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Large forest fire risk assessment and fuel management: operational tools and integrated approach

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FIREfficient
Operational tools for improving efficiency in wildfire risk reduction in EU landscapes

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Content

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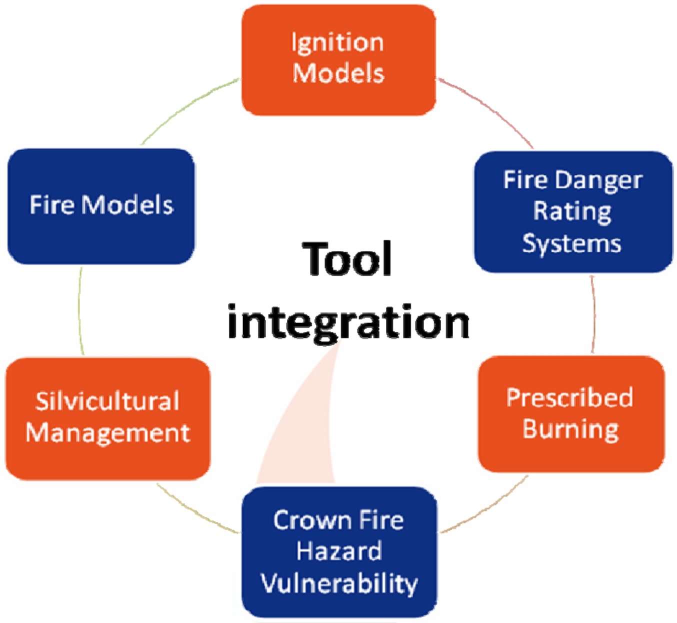
1. INTRODUCTION

There are a number of tools and methods available to obtain estimates on future fire hazard, fire risk, fire ignition probability and fire behavior. When talking about fire hazard, it usually refers to the fuel characteristics or fire related properties of the fuels at one point in time (Keane et al. 2010). While when talking about fire risk, it usually considers the probability that a fire might occur in a certain place and period of time, and also its potential degree of damage, especially if we consider an economic approach, as when planning forest management (Gadow 2000). Therefore, to assess fire risk we have to consider the ignition probability, and the potential that an occurring ignition will translate into a significant fire event (Keane et al. 2010). Such analysis of fire risk will require from the knowledge of the fire ignition sources and subjacent factors, the behavior of fire depending on existing fuels, their distribution, and other surrounding factors (weather, topography, fire extinction resources, etc.). Regarding to the effect of climate change on the risk of fire, it can be mention that it will increase the level of uncertainty to any future predictions about the risk of fire. One way to deal with the uncertainty arisen by climate change can be to apply a large set of possible climatic scenarios and undertake a sensibility analysis with the obtained results.

The assessment of fire occurrence and its potential impact, can be implemented following various and diverse approaches. It can be said that no single approach can tackle effectively the complexity of factors driving fire occurrence and fire behavior (socio-economic, climatic, fuel related, or even accounting for the impact of extinction measures), or even represent the whole set of preventive measures for reducing fire occurrence, spread and impact. The main goal of this review is to provide a compressive overview of the existing tools for assessing fire hazard/risk, as well as to describe their real or potential usefulness as information sources to support decision making processes. Furthermore, the review will describe the existing and potential links between the different tools, providing an integrated view of the processes behind its components and outputs as well and identifying the strengths and weaknesses of their applications.

The current tools that are being assessed are Ignition Models, Fire Danger Rating Systems (FDRSs), Fire Models, Crown Fire Hazard Vulnerability, Silvicultural Management and Prescribed Burning. All these tools can be used in different steps of the decision making process. Accordingly, we have considered different criteria to analyze the decision context in which the tools are used: scale of application (stand, landscape or regional/global), level of planning (operative, tactical or strategic) and strategy used (passive or active). Throughout this review the classification of each tool into a decision making step will be discussed.



2. HAZARD/RISK ASSESSMENT TOOLS

2.1. Fire ignition models

2.1.1. Modeling changes in fuel flammability: Fire Danger Rating Systems

Fire Danger Rating Systems (FDRSs) have a primary objective of assessing fuel and weather conditions, and provide estimates about fuel flammability and the potential fire behavior for every allocation over areas under those conditions. Their provide an idea about the relative seriousness or threat that fire imposes according to the fuel and weather conditions, often as a day by day measure reported as fire danger maps, relate the fire potential behavior to the effort required to extinguish or contain those fire using different suppression efforts.

Some of the most popular systems or models used for this purpose are the Keetch-Byram Drought Index (KBDI; Keetch and Byram 1968), the Canadian Forest Fire Danger Rating / Fire Weather Index (FWI) System (Turner and Lawson 1978; Stocks et al., 1989), the United States National Fire Danger Rating System (NDFRS) (Deeming et al.,1972; Cohen and Deeming; 1982) and the Australian Forest Fire Danger Rating / McArthur index (McArthur FFDI) (McArthur 1967; Noble et al., 1980; Luke and McArthur 1986). These systems often work on coarse resolution scales, for example 12 km in the case of United States NDFRS and Canadian FWI System and 50 km in the case of KBDI using PRECIS outputs. Therefore, their application is restricted to large scale studies or assessments, regional, national or sub national. At EU level, the EFFIS forest fire information system (San-Miguel-Ayanz et al 2012), is primary based on the Canadian FWI, providing the rating of the FWI, and other variables (subcomponents of the FWI) at different scales (10, 16 and 25 km) (**Figure 1**)**.** Their day by day use as fire danger maps is focused on an **operational frame for active prevention decision making**, from helping to set alerts, warnings and restriction to activities that may spark an ignition on highly unfavorable conditions (high to very high danger) and mobilize suppression resources to the more dangerous places.

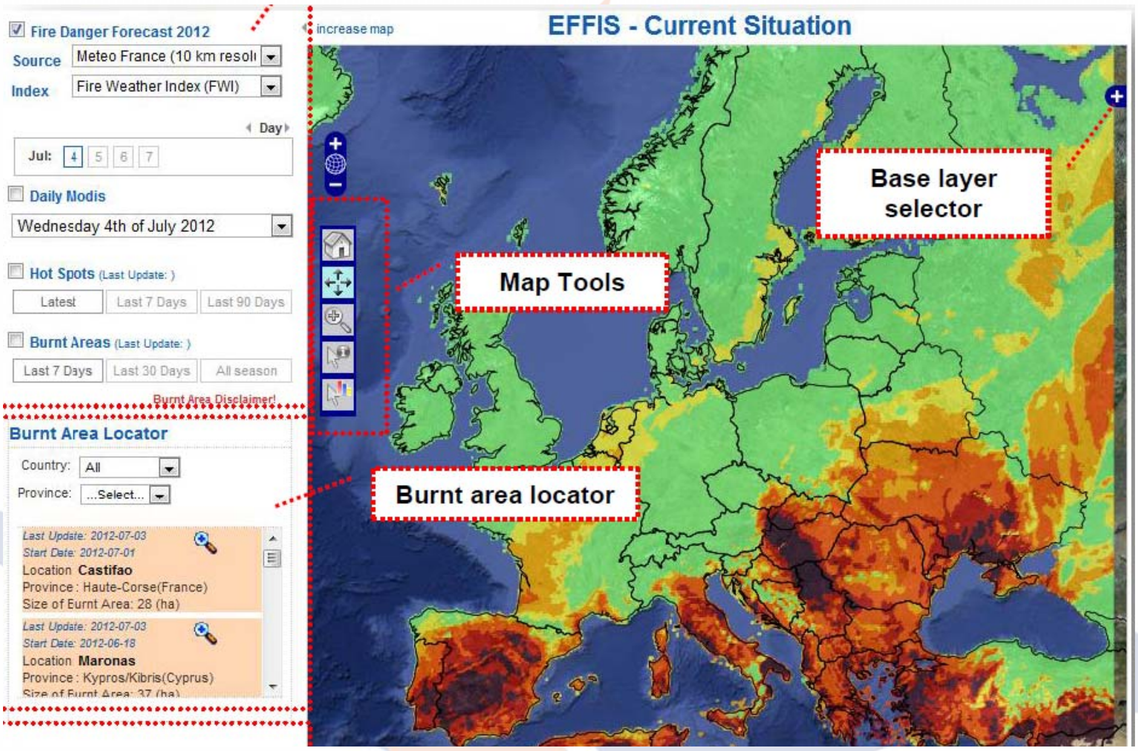


Figure 1: Example of the outputs (FWI from the 4th of July 2012) provided by the EFFIS system (http://forest.jrc.ec.europa.eu/effis/applications/current-situation/)

FDRSs have been used in many parts of the world for quite a long time for assessing climate variability impacts on short term historical and short term future wildfire hazard. For examples it can provide daily reports and maps on fire danger for short term forecast under current climatic conditions. In addition, by comparing larger historic series of both FDRSs results and historic fires, (Goodrick 2002) is possible to validate the relation between fire hazard and fire regime, or identify the potential use of FDRS indexes or their subcomponents as potential predictors on fire occurrence models (Vega-Garcia et al., 1999; Wotton et al., 2003; Wotton and Martell 2005). In this case the use of the tool would be focused on a **tactical or strategic framework of decision making**, for active prevention if it helps to allocate suppression resources, or passive it helps to define with areas are to be treated using fuel reduction measures.

On a **strategic prevention level**, FDRSs also can be used for assessing climate change impacts on long term future wildfire hazard. One of the characteristics of FDRSs is that their outputs are highly dependent on the climatic conditions provided as input. Such characteristic of the FDRSs makes them highly usefully for assessing long-term variations on fire hazard under climate change conditions. Examples of the uses of this tool for assessing impacts of climate change on wildfire using data generated from climatic scenarios to generate future fire hazard assessment can be found in places such as Australia, United States, Canada, Portugal, Russia and Indonesia. The Australian /McArthur **FFDI** for example, has been applied for predicting impacts of climate change on fire hazard in the future (30 years) using CSIRO 9-level GCM climate data, under a doubled atmospheric CO2 emission scenario in Australia, (Williams et al. 2001). Then the US **NDFRS** has been implemented for example in the United States (Fried et al. 2008). For predicting climate change influence on fire hazard for the period of 1950 to 2099, NOAA-GFDL and Department of Energy-NCAR Parallel Climate Model data were used.

Then the Canadian **FWI** has been used for forecasting impacts of climate change on future fire hazard such as in North America and Europe (Flannigan et al. 1998). FWI for examples has been applied for:

- Predicting fire weather for Canada under climate change using Canadian General Circulation Model and doubled CO2 simulation for mid 21st century (Bergeron and Flannigan 1995; Flannigan 2005).
- Predicting impacts of climate change on forest fire danger in Canada and Russia using monthly data from four GCMs (Canadian Climate Centre, the United Kingdom Hadley Centre, the German Max Planck Institute for Meteorology and the US National Centre for Atmospheric Research GCMs) and doubled CO2 simulation) (Stocks et al. 1998)
- Estimating fire season severity under changing climate in North America for 2060 using Hadley Centre and Canadian General Circulation Models (Flannigan et al. 2000)
- Assessing impacts of changing climate on fire weather in Portugal for the period of 2071–2100 using High Resolution Hamburg Model (HIRHAM) and A2 emissions scenario (Carvalho et al. 2010).

Moreover the **KBDI** has been used for assessing global future wildfire potential under climate change (using HadCM3, CGCM2, CSIRO and NIES GCMs) and the results show that because of climate change the wildfire potential for the period of 2070-2100 may increase such as in the United States, South America, central Asia, Southern Europe, Southern Africa, and Australia (Liu et al. 2010). The modified version of KBDI has also been tested to predict climate change impacts on fire hazard in Indonesia for the period of 2070-2100 using PRECIS outputs (Herawati & Santoso 2011).

Information on Fire danger Rating System also available at Annex 1.

2.1.2. Fire ignition modeling

The occurrence of o fire events requires from the presence of an ignition or starting point were a heat source will enable the combustion of nearby fuel and the subsequent spread of the fire. Therefore, model the frequency of fire ignitions and the locations were ignitions are more likely to happens, even if not a high percentage of fire ignitions evolve into large fires, provides highly relevant information to assess fire risk over a study area and period of time. Model fire ignitions and predict where and when they will take place is always accompanied by a high degree of uncertainty, as both natural events and human activities leading to their occurrence are often difficult to predict or measure. Still, several studies have dealt with the topic of ignition modeling using different approaches.

Regarding the spatial scale used for modeling, most studies have been implemented using a single spatial scale, either fine-scale being based on the proximity to hazardous elements (Martell et al, 1987; Vega-Garcia et al., 1998; Pew and Larsen 2001; Vasconcellos et al., 2001; Genton et al., 2006; Yang et al., 2007; Lodoba and Csizar 2007; Gonzalez-Olabarria et al., 2012) or broad-scale being based on the aggregation of both fire ignition events and influencing factors at administrative or ecological level (Gisborne 1926; Chow et al., 1993; Vazquez and Moreno 1993; Vazquez and Moreno 1998; Roig and Ferguson 1999; Guyette et al., 2002; Prestemon et al., 2002; Podur et al., 2003; Wotton et al., 2003; De la Riva et al., 2004; Larjavaara et al., 2004, 2005a, 2005b; Prestemon and Butry 2005; Wotton and Martell 2005; Badia-Perpinya and Pallares-Barbera 2006; Amatulli et al., 2007; Syphard et al., 2007; Martinez et al., 2009; Grala et al., 2010; Oliveira et al., 2012; Gauteaume; et al., 20013; Martinez-Fernandez et al., 2013). However, fire ignitions can be modeled using different spatial scales, as factors or data representing them can be provided at different scales (Cardille et al., 2001; Diaz-Avalos et al., 2001; Gonzalez-Olabarria et al., 2011), or at a single scale, but combining data sources at administrative level and from proximity variables (Vega Garcia et al., 1995, 1998; Romero-Calcerrada et al., 2008; Chuvieco et al., 2010)

One aspect to be considered regarding fire ignitions, is that those factors behind their occurrence as human behavior or electric storms (**Table 1 and 2**). Additionally, in the case human-caused ignitions (**Table 2**), they are often aggregated, but some studies have analyzed the influence of the specific casuistic (arson, smokes, campfires, electric lines….), showing that the ignitions, of can hardly be related with climate change or more knowledge has to be gathered yet, even if a relation can be assumed. Therefore, is the **changing fuel conditions in the area were an ignition is to be expected that will drive the variation on the initiation and spread of fires, rather modifications in the ignition regimes**.

Ignition models have being referred as a useful tool for developing fire prevention measures aiming to reduce the number of fires, or identify with areas are more susceptible to be affected by fires. When policies are to be developed for reducing the number of fires trough: education, punitive actions, development of fire secure technologies (contain sparks on machinery) etc. the use of the tool can be considered as tool for deciding **strategic and passive fire prevention** measures.

Table 1: Studies dealing with ignitions of Natural or Any cause (aggregated)

Autor	Year	Journal	Place	Study period	Cause
Catry et al.	2010	*Int Wildland Fire*	Portugal	2001-2005	all
Maingi and Henry	**2007**	*International Journal of Wildland Fire*	USA	1985-2002	all
Vázquez de la Cueva et al.	2006	*International Journal of Wildland Fire*	Spain	1974-2000	all
Yang et al.	2006	*Knowledge-Based Systems*	United Kingdom	1998-	all
Flannigan et al.	2005	*Mitigation and adaptation strategies for global change*	Siberia, Canada and Alaska	1980-1999	all
De la Riva et al.	2004	*Remote sensing of Environment*	Spain	1983-2001	all
Preisler et al.	2004	*Int J Wildland Fire*	USA	1970-2000	all
Badia et al.	2002	*Environmental Hazards*	Catalonia	1983-1999	all
Cardille et al.	2001	*Ecol Appl*	USA	1985-1995	all
Donnegan et al.	2001	*Can J For Res*	USA	1748, 1851, 1871	all
Sturtevant et al.	2003	*Proc 2nd Int Wildland Fire Ecol and Fire Manag*	USA	1985-2000	all forest fires
Chuvieco et al.	2010	*Ecological Modelling*	Spain	1990-2004//2002-2004	human and lightning
Amantulli et al.	2007	*Ecol Model*	Aragon	1983-2001	human, lightning
Vázquez and Moreno	1998	*Int J Wildland Fire*	Spain	1974-1994	lightning and human
Larjavaara et al	2005	*Forest Ecology and Management*	Finland	1985-1992 // 1996-2001	lightning
Larjavaara et al	2005	*Agricultural and Forest Meteorology*	Finland	1998-2002	lightning
Wotton and Martell	2005	*Can J For Res*	Canada	1991-2001	lightning
Podur et al.	2003	*Ecol Model*	Canada	1976-1998	lightning
Diaz-Avalos et al.	2001	*Can J For Res*	USA	1986-1993	lightning
Rorig and Ferguson	1999	*Journal of applied meteorology*	USA	1948-1977	lightning
Gisborne	1926	*Monthly Weather Review*	USA	1924-1925	lightning
Larjavaara et al	2004	*Silva Fennica*	Finland	1961-1997	natural

Table 2: Studies dealing with ignitions of human causes (aggregated) or specific causes (divided)

Autor	Year	Journal	Place	Study period	Cause
González-Olabarria et al.	2011	*Annals of Forest Science*	Catalonia	1994-2007	human
Martinez et al.	2009	*J Environ Manage*	Spain	1988-2000	human
Romero-Calcerrada et al.	2008	*Landscape ecology*	Spain	2000-2005	human
Loboda and Czizar et al.	2007	*Ecologial Applications*	Russian Far east	2001-2004	human
Syphard et al.	2007	*Ecol Appl*	California	1960-2000	human
Vega Garcia	2007	*Wild-fire 2007*	Cataluña	1996-2000	human
Badia-Perpinya and Pallares-Barbera	2006	*Int J Wildland Fire*	Catalonia	1987-1998	human
Guyette et al.	2002	*Ecosystems*	Missouri	1700-1850	human
Pew and Larsen	2001	*For Ecol Manage*	Canada - Vancouver	1950-1992	human
Vega Garcia et al.	1999	*Invest Agr: Sist Recur For*	Canada	1986-1990	human
Vega García et al.	1995	*Int J Wildland Fire*	Canada	1986-1990	human
Vázquez and Moreno	1993	*Landscape and Urban planning*	Spain	1974-1988	pasture burning, lightning, arsonist, unknow and negligence
Prestemon and Butry	2005	*Am J Agr Econ*	Florida	1995-2001	arson
Prestemon et al.	2002	*Forest science*	Florida	1982-1999	arson, lightning, accident
Yang et al.	2007	*Forest Science*	USA	1970-2002	arson, lightning, others
Vasconcelos et al.	2001	*Photogramm Eng Rem S*	Portugal	1992-1995	arson, negligence, pooled causes
González-Olabarria et al.	2012	*International Journal of Wildland Fire*	Catalonia	1995-2006	All; split by causes
Wotton et al.	2003	*Climatic change*	Canada	1976-1999	Human; aggregated on 2 subgroups
Grala et al.	2010	*Int J Wildland Fire*	USA	1991-2005	All; split by causes
González-Olabarria et al.	2014	*Rev. Risk analysis*	Catalonia	1995-2008	All; split by causes
Ganteaume et al.	2013	*Environmental Management*	Mediterranean Europe	2006-2010 // 1995 - 2010	All; split by cause
Genton et al.	2006	*Int J Wildland Fire*	Florida	1981-2001	lightning, arson, accident, railroad

Still it has to be mentioned that human activities and lightning's have a higher degree of unpredictability and **base prevention measures only on ignition models are not cost-effective, especially when all human causes are aggregated**. Other point, is that ignitions are not exactly fires, and as the size of the fire increases, the human factor (in the case of human caused ignitions) as a precursor of the fire losses strength as predictor, and those components explaining potential fire behaviour, as the ones explained by the FDRSs, gain importance. Subsequently, for modeling purposes, or for applying existing tools for developing prevention measures, have to consider and understand the fire size component, defining on a clear way with of component (ignition source vs spread from the ignition point) is the predominant.

2.1.3. Key messages

- Fire Danger Rating Systems (FDRSs) and their sub-components rely mostly on weather conditions, and the amount and distribution of fuels is often neglected.

- FDRSs require from local adjustment, taking into account historic fires and the specific synoptic conditions that may lead to extreme fire events.

- It has to been observed that in specific sites, those subcomponents of the FDRSs, as the drought code, provides better estimates of the whole FWI.

- The applicability of fire ignition models often requires from its integration with other risk assessment tools, such as FDRSs or fire spread models.

- The definition of the modeling data (minimum fire size, aggregation of ignition causes) and the assessment methodology (statistical method, results spatial frame) will greatly influence the results and their usability for fire prevention.

2.1.4. Integrated approach

<u>Decision-making:</u>
FDRSs, prevention from operational (when used to mobilize extinction resources) to strategic (if used for scenario analysis).

Although Ignition modeling has limited use in prevention, but increases the capacity of other tools when linked to them (FDRSs, fire spread models).

Still, fire ignition modeling can be used on strategic prevention if used to modify regulation on hazardous activities.

<u>Links with other tools:</u>
Ignition models can use the outputs of FDRSs as inputs, or predictions on ignition occurrence can provide the socio-economic variables to improve FDRSs.

When added to large-scale fire simulators, the simulation of multiple fire ignitions based on ignition assessments, can help to map the probability of fire occurrence on a landscape or region.

2.2. Fire behaviour and fire spread models

2.2.1. Introduction

More than half a century ago, it was understood that the principle of energy conservation could provide the basis for simulating the rate at which a fire front spreads across a landscape (Weber, 1991). Amongst the earliest works on this topic are Fons (1946) and Bruce *et al.* (1961), whilst amongst the most widely used is Rothermel (1972). Weber (2001) states the 'fundamental equation for rate of spread' as:

$$\{Rate\ of\ Spread\} = \frac{\{Heat\ flux\ from\ active\ combustion\}}{\{Heat\ required\ for\ fuel\ ignition\}} \quad (1)$$

The behaviour of vegetation fires spreading across landscapes is controlled by a complex mix of characteristics related to the fuel, the topography, the ambient meteorology, and indeed feedbacks between these. As early as 1916 the relationship between fire danger and weather parameters was studied in North America (Hardy and Hardy, 2007). These early studies were rapidly redirected towards focused campaigns aimed at understanding and predicting the physical processes of combustion and aspects of wildfire activity on the landscape (e.g. Byram 1959; Van Wagner 1965; 1968; 1969; 1977; Rothermel 1972; 1991). In the USA, these research campaigns often took the form of detailed laboratory studies (as seen in the work of Byram and Rothermel), while in Canada the use of large scale experimental wildfires were (and remain) more common place in studying wildfire behaviour (e.g. Van Wagner 1963; Stocks and Walker 1972; Stocks and Alexander 1980; Stocks 1987; Stocks and Hartley 1995).

Wildland fire involves physical processes occurring at a wide variety of scales, ranging from the sub-millimetre (fuel-flame interactions, such as combustion) to tens of meters (flame-plume interactions, such as convection and turbulent mixing), and even to tens of kilometers (plume-landscape-atmosphere interactions, such as the effect of orography and atmospheric processing of the smoke pollutants). No simulation model can resolve all these length scales, so a variety of different model types have been developed.

Aiming at building reliable fire tools, equation (1) has been translated in many models reproducing distinct traits of fire behaviour and spread. Models can be broadly differentiated among fire behaviour and fire spread models. While fire behaviour models simulate fire flame characteristics without a spatial scale, fire spread models translate fire behavior into fire propagation in the landscape.

Within models reproducing fire spread with a spatial dimension (ie. considering spatially explicit fire spread), two groups of models can be found according to the number of events modeled, the scale and the processes. The first are models reproducing the growth of single fire events, and the other reproduce several fire events and are centered in the understand of more general traits of fire regimes, as a distribution of sizes, or spatial risk allocation. Probabilistic models based on cellular automata methods that are designed primarily to examine probabilistic fire growth at landscape scales (e.g. Clarke *et al.* 1994) and serve the purpose of allowing researchers to simulate long term fire regimes over large areas.

A complete introduction to the principles of fire models and in particular to physical models is addressed in the work of Sun *et al.* (2006) and in the review of Porterie *et al.* (2002). The website maintained by Jan Mandel http://www.openwfm.org/wiki/ is also a good source of information where many models used in the fire modelling community are listed and described.

2.2.2. Fire behaviour models

2.2.2.1. Presentation

Fire behaviour models reproduce fire intensity characteristics in a single site, interacting fuel and moisture conditions with fine weather conditions and reproducing fire effects. They usually simulate rate of fire spread, spotting potential, scorch height, tree mortality, fuel moisture, and many other fire behaviors and effects.

2.2.2.2. Main models used nowadays

Within the USDA-Fire models (on of the main source of multi-purpose fire models source at a global scale), the BehavePlus fire modeling system (http://www.firelab.org/project/behaveplus) is a Windows-based computer program that can be used for any fire management application that involves modeling fire behavior and fire effects. The system is composed of a collection of mathematical models that describe fire behavior, fire effects, and the fire environment based on specified fuel and moisture conditions. BehavePlus is based, as most models in the world, on Rothermel fire spread equations (Rothermel 1972).

The BehavePlus principles have been also applied to other modelling platforms.
Nexus, for instance
(http://fire.org/index.php?option=content&task=category&sectionid=2&id=13&Itemid=32)
links surface and crown fire prediction models in a simpler way with the BehavePlus bases. NEXUS is useful for evaluating alternative treatments for reducing crown fire risk and assessing the potential for crown fire activity.

2.2.2.3. Links with other tools

Fire behaviour models closely rely on detailed fire weather indices that describe fuel state affecting fire effects. For instance, in Canada, the FWI indices were adapted into tools for forecasting fire behaviour in a series of typical fuel types with the culmination of the work being released as the Canadian Forest Fire Behaviour Prediction System (CFFBPS, or more commonly FBP system) in 1992 (Forestry Canada Fire Danger Group 1992). In the United States the regional systems for predicting fire danger were progressively modified and combined resulting in the release of the National Fire-Danger Rating System first introduced in 1964 (Hardy and Hardy 2007). In both cases not long after the introduction of these models they became widely used within the countries for the purposes of fire management.

The fire behaviour models are often the basics for fire spread models. They can give the infrastructure for fire behaviour at detailed scales that can be further applied to models simulating fire spread across the landscape at the result of fire behaviour outputs. Furthermore, fire behaviour models can be used to propose silvicultural management prospections aiming at reduce fire risk, as they can test the relations between fuel structure and fire effects. Besides, fire behaviour models often need on field validation and detailed knowledge on the relations between forest structure and fire effects. Thus, there is also a feedback between these models and crown fire hazard models with the final goal of improving both tools.

2.2.3. Spatial explicit fire spread models

2.2.3.1. Single event Models

2.2.3.1.1. Physical models

Physical models include models that focus on fuel-flame-plume interactions, such as Wildland Fire Dynamics Simulator (WFDS) (Mell et al. 2009). These models include physical processes such as fluid dynamics, combustion, heat transfer, pyrolysis, microphysics and turbulence, which are generally resolved at a high spatial resolution (cm-scale). As such, these models typically require more than the standard desktop PC to run efficiently and operate significantly slower than real-time. Other physically-based models are concerned with plume-atmosphere interactions, which usually involve coupling relatively simple fire models within a high resolution mesoscale atmospheric model such as the Weather Research and Forecasting model (WRF) (Mandel et al. 2011).

2.2.3.1.2. Empirical models

Presentation

Whilst physically-based models maybe well suited to the requirements of many scientific studies, there is a need by fire managers to simulate the spread of fire across landscapes in real-time, or ideally faster than real-time, in order, for example, to help plan prescribed burning campaigns, to help deliver scenarios for fire response operations and to help manage landscapes for fire risk. Hence the development of fully empirical fire spread models that can be run in faster than real time on standard desktop computers with little specialist computing knowledge required.

The Fire Area Simulator (FARSITE; Finney, 2004) and Prometheus are the primary examples of this type of fire growth model, and both are fully publically available systems that use spatial data on fuel characteristics (e.g. type, loading, moisture content), topography (elevation, slope, aspect) and weather (temperature, relative humidity, wind speed, wind direction) to simulate a fire's spread across a landscape using Huygens' principle of elliptical wave propagation, as described in Richards (1990), Finney (2004) and Tymstra et al. (2010).

Whilst Prometheus and FARSITE are both open-source software and freely available to download from the Internet, alternative customized commercial software is also available. Wildfire Analyst (Technosylva, www.wildfireanalyst.com), for example, uses the same fire behaviour and fire spread equations as FARSITE, but with an enhanced GUI and functionality (e.g. ensemble fire spread mode). However, it is not free-available for the moment.

FARSITE

FARSITE has been developed by the U.S. Forest Service (USFS) as a 'National System' for predicting wildland fire behaviour and spread in areas of the United States. The model is openly available to users and is widely used by USFS, the National Parks Service (NPS) and other federal/state land management agencies, mainly as an operational tool for planning land management fires, responding to escaped fires, and responding to wildfire incidents. To run FARSITE for an area requires specific georeferenced input layers (elevation, slope, aspect, fuel type, and percentage canopy cover). The fuels physical properties (loading, moisture, moisture of extinction, heat content, density etc.) are determined using a set of standard fuel models that are built into the FARSITE computer code (Anderson, 1982; Scott and Burgan, 2005). Customised fuel models can be developed for fuels absent from Scott and Burgan (2005), and this is often necessary for non-US scenarios (e.g. Arca *et al.* 2007; De Luis *et al.* 2004; Bilgili and Saglam, 2003). FARSITE provides the user with a suite of spatio-temporal outputs, including fire perimeter growth vectors and maps of fireline intensity (kW m^{-1}), flame length (m), rate of spread (m min^{-1}), heat release density (kJ m^{-2}), reaction intensity (kW m^{-2}), along with information about such behaviours as crown fire activity.

Unlike Prometheus, whose underlying fire behaviour model is based upon measurements of landscape scale fires, FARSITE relies upon the surface fire predictions of Rothermel (1972), whose equations were derived from a series of small-scale laboratory burns based on homogeneous dead fuel beds. This has led to some criticism (e.g. van Wagtendonk, 1996) that the fire behaviour model governing fire spread in FARSITE is not representative of true landscape scale fires, whose fuel beds are generally complex, discontinuous and heterogeneous. Consequently, many studies have highlighted inaccuracies in FARSITE simulations, and suggest that FARSITE can be difficult to calibrate (e.g. Andrews and Queen, 2001; Zhou *et al.* 2005).

Given that FARSITE was mainly developed for simulating large-scale fires in US forests, parks and wilderness areas, its evaluation has focussed on fires in these areas. In areas subject to different fuel characteristics and climate, model calibration and evaluation can be difficult (Arca *et al.* 2007), though a number of studies have attempted this (e.g. Perry *et al.* 1999 in New Zealand; Arca *et al.* 2007 in Sardinia; and Dimitrakopoulos (2001) in Greece). These studies emphasize the importance of using custom fuel models and accurate, high-resolution wind fields if FARSITE is to be applied to non-US situations.

Prometheus

Prometheus has been in development for well over a decade, and has been freely available to users for nearly as long. However, despite Prometheus being the dominant spatial fire growth model in Canada (Cui and Perera, 2008), it is still not commonly used in fire response operations. Canada's fire suppression system is mainly focused on 'initial attack', where the rapid (if perhaps somewhat vague) outputs of fire danger rating systems are generally believed sufficient for response operations. Instead, the true use of Prometheus is mainly to provide a decision support tool to aid fire managers planning prescribed fires, and in responding to escaped fires which necessitate the need to fight fire on the landscape. Even so, in Canada the possibility to apply Prometheus in such situations is often forfeited due to a perceived limited availability of the necessary input datasets, lack of widespread experience with the model, and suspected or known issues with its outputs. For example, Prometheus is known to typically over-predict the total growth area of fires by around 30% (Anderson *et al.* 2007; Cui and Perera, 2008), primarily due to over sensitivity to wind (Anderson *et al.* 2007). This has been shown to be mostly due to the models fire propagation mechanism, as opposed to the underlying FBP system (Cui and Perera, 2008). Issues such as this can require users to carefully observe the progress of simulations, and at times adjust parameters to "enforce" more correct behaviour (Tymstra *et al.* 2010). In essence to get best results from the model a user may need to have the experience to know whether or not a simulation is behaving in accordance with the anticipated real fire behaviour, and this presumed need for 'expert knowledge' has often prevented the implementation of Prometheus under the types of high stress scenarios relevant to escaped fire response. Thus, instead of its designed purpose, Prometheus has taken up a predominant role related to research applications examining fire risk, burned area variations under various scenarios, and integration with remote sensing burned area products (Anderson *et al.* 2005; Tymstra *et al.* 2007; Anderson *et al.* 2009; Beverly *et al.* 2009).

Prometheus is undergoing almost continuous development, and as part of this process each new version is put through a rigorous evaluation procedure to ensure it is performing to specification. The evaluations involve 20 tests across 36 separate environments, with 486 input files developed by the Canadian Forest Service to ensure compliance with FBP outputs under a wide range of conditions (Tymstra *et al.* 2010). Despite close adherence to FBP predictions, Anderson *et al.* (2007) found that Prometheus still typically overestimated fire growth area by around 27%, and through perturbations of the input data found that differences in area burned could be attributed to wind speed, relative humidity and temperature, 44%, 52% and 16% of the time respectively. The significance of these three variables links fire growth strongly to the Canadian Fire Weather Index (FWI) Initial Spread Index (ISI) parameter, which is the dominant factor in determining rate of spread in the Canadian FBP system. However, in a comparison of three fire growth models using the Canadian FBP system as the driving fire behaviour component, Cui and Pereira (2008) were able to ascribe the main responsibility for these simulation errors to the fire growth algorithm, which is shared between Prometheus and FARSITE, as opposed to the underlying fire behaviour model (which is different between the two models).

Links with other tools

Fire spread models of single events are greatly associated to other fire models. On the one hand, they may be based on behaviour models for the simulation of fire intensity in the landscape. On the other hand, they can also be used for multiple fire events simulation if time lapse and spatial scale don't pose limits to its computational implementation.
Furthermore, fire growth models (this is an equivalent term for "single event fire models") use inputs from Fire Danger Rating Systems. The Canadian model Prometheus relies entirely on the Canadian FWI and FBP systems (Tymstra et al. 2010), while the American model FARSITE is primarily based on the US National Fire-Danger Rating System, with surface fire predictions from Rothermel (1972) and components of various other models for specific parameters (Finney, 2004).

2.2.3.2. Multiple events models

2.2.3.2.1. Cellular automata models

Presentation

Cellular Automata (CA) approaches to modelling fire spread are generally focused on representing burned area in a spatially-explicit manner. They have little to say about the plume or atmospheric components of wildland fires, but can be relatively informative with regard to simulating frequency-size distributions of burned area, which are an important component of an area's fire regime. As with the other approaches considered here, CA method represent the landscape as a lattice, with conditions within each cell assumed to be homogenous in its attributes (fuel type, slope, etc.). CA approaches represent space and time explicitly using local rules to control the propagation of the fire front from one cell to the next. In terms of representing the real physical processes determining fire spread, CA approaches range from highly simplistic 'toy' models, through physically-informed probabilistic models, to physically-based deterministic models. Consequently, the number and detail of data inputs required, the computational demands, and the information content of the outputs varies widely between different implementations. Furthermore, although the flexibility of the CA approach means it has been widely applied, its development and application has largely been bespoke for individual projects and (other than for 'toy' models) there are rather few examples available publicly online.

Physically-informed probabilistic cellular automata models (PIPCA)

Here we focus on Physically-informed probabilistic cellular automata (PIPCA) models, as these have historically been applied to European landscapes, both for understanding individual fire spread, and fire regimes. PIPCA models use environmental variables such as fuel (vegetation) conditions, landscape relief, and meteorology to produce variable spread probabilities between neighbouring cells. PIPCA models assume that cell contact is the driver of wildland fire spread. Whilst some studies have used PIPCA models to simulate the spread of a single fire (e.g. Clarke *et al.* 1994; 1996, Karfyllidis and Thanailakis, 1997; Alexandridis *et al.* 2008; 2011), probabilistic models are most often used to examine the long-term dynamics of fire-prone landscapes, typically characterising the broad-scale heterogeneity and final pattern of burned area (e.g. Anderson, 1982; Green, 1983).

PIPCA models are widely used to examine the interaction of fire regimes with vegetation dynamics (i.e. Landscape Fire Simulation Models, see Keane *et al.* 2004). To be spatially-explicit, these models must represent the spread of individual fires across a landscape, and primary examples are Perry and Enright (2002), Pausas (2006), and Millington *et al.* (2009). Because these CA models are designed to simulate the multiple fires that characterises a regions wildfire 'regime', they also typically account for factors influencing fire ignition, and the specific location of ignition does not need to be specified by the user. Succession-disturbance dynamics and other environmental variables (e.g. wind) result in changes in spread probabilities between cells for individual fire simulations.

The evaluation of PIPCA models in terms of realism and accuracy is limited to a relatively few studies (e.g. Alexandridis *et al.* (2008) for individual fires; and Millington *et al.* (2009) for wildfire regimes). Alexandridis *et al.* (2008) use a PIPCA model for simulating an August 1990 wildfire on the Greek island of Spetses, concluding that the simulated fire evolution characteristics in both space and time agreed with those of the real incident rather well. Similarly, Millington *et al.* (2009) found that their PIPCA model reproduced the observed frequency-size distribution of burned areas for their Mediterranean study area.

The computational requirements of PIPCA are reasonably low, and the outputs expected from these approaches are burned area maps, metrics related to spatio-temporal patterns of burned area and rates of spread, and probabilistic assessments of burn susceptibility (when used in a Monte Carlo fashion).

Links with other tools

Multiple fire events simulators can be reliable tools to help make silvicultural decisions at large scales and at long term time spans. They can directly influence on the spatial allocation of prescribed burning for reduce landscape vulnerability to fire regimes. On the contrary, prescribed burning can help to calibrate and test certain processes of these models. Fire ignition models are also a tool that can be integrated in multiple fire events simulators, by the integration of sterling ignition patterns on fire regime modelling.

2.2.4. Potential uses and requirements of fire simulation models

Fire growth simulation models have a multitude of uses that may be split into three broad categories: (i) operational firefighting; (ii) wildfire preparedness; (iii) wildfire investigation. This section largely draws on work by Pearce (2009) who identifies a variety of wildfire growth simulation model applications.

2.2.4.1. Uses for operational firefighting (after Pearce 2009)

- Projecting fire growth for use in determining appropriate suppression strategies and resource requirements.
- Supporting incident management options through different simulated wildfire spread scenarios.
- Assessing values-at-risk based on the predicted spread direction.
- Determining evacuation needs based on predicted rate-of-spread.
- Conducting escape fire analysis to predict the likelihood and locations of fire break-outs.
- Predicting fire behaviour at prescribed burns.

2.2.4.2. Uses for wildfire preparedness (Pearce 2009, after Finney 2003; Tymstra 2006)

- Evaluating threats to values-at-risk – conducting “what-if” scenarios in a planning mode to determine the threat of potential wildfires to important values (e.g. communities, recreation areas, conservation values, etc.).
- Fuels management – assessing the effectiveness of alternative fuel management strategies (e.g., harvest scheduling, cut block design, silviculture, stand density management) at reducing the threat of large fires (e.g. Finney 2001).
- Evaluating burn probabilities across a landscape – use of stochastic modelling (e.g. Burn-P3; Parisien *et al.* 2005) to produce a burn probability map for all points on the landscape under different fuel and weather conditions.

- Spatial and temporal variation in fire behaviour – determining spatial and temporal (diurnal, seasonal) differences in predicted fire behaviour for areas of interest based on various combinations of fuels, weather and topography (e.g. FlamMap, Finney 2006).
- Fire severity mapping – evaluation of likely fire severity based on predicted fire behaviour (fire intensity, fuel consumption, crown fire occurrence) for various fire weather scenarios.
- Budget justification – evaluation of the impact of escaped fires on area burned based on various budget scenarios
- Ecological applications – function of fire as a landscape disturbance – use of a process-based
- Fire growth model to investigate the role of fire in establishing and maintaining landscape patterns
- Training tools – to enhance fire management skills, to help explain fire behaviour to those unfamiliar with fire, particularly the public, media and government officials (Albright and Mesiner 1999).

2.2.4.3. Uses for wildfire investigation (after Pearce, 2009)

- Post-fire analysis – cost/benefit analyses evaluating suppression effectiveness (area/values saved).
- Forensic support – evaluation of probable ignition times and/or fire locations to support fire investigations.

2.2.5. Fire simulation modelling in Europe

There is no published literature on operational use of wildfire growth models within European fire services and there is no dedicated effort to formulate a European-specific wildfire growth simulation system equivalent to FARSITE in the USA, and Prometheus in Canada. It may be the case that individual nation states or administrative regions within Europe are using wildfire simulation models to some degree for wildfire preparedness (e.g. Catalonia, Spain) (M Castellnou, pers. comm.); where this is the case, the models are often those developed for elsewhere (e.g. FARSITE) that have been customised for use in European fuels.

In the research literature, there are some examples of wildfire growth simulation models being used for case studies in Europe. There are a number of examples of the application of FARSITE to European situations, for example. These are predominantly focussed on the Mediterranean shrubland biome, with very little focus on forested/non-Mediterranean fuels. FARSITE has been applied exclusively to the study of fire spread in Mediterranean shrublands (e.g. Bigili & Saglam [2003] in Turkish maquis; De Luis et al. [2004] in Mediterranean gorse shrublands; and Dimitrakopoulos [2001] in Greek shrublands).

Whilst there is little evidence of Prometheus being used in European settings, the main advantage of Prometheus is that the fire behaviour is predicted using the Fire Weather

Index. From a European context, this may be useful for nation states which are adapting a Fire Danger System (FDS) based on the Canadian Fire Weather Indices (e.g. the UK: Kitchen, 2012). New Zealand has adopted the FWI as a key component of their Wildfire Threat Analysis, and therefore use Prometheus as their preferred model of wildfire spread (Pearce, 2009). To enable the use of Prometheus in New Zealand fuel types, fuel models were parameterized for Prometheus through a series of experimental fires in New Zealand fuels.

Cellular automata models have also been used in European situations, but these are mostly dominated by studies of ecological fire regimes (multiple fires), rather than for operational firefighting. Some examples include the application of a cellular automata model by Alexandridis et al. (2008) who modelled individual fires on the Greek island of Spetses, Millington et al. (2009) who consider multiple fires spreading across landscapes in Spain, or Regos et al. 2014, who assessed the effect of different suppression strategies on resulting burnt area in Mediterranean Ecosystems with the MedFire model.

2.2.6. Key messages for practitioners in Europe

Improvements in computing technology, and increasing interest in the behaviour of wildland fires and in their numerical simulation, has seen the expansion of fire behaviour prediction tools (mostly based on weather and fuel information) into spatially explicit fire growth models over the past few decades. Whilst software with graphical user-interfaces have been developed for interacting with fire models, these have mostly been used by academic communities rather than fire practitioners, as the use of this software often requires specialist training/knowledge in the use of spatial data/models.

The successful application of fire simulation models relies upon good quality input data (e.g. fuel maps, terrain, and meteorology) and the underlying fire behaviour prediction system. For practitioners, fire simulators must not only be accurate, but more importantly, the software must be "easy to use (i.e. easy to enter data, easy to modify data), have good presentation of output (i.e. easy to understand) and [be computationally] fast (results of a simulation available in minutes)" (Johnston *et al.* 2005). Despite the availability of user-friendly fire spread software (e.g. Prometheus), fire practitioners must possess or have access to staff with Geographical Information Systems (GIS) expertise, particularly for assembling the required input data, and interpreting and presenting model outputs. Furthermore, in northern European settings, where planning for wildfire preparedness is only beginning to be realised, it is important that any simulation software be compatible with existing data. It is important to note, that in all cases, fire simulation models should be used by professionals specialized in forest fire growth and behavior, given the importance of a correct interpretation of the results.

With these considerations in mind, **Table 3** forms a comparison of FARSITE, Prometheus and generic cellular automata models. The 'design purpose' refers to whether the application is used mainly for operational firefighting or for land management purposes. The 'computing requirement' describes the computer processing requirements; generally the selected models require only moderate processing power, however this will depend on the spatial resolution of the inputs. The ‘simulation technique’ refers to whether the modelling environment uses a vector (perimeter wave propagation) or a raster (cellular) approach. ‘European fuels’ refers to the capability of the models to predict fire spread in European fuels; this is governed by how customisability of the built-in fuel models and the ability to specify new fuel models. The table continues to outline whether the fire spread models have crowning, spotting, firebreak breaching, and suppression (firefighting) modules and whether the key variables of flame length and fire intensity are output by the models. References are provided for examples of model evaluation in European fuels. ‘Ensemble fire modelling’ refers to the ability to simulate multiple fire events in the same model (e.g. for ecological fire regime investigations/fire risk mapping). The remainder of the table compares the support, maintenance and availability of the models.

Table 3: Review of freely available fire growth simulation model characteristics & capacity for modification for use in Europe (following approach of Pearce, 2009).

Simulation modelling characteristic or capability/ compatibility	FARSITE	Prometheus	Cellular automata (generic grid-based)
Design purpose	• Operational & strategic prediction of fire behaviour & fire growth • Land management/fire use for resource benefit	• Operational & strategic prediction of fire behaviour & fire growth • Some studies of landscape burn probability mapping	• Ecological applications (e.g. controls on fire regime) • Land management for fire risk • Some focus on individual fires
Computing requirement	PC (mod)	PC (mod)	PC (low)
Simulation technique	vector	vector	raster
European fuels	• Possible to specify customised fuel models	Possible to specify customised fuel models if relationship between FWI and fire behaviour is known	• Purposefully generic and so can be widely applied
Crowning	yes	yes	no
Spotting	yes	coming	possible
Firebreak breaching	yes	yes	possible
Suppression	yes	partially	no
Flame length output	yes	yes	no
Fire intensity output	yes	yes	no
Evaluated for European fuels	yes (e.g. Arca et al. 2007)	no	yes (e.g. Alexandridis et al. 2008)
Ensemble fire modelling	not native, but possible using *Wildfire Analyst*	no, but possible using *Burn-P3* add-on tool	yes
Tech support availability	online tutorials, training course, email support	online tutorials, training course, email support	n/a
Maintenance	Ongoing updates and reissuing	Ongoing updates and reissuing	n/a
Availability	free: www.firegrowthmodel.ca	free: www.firemodels.org	models usually bespoke

2.3. Crown fire hazard assessment

2.3.1. Introduction

There are different forest fire types depending on the layer involved in its spread: a) ground fires, in which duff, organic soils and roots are consumed (Frandsen, 1987), b) surface fires, where needles, leaves, grass, dead and down branch wood and logs, low brush and short trees are implicated in the combustion, and c) crown fires, in which canopy fuels are involved (Van Wagner, 1977). Furthermore, crown fires are divided into three categories: a) passive crown fires (individual or small groups of trees torch out but flames are not maintained in canopy), b) active crown fires (surface and canopy fuel stratum burn and crown fire spread depends on the heat released by the surface fuel layers), and c) independent crown fires (fire spreads in the canopy independently of the heat released from the surface fire), which occur rarely and under extreme conditions (Van Wagner, 1993).

Undoubtedly, from all these types of fires, active crown fire is the one that poses the greatest **threat to the extinction systems and fire managers** (Albini and Stocks, 1986), often spreading rapidly (Wade and Ward, 1973) and burning with greater intensity and faster spread than surface fires (Rothermel, 1983). Traditional direct attack is impossible to undertake in these type of fires because fire behaviour characteristics are extreme, i.e. high eat intensity, long spotting distances and large flame lengths and rates of spread (Scott and Reinhardt, 2001). So then, prediction of the conditions under which crown fires initiate and propagate are thus of primary concern in fire management (Rusell et al, 2011).

To avoid such situations a good step forwards is an **active forest management** with the goal **to create forest structures that difficult the development of crown fires and facilitate the fire extinction tasks**, acknowledging the major role of weather in fires behaviour and regime. In this sense, role of fuels and forest structure is very important to reduce the risk of transition of surface fires to active crown fires (Fernandes, 2009; Álvarez et al., 2012; Fernandez-Alonso et al., 2013).

However, for integrating the risk of large forest fires (LFF) into the forest planning and management it is necessary to have tools that help to identify the degree of vulnerability to crown fires of the forests and to guide stands, through forest management, to a more fire resistant and resilient structures.

There are fire simulators softwares that evaluate whether within a stand an ignition will develop a crown or a surface fire, and therefore the effectiveness of silvicultural treatments in crown fire behaviour, they have little practical application because they require variables that are not estimated in conventional forest inventories and are difficult to measure. Thus, the forest structural characteristics usually recognized as determining canopy fire spread are canopy fuel load (CFL), canopy bulk density (CBD) and canopy base height (CBH) (Cruz et al. 2003). CFL is the available canopy fuel per surface unity; CBD indicates the fuel available for combustion per volume unity in the aerial layer; and CBH is the lowest height above ground level at which there is sufficient canopy fuel to propagate fire vertically through the canopy (Sando and Wick 1972; Scott and Reinhardt 2001).

Furthermore, there are few crown fire hazard assessment tools to evaluate easily whether a forest stand with a given silvicultural structure will be capable of generating crown fires and therefore to estimate the effectiveness of silvicultural treatments with the objective of fire prevention.

Crown fire hazard assessment tools give information on the structural characteristics of the forest stand and its relationship with the vulnerability to generate and maintain high intensity-crown fires. Therefore, **they are useful to assess crown fire potential behaviour and guide forest management for reduce risk of crown fires**.

They are used **to identify how vulnerable is a forest stand**, in relation to the structure and other ecological conditions, to generate and propagate a crown fire. So then, they are handy to **classify priority areas where silvicultural treatments should be implemented in order to reduce risk of LFF**.

Tools for assessing crown fire should be simple and easy to use by forest managers, so then it is important the development of classification criterion of the potential of a stand to sustain different crown fire types, based on forest stand variables that are easily obtained in common inventories.

2.3.2. Forest structure and fire behavior

Increase crown base height, reduce surface fuel load and modify the stand density of are some of the main actions that managers can carry out to increase the resistance of a forest stand to crown fire and, at the same time, create useful and more safe areas for the extinction systems and facilitate the tasks of fire fighting. However, silvicultural treatments for fire prevention are very expensive, so managers require technical and numerical data on what are the most optimal forest structure to reduce crown fire vulnerability in the most effective way and economically viable, and from it the most suitable forest treatments to reduce efficiently crown fire hazard in a stand, such as clearing and thinning intensity and rotation, pruning intensity or optimum remaining basal area and canopy cover after a silvicultural treatments.

Tools for assessing crown fire potential from information of forest structure, among other variables, are of great utility for understanding crown fire behaviour and guide forest management to reduce risk of crown fires. In this sense, it is important to differentiate **tools that use variables related to the crown** difficult to obtain in common forest inventories, from **tools that use variables measured normally in forest inventories**.

2.3.3. Review of the state of the art

2.3.3.1. Crown models

Managers rely on fire simulator models to make fuel management decisions. Nevertheless, users need to identify variables that are neither easy to estimate nor useful for practical fuel management purposes. Most typical variables used for predict crown fire ignition and propagation are: Canopy bulk density (CBD), measured in Kg/m^3, is one of the most used variables for monitoring fire behaviour but is difficult to estimate. The general method to obtain CBD is by diving canopy fuel load between canopy depths; although it assumes that canopy biomass is homogeneously distributed within the stand. Agee (1996), suggest that 0,10 Kg/m^3 is the threshold below which an active crown fire is unlikely to occur after analyze post fire data. Canopy fuel load (CFL), measured in Kg/m^2, is the part of the aerial crown that is consumed in a crown fire and it can be obtained by using allometric equations to estimate foliage biomass. Canopy base height (CBH), measured in metres, generally responds to the distance from the forest floor to the live crown base. Mitsopoulos and Dimitrakopoulos (2007), characterised canopy fuel variables to predict canopy fire hazard potential of *Pinus halepensis* using simulation models. Destructive sampling of 40 trees suggests that CBH of Aleppo pines is low, 3 - 6,5 m, while CFL and CBD are similar to other conifers. Alternatively, Cruz et al (2004) present another term named Fuel Strata Gap (FSG), similar to CBH, but in which the gap is the distance from the top of the fuel bed to the lower limit of the canopy fuel layer. The limits of the canopy layer are the live needles and ladder fuels that allow fire to propagate vertically. Several studies predict CBD from tree dimensions such as diameter, height or crown ratio. For example, Duveneck and Patterson (2007) uses diameter as an independent variable for predicting CBD for *Pinus rigida.* Fernandez-Alonso et al. (2013) they fit prediction equations relating to CFL, CBD and CBH, using as input forest stand variables that are easily obtained from common inventories in pine stands in Galicia. Early studies of relevance to these concerns were in the prediction of slash weights and fuel load distributions, such as Brown's (1978) study, where allometric relationships of CBH and CBD to tree measurements (dbh, crown length, tree height, and live crown ratio) were determined.

Hall et al. (2005) uses LIDAR technology to estimate CBH and CBD, results are promising but the relationships are still not robust enough. Roccaforte et al. (2008) pointed out that simulation programs are very sensitive to the equation selected to calculate CFL and subsequently results vary significantly.

So then, in general the variables CFL, CBD and CBH are relatively unknown by forest managers and there are few tools available to estimate these variables, and therefore, forest managers cannot use fire behaviour simulator systems correctly in order to select the most appropriate fuel treatments (e.g. reduction or modification of surface fuels, elimination of ladder fuels, raising the canopy base height or reduction of the canopy bulk density).

2.3.3.2. Crown fire behaviour models

In the past, fire behaviour models were used in fire management support systems, mainly to simulate surface fires. However, crown fire behaviour modelling has gained importance and fire modelling research has been focus on determining crown fire initiation and spread models. In all fire simulation programs surface fuel load has to be estimated, although as it occurs with canopy fuel characterization, measurements are empirical estimated. The user has to identify which surface fuel model, from those defined by Rothermel (1972), is more accurate for their stand conditions.

Nowadays, the use of different fire behaviour simulation systems enables predictions of the surface rate of fire spread, fireline intensity or flame length. These systems also enable assessment of the possibility of torching and the subsequent fire spread over the stand canopy in coniferous stands. Some of the more relevant examples of various fire modelling systems, such as NEXUS (Scott and Reinhardt 2001), Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003), FARSITE (Finney 2004), Fuel Management Analyst (FMAPlus) (Carlton 2005), FlamMap (Finney 2006) and BehavePlus (Andrews et al. 2008), Crown Fire Initiation and Spread (CFIS) (Alexander et al. 2006) and Pine Plantation Pyrometrics (PPPY) (Cruz et al. 2007, 2008) are extensively used to assess potential crown fire behaviour.

All of the fire modelling systems referred to previously implement, link or integrate (or both) Rothermel's (1972, 1991) models for predicting surface and crown fire rates of spread with Van Wagner's (1977, 1993) crown fire transition and propagation models in various ways, and provide an output of several fire behaviour characteristics (e.g. rate of fire spread, fireline intensity, type of fire, crown fraction burned).

In those modeling systems, surface fuels are assumed to be homogeneous, continuous and contiguous to the ground and crown fuels are considered as a homogeneous layer of uniform height above the ground, depth and bulk density (Parsons et al., 2011).

The assumption of a homogeneous crown layer is thus a central component in current models used to predict crown fire behaviour.

In reality, vegetation is never homogenous nor continuous but this assumption may be reasonable at coarse scales for dense forests of trees very similar in size and age, typified by the stands used in Van Wagner's analysis (Van Wagner, 1964). However, many stands are characterized by variability in size and numbers of trees, where between-tree heterogeneity could be expected to be significant. An homogeneous tree crown burns faster and more consistently than the spatially variable crown. Fire behaviour modeled with homogeneous fuels may thus tend to overestimate forward spreat rates (Parsons et al, 2011). Recent critiques argue that the assumptions and empirical basis of the modeling framework used for crown fire in the United States are inconsistent with active spreading crown fire conditions and characteristics (Cohen et al., 2006) and often result in inaccurate predictions (Cruz and Alexander, 2010).

2.3.3.3. Tools for assessing crown fire hazard from forest stand variables of easy measurement

In the practice, users of fire simulation models need a good knowledge about the assumptions made in the models they use and accurately data gather to characterize canopy and surface fuels. To overcome these difficulties other types of tools such as nomographs or keys have been devised. Worldwide, nomographs are created to provide managers with an easy way to assess the likelihood of crown fire initiation. Nomographs for *Pinus halepensis* have been devised using Van Wagner (1977) initiation model and Byram's (1959) surface fire model (Dimitrakopoulos et al., 2007). The nomographs determinine the critical values of flame length and spread rate of surface fire, needed for the transition from surface to crown fire. Also, for *Pinus halepensis* forests Alvarez et al. (2012) they classify forest structures of into fuel types as a function of crown fire potential. Forest structures identified (fourteen in total) depend on canopy closure, number of tree layers, percentage of the different tree layers and overall tree density. Fernández-Alonso et al. (2013) develop a classification criterion of the potential of pine stands to sustain different crowns fire types, based on stand-level variables (basal area and dominant height). The likelihood of crown fire occurrence was simulated using the logistic crown fire initiation model proposed by Cruz et al. (2004).

Alternatively, heuristic and expert opinion approaches have not escaped to the attempts of appraising crown fire potential. Fahnestock (1970) designed two keys for determining rate of spread and crowning potential. The second key for determining crown fire potential is based on forest cover, crown density and the presence or absence of ladder fuels. Later, Menning and Stephens (2007) developed a ladder fuel hazard assessment flow chart (LaFHA). The aim was to rank to what extend a surface fire and is able to climb to the canopy, by quantifying ladder fuels in a defined area. The LaFHA approach evaluates ladder fuels by estimating clumping of low aerial fuels and maximum gaps in vertical fuel ladders. More recently, Piqué et al. (2011) developed a key to determine quickly the vulnerability of a forest stand to generate crown fires (CVFoC). The CVFoC serve to the manager for appropriate treatments planning to obtain forest structures resistant to crown fires given a stand with high crown fire vulnerability, previously identified. They identified structural types for *Pinus* and *Quercus* forests classified in types A, B and C, based on forest variables as: surface covers of different layers of fuel (aerial, ladder, and surface) and vertical projection distances between them, being A high vulnerability to active crown fire structures, B medium vulnerability structures and C low vulnerability structures.

These types of tools present some advantages in front of the use of fire simulation models for assessing crown fire hazard, as the user does not need excellent fire behaviour knowledge and, in addition, these tools are faster and simple for using in the field. In applying these tools, it is important to note that it is likely that the fuel management operations do not prevent a forest fire to occur, but it will avoid a high intensity fire. Furthermore, as long as the ignition occurs in the managed area, crown fires can be avoided in most cases and fire may burn only the surface fuel layer.

2.3.4. Application of tools for crown fire hazard assessment

Nowadays, we have a large variety of tools to model fire behaviour and extensively used to assess potential crown fire initiation and behavior. Nevertheless, tools for assessing crown fire potential from information of forest stand variables of easy measurement are not as abundant or widely used.

We focus in this type of tools because the user does not need excellent fire behaviour knowledge and are faster and simple to use for forest and fire managers (**Table 4**). Some general applications of the crown fire hazard assessment tools would be:

- Assessment of crown fire occurrence at stand level and ranking the risk of a surface fire to climb to the canopy and advance to a crown fire.
- Improve knowledge about which forest structures are dangerous because their vulnerability to generate crown fires, both for fire prevention purposes and fire fighting operations.
- Give practical information to forests managers about which are the optimum forest structures and, so then, most efficient silvicultural treatments to reduce risk of crown fires and facilitate fire extinction tasks.
- Evaluate the effectiveness of different fuel treatments aiming at crown fire hazard reduction.
- Given areas with a high risk of forest fires, due to climatic or socioeconomic factors, to identify priority areas more vulnerable to crown fires, where proper forest management should be implemented in order to reduce risk of LFF.

Table 4: Crown fire hazard assessment tools of easy use by fire managers: general overview of their application.

Tool	Author	Application (in forest fire prevention/ forest fire fighting)
Keys for Appraising Forest Fire Fuels	Fahnestock, 1970	General application, EEUU. Different species. Tactical and strategic - Assessment of crown fire occurrence in a forest stand. - Classification of crown potential of a forest stand based on forest cover, crown density and the presence or absence of ladder fuels. - Classification of fuel characteristics in terms of potential rate of fire spread. - Planning and analysis of the effectiveness of different fuel treatment options aiming at crown fire hazard reduction.
Nomographs for predicting crown fire initiation	Dimitrakopoulos et al., 2007	Mediterranean Greece. *Pinus halepensis.* Tactical and Strategic. - Assessment of crown fire occurrence in a forest stand. - Calculation of the threshold conditions that are necessary for the transition of a surface fire to a crown fire. - Determination of the critical values of flame length based on crown base height and foliar moisture content. - Determination of the critical surface fire spread rate for the transition from surface fire to crown fire, from critical value of flame length, for forest with understory of maquis or pine litter. - Planning and analysis of the effectiveness of different fuel treatment options aiming at crown fire hazard reduction.
Ladder Fuel Hazard Assessment flow chart (LaFHA)	Menning and Stephens, 2007	Sierra Nevada, California, EEUU. Conifer forests. Tactical and strategic. - Assessment of crown fire occurrence in a forest stand. - Identify clumping and vertical continuity of fuels. - Ranking risk of a surface fire to climb to the canopy. - Planning and analysis of the effectiveness of different fuel treatment options aiming at crown fire hazard reduction.
Chart for Ranking crown fire hazard (CVFoC)	Piqué et al., 2011	North-East Spain. *Pinus* and *Quercu*s forests. Tactical and strategic. - Assessment of crown fire occurrence in a forest stand. - Determination of the vulnerability of a forest stand to generate crown fires, from forest variablea as surface covers of different layers of fuel and vertical projection distances between them. - Planning and analysis of the effectiveness of different fuel treatment options aiming at crown fire hazard reduction.
Fuel types and crown fire potential	Álvarez et al., 2012	Girona province, Spain. *Pinus halepensis.* Tactical and strategic. - Assessment of crown fire occurrence in a forest stand. - Classification of forest structures into fuel types as a function of crown fire potential (forest structures depend on canopy closure, number of tree layers, percentage of the different tree layers and overall tree density). - Planning and analysis of the effectiveness of different fuel treatment options aiming at crown fire hazard reduction.
Canopy fuel classification in relation to crown fire potential	Fernandez-Alonso et al., 2013	Galia Region, Spain. *P. pinaster, P. Radiata, P. Sylvetris*, Mixed pine. Tactical and strategic. - Assessment of crown fire occurrence in a forest stand. - Classification of the potential of a forest stand to sustain different crowns fire types, based on stand-level variables (basal area and dominant height). - Planning and analysis of the effectiveness of different fuel treatment options aiming at crown fire hazard reduction.

2.3.5. Key messages related to the tools for crown fire hazard assessment

- **Need of crown fuel modeling improvement.** Advancements in the accuracy and resolution of individual crown models are needed to better inform fuels management and fire behavior simulations (Affleck, 2102). The theme of **better characterizing crown fuel loads in space and time is important**. The current quality of crown fuel modeling efforts has been demonstrated to be inadequate in meeting the needs of empirical fire behavior simulation models (Cruz and Alexander 2010).

- By the other hand, the application of crown fire behaviour models in fire management decision-making has been limited by the difficulty in measuring canopy fuel stratum characteristics and the lack of models for estimating these from easy to measure stand variables (Piqué et al., 2011; Álvarez et al., 2012; Fernandez-Alonso et al., 2013)**.** In this sense it is **necessary to advance in the development of crown fire hazard assessment tools of easy use,** to rank risk of crown fire from variables of quickly estimation and develop models for predict them**.**

- These types of tools present some advantages in front of the use of fire simulation models for assessing crown fire hazard, as the user does not need excellent fire behaviour knowledge and, in addition, **these tools are faster and simple for using in the field.** They, also, can be used as forest management tool to guide efficient silvicultural treatments to reduce risk of crown fires and facilitate fire extinction tasks.

- The role of forest structure in crown fire risk reduction is strong, so **forest and fire managers they should improve knowledge about which forest structures**, in their areas of work, **are less vulnerable to generate crown fires** and more safety for firefighting operations.

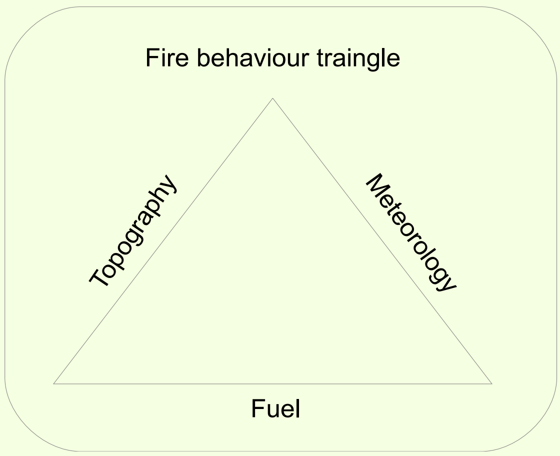
3. FUEL MANAGEMENT TOOLS FOR FIRE HAZARD REDUCTION

3.1. Silvicultural treatments and management guidelines for fuel reduction

3.1.1. Introduction: forest management and fire behavior

Forest planning and management should consider more than ever forest fires. However, for integrating the risk of large forest fires into forest management is necessary to have tools that help to identify the degree of vulnerability to crown fires of the forests and guide forest stands through forest management to more fire resistant and resilient structures.

In this regard, it is important to consider the **main factors that influence the behavior and spread of a fire (topography, meteorology and fuel)** (Rothermel, 1983) and pay special attention to those who can be modify through forest management, such as fuel (vegetation), (**Figure 2**).



From the perspective of forest management and fire prevention, the **fuel is the only factor that can be altered to modify fire behaviour** (Graham et al., 2004).

Figure 2: Fire behavior triangle (Rothermel, 1983)

While extinction systems are able to fight fires of low to medium intensity, which are the majority, the few fires of high intensity and extreme behaviour often exceed the capacity of extinction, affecting large areas of forest.

The real challenge in order to reduce the negative effects of the LFF is to strength the prevention measures of the fire risk. Such prevention should be understood as an active performance through spatial planning, proper management of forests and the efficiency of management fire during extinction.

Since vegetation is the only factor that can be altered to influence the characteristics of forest fires and prevent them from becoming LFF, there is a need of a more widespread practice of preventive silviculture that modifies forest structures stands in order to make them more resistant to high intensity fire, reducing the amount and continuity of fuel and foster the growth and development of trees.

Some measures to achieve this are: reduction of the density in dense stands that currently exist in the forest, understory development control to prevent vertical continuity of vegetation and creating discontinuities in the landscape with a combination of woodland with open areas.

In short, only by fuel management and land planning, and taking into account the fire type, its recurrence and fire ecology is possible to reduce the risk of large forest fires. Treatments for reducing the vulnearability of a forest to generate crown fires, they can be manual, mechanical and prescribed burning and they should be implemented in the framework of a forest management plan.

To prevent the spread of an existing fire or to transform an aerial fire into an easier to extinguish ground fire by depriving it of readily flammable material, silvicultural and technical measures need to be constructed or introduced in areas with high forest fire risks. In this sense, it is important to take into account that a number of silvicultural measures can only achieve their preventative or damage-minimising effect after several years.

Finally, fire management policies in rely heavily on fire suppression and do not sufficiently address the socio-economic and land management issues behind the inception and spread of fires (Fernandes, 2008). Fire control technology succeeds only within the lower range of fire intensity (Gill, 2005). The effectiveness of firefighting operations is therefore greatly reduced when unfavourable weather and fuel accumulation coincide.

3.1.2. Review of the state of the art

3.1.2.1. Fuel treatments

The interaction of meteorology, topography and fuel determines the behaviour of fire (Rothermel, 1983). Nevertheless, the role that these factors play in the behaviour of fire has been discussed by a number of authors (Omi and Martinson, 2002; Graham et al., 2004; Carey and Schuman, 2003). Some of them have suggested that under extreme weather conditions and steep slopes, fuel plays a minor role (Carey and Schuman, 2003). However, from all of these parameters, we can only alter fuel and therefore to some extend fire behaviour.

Fuel management strategies aim to contain or modify fire behaviour by isolating, modifying or converting fuel (Pyne et al., 1996). Fuel isolation management aims to control fire in an area, making direct attack easier. Forests where fuels have been modified or converted might serve also to enclose fire but their primarily objective is to modify its behaviour.

Linear fuel treatments are the prevailing option in the forest fire prevention (Xanthopoulos et al., 2006), but their performance in face of fire is uncertain. So then, the most recommended in fire prevention is a fire-smart silviculture for more efficient large forest fire risk reduction (Fernandes, 2013), following four fuel treatment principles and priorities to increase resistance to fire (Agee and Skinner, 2005; Graham, McCaffre and Jain, 2004):

1. Decrease the accumulation or modify the structure of surface fuels to limit potential fire intensity, hence decreasing tree injury and facilitating effective fire suppression.

2. Raise the canopy base by pruning the trees and remove ladder fuels, minimizing the likelihood of vertical fire development, i.e. passive crown fire.

3. Thin the stand to decrease foliage density, impeding the transmission of fire between adjacent trees, i.e. active crown fire.

4. Maintain large trees of fire resistant species.

Hirsch et al. (2001) defined fire-smart forest management as an integrated approach primarily based on fuel treatments through which the socio-economic impacts of fire are minimized while its ecological benefits are maintained and maximized; by lowering ignition likelihood and fire behaviour potential, fire suppression capacity is increased and forests and landscapes become more resistant to fire spread and more resilient to its occurrence.

Treatments such thinning, pruning or the removal of surface fuels (using prescribe fire or mechanical tools) are advised. The effectiveness of these treatments in reducing fire hazard has been largely demonstrated in experimental fires and wildfire case studies using simulators models, mostly for dry conifers of western EEUU (Carey and Schumann, 2003; Graham et al., 2004; Peterson et al., 2005). Nevertheless how long treatments last for different types of ecosystems and fire regimes has not been deeply studied.

Thus, the main stand level management measures proposed for reduce de risk of large forest fires is to shape formations less vulnerable (more resilient) to LFF, by applying silvicultural models and silvicultural treatments for structuring the forest cover.

The strategy to reduce or remove fuel from the understory and dominant trees by clearings and by thinning of the stands is one of the most used treatment with the aim of preventing forest fires.

However, this measure is very costly and therefore impractical to perform at larger scales. Thus, the challenge for efficient LFF prevention could be based on the following principles (Piqué, 2012):

- Treatments to **reduce forest fuel in strategic areas** facing the prevention and suppression of forest fires at the mountain scale (see section 3.1.2.3).
- Treatments that actually cause **changes in forest structure** and **influence fire behaviour** in the desired way.
- Treatments that take into account the **natural dynamics** and are based in adaptive management.
- Minimal intervention treatments, **low cost** and its **effect should last a** maximum time.

3.1.2.2. Increasing fire resistance: promoting forest structures resistant to crown fires that facilitate fire fighting

Forests with little accumulation of fuel and forest structures with vertical discontinuity with respect to vegetation strata, and horizontal with respect to the canopy and understory cover, are more resistant to crown fire spread and less intense. This is demonstrated in many studies and it has been found that altering fuel loads and fuel continuity through silvicultural treatments, causes a decrease in the vulnerability to crown fires (Fule et al., 2001, Brown et al ., 2004; Agee and Skinner, 2005, Johnson et al., 2007).

Currently, there are numerous publications that aim to inform managers on how to create crown fire resistant forest structures using silvicultural treatments (Weatherspoon, 1996; Velez, 2000, Johnson et al., 2007; Serrada et al., 2008). At the stand level, as Fernandes and Rigolot (2007) suggested the sequence of treatments to reduce the vulnerability of a stand to crown fire would be:

- Reducing surface fuel load to limit the potential intensity of the surface fire.
- Removal of ladder fuels and pruning for reducing the likelihood of fire to climb to the canopy.
- Thinning to minimize the likelihood of fire spread through crowns.

To the operations mentioned above, the following could be added (Piqué, 2012):

- Silvicultural treatments to reduce resources competition and to promote growth and vitality of the tree species.
- Extend cut rotation so that the forests are more mature, to conform forest structures with vertical discontinuity.

At the stand level, treatments are sometimes unsatisfactory because catastrophic fires go beyond the stand-scale creating their own fire environment. Additionally, at the landscape level, fuel treatments might be insufficient or located in wrong places being ineffective (Agee and Skinner, 2005). Both, the temporal and spatial scale of treatments are a difficult issue when planning fuel management strategies. In this sense, Finney (2001) has defined an algorithm to describe management strategies that optimize treatments and eventually interrupt the movement of fire at the landscape level. The modification or conversion of fuel in a stand cannot alter fire size per se but it can change the fire behaviour and might reduce, in most of the cases, its severity.

Case studies of the effects of fuel treatments on large fire growth do exist, e.g. Finney et al. (2005). However, understanding of the effects of fuel treatments at the scale of the landscape is mostly theoretical and relies heavily on fire simulation modelling (Finney, 2001). The long-term, cumulative impacts of fuel management on fire incidence depend on how the rates of treatment effort and fuel re-accumulation relate with each other (Finney et al., 2007; King, Bradstock, Cary, Chapman, & Marsden-Smedley, 2008). Therefore, the ratio invest in forest management-fire prevention efficiency it is not always optimum, and often are needed high efforts of fuel treatment for really influence on fire behavior and reduce the fire hazard. In this sense, it is important to carry out treatments in strategic areas facing the prevention and suppression of forest fires at the landscape scale.

3.1.2.3 Reducing vulnerability to large forest fires (LFF): measures at landscape level

Among the measures to be integrated into forest management to prevent LFF, those related to the landscape level are of great importance.

For some areas there is information about the influence of the physical environment on fire behaviour, from the study of different types of fire, so as to know the features that a certain area must have to be considered strategic for the development of a LFF (Costa et al., 2011), being useful information in the face of efficient planning at the landscape scale.

The landscape level measures allow building "fire smart" landscapes with forest structures and spatial distribution patterns that contribute to difficult the spread of crown fires and facilitate the extinction of forest fires (Fernandes, 2013).

In this regard, Costa et al. (2011) they differentiate three types of actions or measures to be applied at landscape level for reduce fire hazard.

a) **Punctual specific actions of defence against fire** associated with fire suppression operations: determined according to the characteristics and pattern of spread of the different types of fires that may occur in an area, especially the most dangerous. These actions relate to Strategic Management Points (SMP), bands of low fuel or auxiliary bands anchored to paths.

b) Actions for the **formation of a matrix of forest cover with a structure that hinders the development and spread of LFF,** and also contribute indirectly to increase fire fighting opportunities and capability.

c) Actions to **promote** landscape-scale **heterogeneity,** in terms of structure and species.

3.1.3. Application of silvicultural treatments

Silvicultural treatments for fuel reduction and fire prevention generally refers to clearing for removing surface and ladder fuels, thinning or pruning. These treatments can be done mechanically or using prescribed burning. **Tables 5 and 6** show some recent studies about silvicultural treatments, and their effect in fire hazard reduction (most of them they combine treatments as thinning or clearing with prescribed burning).

In general, prescribed burning aim to reduce fuel loads to avoid creating intense and devastating fires and facilitate extinction tasks, but can also have other silvicultural objectives such as shrub clearing when regeneration cutting is applied, slash removal or tree competition reduction. They have been widely used and should be integrated in management schemes as another silvicultural tool for forest fire prevention, always under the control of specialists.

Other interesting option to reduce fuel loads with the objective of fire prevention, mainly surface fuels, is the use of livestock.

Table 5: Example of recent studies about fuel treatments and their effect in fire risk reduction.

	Treatment	Treatment description	Effect in fire risk reduction	Effectiveness (application, cost and duration)	Reference
Without combining prescribed burning	**Aerial, ladder and surface fuel reduction**	Moderate and heavy thinning, pruning and mastication in polewoods	Crown treatments alone cannot change potential fire behavior or effects	It is needed a spatial optimization of joint surface-crown fuel treatments using cost-benefit analysis	Molina *et al.* (2011)
		Selection thinning, surface and ladder fuels removal and pile-burning	Treatments substantially moderated fire severity and reduced tree mortality during wildfire. Crown fire reduced to surface fire in 50 m	Steep slopes require more fuel removal than flat ground	Safford *et al.* (2009)
	Aerial-ladder fuel reduction	Thin from below, all ladder fuels and snags removed (including dominated trees) and whole-tree harvesting. Slash piled and burned	Reduced fire severity (with some metrics) in treated areas during a wildfire	Area burned 1 to 7 years after treatments	Kennedy and Johnson (2014)
		Thinning to 50% canopy cover, to 30% canopy cover and single group selection opening. Whole trees skidded	Reduced fuel availability, but some microclimate effects may counteract. Risk for more severe fire behavior in group selection due to increased wind speeds and higher surface temperature	Fire spread models are limited in their prediction ability under various silvicultural treatments	Bigelow and North (2012)
	Surface-ladder fuel reduction	Mastication of ladder and surface fuels, in forest (including small, dominated trees) and shrubland	Enhancement of suppression efficacy. Reduced fire intensity and slow rate of spread	Caution: fire behavior in masticated fuels is poorly understood	Kreye *et al.* (2014a)
		Understory shrubs and small trees mechanical mowing. Debris left	Stand-alone mechanical treatments did not reduce overall fuel loads	Shrub layer recovered quickly (16 months). Litter dominated surface fuels following mastication is much different than in other ecosystems	Kreye *et al.* (2014b)

Table 6: Example of recent studies about fuel treatments (combination of mechanical treatments and prescribed burning) and their effect in fire risk reduction.

	Treatment	Treatment description	Effect in fire risk reduction	Effectiveness (application, cost and duration)	Reference
Combining prescribed burning	Aerial, ladder and surface fuel reduction	Landscape fuel treatment network: thin from below & pile-burned; shrubs and small trees mastication; prescribed burning; thin from below to 40% canopy cover with whole tree and underburned; group selection harvested and slash removal and re-planting	Reduction in hazardous fire potential across landscape	Hazard grows in untreated areas over time, resulting in an increase in overall fire hazard. Suggested 10-20 years cycle to long-lasting effect	Collins *et al.* (2013)
		Prescribed burning; thinning and mastication; herbicide application	Reduced reaction intensity, rate of spread and flamelength	Overall hazard is low to moderate with localized areas of high surface fire and crown fire potential	Ottmar and Prichard (2012)
		Mechanical only, mechanical plus fire, fire only	Decreased fire hazard	Longevity to 20 years	Stephens *et al.* (2012)
		Mechanical only, mechanical plus fire, fire only	Mechanical treatment followed by burning produced the strongest result, with more resilient forest structures, lower surface fuel loads and reduced rate of accumulation of surface fuels	Longer-term responses information is needed	Schwilk *et al.* (2009)
		Mechanical thinning alone or in combination with broadcast or pile burning	Fuel loads reduction	Effects present 15 years after treatment	Chiono *et al.* (2012)
	Surface-ladder fuel reduction	Landscape-scale fuel treatment based on maps of burn probability. Prescribed burning and mechanical removal of coarse fuel	Reduced overall fire risk, the burned area and number of fires of different intensities. Facilitation of fire suppression	Stand-scale fuel treatments cannot be directly scaled up, should consider overall fire risk	Liu *et al.* (2013)
		Removed surface and ladder fuels (mechanical only and mechanical plus fire)	Measures of fire severity significantly reduced and tree survivorship increased. Crown fire to surface fire in 70 m	Effects present 9 years after treatment	Safford *et al.* (2012)
		Fuel treatments in shrublands: Clearing and crushing, clearing and removal or burned	Effectively reduced fire initiation risk. Clearing with removal was more effective	Initial fire spread rate in regenerated shrubs 2 year after treatments was similar to that in untreated vegetation. Following fine fuel control (eg grazing) may be useful	Marino *et al.* (2012)
		Mastication of small trees and surface fuels, material left; Mastication and burning; understory burning alone	Prescribed fire was the most effective fuels reduction technique. There are important fire hazard tradeoffs between the treatment types that should be considered	Spatial scale and patterning of treatments is critical to successfully reducing large fire potential. Costs higher in burning plots than mastication. Plantations	Kobziar *et al.* (2009)

3.1.4. Key messages

- It exist abundant information about how to manage forest for reduce fire hazard, but it is mainly regarding to general guidelines and rules. Nevertheless, there is a need of technical information and more concrete silvicultural references. For example: optimum residual basal area or forest cover after a fire prevention treatment, thinning intensity and rotation, pruning height, etc.

- The real challenge for fire hazard reduction is to strength the prevention measures. Such prevention should be understood as an active performance through spatial planning and proper management of forests. It is crucial the correct localization of treatments in the space, depending on the type of forest fires in the area, for ensuring the treatments effectiveness.

- There is a need of a more widespread practice of preventive silviculture that modifies forest structures stands in order to make them more resistant and resilient to forest fires. It is crucial the correct localization of treatments in space.

- In short, only by fuel management and land planning, taking into account the fire types, its recurrence and fire ecology, would be possible to reduce the risk of large forest fires. Silvicultural treatments can decrease landscape fire severity rather than decrease area burned.

- In any case, a correct fuel management, creating forest structures less vulnerable to generate crows fires, is positive in terms of facilitating extinction tasks.

3.1.5. Integrated approach

<u>Decision-making:</u>
Prevention from tactical to strategic (if used for scenario analysis).

<u>Links with other tools:</u>
They can be validated using fire behaviour simulators at a stand level.
When allocating them spatially, they can provide landscape level candidate plans for fire risk reduction optimization (using fire spread simulators: risk reduction + other management criteria).

3.2. Prescribed burning

Prescribed burning (PB) is the careful application of fire under mild weather conditions to meet a defined management objective being the reduction in fire hazard the initial motivation of using PB across many areas of the world. However, its use has been expanded to include a wide array of objectives, including site preparation for tree regeneration, silvicultural improvements, range and wildlife habitat management, control of weeds, insects and diseases, and biodiversity maintenance (Kilgore and Curtis, 1987).

In the southern forest of the United States PB was officially authorized approximately in the 40´s because of the need to reduce the impact of extensive, high intensity fires on commercial forest values, properties and lifes. In southern Australia, PB has been used in a coordinated manner to manage fuels in eucalypt forests since the 1950s. In Europe, PB was introduced in the early 1980 in southern countries mainly in Portugal, France and Spain for fire hazard reduction while in central Europe PB is used mainly for biodiversity management. After an experimental period in the late 1970s, PB was implemented in Portuguese and Spanish pine forests (early 1980s) and in French shrublands (late 1980s). By contrast, Italy is currently undergoing an experimental PB phase (Ascoli and Bovio, 2013). Nowadays, PB in the Mediterranean region covers an area of approximately 10 000 ha yr–1; by way of comparison, this is only about 3% of the extent of wildfire in Portugal, Spain, and France (Ascoli and Bovio 2013).

Landscape-level fuel treatments strategically allocated in time and space can be combined with forest management efforts to reduce the extent and severity of forest fires, depending on vegetation type and historical fire regime (Agee*,* 1996). Fuel management in Europe traditionally relies on mechanical tools, but 10,000 ha yr^{-1} of forest is currently being managed by prescribed burning (PB) in which planned fires are set and used by fire experts under mild weather conditions to meet a defined management objective (Fernandes *et al.*, 2013). PB is widely recognized in North America, South Africa and Australia, but it is still questioned in Europe although used marginally in Mediterranean countries like Portugal, Spain and France. The increase in number of large catastrophic fires in past decades in Southern Europe has prompted the idea of establishing a less harmful fire regime, where the controlled spread of low-intensity unplanned fires is to be allowed and PB extensively applied as a cost-efficient way to reduce fuel continuities. However, the requisite changes to the social, economic and legal restrictions limit the deployment of this new fire management policy for PB (Fernandes *et al.*, 2013) and especially for unplanned fires. Besides, research of its potential effects on forest ecosystems and their accompanying services is still required, adding uncertainty.

3.2.1. State of the art

The following review is structured in four major aspects concerning PB: (i) a synthesis of published papers about PB effectiveness in fire hazard reduction, (ii) impact of PB on tree mortality and its management implications, (iii) impact of PB on the vitality of surviving trees and lastly, (iv) available decision support tools for planning PB prescription's.

3.2.1.1. PB effectiveness for fire hazard reduction

Here, we have summarized the main papers cited in three literature reviews about the effectiveness of PB for fire hazard reduction published by Fernandes & Botelho (2003), McCaw (2013) and Fernandes (2013). According with Fernandes & Botelho (2003) the effectiveness of PB in reducing fire hazard can be measured in a variety of ways using basic **combustion science, well-documented case studies**, **simulation software's** and **analysis of fire statistics** (Fernandes & Botelho, 2003; McCaw, 2013).

There are few studies in which quantitative information on fuel reduction is translated into classifications of effectiveness (Fernandes & Botelho, 2003). For instance, in *Eucalyptus* woodland of south-eastern Australia, James (1999) considers that a burn is effective when fine fuel reduction surpasses 50% of the pre- burn quantity and propose a methodology based on visual estimates of both reduced and created fuel to verify if fuel management objectives are met. Buckley & Corkish (1991) also propose a visual method of rating fuel reduction in thinning slash of *Eucalyptus sieberi*: a very good effectiveness of fire hazard reduction is reached if more than 50%, 75% and 75% of litter, slash and shrub are reduced respectively.

Besides, there are well-documented **case studies** reporting the effects of real wildfires that run into fuel managed areas with PB (Fernandes & Botelho, 2003). A number of examples are available around the world showing the qualities and limitations of hazard-reduction burning. In the United States effectiveness of PB in reducing severity of wildfire has been proof in several case studies in which *Pinus* mortality was lower compared with adyacent untreated stands after a wildfire PB (Wagle & Eakle, 1979) even after 5 years (Pollet & Omi, 2002) and 6 years (Martin *et al.*, 1988). Finney *et al.* (2005) using satellite imagery and PB records from two Arizona wildfires found that fire severity increased with time since treatment but decreased with unit size and number of repeated prescribed burn treatments. Martinson & Omi (2008) observed significantly lower scorch heights, crown damage, and ground char in the treated area of an escaped PB that burned into an area previously treated with repeated PB. Contrary, PB was not effective for containing a wildfire and swept across 10 000 ha of a regular PB program but severity was lower in fuel managed areas (Outcalt & Wade, 2000). Recently, Fernandes (2013) presented several case studies conducted in Australia and USA showing evidence of decreased fire severity in areas treated with PB compare with unmanaged zones after large wildfires. PB programs in **Europe** are less common, relatively recent and very localized but some examples of PB effectiveness can be found in Moreira da Silva (1997) and Rigolot (1997).

Computer simulation is also used to assess the effectiveness of PB in reducing fire hazard. In the United States, simulations using BEHAVE (Andrews, 1986) showed post-treatment reductions in fireline intensity between 80% and 96% compared with that reached in untreated fuels. FARSITE (Finney, 1998), a spatial fire growth model that integrates spatial (fuels and topography) and temporal (weather, fuel moisture) data, is used for making detail predictions at the landscape level. For instance, in Sierra Nevada of California, Van Wagtendonk *et al.* (1998) stated that PB was the most effective technique among other fuel treatments, under severe weather conditions, average fireline intensity of a wildfire was reduced by 76% and its burned area by 37%. In the same way, Stephens (1998), also, using FARSITE, compared the effects of 12 different fuel and silvicultural treatments where PB alone, or in combination with thinning, was the most effective method to reduce fireline intensity. In this line, a recent meta-analyis of Fulé *et al.* (2012) conclude that combined treatments (thinning + burning) tended to have the greatest effect on reducing surface fuels and stand density as compared to burning or thinning alone. By contrast, Cary *et al.* (2009) compared the outputs of different landscape fire models (CAFÉ, FIRESCAPE, LAMOS(HS), LANDSUM and SEM-LAND) concluding that year-to-year variation in weather and the success of ignition management consistently prevail over the effects of fuel management on area burned in a range of modelled ecosystems. Australian models and guides for fire spread in eucalypt forest, derived from experimental fires under relatively mild weather, use a directly proportional relationship between rate of fire spread and fuel load (McArthur, 1962). Consequently, they predict that a 50% reduction in fuel load will halve the rate of spread but reduce fireline intensity fourfold. In southern European pine stands after experimental PB, fireline intensity was reduced in the range of 80-98% compared with unmanaged sites (Rego *et al.*, 1987; Fernandes *et al.*, 1999). In addition, Cassagne *et al.* (2011) using FIRETEC (Linn & Harlow, 1997) showed that PB treatment was effective for the first two years in most of the Mediterranean plant or Moghaddas *et al.* (2010) using FlamMap (Finney, 2006) revealed a 39% reduction in final fire size for the treated landscape relative to the pre-treatment condition.

Another way of examining the effectiveness of PB is by means of analysis of fire statics, specifically by characterizing the occurrence and extent of PB and unplanned fires. For instance, Boer *et al.* (2009) demonstrated a strong inverse relationship between the extent of PB and unplanned fire in south-west Western Australia over 45 years. Price & Bradstock (2011) suggested that in open eucalypt forests of southern Australia approximately three units of planned fire are required to reduce the unplanned fire area by one unit. For the Sydney region, this implies an annual PB program of around 5% of the landscape would be required to halve the current extent of unplanned fire.

3.2.1.2. Impact on upper vegetation: Post-fire tree mortality

Predicting post-fire tree mortality is important to aid in post-fire salvage operations, rehabilitation and conservation efforts (Scott, 2002) after wildfires but also after PB as it is used widely in USA and increasingly in Europe.
Fire damage in the crown and the stem are most widely explanatory variables of post-fire

tree mortality together with an injury resistance variable such as diameter or bark thickness (Woolley *et al.*, 2012). Other variables such as fuel consumption on the forest floor, indicating fire severity at the ground level, or fire intensity measures are also used.

In the United States, the number of studies of PB is larger than for wildfires (22 and 13 studies respectively), and these studies are focussed more heavily on ponderosa pine compared with other conifer species (Woolley *et al.*, 2012). In Europe, the type and quality of the current information on fire resistance of the various European species is quite variable (Fernandes *et al.*, 2008). Information for *Pinus pinaster* and *Pinus sylvestris* is relatively abundant for low intensity fires while tree survival after wildfire has been modelled for *Pinus pinea* and *Pinus halepensis* (Fernandes *et al.*, 2008). The probability to survive is greater for *Pinus pinaster*, *Pinus pinea*, *Pinus canariensis* but low-intensity fire is tolerated even for species considered fire sensitive (*P. halepensis* and *Pinus radiata*) (Fernandes *et al.*, 2008).

Several applications using post-fire predictive models have been developed in a management context, such us nomograms (Reinhardt & Ryan, 1988), a mortality probability calculator, based on the proportion of bole scorch and crown scorch to predict tree mortality in prescribed and wildfires in eastern Oregon (Thies *et al.*, 2008) or guidelines for assessing tree injury and mortality following fire in the Blue Mountains of Oregon Prior (Scott, 2002). However, in the USA the most frequent and widespread use of post-fire tree mortality logistic regression models are softwares such as FOFEM (Reinhardt *et al.*, 1997), FFE-FVS (Reinhardt & Crookston, 2003) and Behave-Plus(Andrews *et al.*, 2005). In Europe we found the *Fire Paradox Fuel Manager* (Krivtsov *et al.*, 2009) is a computer software integrated in the data processing chain between the European data and knowledge base on fuels (which includes the FireParadox OODB) and the 3D physical-based fire propagation models. It is a key application in the fire modelling process with three main functionalities: (i) creation of vegetation scenes in 3D to be used as input data for fire behaviour models, (ii) fire effects visualisation on shrubs and trees, and (iii) fuel succession visualisation after fire occurrence by coupling a vegetation visualisation system with plant growth models (Krivtsov *et al.*, 2009). Ongoing research effort is focused on linking fire model outputs with fire impacts on individual plants with the objective of predicting fire-induced tree mortality. In that perspective, several fire impacts on the crowns and trunks of trees have been defined and can be visualised with the Fuel Manager at the scene scale (Krivtsov *et al.*, 2009).

As pointed by Fernandes et al. (2008) a deep understanding of physiological-based variables and the biophysical mechanisms behind fire behaviour and the relationships between these and tree mortality are crucial to improved modelling of post-fire tree mortality. Last but not least, linking current research and model development with management applications is primordial.

3.2.1.3. Impact on upper vegetation: vitality of surviving trees

The ecological and forest management consequences for forest areas treated by PB, including the development and growth of trees surviving a surface fire, remain poorly understood. Post-fire tree-growth is better documented in North America and Australia while this information is relatively scarce for European pine species. In the United States, the number of studies analysing post-fire growth is larger for PB than for wildfires (66 and 10 studies respectively), and these studies are focussed more heavily on *Pinus ponderosa* and *Pinus taeda* compared with other conifer species. The origins of the fires in European fire-growth studies are mainly forest fires (Drobyshev et al., 2004; Beghin et al., 2011; Rozas et al., 2011; Blanck et al., 2013; Valor et al., 2013), few examine the effects after PB (Botelho et al., 1998) or control heating (Ducrey et al., 1996; Jimenez et al., 2012) and most of them focus on fire resisters species adapted to low and moderate fire regimes and rarely on fire evader species.

Studies analyzing post-fire tree growth differ strongly in terms of origin of the fire affecting the trees (wildfire vs. PB), estimators used to assess fire severity (e.g., crown scorch volume, loss of litter and duff layer, bole char height, in-stand tree mortality, or fire recurrence), spatial scale of the study (tree level vs. stand level), and tree species studied. Even so, this variability in methodological approaches has not been reflected in the selection of different study timeframes (Keyser et al., 2010). Most studies analyzing post-fire tree growth have relied on short-term data, with only rare studies extending their analysis to over 10 years after the fire scar (Keeling & Sala, 2012). Growth after fire is regulated principally by fire characteristic (e.g. origin, severity, season), tree attributes (e.g. specie, size, tree competition) and time since fire. Reductions in growth result from alterations of the photosynthesis processes due to physical damages (e.g. crown scorch, cambium or root damage) caused by the fire where less important processes for the tree such as stem growth are reduced in favours to others (e.g. foliage growth, production of secondary metabolites) (Dobbertin, 2005). Examples of short-term growth reductions are found in many studies for different species (Sutherland et al., 1987; Botelho et al., 1998; Beghin et al., 2011; Rozas et al., 2011; Valor et al., 2013). In addition, increased short-term post-fire growth have been reported, when severity is low, due to enhanced nutrient and light availability (Peterson et al., 1991; Mutch & Swetnam, 1995; Valor et al., 2013)

3.2.1.4. Decision-support tools for PB prescriptions

Supporting tools for PB operations such as prescriptions, guidelines, softwares and expert systems (Kilgore & Curtis, 1987; Andrews et al., 2005, Reinhardt et al., 1989; Pivello & Norton, 1996) are used worldwide to minimize potential negative impact of PB (Fernandes et al., 2012). In Europe, PiroPinus (Fernandes et al., 2012) is a user-friendly, portable, cost-effective and adaptable, and is being used for PB training and planning in Portugal. PiroPinus as pointed by the authors complements the skills and experience of fire managers, and increases their competence by reconciling efficient fuel reduction with low-impact burn operations. In adittion, Ascoli *et al.* (2010) used PiroPinus in a *Pinus halepensis* stand in Italy with remarkable success and could be adapted for use in other medium to long-needled mediterranean pines (*Pinus pinea, P. canariensis, P. brutia, P. halepensis, P. nigra, P. radiata*). Also, there is PB handbook with prescription's from all around Europe, where the information is presented mostly in tables, which are organized by management objective and vegetation type (Fernandes & Loureiro, 2010).

3.2.2. Use of tools for PB: from strategic to tactic-operational point of view

Decision support tools shown in Table 7 can help to develop PB management strategies, planning and operational tactics.

Table 7: Principal tools developed for assessing PB effectiveness, its effects and prescriptions.

Tool	Tool type	Decision tool for PB	End-user	Scope	Scale	Reference
Firetec	Simulator	Effectiveness Planning	Fire manager Land manager	Worldwide	Landscape	Linn (1997)
BehavePlus	Simulator	Effectiveness Planning Effects	Fire manager Land manager	Worldwide	Stand	Andrews et al. (2003)
Farsite	Simulator	Effectiveness Planning	Fire manager Land manager	Worldwide	Landscape	Finney (2004)
FlamMap	Simulator	Effectiveness Planning	Fire manager Land manager	Worldwide	Landscape	Finney (2006)
FOFEM	Simulator	Effectiveness Effects	Fire manager Land manager Forest manager	USA	Stand	Reinhardt (2003)
FFE-FVS	Simulator	Effectiveness Effects	Fire manager Land manager Forest manager	USA	Stand	Reinhardt and Crookston (2003)
Fuel manager	Simulator	Effectiveness Effects	Fire manager Land manager	Europe	Stand	Krivtsov et al. (2009)
Nomographs	Nomographs	Effectiveness Prescriptions	Fire manager Land manager Forest manager	Conifers from USA	Tree	Reinhardt and Ryan (1988)
Mortality Probability Calculator	Graphs	Effects	Fire manager Land manager Forest manager	*Pinus ponderosa*	Tree	Thies et al. (2008)
Software	Software	Planning	Fire manager	Australia	District	Higgins et al.(2011)
Guideline	Guideline	Prescriptions Monitoring	Fire manager Forest manager	*Pinus ponderosa*	Stand	Kilgore and Curtis (1987)
Guideline	Guideline	Prescriptions Monitoring	Fire manager Forest manager	Southern USA	Stand	Wade et al. (1989)
Expert system	Expert system	Prescriptions	Fire manager	USA	Plot	Reinhardt et al. (1989)
FireTool	Expert system	Prescriptions	Fire manager	Brazilian savannas	Stand	Pivello and Norton (1996)
Handbook	Handbook	Prescriptions	Fire manager	Europe	Stand	Fernandes & Loureiro (2010)
PiroPinus	Excel sheet	Prescriptions	Fire manager	*Pinus pinaster*	Stand	Fernandes et. al (2012)

Several tools exist for strategically allocate PB at the landscape level to assess the effectiveness in fire hazard reduction level that can be used by land, forest and fire agencies (e.g. Farsite and FlamMap) to zone systems and set priorities for fuel reduction based on all the values at risk, the risk potential and the range of fire suppression options desired under most weather conditions. These fire simulators software's that are commonly run for simulating fire behaviour under specific fuel and weather conditions and are designed to be used by fire and land managers who have training and fire experience. However, fire behaviour models calibration is fundamental to correctly analyse simulations and interpret their management implications. Contrary to USA and Australia, in Europe the spatial pattern of PB is either random or strategic (i.e. linear strips), and strategically landscape-scale fuel treatment projects are uncommon (Fernandes et al., 2013).

From a tactical- operational level the review made clear, that there is a need of more quantitative information on fuel reduction that is translated into classifications of effectiveness. In terms of fire effects, there are a considerable number of tools to estimate post-burning mortality after PB or wildfires in USA to a lesser extend for European pines. Moreover some mortality models are integrated in fire simulators software's such FFE-FVS and Fuel Manager but none of these programs have incorporate models that take into account post-fire growth of surviving trees. Tools for setting PB prescriptions are prolific, but in the case of Europe there is a need that tools such as PiroPinus are used widely and adjusted for other pine species. The decision-making and planning process of PB can thus benefit from decision-support tools that will enhance the proficiency of planners and practitioners.

3.2.3 Key messages

- Integration of PB into management to mitigate the effects of global change on European ecosystems.
- Enhance European capacity to use PB for effective ecosystem management
- Need of a geo-database of PB sites in Europe accessible to researchers, managers for collaborative research and to policy makers.
- A methodological guide with standard protocols and indicators for the medium- and long-term monitoring of experimental PB sites
- Linking approaches to PB and traditional managed burning in Temperate, Boreal and Mediterranean regions.
- Improved spatial and temporal planning is also required, implying a need for greater reliance on decision-support and reporting tools.
- Facilitate to decision support tool development, improvement and adoption.
- Attention needs to be paid to linking current research and model development with management applications.

3.2.4. Integrated approach

Decision-making:
Prevention from tactical to strategic (if used for scenario analysis).

Links with other tools:
PB effectiveness can be validated using fire behaviour simulators at a stand and landscape level.

4. INTEGRATED APPROACH FOR FIRE RISK ASSESSMENT AND FUEL MANAGEMENT: USE OF TOOLS

Decision-making:

Level of planning:

Operational: decisions use to have short-term impacts. They arise from the need of "How to do things?".
Tactical: decisions that respond to mid-term results. They arise from the need of "What to do? When do it? Where do it?".
Strategic: decisions made for a long term planning level. They arise from the need of "What's our objective? Which direction we want to set?".

Types of strategy:

Active prevention: direct support to facilitate fire suppression. The main examples are: maintenance of an updated accessible road network, implementation and location of water, safety points, or early detection infrastructures (vigilance towers), fire fighters training, etc.

Passive prevention: actions and decisions that modify fire behaviour by themselves. For example: reducing fire hazard, reducing potential fire intensity, reducing ignition/fires number, generating fuel discontinuities, etc.

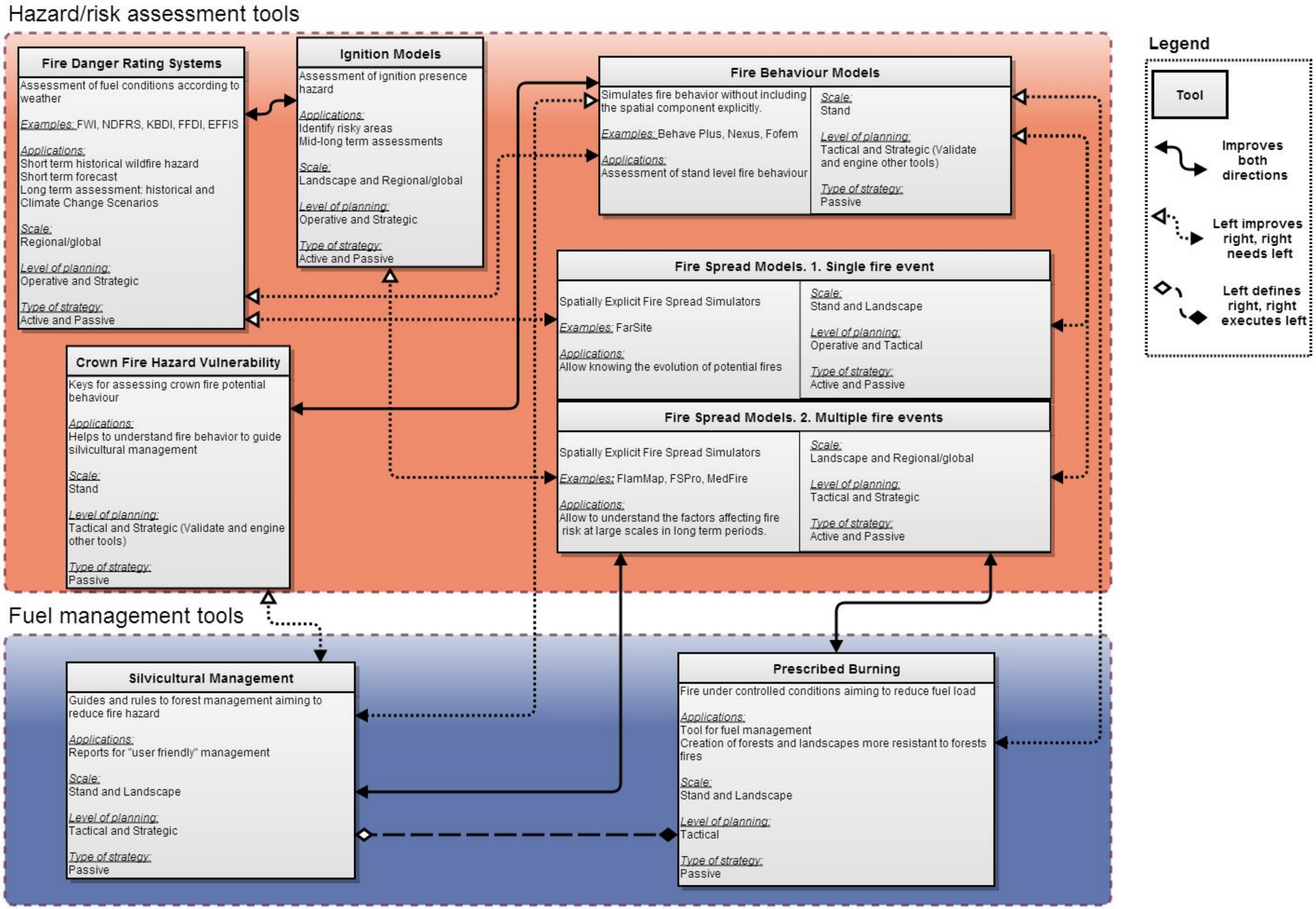
Note: Suppression is not considered as a decision under this context as are related to decisions when the fire starts, and this review focuses on prevention or support to suppression.

Scale of application:

Stand: in this context, stand is assumed to be a homogeneous area in terms of fire behaviour (same fuel pattern, topography, etc.), even if forest management is not considered.
Landscape: Arrange of stands over an area (usually less than "*nuts 3"* administration level) with similar spatial patterns, climatic condition and socioeconomic reality.
Regional and higher level: this scale includes several administration levels encompassing different fire, fuel, climate and socioeconomic conditions.

Links:

Improves both directions.
Left improves right, right needs left.
Left defines right, right executes left.


Hazard/risk assessment tools
Fire Danger Rating Systems
Assessment of fuel conditions according to weather
Examples: FWI, NDFRS, KBDI, FFDI, EFFIS
Applications:
Short term historical wildfire hazard
Short term forecast
Long term assessment: historical and Climate Change Scenarios
Scale:
Regional/global
Level of planning:
Operative and Strategic
Type of strategy:
Active and Passive
Ignition Models
Assessment of ignition presence hazard
Applications:
Identify risky areas
Mid-long term assessments
Scale:
Landscape and Regional/global
Level of planning:
Operative and Strategic
Type of strategy:
Active and Passive
Fire Behaviour Models
Simulates fire behavior without including the spatial component explicitly.
Examples: Behave Plus, Nexus, Fofem
Applications:
Assessment of stand level fire behaviour
Scale:
Stand
Level of planning:
Tactical and Strategic (Validate and engine other tools)
Type of strategy:
Passive
Fire Spread Models. 1. Single fire event
Spatially Explicit Fire Spread Simulators
Examples: FarSite
Applications:
Allow knowing the evolution of potential fires
Scale:
Stand and Landscape
Level of planning:
Operative and Tactical
Type of strategy:
Active and Passive
Crown Fire Hazard Vulnerability
Keys for assessing crown fire potential behaviour
Applications:
Helps to understand fire behavior to guide silvicultural management
Scale:
Stand
Level of planning:
Tactical and Strategic (Validate and engine other tools)
Type of strategy:
Passive
Fire Spread Models. 2. Multiple fire events
Spatially Explicit Fire Spread Simulators
Examples: FlamMap, FSPro, MedFire
Applications:
Allow to understand the factors affecting fire risk at large scales in long term periods.
Scale:
Landscape and Regional/global
Level of planning:
Tactical and Strategic
Type of strategy:
Active and Passive
Fuel management tools
Silvicultural Management
Guides and rules to forest management aiming to reduce fire hazard
Applications:
Reports for "user friendly" management
Scale:
Stand and Landscape
Level of planning:
Tactical and Strategic
Type of strategy:
Passive
Prescribed Burning
Fire under controlled conditions aiming to reduce fuel load
Applications:
Tool for fuel management
Creation of forests and landscapes more resistant to forests fires
Scale:
Stand and Landscape
Level of planning:
Tactical
Type of strategy:
Passive
Legend
Tool
Improves both directions
Left improves right, right needs left
Left defines right, right executes left

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ANNEX 1

Fire Danger Rating Systems (FDRS)

Keetch-Byram Drought Index (KBDI)

Keetch-Byram Drought Index (KBDI) describes soil moisture deficit that is used to assess wildfire potential. It needs climatic data of maximum air temperature and the total rainfall for the past 24 hours. The equation for computing the drought factor (dQ), is as follows (Keetch and Byram 1968):

$$dQ = \frac{[800 - Q][0.968\exp(0.0486T) - 8.3]\,dt}{1 + 10.88\exp(-0.0441R)} \times 10^{-3}$$

dQ = Drought factor
Q = Moisture deficiency
T = Maximum daily temperature
dt = a time increment set equal to 1 day
R = Mean annual rainfall

Drought index number expresses moisture deficiency. The index is ranging from 0 (zero) to 800. Zero is the point of no moisture deficiency and 800 is the maximum drought that is possible.

The Canadian Fire Weather Index System (FWI)

The Canadian Fire Weather Index (FWI) System was developed from statistical analysis of field data. The index is based on daily measurements of weather factors such as rainfall, temperature, relative air humidity and wind speed. It is consists of six components that represents moisture content of litter and other fine fuels (Fine Fuel Moisture Code/FFMC); moisture content of loosely compacted organic layers (The Duff Moisture Code/DMC); moisture content of deep, compact, organic layers (The Drought Code/DC); fire spread (The Initial Spread Index/ISI, it is wind and FFMC combined); total amount of fuel available (Buildup Index/BUI, it is a combination of DMC and DC) and fire spread (Fire Weather Index/FWI, it is influenced by ISI and BUI factors) (Van Wagner 1987).