Fuelbreaks: a part of wildfire prevention

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Introduction

Following a study published in 2010 (Giglio et al 2010) from satellite observations and fire data collected on the field, during the period 1997-2008, the average surface burned worldwide every year represented 371 Million ha (savanna, grassland, shrubland, forest …), 69% (256 Million ha) in Africa, 14.5% (54 Million ha) in Australia, , 5.8% (22 Million ha) in South America (mainly in Amazonia), 4% (15 Million ha) in Central Asia, and the rest (24 Million ha) concerned mainly the boreal forests in North America and in Asia, the contribution of fires in Europe represented around 0.7 Million ha / year (essentially in Iberian peninsula, in Italy, in Greece and in Southern France). A great part of these fires took place in savanna and grassland, which represent, after a longtime evolution, the ecosystems the most adapted to fire. From an ecological point of view, these fires are necessary to maintain an open environment, the renewal of species, and to guarantee a good quality of pasture for great herbivores (Morvan, 2018).

During the last decades the increasing influence of global warming on the environment in addition to the changes in land use (decrease of agriculture activity) has produced periods of drought and heat wave, infestation of xylophage insects, which in turn have led to weaken many ecosystems and increasing wildfires hazard that caused degradation of ecosystems, economic loss and human suffering (Tang et al., 2015; Fernandes, 2013; San-Miguel-Ayanz et al., 2013; Running, 2006; Wotton et al., 2003). Wildland fires represent a growing threat on human activities, particularly due to urban sprawling at the Wildland-Urban interface (Keane et al., 2010; Radeloff et al., 2005).

For example, in California the expansion of low-density housing located in close proximity to wildland fuels, has contributed to a continuous increase of the number of structures destroyed during a wildfire: 3533 between 1955 and1985, 7467 between 1985 and 2000 and 3710 only in 2003! (Hammer et al., 2007).

A rapid evaluation of the intensity of fires observed worldwide compared to the limit of efficiency characterizing the firefighting means (even with aerial means), highlights that very often the gap is too large to hope that, the management of the fire risk can only be based on an increase of firefighting equipment (Lahaye et al., 2018; Venn and Calkin, 2011). In order to reduce the level of fire hazard, the strategy must be more global, in integrating also an ambitious program of prevention, based on one of the three factors affecting the behavior of a wildfire (fire triangle: weather/topography/fuel), i.e. the reduction of the fuel load.

Fire prevention covers controlling both fire hazards and fire risks (Brown and Davis, 1973). Preventing wildfires through controlling the quantity or arrangement of forest fuels can be a solution. Fuelbreaks are a common method of applying hazard reduction. Fuelbreaks are man-made areas with a reduced fuel load that act as barriers to stop or slow down fire spread. They are also designed to provide firefighters access and to act as a retreat for personnel and equipment to escape injury. A fuelbreak is always constructed in anticipation of future fires. Dimensions and locations of these barriers are often settled on the basis of expert's judgment with very little scientific basis. Prediction of fuelbreaks width can be very difficult even with the use of sophisticated models. This article is divided into these following sections: Firstly, background information on wildfire mechanism is given. Secondly, global trends in forest fires and their impacts are detailed. Thirdly, the use of fuelbreaks in fire management is explained. After that, examples of operational tools are shown and discussed. And finally, a conclusion on this issue and a summary of future needs are proposed.

Wildfire basic mechanisms

If one considers an unburned small piece of vegetation ahead of a spreading fire front, this small element is submitted to an increasing heat when the fire front is getting closer.

The heat transfer will essentially happen in two ways: through radiation and convection. Radiative transfer has usually a longer reach than convective transfer ahead of the fire front. Radiant sources are the flame front and the smoldering parts of vegetation. Heating by convective heat transfer happens through the heating of unburned vegetation by hot gases. It should be noted that it can also happen the other way when vegetation is cooled by fresh air. When a vegetation element is exposed to thermal transfer from the fire front, it heats up. When its temperature is close to 100°C, it starts to dry up. The quantity of water in vegetation, called Fuel Moisture Content (FMC), is playing an important role in fire spread because it acts as a heat sink, which can delay or even prevent fuel ignition. Once the vegetation particle has dried up, it starts to degrade and emit gases by pyrolysis, which are flammable. When enough gases are produced to create a flammable mixture in air (usually, when the fuel temperature is around 300 °C), the proximity of flames makes the mixture ignite and the fire has spread. Flames appear and the mixture burns in the gas phase. When the pyrolysis gases are almost all exhausted, the remaining char start to burn by oxygen contact at its surface and the fuel element starts glowing. The embers emit a large amount of radiation and burn slowly. When the embers are fully consumed only mineral ash remains and the fuel element is fully consumed. The most obvious parameters driving fire behavior are the fuel, the weather conditions, and the topography (fire triangle):

- Fuel: The properties of vegetation influence how it burns. For instance, some vegetal species are more flammable than others, such as sapwood compared to hardwood. The thickness of the fuel is also an important factor, all experimental studies have emphasized the major role played by the fine fuel (thickness less than 6 mm) in the propagation of a fire through a fuel complex. For a single element of vegetation, its thin particles, such as leaves or needles will burn quickly and support the fire spread. Fuel Moisture Content is one of the most critical parameters. Its value will condition the ability of a fire to spread and its rate of spread. At a larger scale, the spatial distribution of the fuel can influence greatly fire spread. There are two types of spatial distributions: vertical and horizontal. Vertical distribution is related to fuel layers (from duff to tree canopies). If these layers get very close to each other or overlap, a ‘fuel ladder’ exists that may create very intense, fires involving all vegetation at once. The horizontal distribution represents the fuel layout on the ground and has a strong influence on fire spread. They condition the occurrence of crown fires and can create heterogeneous fire patterns (Simeoni et al., 2011).

- Weather conditions: wind has the obvious effect of tilting flames. It also brings fresh oxygen to enhance combustion and make flames longer. The flames being longer and tilted, the thermal transfer towards the unburned fuel will be greatly increased and create steep accelerations of the fire front. The resulting fires are usually very intense and very difficult to fight. Air temperature and relative humidity constitute also an important factor contributing to the occurrence of a severe wildfire event. As an example, in February 2009, the catastrophic fires occurred during the Black Saturday in the Victoria district in Australia, were preceded by a very severe heat wave and strong wind (Cruz et al 2012).
- Topography: in a slope, the flame front is closer to vegetation so it will heat up vegetation in the direction of slope more than in any other direction. The fire head will then spread faster than the flanks and it will accelerate, creating a pointed head. Since a down slope contributes to reduce the intensity of a fire front, this configuration is very often chosen to carry out operational works such as prescribed burning and counter fires. The general configuration of the terrain plays also a great role in the fire behavior, for instance, a canyon configuration contributes a lot to a sudden acceleration of the fire front (chimney effect).

This general description of fire spread is quite simple it can be very different in the case of extreme fire behavior, with each type of extreme fire involving different specific mechanisms (Simeoni, 2016).

Any fire needs three simultaneous factors to burn: flammable gases, oxygen (in air) and a heat source strong enough to ignite the flammable mixture. This is what is commonly called the “Fire Triangle” by structural firefighters and it also applies to wildland fires. However, a different fire triangle is used to specifically describe wildland fire behavior.

The three components are: weather, topography and fuel. Among them, the only factor that can be managed is fuel and the primary motivation of fuel treatment is to alter wildfire behavior.

Global trends in forest fires and its impacts

As indicated in the introduction, it is well known that climatic and weather factors constitute one of the major source of modification of fire regime characterizing the capacity of adaptation of an ecosystem to fire hazard (Sommers et al., 2011; Benson et al., 2008). Most research concerning the evolution of the climate indicates that whatever the scenario in terms of control of the quantity of carbon release in the atmosphere, in a near future the global temperatures will be warmer than current levels and that severe droughts will be more frequent. In these conditions, it can be considered as quasi certain that fires season will be longer in numerous ecosystems and that new regions in the world, will be potentially affected by wildfire risk (as Greenland in 2017!).

In addition to climate factors, we already know that other anthropogenic factors have contributed to increase the level of fire hazard worldwide (Sommers et al., 2011):

- The modification of the land use, as a consequence of European settlement in different countries all around the world (in North America, in Australia, …)
- The rural exodus during the second part of the XXth century promoting a desertion of cultivated land and the associated way of life
- The generalized fire exclusion policy proposed after some big fires in US (Cohen, 2008) between the end of the XIXth century (Peshtigo fire in Wisconsin in 1871, 2500 deaths and 486 000 ha burned) and at the beginning of the XXth (the big blowup in Idaho and Montana, 87 deaths and 1 million ha burned) as the main solution to reduce wildfire hazard
- The increase of the number of vulnerable houses located in the wildland urban interfaces (WUI) (+52% in United States between 1970 and 2000) (Theobald and Romme, 2007)

All these factors have promoted a great modification of the landscapes, with less open ecosystems, a considerable fuel accumulation from the understory near the ground to the forest canopy, with a densification of the forests. With the intensification of the secondary residence phenomena (especially in Mediterranean regions) the wild vegetation has replaced the gardens and many villages are surrounded by a dense and highly flammable vegetation. With the combination of the impacts of global warming on the ecosystems, the continuous growth of the WUI, all studies show that the problem of wildfire hazard will be worst in the future, and more and more catastrophic fire events (such as the Black Saturday in Australia in February 2009 and the fire near Fort Mc Murray in Canada, in May 2016) could occur more frequently. To have an idea of the destructive power of these exceptional fires, a firestorm occurs during the Black Saturday in the small town of Kinglake, in 12h the fire has burned 100 000 ha, the average fire intensity reached 80 000 kW/m (more than ten times the limit of efficiency of aerial means) and 120 peoples died. During the Fort McMurray fire, 600 000 ha burned, 2400 houses were destroyed, more than 88 000 peoples were evacuated and the global cost was evaluated to 6 Billion Euros.

The use of fuelbreaks in fire management

Fire prevention concerns control of both fire hazards and fire risks. Fire hazard is generally independent of weather and describes fuel characteristics. It can be expressed as potential fire behavior or fuel property (Keane et al., 2010). Fire risk is the probability that a fire might start, as affected by activities of causative agents (Hardy, 2005). Indeed, the benefits of hazard reduction extend much further than fire prevention. For instance, surface fuel management can limit fire intensity (Byram, 1959) and lower potential severity (Ryan and Noste, 1985). So, fuel management also means control of the difficulty of the entire firefighting activity (Agee et al., 2000).

This section is devoted to a particular method of preventing fires through control of quantity, continuity and arrangement of forest fuels: clearing flammable material from a strip of specified width. These specific areas are referred as fuelbreaks.

Fuelbreaks (FIGURE 1) have been used for decades in Mediterranean region (Rigolot and Costa, 2000), in Australia (Stocks et al., 2004) and in the western United States (Green, 1977; Green and Schimke, 1971). But, the use of this fire control devices has always been controversial. Despite the recent interest in these cleared zones, questions regarding construction, maintenance and effectiveness remain (Weatherspoon and Skinner, 1996). For instance, a tricky challenge is to determine accurately the width of a fuelbreak required to prevent firefighters from injuries (Butler, 2014).

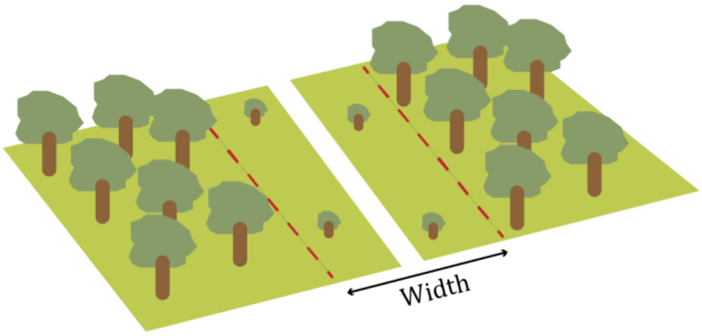

FIGURE 1. Typical fuelbreak configuration.

Methods of forest fuel control

Usually, direct prevention of fires through hazard reduction means the removal of fuels exposed to a high-risk source. But, there is an extension beyond the concept of mere prevention of ignitions which is to limit the spread of forest fires in order to prevent dangerous and uncontrollable fires. In other words, in term of prevention, the goal is prevention of large fires rather than a reduction in the total number of fires.

Thus, with this extended objective in mind, the TABLE 1 proposes a classification of the hazard reduction methods according to its main purpose inspired by a former work (Brown and Davis, 1973).

TABLE 1. Classification of fuel removal methods (inspired by (Brown and Davis, 1973)).

Fuel removal method	Main purpose	Example of application
Removal all ignitable fuel in limited zones.	Automatic prevention of ignitions.	Area kept clear of fuels around power stations.
Removal of all fuel in an area around a determined source of risk.	Confine any fire that may be ignited to an isolated area.	Cleanup of fuels in a strip along roads.
Removal of fuel in a zone.	Exclude fire from a high-value area.	Fuelbreaks around a forest.
Removal of fuel using fire.	Remove fuels from considerable areas in order to reduce the rate of spread of wildfires.	Prescribed burnings.
Breaking the vertical continuity of fuels and the horizontal continuity of tree crowns by cultural measures.	Reduce the threat of crown fires.	Creation of “crown fire free” around towns, cities or villages.
Removal of dead trees that would throw spot fires if ignited.	Reduce the spot fires embers.	Requirement in sale timber area.

In theory, except under extreme fire danger conditions, a policy of forest fire prevention should maintain fuel hazards at a level that will permit the local first attack force to control any fire that starts before it causes unacceptable damage.

Of the different methods listed above in TABLE 1 only the use of controlled fires and the removal of dead trees are generally applied in depth. All other types of hazard reduction are restricted to limited zones.

Experiences with fuelbreaks

Already in 1886, a recommendation to the State Board of Forestry in California has been made for blocking out the forest with cleared strips land wide enough to prevent wildfires from crossing (Weatherspoon and Skinner, 1996). These predecessors of the current fuelbreaks were called firebreaks. Firebreaks were narrower areas generally cleared to mineral soil. A definition of a fuelbreak can be found in the Glossary of wildland fire management terms used in the United States (McPherson and Wright, 1990): "*Generally wide (60-1000 feet) strips of land on which native vegetation has been permanently modified so that fires burning into them can be more readily controlled*".

Nevertheless, many specialists have considered fuelbreaks as being of little value. In particular, their main reasons were: (1) to be effective for stopping wildfires, fuelbreaks need to be staffed by firefighters; (2) recommended fuelbreak widths have often been considered too narrow under critical conditions; (3) fire control has been viewed as the sole beneficiary of these managed areas; (4) if the method chosen is to maintain a fuelbreak with a reduced fuel load, spreading fires can ignite another side. So, in the past, most fuel management policies in forested areas over the globe have been dominated by support of the timber exploitation program. With the consequence that budgets for fuelbreaks have been quite limited.

The recent interest in fuelbreaks over the last two decades has even given rise to similar concepts, such as wildland firefighter safety zones, shaded fuelbreaks or community defense zones (Rossi et al., 2018; Butler, 2014; Ruiz-Mirazo et al., 2011; Agee et al., 2000). For instance, some studies (Cohen, 2000; Arno and Brown, 1989) suggested their use around buildings and development in the wildland-urban interface. Therefore, some works have shown that fuelbreaks construction increased timber values within these fuelbreaks (Grah and Long, 1971). So, a portion of fuelbreak costs, can be set off by benefit to the timber resource.

The last fire events with fatalities, damage to property, infrastructure and the natural environment in Mediterranean region and in the United Sates provided a stark reminder of the destructive potential of wildfires (Lahaye et al., 2018; Teague et al., 2010). Despite, the large expenditure devoted to forest fire suppression these resources have proved insufficient to control severe forest fires (Fernandes et al., 2016; Moreira et al., 2011). So, it is obvious that there is a real necessity to improve current policies in order to integrate the use of fuelbreaks in a more comprehensive strategy that will result in a decrease in fire activity, especially in terms of area burned.

Location, creation and maintenance of fuelbreaks

As explained above, a fuelbreak is a form of hazard reduction restricted to a limited zone and that can be used as escape routes. This usually takes the form of clearing vegetation from a strip of specified width and location. This can be carried out to the point of complete exposure of mineral soil or only with a reduced fuel load. Fuelbreaks are created in the context of the territory within which they are located. They are all strategically positioned to protect specific areas, but above all to provide quick access for firefighters (Dennis, n.d.). It is essential to keep in mind that fuelbreaks can only aid firefighting forces under normal conditions. Under extreme conditions, they stand little chance of arresting a large fire, regardless of firefighting efforts. These kinds of hazardous fires may continue until there is a notable change in topography, fuel type or weather conditions.

Many factors determine the need for fuelbreaks in landscape. Some of them can be positioned to separate vegetation types, but others may be designed as networks of primary and secondary fuelbreaks. As they should provide faster and safer access to firefighters and their equipment, they are preferably connected with road networks. But, fuelbreaks with no link to a road system are still useful during a fire suppression stage. For instance, these types of cleared strips can be strengthened using aerial retardant drops until fire ground crews move in. Usually, a fuelbreak is located along a ridge top in order to help stop wildfires at the end of their spreads. Where possible, it should be tied into existing natural openings or recent burns (Dennis, n.d.). *In order to create an effective fuelbreak, the location should be chosen primarily depending on how the fire could spread due to local conditions*.

Currently, there are no absolute standards for their width. In 1971, (Green and Schimke, 1971) showed that widths at least 65m were necessary under high intensity chaparral fires. In 1977, (Green, 1977) recommended that a minimum of 90m was specified for fuelbreaks. In Corsica, a width of 100m is assumed on expert’s judgment without any scientific studies for fuelbreaks named ZAL (Zone d’Appui à la Lutte) (Rigolot and Costa, 2000). In the USA, the Quincy Library Group proposes fuelbreaks of 400m wide (Agee et al., 2000). It can be noted that some agencies use sciences and existing operational tools in order to create fuelbreaks. These simulators, which are often based on the Rothermel’s model (BEHAVE, FARSITE, FIRESTATION, SIROFIRE etc.) provide acceptable results only when coupled with realistic fuel models and precise meteorological data (Sullivan, 2009a).

Fuelbreaks are often viewed as initial treatments. Indeed, there is a consensus that coupling fuelbreaks with a wide landscape fuel treatment can reduce the intensity and effects of wildfires (Agee et al., 2000; Omi, 1996). In this case, this first stage of landscape management will be followed by more extensive area fuel manipulations in order to reduce gradually potential fire damage within interior untreated zones. For instance, theoretical studies have estimated that 54% and 88% of a forest would need to be treated to obtain an area with an acceptable reduced fire hazard (Bevers et al., 2004).

Several methods of creating and maintaining fuelbreaks exist and may be employed singly or in combination (Green, 1977; Brown and Davis, 1973). The goal of these fuel manipulations is to remove surface fuels, increase the height to the live crown of residual trees, and to space the crowns. Most of fuelbreaks can be constructed by mechanical means employing clearing equipment, and prescribed fires are used where topography permits.

Maintenance is a major issue in fuelbreak investment and it usually costs more than initial construction. These areas revegetate quickly with trees, shrubs or other fuels. So, they require effective maintenance and therefore long-term funding. As lush ground vegetation is an excellent fuelbreaks cover so long as it remains green, the maintenance of a green fuelbreak during the critical season can offer an alternative way in specific cases. For instance, studies have shown that seeding perennial grass cover can reduce brush and conifer invasion for at least 5 years in mixed-conifer fuelbreaks (Schimke et al., 1970). In addition, maintenance is essential because an un-maintained fuelbreak may conduct to a false sense of security among firefighters and the people who stay around (Dennis, n.d.). Maintenance problems are often caused by lack of funding. But these costs must be balanced against properties, money or lives saved because of hazard reduction (Petrovic and Carlson, 2012).

Proposal of an integrated fire management strategy based on fuelbreaks

Since a long time, fuelbreaks have been recognized as a relevant fire management strategy (Ingalsbee, 2005; Weatherspoon and Skinner, 1996; Dennis, n.d.). However, there are wide differences of opinion as to their effectiveness (Agee et al., 2000). It is difficult to assess this effectiveness because fuelbreaks prescriptions may vary, fuelbreaks location may vary, level of suppression may vary and, intensity of the fires approaching them may vary. Furthermore, fuel treatment outside these cleared areas may also contribute to their efficiency. Fuel treatments such as prescribed fires are commonly used outside fuelbreaks to reduce spotting as a fire approaches them. An important aspect that must be taken into account is the psychology of the firefighters regarding their safety. Indeed, firefighting forces are more likely to select a large cleared fuel zone than a narrow and unmaintained area. Some studies accounts of fuelbreak effectiveness (Graham Technical Editor, 2003; Green, 1977) but these often fail to provide detailed information that is necessary for a thorough analysis and validation with theoretical models (Dupuy and Morvan, 2005; Bevers et al., 2004; van Wagtendonk, 1996).

Fuelbreaks should not be considered a stand-alone strategy because fuelbreaks close to the fire source for containment purposes are generally effective, but fuelbreaks to break up large wildland areas are seldom effective as direct barriers. The need to link them together into a network system has been emphasized in many works (Agee et al., 2000; Dennis, n.d.). Furthermore, disconnected cleared areas that overlap in the main fire spread direction have been shown to be effective in reducing fire intensity (Finney, 2001). The local capabilities of the firefighters are also of paramount importance in developing an effective fire management strategy based on fuelbreaks (Brown and Davis, 1973). It is undeniable that a fast-moving and well-equipped crew finds limited use of preconstructed fuelbreaks except in extreme fire hazard areas or under critical conditions.

Fire suppression is often prioritized over fire prevention. But, it is obvious that a fire prevented does not have to be suppressed and causes no damage. Consequently, the first line of defense for a fire control agency is to carry out their jobs to preventing as many fires as possible. Moreover, the need of controlling fire risk increases as fuel hazards increase. In addition, the fire issue is linked to socioeconomic factors behind fire occurrence (Mateus and Fernandes, 2014; Gill and Allan, 2008). So, managing vegetation and changing human behavior are needed.

Thus, the different items of an integrated fire management policy could be subdivided in the following steps:

- Creation of a system of roads and tracks with associated fuelbreaks that break up the continuity of the fuels: to help firefighters stop fires, while providing safer places.
- Creation of areas where the fuel cover is well managed over time: to reduce fire hazard and help decrease the intensity of fire in the event of a large fire under extreme conditions.
- Constrain by law individual homes to have defensible area around them: to make these properties much easier to defend, while also protecting the surrounding fuels from accidental fires.
- Theoretical and practical training of firefighters on the use of fuelbreaks during forest fires: optimization of the firefighters ‘actions.
- Get more specific information about caused fires: to control fire risk.
- Educate the public and the lawmakers: to create a fire consciousness in all the population.
- Regulate the public use: to prevent accidental fires.

In most current cases around the world, allocation of resources should shift from fire suppression to fire prevention under a such fire management policy.

The use of operational tools in landscape fire management

Wildfire managers operate in a difficult decision environment because of the understanding effectiveness of fuelbreak which is limited by a lack of information on several points (Minas et al., 2012). Among them, the effect that fuelbreaks have on fire behavior under various conditions or the minimum width of these cleared areas are of primary interest. Thus, operational tools can assist managers operating in this task. The objectives of this section are to briefly review current research methods applicable to help these managers.

From a theoretical point of view, few models exist. For instance, a former model is proposed by Emmons (Emmons, 1965). This semi-empirical approach assumes that the quantity of energy released by combustion is proportional to the fire rate of spread. In addition, an exponential law is used to describe the attenuation of radiation by the medium. This author found that a wildfire would jump a fuelbreak if a condition was fulfilled:

$$D \leq \alpha . e . c \tag{1}$$

where D is the fuelbreak width, ⊠ is an empirical parameter (determined for each studied case), e is the fuel depth and c the width of the combustion zone. But, in this work, no attempt has been made to compare this theory with experimental data.

Safety Distance estimation and fuelbreak width

As shown in a previous section, fuelbreaks are man-made areas with a reduced fuel load that act as barriers to stop or slow down a fire spread but they are also designed for providing firefighters access and to which the firefighters and their equipment can retreat to escape injury. For instance, in Corsica, a width of one hundred meters is settled on the basis of the expert's judgment without any scientific studies (FIGURE 2).

FIGURE 2. Fuelbreak in Corsica located in the north of the island.

In order to evaluate the dimension of a fuelbreak, the concept of Safety Distance (SD) is often introduced. The term of Safety Distance has been widely used and may be perceived in different way depending on who is using it (Marangon et al., 2007). The definition of this Safety Distance is based on a fixed human exposure criterion, namely, threshold heat flux level (Viskanta, 2008; Sacadura, 2005). This SD is the distance between the firefighters and the fire required to prevent them from injuries (FIGURE 3).

(Green and Schimke, 1971) estimated that the distances from the flame front necessary to prevent ignition from radiation are half of the distances considered necessary to prevent disabling burns. Hence, ignition from radiation across a wide fuelbreak should not be a problem. Assuming that the Safety Distance is in the center of the break, the total width of a fuelbreak is theoretically supposed at least twice as big as this SD.

FIGURE 3. Safety Distance definition.

The main hazard for firefighters located in the vicinity of a fire front and who are not in danger of being impinged by the flames arises from the heat flux emanating from the fire front (Butler and Cohen, 1998). A common assumption is to consider that the radiant heat is the main hazard for firefighters. Thus, convective energy transport is often neglected in models (Rossi et al., 2010; Zárate et al., 2008). But without a doubt, convection can play a significant role (Page and Butler, 2017). So, the estimation of this heat flux is of primary importance and a real challenge in future works. The studies reported to date suggest that heating levels of 4 to 7 kW m^{-2} usually represent burn injury limits for firefighters (Raj, 2007, 2008).

Commonly, in operational conditions, a rule-of-thumb is applied to evaluate a safety distance: the distance between the fire and the firefighters should be at least *x* times the maximum flame height (Butler, 2014).

$$SD = x.h_f \tag{2}$$

where h_f is the flame height. The usual value of this parameter *x* is 4 but recent studies have shown that this constant could be different (Page and Butler, 2017). In addition, one hypothesis consists in correlating fireline intensity with flame length (Fernandes et al., 2009):

$$l_f = aI_B^b \tag{3}$$

where I_B is the fireline intensity, *a* and *b* two empirical parameters. The model's parameters are always estimated using statistical fitting procedures from experimental data in the field or at laboratory scale. Consequently, these relationships need a solid understanding of the limitations of these models (Alexander and Cruz, 2012).

To estimate this SD, a physical simplified model may also be used (Rossi et al., 2011). In this case, the safety distance is expressed as a function of flame characteristics (title angle, length, emissivity, transmissivity, average temperature) and threshold heat flux level.

$$SD = SD_1^{WI}\left(1 - exp\left(-k_{thres}\frac{2L}{l_f}\right)\right) \tag{4}$$

with

$$SD_1^{WI} = \frac{l_f\Phi_{thres}cos\gamma\sqrt{-4l_f\Phi_{thres}+(BT_f^4\varepsilon\tau)^2}}{2\Phi_{thres}} + l_f\sin\gamma \tag{5}$$

Where Φ_{thres} is the threshold heat flux level, k_{thres} is an empirical parameter that must be determined for each selected threshold of the heat flux, τ is the atmospheric transmissivity, ε is the equivalent flame emissivity, *B* is the Stephan-Boltzmann constant and T_f is the flame average temperature.

Therefore, this approach requires precise fuel models and accurate wildfire behavior models (Rossi et al., 2009). Some of them are described below.

Different research approaches to estimate wildfire behavior

The use of mathematical models may enable managers to plan strategic prevention activities (Minas et al., 2012; Bellemare et al., 2001). For instance, these models provide estimation of fire characteristics such as fire front geometry, rate of spread or fire intensity that determine limits beyond which fire control becomes difficult.

Forest fire modelling deals with several different approaches (Sullivan, 2009b, 2009c). Usually, three kinds of modelling, in accordance with the methods used in their construction, are defined (Perry, 1998). The simplest models are the empirical ones, which do not try to involve physical mechanisms (McArthur, 1966). Semi-physical models (Rothermel, 1972) are based upon the conservation of energy, but they do not distinguish the mode of heat transfer. Finally, physical models differentiate the various kinds of heat transfer in order to predict fire behavior (Chatelon et al., 2017; Balbi et al., 2010; Albini, 1985). Among these, multiphase modelling, which takes into account the detailed physical phenomena involved in forest fires, represents the most complete approach proposed so far (Morvan, 2008, 2013; Mell et al., 2007; Grishin, 1997).

Illustrative examples of operations research methods applicable to fuelbreaks evaluation

In this section, a presentation of the applicability of some research methods to fuelbreak evaluation are made.

The propagation of a wildfire through a vegetation can be simulated using a fully physical model (Morvan, 2011; Dupuy and Morvan, 2005). In this approach, the heterogeneous character of the vegetation is taken into account using families of solid particles. Convective and radiative heat transfer between the gas and the vegetation, as well as, the thermal decomposition of the solid fuel by drying and pyrolysis, and the combustion of chars are considered. In the gaseous phase, turbulence is also modelled. These studies have shown the ability of this approach to evaluate fuelbreaks (FIGURE 4).

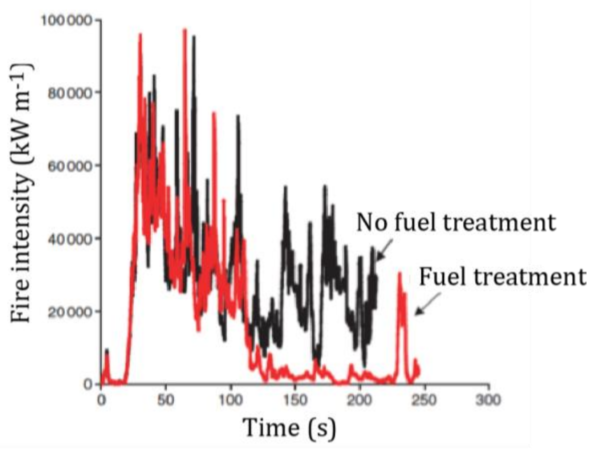

FIGURE 4. Example of fully physical results to evaluate fuelbreaks width (Dupuy and Morvan, 2005).

A stochastic model can also be applied to predict fire spread through a forest landscape (Innocenti et al., 2009). This approach includes the short-range radiative and convective effect from the flame. The long-range spotting effect of firebrands is also considered (FIGURE 5). Using this approach, works have shown that for cleared totally fuelbreaks an analytical efficiency criterion exists (Kaiss et al., 2007). For partially cleared fuelbreaks, this efficiency criterion depends on tree density.

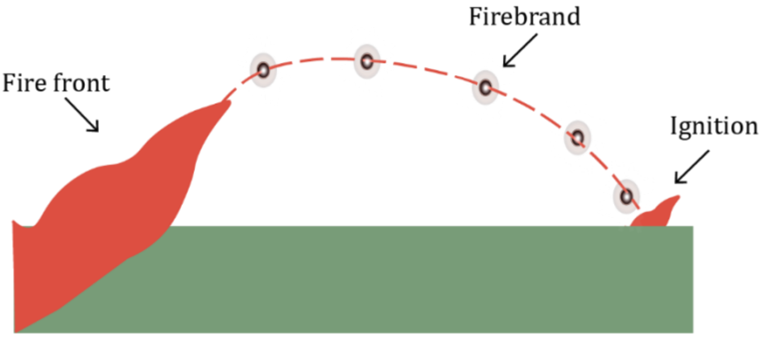

FIGURE 5. Long-range spotting effect of firebrands.

An operational tool named DIMZA developed at the University of Corsica (France), which consists in coupling a physical surface fire model (Balbi et al., 2007, 2010, 2018) with a flame length sub-model and an operational relationship for the safety distance is proposed to display safety zones on a map (Bisgambiglia et al., 2017). The software architecture of this tool begins with the end user (FIGURE 6). When the user launches the application, he has to define the path of the safety zone. Once the coordinates defining the path are recorded, the type of the vegetation and the fuel height are selected**,** these data are sent to a web service. Before launching the computation, the web service fetches topographical and meteorological data for each point. Finally, the results are sent back to the client for displaying.

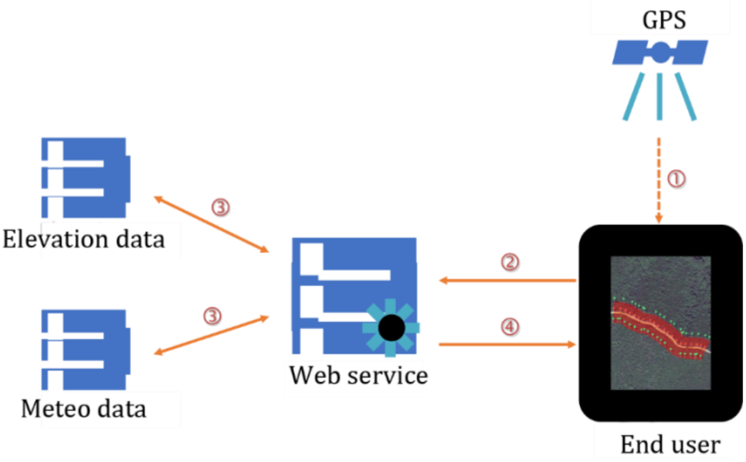

FIGURE 6. DIMZAL software architecture.

Knowledge gaps and future needs

In order to apply best-practices, operational tools including accurate models are needed to assist wildfire managers. Nevertheless, there appears to be still a gap between needs of managers and the tools currently available (Martell, 2011). Accordingly, the prediction of fuelbreaks efficiency can be very difficult even with access to sophisticated models. For example, questions remain: (1) How to compare theoretical and experimental data under various weather conditions? (2) How to select the best fuel cover to maintain on the fuelbreak? (3) How to determine the amount of canopy to remove?

Then, some additional studies are needed. For instance, additional works on burn injury limits based on heating method or heating time and with understanding of the role of clothing are essential. The inclusion of convective heat transfer and spotting in all operational tools represents a very interesting challenge. Finally, experimental and numerical studies should be conducted to identify the parameters that must be chosen with care because of their significant impact on fuelbreaks dimension (Rossi et al., 2018).

Conclusion and future needs

In this contribution, it has been shown that many countries around the world still face severe fire events, despite an increase in fire suppression costs. Hence, a fire management policy including fuel treatments, best-practice methods, and fire suppression is needed to assist wildfire managers. In this context, partnerships between different agencies and adoption of common programs are of the utmost importance and the guarantee of success. In addition, the fire issue is linked to socioeconomic factors behind fire occurrence. So, changing human behavior is also necessary. An adequate allocation of resources between education, suppression and prevention is crucial. This effective policy will require financial support with a good understanding of the interdependence of different actions.

As it has been shown, for example, the use of prescribed fires may be useful. It is therefore important to review the existing restrictions on air quality. The legislator must consider the benefit of using this method.

It has been demonstrated that combining fuelbreaks with other fuel treatments in different areas can reduce the size, intensity of forest fires and allow firefighters to extinguish them more easily. Fire managers have to solve many problems because a forest fire is a complex phenomenon. One of these challenges for managers is to achieve as complete an understanding as possible of what wildfire behaviors can be expected under different conditions.

Thus, operational tools can help them in this critical task. But, there appears to be a gap between operational tools available and fire manager's needs. Scientists can develop models, prototypes and simulators but cannot replace the experience of fire managers. So, close work between scientists and fire managers is crucial in the future.

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