examined.

Acknowledgments

Work conducted within the European Project AF3 - Advanced Forest Fire Fighting. FP7 THEME [SEC-2013.4.1-6] Preparedness for and management of large scale forest fires. Grant agreement no: 607276

References

Alexander et al 2015 Proceedings of the 13th International Wildland Fire Safety Summit & 4th Human Dimensions of Wildland Fire Conference April 20-24 2015 Bolse Idaho USA

Alexandridis, A., Vakalis, D., Siettos, C. I., & Bafas, G. V. (2008). A cellular automata model for forest fire spread prediction: The case of the wildfire that swept through Spetses Island in 1990. Applied Mathematics and Computation, 204(1), 191-201.

Anderson, D. H., Catchpole, E. A., De Mestre, N. J., & Parkes, T. (1982). Modelling the spread of grass fires. The Journal of the Australian Mathematical Society. Series B. Applied Mathematics, 23(04), 451-466.

Ascoli D, Bovio G (2009). Il fuoco prescritto in Italia e l'esperienza in Piemonte. In: Atti del "III Congresso Nazionale di Selvicoltura". Taormina (CT), 16-19 ott. 2008. Accademia Italiana di Scienze Forestali, Firenze, pp. 378-384.

Ascoli D., Catalanotti A., Valese E., Cabiddu S., Delogu G., Driussi M., Esposito A., Leone V., Lovreglio R., Marchi E., Mazzoleni S., Rutigliano F.A., Strumia S., Bovio G. (2012) Prescribed burning experiences in Italy: an integrated approach to prevent forest fires Forest@

Barrows, 1951 Fire Behavior in Northern Rocky Mountain Forests

Benali A.(2016) Fire Detection and Monitoring, Presentation at AF3 Conference & Summer School on Forest Fire Management, Rome, Italy, Sept. 20-22, 2016

Butler & Cohen (1998), Int. J. Wildland Fire 8: 73-77

Cheney, P., Gould, J., & McCaw, L. (2001). The dead-man zone—a neglected area of firefighter safety. Australian Forestry, 64(1), 45-50.

Demir, M., Kucukosmanoglu, A., Hasdemir, M., Acar, H., & Ozturk, T. (2009). Assessment of forest roads and firebreaks in Turkey. African Journal of Biotechnology, 8(18).

Dimopoulou, M., & Giannikos, I. (2004). Towards an integrated framework for forest fire control. European journal of operational Research, 152(2), 476-486.

Fernandes P. (2016) Fire behavior and firefighter safety, Presentation at AF3 Conference & Summer School on Forest Fire Management, Rome, Italy, Sept. 20-22, 2016

Fernandes, P. M., Davies, G. M., Ascoli, D., Fernández, C., Moreira, F., Rigolot, E., ... & Molina, D. (2013). Prescribed burning in southern Europe: developing fire management in a dynamic landscape. Frontiers in

Ecology and the Environment, 11(s1)

Filizzola, C., Corrado, R., Marchese, F., Mazzeo, G., Paciello, R., Pergola, N., & Tramutoli, V. (2016). RST-FIRES, an exportable algorithm for early-fire detection and monitoring: description, implementation, and field validation in the case of the MSG-SEVIRI sensor. Remote Sensing of Environment, 186, 196-216.

Finney, M. A. (2002). Fire growth using minimum travel time methods. Canadian Journal of Forest Research, 32(8), 1420-1424.

Guelpa, E. (2016). Modeling strategies for multiple scenarios and fast simulations in large systems: applications to fire safety and energy engineering(Doctoral dissertation, Politecnico di Torino)

Guelpa, E., Sciacovelli, A., Verda, V., & Ascoli, D. (2016). Faster prediction of wildfire behaviour by physical models through application of proper orthogonal decomposition. International Journal of Wildland Fire, 25(11), 1181-1192.

Hawbaker, T. J., Radeloff, V. C., Syphard, A. D., Zhu, Z., & Stewart, S. I. (2008). Detection rates of the MODIS active fire product in the United States. Remote Sensing of Environment, 112(5), 2656-2664.

Lloret, J., Garcia, M., Bri, D., & Sendra, S. (2009). A wireless sensor network deployment for rural and forest fire detection and verification. sensors, 9(11), 8722-8747.

McArthur AG. (1966) Weather and Grassland Fire Behaviour. Forestry and Timber Bureau Leaflet 100, Commonwealth Department of National Development Canberra, 23 pp.

Mell W, Jenkins MA, Gould J, Cheney P (2007) A physics based approach to modeling grassland fires. International Journal of Wildland Fire 16,1–22

Moreno JM, Va´zquez A, Ve´lez R (1998) Recent history of forest fires in Spain. In ‘Large Forest Fires’. (Ed. JM Moreno) pp. 159–185. (Backhuys Publishers: Leiden, the Netherlands)

Moriondo M, Good P, Durao R, Bindi M, Giannakopoulos C, Corte-Real J(2006) Potential impact of climate change on fire risk in the Mediterranean area. Climate Research 31, 85–95. doi:10.3354/CR031085

Morvan 2011 - Numerical simulation of the interaction between two fire fronts in grassland and shrubland

NSW Rural Fire Service - http://www.rfs.nsw.gov.au/

Pyne, S. J. (1996). Wild hearth a prolegomenon to the cultural fire history of northern Eurasia. In Fire in Ecosystems of Boreal Eurasia (pp. 21-44). Springer Netherlands.

Rothermel RC, (1972). A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-11. (Ogden, UT)

Salis, M., Ager, A. A., Arca, B., Finney, M. A., Bacciu, V., Duce, P., & Spano, D. (2013). Assessing exposure of human and ecological values to wildfire in Sardinia, Italy. International Journal of Wildland Fire, 22(4), 549-565.

Salis M. (2016) Forest Fire Behavior, Presentation at AF3 Conference & Summer School on Forest Fire Management, Rome, Italy, Sept. 20-22, 2016

Sullivan, A. L. (2009). Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. International Journal of Wildland Fire, 18(4), 349-368.

Sullivan, A. L. (2009). Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models. International Journal of Wildland Fire, 18(4), 369-386.

Sullivan, A. L. (2009). Wildland surface fire spread modelling, 1990–2007. 3: Simulation and mathematical analogue models. International Journal of Wildland Fire, 18(4), 387-403.

Thorburn, R. W., & Alexander, M. E. (2001, November). LACES versus LCES: adopting an “A” for “anchor points” to improve wildland firefighter safety. In Proceedings of (pp. 6-8).

Tonarelli L. (2016) Forest Fire Management, Presentation at AF3 Conference & Summer School on Forest Fire Management, Rome, Italy, Sept. 20-22, 2016

USDA "Standard Firefighting Orders and 18 Watchout Situations". Risk Management. USDA Forest Service. Retrieved 2 July 2013.

Viegas DX, Abrantes T, Palheiro P, Santo FE, Viegas MT, Silva J, Pessanha L (2006) Fire weather during the 2003, 2004 and 2005 fire seasons in Portugal. In ‘V International Conference on Forest Fire Research’, 27–30 November 2006, Figueira da Foz, Portugal. (Ed. DX Viegas)

Zhang, X., Friedl, M. A., Schaaf, C. B., Strahler, A. H., Hodges, J. C., Gao, F., ... & Huete, A. (2003). Monitoring vegetation phenology using MODIS. Remote sensing of environment, 84(3), 471-475.

Vivalda C, Verda V, Carpignano A, Dell’Erba C, Cagliero D, Guelpa E (2017) Forest Fire Risk Analysis Methods and Simulation Tools 27TH European safety and reliability conference ESREL 2017 June 18-22 Portoroz Slovenia.