Prevention of Large Wildfires using the Fire Types Concept

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To Pau Costa Alcubierre,
who never stopped fighting for his greatest dream.
Without your enthusiasm this handbook would have never become reality.

To Jaume Arpa, Jordi Moré, Ramon Espinet and David Duaigües,
for always leading the way ahead.

Introduction to the handbook

This handbook, entitled *Prevention of Large Wildfires using the Fire Types Concept*, is an attempt to introduce the methodology of the Fire Types Concept as a prevention and pre-suppression tool. The scope of this handbook includes the integration of fire use into forest planning and the prevention of large wildfires.

The purpose of the handbook is to provide the knowledge for the integration of fire into forest planning and wildfire prevention so that it can be used as a tool to complement and support forest policies. The handbook seeks to provide a European perspective on fire prevention considering the different fire regimes and vegetation structures as well as the heterogeneous socioeconomic conditions in Europe.

The structure of the handbook consists of the main text that describes the context of its field of application and a series of appendices where more technical information can be found. The first part of the document gives an overview on the current state of European forests and the evolution of large wildfires related to the socioeconomic processes in the second half of the 20th century. The causes of the increase in the occurrence of large wildfires are explained, with a focus given on land use changes and policies to increase suppression capacity.

In the second and third parts, strategies are recommended to minimise the effects of large wildfires, to reduce their intensity and to improve the safety of firefighting personnel. The second part explains the Fire Type Concept, spread patterns and the detailed determination of a Fire Type. The third part describes these concepts and their applicability when it comes to landscape planning to establish strategic management points.

The appendices that complete the handbook go into greater depth on: (1) the use of fire as a landscape management tool, based on fire ecology and historical fire use, (2) fire prevention strategies considering the fire generations and (3) recommended strategies and tactics for each fire spread type.

References to literature used in the handbook are numbered, whereas letters are used for terminology explained in the glossary to improve readability of the handbook.

1. The paradigm of large wildfires in Europe

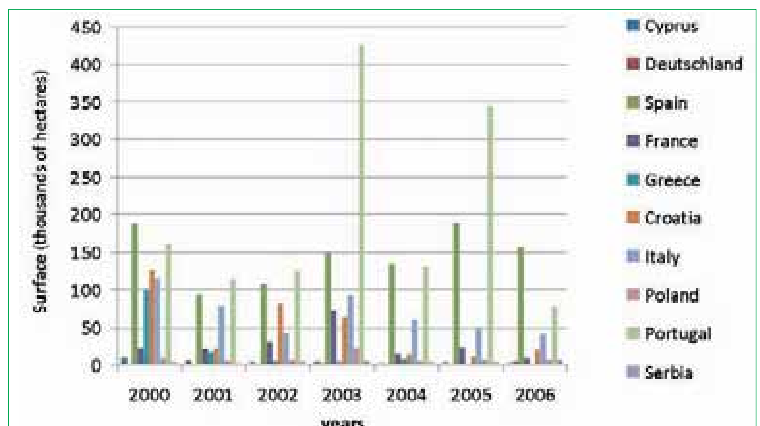
1.1. Fire as a tool to mitigate the problem of large wildfires

In Mediterranean Europe the last few decades have been characterised by dramatic land use changes. The abandonment of farmland and reduced grazing have led to an increase in wildland areas. These changes in the landscape have contributed to a more aggressive spread of large wildfires (LWF) all over Europe[18].

Currently, in the Mediterranean region wildfires larger than 50 ha represent more than 75% of the area burned, although they represent only 2.6% of the total number of wildfires[24]. Over the last few years, the occurrence of large wildfire episodes with extreme fire behaviour has affected different regions of Europe: Portugal (2003 and 2005), south-eastern France (2003), Spain (2006 and 2009), and Greece (2000, 2007 and 2009)[8] , *see Graph 1.*

The response of most European societies to this problem has generally been to strengthen fire suppression policies[9] with the overall aim to increase their fire suppression capacity. However, these large wildfire episodes have clearly shown the limitations of the suppression systems[20] which have been overwhelmed by fire fronts of very high intensity and fire spread. Prevention and suppression systems with large budgets began to recognise that they became victims of their own success: the heavy investment reduced fires of medium and low intensity, while the more intense wildfires continued to spread unhindered through the landscape, remaining beyond the suppression capacity. Additionally, the reduction of low- and medium-intensity disturbances paradoxically ensured the persistence of high-intensity wildfires[6], which resembles the application of a negative selection to our wildfires.

This strategy to improve and increase suppression resources has resulted in a scenario with a rather constant area burned over the years and with only few years where several thousands of hectares are affected by large wildfires. The problem is thus concentrated in years with droughts and/or adverse weather conditions that may produce combustion processes with extreme fire behaviour.



Graph 1. **Area burned (thousands of hectares) by large wildfires during the period 2000-2006 in different European countries.** Source: European Forest Fire Information System (EFFIS).

Despite the high investment in fire suppression efforts, wildfires are becoming larger and more intensive, with faster spread rates[8], which offers only few opportunities for the suppression systems, *see Figure 1*.

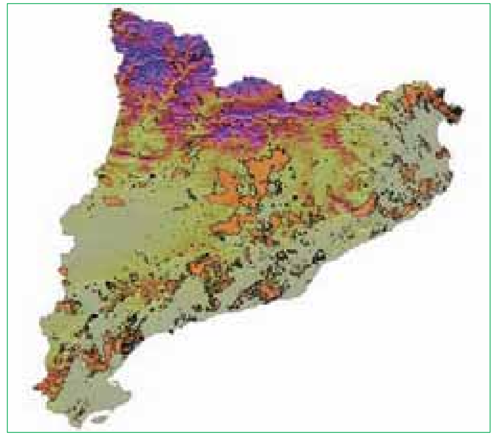


Fig. 1. **Patterns of wildfires in Catalonia over the last 50 years.** The surface affected by fire at least once in this period is shown in orange. 94.6% of that area was burnt by fires larger than 100 hectares. Consequently, not fire in general can be considered the main ecosystem driver but only those fires with the highest intensities are forming ecosystems. Source: Bombers de la Generalitat de Catalunya.

Fire is a widespread phenomenon in many European ecosystems and it has always coexisted with human activity, see *appendix 1a*, as either natural ignition from dry lightning storms or as a tool in agriculture and silvo-pastoral systems[9].

Fire has traditionally been used for the reduction of plant residue, improving of grazing conditions, removal of moribund plant material and improved regeneration of plant species requiring open habitats[16]. Despite these widespread traditional uses of fire, the fire culture in Europe has been lost as a consequence of the rural exodus that occurred during the second half of the 20th century, and the perception of this element has changed from being a tool to being a threat[19]. *Appendix 1b* gives more detailed information concerning the traditional uses of fire in Europe.

Fire is a natural element of Mediterranean ecosystems, and large wildfires are no particular single events but part of a defined disturbance regime. For that reason the challenge that needs to be faced from both a prevention and suppression point of view, is to anticipate and reduce the spread potential of large wildfires, as well as potential risk for lives, property and land use systems.

The main focus of this handbook will be: to identify tools to reduce spread potential. Factors that determine extreme fire behaviour are analysed and then appropriate preventive strategies are determined.

1.2. Land use change and landscape evolution as a main driver for the large wildfire phenomenon

An analysis of the importance of the determining parameters of fire behaviour is necessary to understand the problem: topography, weather and fuel (biomass).

Topography

In the time scale analysed (<100 years), it can be said that topography as a factor has remained unchanged, and is therefore considered not very important.

Weather

According to climate scientists, the average weather as well as the distribution of weather events is subject to a relatively rapid anthropogenic climate change, more generally known as global warming. Most of the observed temperature increase since the middle of the 20th century was caused by increasing concentrations of greenhouse gases, which results from human activity such as fossil fuel burning and deforestation. The observed increase in average temperatures over the last 50 years (0.13°C [0.10°C – 0.16°C] per decade)[(15)] shows a rather unfavourable trend in terms of occurrence of wildfires, but cannot explain the entire problem. In fact, there were hot and dry years recorded for the first half of the 20th century that clearly were not linked to the occurrence of catastrophic wildfires. Quite on the contrary, fire seasons today facing those meteorological conditions would challenge almost any modern fire suppression system at present. Studies conclude that the number and area of wildfires between 1968 and 1994 increased due to climate change[(22)], however, such statements are only based on meteorological data, whereas the occurrence of wildfires also depends on many other factors. Nevertheless, the role of climate for the increase of adverse weather episodes (drought and high temperatures) is relevant for the development of large wildfire episodes, particularly where most climate models predict even more unfavourable conditions than present ones.

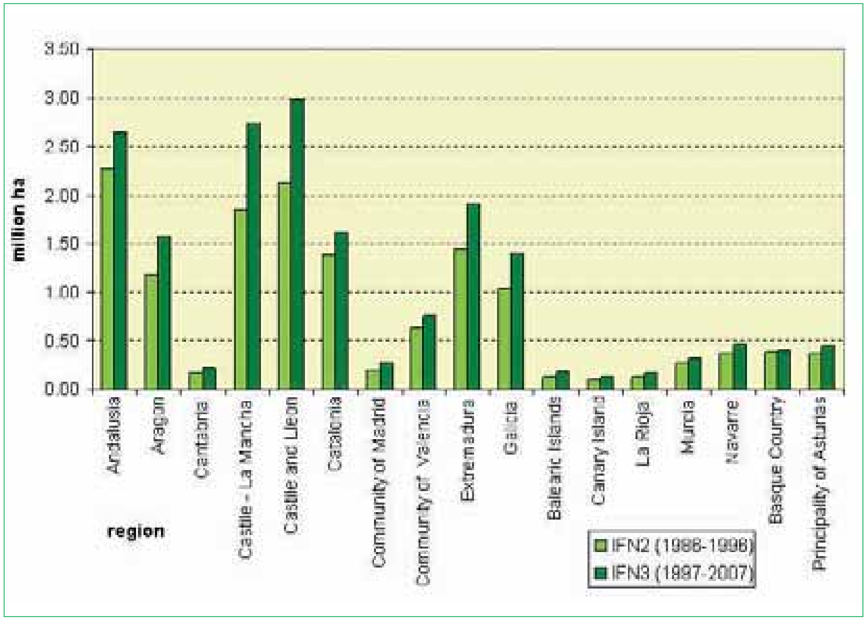
Fuel (biomass)

When leaving aside the relative effect of climate change in explaining large wildfire episodes, wildland and forest fuels (i.e. bio- and necromass of an ecosystem consumed by fire) become the factor that has changed most significantly, and this has also affected the development of wildfires showing extreme fire behaviour[(17)]:

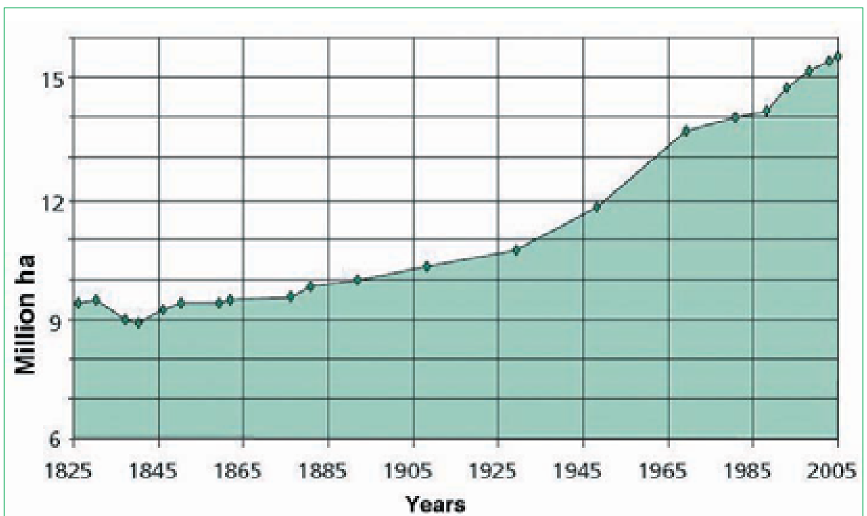
- The main change has occurred in the fuel build-up through the development of forest and other woodland compared to the first half of the 20th century. The increasing accumulation of fine fuels allows fast-moving fires to spread through the landscape with long distance spotting ahead of the fire front.

- Increasing continuity of forest and other wildland areas on abandoned farm and pasture land allows the development of long fire perimeters with difficult access. This is a common phenomenon in regions that have suffered from a rural exodus process which is affecting a good part of the rural areas of the EU with a large wildfire problem, *see Graph 2 and 3*.

- The current trend leads to forests and other woodlands that are increasing in extent, fuel load and continuity, with very high densities of low-diameter trees, a situation inevitably developing towards large wildfire scenarios. The steady accumulation of biomass has not only increased horizontal continuity at surface level, but also vertical and tangential continuity of tree crowns, resulting in vegetation structures that can burn at very high intensity[(6)].



Graph 2. **Evolution of forest area for each Autonomous Community in Spain between 1980 and 1990, in percentage.** Source: National Forest Inventory (IFN), 2 and 3.



Graph 3: **Evolution of forest area in France between 1825 and 2005 in million hectares.** Source: Cinotti (1996)[14].

As a consequence, the continuity of forest and other woodland, together with the immense accumulation of forest fuels, has led to the appearance of large wildfires with crowning and massive spotting activity. Other aspects contributing to a landscape evolution favouring a scenario with more large wildfires that are showing extreme fire behaviour, are:

- fire suppression policies have led to a reduction of low- and medium-intensity fires in the landscape to the point of virtual disappearance, allowing fuel to accumulate: this is known as the suppression policy paradox[9, 23].
- the decrease or abandonment of agro-forestry and silvo-pastoral land-use practices due to a rural exodus, leading to the conversion of pasture and farmland into forest areas.
- the dominance of high-intensity wildfires is considered a major factor in homogenising the landscape and present vegetation structure.
- the socio-economic and political context of the forest sector resulting in a general decrease in active forest management, *see figures 2 and 3*.

By linking these two factors (weather and fuel), we can conclude that large wildfires are generated in situations where a major part of the fuel is available and under adverse weather conditions.

Figure 2 (left) and Figure 3 (right). **Comparison between two photos of the same area (1908-2001) where fuel accumulation can be seen as a result of the abandonment of agroforestry activity. Masia Can Tardà (Castellolí, Catalonia).** Source: Bombers de la Generalitat de Catalunya.

1.3. Why do large wildfires overcome our suppression capacity?

When called to a wildfire in a forest, the strategy applied by the vast majority of prevention and suppression services is based on a rapid, hard-hitting initial attack on all ignitions, regardless where it occurs and the weather conditions. This strategy is highly effective and manages to restrict the majority of ignitions to small-scale fires. By contrast, when the balance between the suppression force and the fire behaviour is clearly favourable to the latter, the system collapses, showing itself to be inefficient. It is then that the window for large wildfires opens.

In this context, a large wildfire can be defined as a fire that maintains a spread rate, intensity and flame length that overcomes the capacity of the suppression system for a reasonably sustained period, and which therefore offers few suppression opportunities.

There are several possibilities how fire behaviour can overcome suppression capacity, depending on the type of landscape:

- Growth rates of perimeter length are greater than the capacity of the containing lines, due to the continuity of the landscape.

- Rate of spread is greater than suppression progress. Resource deployment along the perimeter is slower than the rate of perimeter growth. This includes the speed at which resources are allocated and provided with supplies, as well as the speed at which information on changes in fire behaviour and change of plans circulate through the chain of command. Examples: *Sardinia (Italy) 2007, Catalonia (Spain) 1986 and 2000 and Northumberland (England) 2006.*

- The suppression system cannot carry out effective operations to the same degree as under normal circumstances due to high fire intensities. The high intensity associated with crown fires exceeds suppression capacity and no ground force or airborne resource can deal with it. Examples: *Spain 1994 or 1998.*

- Effects on property and people are increasing the requirement for suppression resources to protect them. At the wildland-urban interface (WUI) there is a negative feedback process which translates into a relative reduction in the quantity of resources set aside for containing the actual wildfire in favour of the quantity of resources given over to protecting property and people. Every piece of property is considered an emergency. Example: *Catalonia 2003 and 2007, Greece 2009.*

- Simultaneous large wildfires are reducing the number of resources available still further. Example: *California 2003, Portugal 2003, Greece 2007*.

2. Planning for the limitation of fire spread potential

At the same pace as the responses to current wildfires are established and the landscape evolves, the same wildfires change their fire behaviour, thereby evolving into the next generation of wildfires. As an example, the success of the investment in suppressing fires burning out of control due to their rate of spread in Catalonia (1986-1993) finally ended in 1994-1998 with large wildfires getting out of control in the form of crown fires.

While the fuel load and its distribution in the landscape remain unchanged, wildfires beyond suppression capacity which can neither be prevented nor halted, continue to occur. It is a long-term problem.

In the short term, the only solution would be to slow down (if not stop) the spread of a wildfire, preparing opportunities for redirecting, modifying or delaying the fire spread.

2.1. Reducing fire spread potential. Extensive fuel management

Which fuel load and distribution over the landscape allows fires to burn within capacity for control? How should the fuel load be reduced or redistributed? The possibility of the suppression system to controlling a wildfire is determined by the stabilisation capacity along the perimeter. It is therefore necessary to specify the fire behaviour of that part of the perimeter that is beyond suppression capacity, *see Figure 4.*

Figure 4. **Large Wildfire of the Solsona region in 1998 crossing 200 m of ploughed fields and a road in downhill direction.** Large Wildfires are characterized by long distance spotting, starting independent fires ahead of the fire front that may join and interact, and by the creation of their own fire environment[(a)]. Source: Bombers de la Generalitatde Catalunya.

Suppression capacity

Parametrising a large wildfire can become a complex task, because whether a wildfire is out of control depends not only on the fire behaviour but also on suppression capacity (types of suppression tools, long initial perimeters due to lack of access, resources tied off for protecting people and property, etc.).

If different suppression forces are compared, fire behaviour thresholds can be established – i.e. thresholds for rate of spread and fire front intensity beyond which modern suppression systems begin to have serious problems in controlling an ignition. Each suppression system must know its suppression capacity thresholds, that are determining the technological limits for its ability to fight flames and put them out, *table 1.*

The key parameters limiting suppression capacity are fire front intensity and rate of spread. The two factors are often related, but they can be treated independently.

Limiting fire front intensity in large wildfires

Fires causing problems because of their high intensity are in most cases related to vegetation structure. When trying to stabilise fire fronts capable of maintaining passive and active crown fires in a sustained way for a period of time, the opportunities for attack (indirect, parallel or direct) decrease in inverse proportion to fuel availability, adverse weather conditions and landscape continuity in terms of fuel patches.

Table 1. **Technological limit of the Catalan suppression systems**

LWF parameter	Limits of the Catalan suppression system
Flame length	more than3 m
Rate of spread	more than 2 km/h
Crown fire activity equal to or greater than	passive crown fire

In this context of a technological limit facing fire fronts that cannot be dealt with because of the high level of crown involvement, it is necessary to reduce the total fuel load and modify the distribution of fuel loads between the different tree strata.

In order to create forest structures that are resistant to fire spread, and that are allowing only fires that burn with intensities that can be dealt with by the suppression systems, it is necessary to implement forest management concepts for each type of structure that are capable of minimising vulnerability to the development of crown fires.

Forest management guidelines that include the possibility of fire occurrence must be implemented on a large scale rather than locally in order to achieve a plausible effect on large wildfires. This approach would ensure to succeed if applied on landscape level.

Limiting rate of spread

Rate of spread overcoming suppression capacity is related to different factors depending on the type of spread:

- in topographic and convection dominated fires the rate of spread will be determined by the spotting distance. The greater the distance, the greater the potential to affect large areas in short time and, therefore, the greater the rate of spread. The convective potential of a fire is linked to the quantity of fuel burning; treatments to reduce fuel loads therefore limit convective potential which, at the same time, limits spotting potential and spotting distance, and finally reduces rate of spread. For convection dominated fires, targeted forest management can be sufficient to limit fire spread.

- in wind-driven fires the wind speed has the main direct effect on the wildfire's general rate of spread. In this case, fuel treatments limit the intensity and, to a lesser extent, restrict fire spread.

A commitment to forest management that is oriented towards limiting fire spread is a pre-requisite to manage large wildfires, although its beneficial effects will only be seen in the long term. It is therefore also necessary to develop and implement alternative concepts to improve the capacities of both prevention and suppression systems.

2.2. Slowing down fire spread. Anticipating and preparing suppression opportunities

Any increase in airborne and ground-based suppression resources or even the use of larger and larger aircraft do still not permit a direct confrontation with fire behaviour that exceeds the system's suppression capacity. At the moment, we can only slow down rather than prevent the spread of a wildfire, and prepare opportunities where the suppression service can redirect, modify and slow down fire spread.

For the different fire generations, different suppression response strategies have been shown useful. These can serve as guidelines when it comes to suggesting pre-suppression tools to slow down fire spread:

- Improving road network in terrain with difficult access (for large wildfires occurring in fuel continuity).
- Improving distribution of lookouts, water points, ground-based and airborne resources according to fire risk, in combination with prescribed burning programmes to accumulate experience in the use of fire for suppression purposes (for large wildfires occurring with high spread rates).
- Introducing self-protection measures, specialised strike teams and logistical tools (for large wildfires crossing the Wildland Urban Interface, WUI).
- Anticipating suppression opportunities, for all wildfires. The concept of anticipation can be explained best through how a professional tennis player can return an opponent's serve even though it travels faster than 200 km/h, by positioning himself on predicting the trajectory the ball will follow. He anticipates this movement by placing himself in the best possible position with the right conditions to be able to return the serve.

For the build up of anticipation capacity within suppression systems, new tools to predict fire behaviour had to be developed, such as:

- Identifying spread patterns to identify changes of the dominant factors in wildfires that create suppression opportunities (developed in the first half of the 20th century).
- Use of static area (BEHAVE)(1) and spatial (Farsite)(11) fire behaviour simulators to predict areas of lower fire intensity.
- Use of simulators based on minimum fire travel paths and time to locate suppression opportunities(12, 13).
- CPSL (Campbell Prediction System Language) analysis to predict where fire behaviour will change(3).
- Model Fires Concept(5) to identify the expected Fire Type for each geographical unit, and fire regions(4).
- Planning based on problem fires with a link to fireshed assessment(2).

The use of simulators requires sufficient time for the processing, precise fuel model data and an accurate knowledge of small- and large-scale interaction of weather (largely wind) and topography. The application of simulators for fire suppression in Europe is limited since the majority of fires occurring in Mediterranean Europe usually lasts less than 48hrs.

In planning, however, simulators allow us to predict general and approximate directions of fire spread, provided there is a source of information available on the interaction of wind and landscape, that takes fire behaviour of historical fires in the area(2, 4, 11) into account and can adjust the simulation.

2.3. Adapting forest fire prevention to current large wildfires

Apparently though, the use of fire interpretation tools alone cannot be considered sufficient to accurately implement planning in a certain area. It needs an answer first to the basic questions that are essential to anticipation:

- Probability of having a large wildfire in a specific area
- Expected movement of the fire in the area

A new tool to master this step is necessary to classify, organise and typify wildfires that occur in a specific area. The basis for this is the observation that fires under the same topography and weather conditions follow similar spread patterns[5, 10], with only fire intensity changing due to varying fuel availability (greater accumulated drought stress, fuel accumulation, etc.).

Fuel availability depends on form and size of a fuel particle and its moisture content. Time lag [b] is related to these two factors.

The qualitative approach to fire spread patterns clearly reveals typical spread patterns for a region (topographic, wind-driven and convection dominated fires), which show particular features and geographical variation in terms of occurrence. This may give the idea that each individual wildfire is different and does not follow a certain pattern. However, by using an analytical approach it can be seen that reality is quite different, and that it is possible to simplify the study of wildfires by establishing a set of different Fire Types.

The Fire Types Concept

When analysing historical fires it becomes obvious that under the same topography and weather (synoptic situation) conditions, fire spreads following similar spread schemes, see *Figure 5*. The Fire Types are derived from the analysis of common factors in these spread schemes, *see appendix 3a*.

A certain Fire Type does not necessarily implicate a certain fire behaviour. It is the difference in the fuel structure, land use or in ignition points that causes variation in fire behaviour. However, the spread scheme typically is maintained. Also the types of suppression opportunities and points where fire behaviour changes will be the same when the relief is taken into account.

The starting point to determine whether a Fire Type follows a common spread scheme is the spread pattern as the dominant factor in the wildfire. The concept of spread patterns refers to the key element to outline the way in which the fire spreads over the terrain. Depending on the spread pattern, three main types of fire can be distinguished, see *table 2*:

Figure 5. **Perimeters of wildfires from 1949, 1970, and 2000 in L'Albiol (Catalonia).** Compare the three fires following a similar spread pattern. The difference between the ignition points determines whether a fire will affect one or two crest lines. Source: Bombers de la Generalitat de Catalunya.

Table 2. **Classification of fires according to spread pattern and the dominant factors.**

Classification of fires according to spread patterns	Dominant factors
Topographic fires	Local topographic winds, fuel heating and slope
Wind-driven fires	Wind speed and direction, as well as duration of the meteorological window that produces the fire conditions
Convection/Plume dominated fires	Accumulation of highly available fuel

The type of spread pattern determines the fire behaviour and the effective suppression opportunities for the suppression services.

Classification of the Fire Types

For a region like Catalonia, nine Fire Types have been identified that are based on common spread patterns and classified by characteristic factors, *table 3* [7]. Each of these Fire Types has been linked to specific synoptic weather conditions with a set of meteorological parameters that determine fire behaviour.

Table 3. **Fire Types with description of spread scheme and strategies or opportunities for control.**
Source: Castellnou et al., 2009[7].

Spread pattern	Dominant factor	Fire Type	Spread scheme and strategies (or control opportunities)
Topographic	Topographic slope winds	Standard topographic fires	Follows the slopes with the steepest gradient and highest insolation at daytime. Forms of the perimeter: slopes and hydrographic basins. The critical points are ravines, intersections of ravines, and the position of back and flanks of the fire at a point with the potential for new runs.
	Sea breeze	Coastal topographic fires	Follows the steepest slope and the defined and predictible turn of the sea breeze. Opening of the flanks dominated by sea breeze.
	Topographic winds of the main valleys	Topographic fires in main valleys and canyons	The main direction of the perimeter is in direction of the main valley. A suction of the fire toward the main valley is generated by the venturi effect. Change of the ascending daytime suction to a descend at night.
Wind-driven	In level terrain	Wind-driven fires in level terrain	Follows the wind direction and opens in an angle of 30° to 60° depending on the strength of the wind.
	In mountainous terrain	Wind-driven fires in mountainous terrain	In mountain ranges aligned with the wind direction it follows the ridge lines. In mountain ranges perpendicular to the wind direction, counterwinds occur that facilitate the ascending spread because of turbulences on the slope of the opposite site that is not directly exposed to the wind. Opportunities: at the end of the water divide, or when the divide changes the direction, at bifurcations, or when counterwinds occur.
	In subsidence zones with descending winds. With general winds along the surface at night and rising up during daytime.	Wind-driven with subsidence	Phenomenon of coastal ranges in front of a large plateau that falls abruptly (central eastern coast of the Iberian peninsula, coast of California, Greek Peloponnese), when the diurnal topographic winds are able to compensate the northerly winds at altitude. When this happens, the topographic winds are descending at night while the northerly winds descend along the surface and are reinforced by the topographic winds. Therefore, the fire behaves like a topographic fire during the day and like a wind driven fire during the night. This dynamic implies that the back of the day-time fire is transformed into its head at night and viceversa. This imposes difficulties to the incident management.
Convection dominated	Without significant winds	Standard convection dominated fires	Follows the macro-topography and the wind. Opportunities: confining the head or measures to reduce spotting activity.
	With significant wind. In Catalonia in situations with hot west winds and very occasionally with intrusions of hot Saharan air masses from the south	Convection dominated fires with wind	Convective behaviour plus the wind affecting fire spread. The wind increases the spotting distance, creating new ignition points outside of the influence zone of the convective column and accelerating the general spread of the fire. The column and the spots follow the wind direction. However, the fire ends up burning large topographical basins.
	With the collapse of a pyrocumulus cloud	Convection dominated fires producing pyrocumulus clouds	The pyrocumulus collapses once it condensates and gains weight. This collapse of the convective column generates winds that can tear out trees. Massive spotting and extention of the fire in all directions.

Note: Wildfires with storm-dominated spread patterns are not included in this table, nor in the whole document because at present there exists no knowledge about their management.

Zoning of large wildfires

The relationship between spread patterns, relief and synoptic weather situation allows to classify wildfires by their type of spread, a fundamental aspect for anticipating the spread of future fires, but it also allows to go a step further.

A geographical region can be divided up according to its Fire Types when the effect of the relief is considered a fixed and unchanging factor and that the same synoptic weather situation may have different effects on a region, i.e. causing adverse fire weather in some areas (strong winds, low relative humidity, high temperatures, etc.) and leaving other areas with normal meteorological conditions from a fire behaviour point of view. This step allows to predict the Fire Types that will occur in different areas of a region.

In order to be able to classify and zone Fire Types, historical fires must be documented and analysed by characterising at least:

- the weather period at synoptic level(4,21) that determines the characteristic factors
- the type of fire spread pattern and the spread scheme
- the Fire Type
- the date and time of day.

The Recurrence of Large Wildland Fires. Homogeneous Fire Regime Zones

Some extrapolation effort is necessary to enhance the information derived from the analysis of historical fires that are classified according to the Fire Types Concept for an entire region. It is assumed that the same Fire Type will occur in similar zones of a region under the same weather conditions, *see Figures 6 and 7*.

Similar zones of a region must have the following characteristics in common that are determining fire spread:

- Relief
- General wind system
- Local wind regime during specific meteorological conditions
- Vegetation type
- Fire Type

Figure 6.

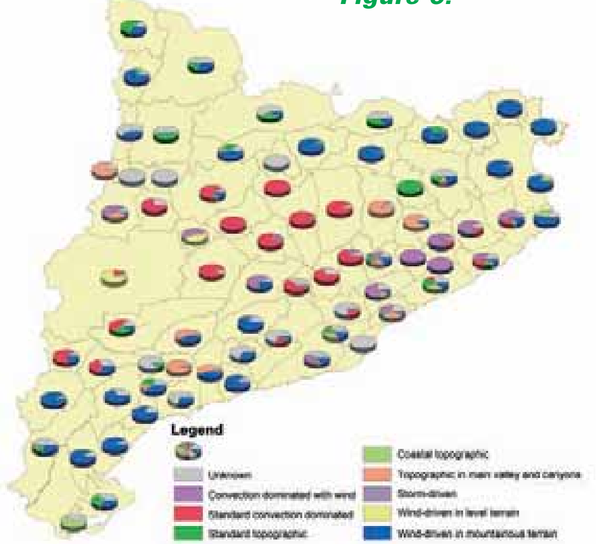


Figure 7.

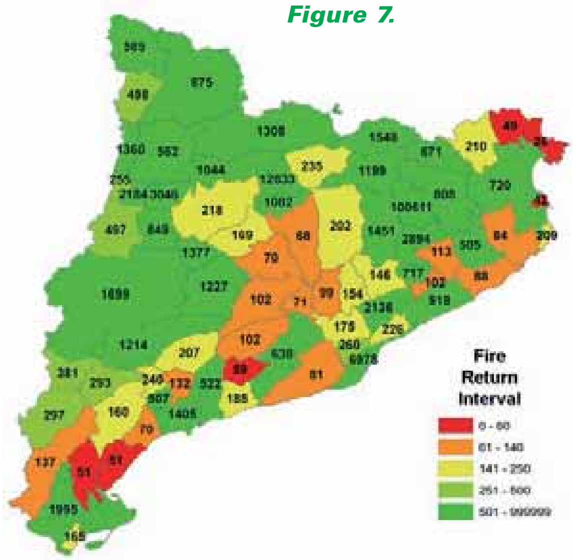


Figure 6. **Percentage of area burnt by each Fire Type in different Homo-geneous fire regime zones (HRZs).** Source: Castellnou et al., 2009.

Figure 7. **Recurrence of wildfires based on the natural fire regime of the last 40 years in Catalonia.** The map shows the fire return interval for each area. Source: Castellnou et al., 2009.

Suppression opportunities

One last field to complete the working methodology based on anticipation proposed in this handbook must be accomplished. Once the predictable spread pattern of a wildfire in an area and the specific synoptic weather conditions are known, the next step is to identify the suppression operations that have been successful in order to characterise the opportunities for suppressing a certain fire, particularly in terms of "where?" and "how?"

The compilation of operational experiences becomes the basic tool for developing this section, characterising the opportunities with the following data, *see Figure 8:*

- location and description of the operation
- spread pattern and behaviour of the fire
- type and number of the resources involved

The Castellnou de Bages Fire, covering 963 ha on 18/07/2005

Initial strategy: STABILIZE THE HEAD of the fire before it crosses the Llobregat river and ANCHOR THE FLANKS.

Opportunity 1: STABILISING THE HEAD BEFORE IT REACHES THE RAVINE: Descending fire spread along the crest line allows the use of a backfiring operation on the ravine bottom to prevent the fire from reaching the next slope in full alignment. Spotting activity 300 metres ahead of the front significantly shortens the time window for carrying out this operation, and the fire is able to jump the ravine.

Opportunity 2: STABILISING THE HEAD BEFORE IT JUMPS THE RIVER LLOBREGAT: the light backwind effect created by the precipices above the river is used to set backfires. Resources are concentrated on the river plain to confine the spotfires falling on stubble fields.

Opportunity 3: DESCENDING RIGHT FLANK: the right flank begins to descend out of alignment, allowing to anchor it before it reaches the ravine bottom. The length of the flank > 2 km does not give sufficient time to stabilise it. Because the flank spreads beyond the ravine it opens up with the backwind from the southern crest.

Opportunity 4: CLOSURE OF THE LEFT FLANK BEFORE THE RAVINE JUNCTION: the left flank spreads downward, fanned by the general wind. At the ravine junction it reaches a perpendicular ravine protected from the general wind that allows it to open up to the north, generating new runs in full alignment.

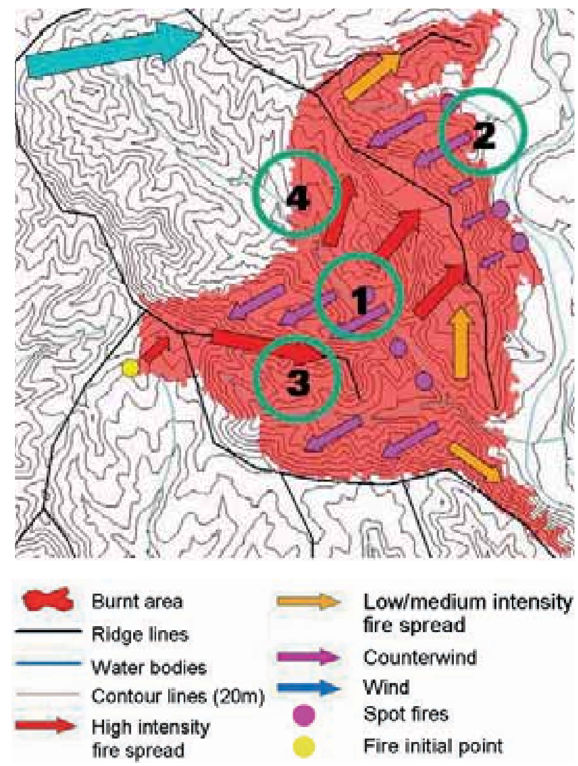


Figure 8. **Simple diagram of operational data on strategy and opportunities at a wildfire.** Source: Bombers de la Generalitat de Catalunya.

The analysis of past fires also serves for evaluation of the effectiveness of planned prevention infrastructures and reconsideration of fundamental aspects of their conceptual design, placement and adequacy under observed fire behaviour. Preventive infrastructure in place overcome by fire behaviour is shown in *Figure 9.*

Figure 9. **Example of preventive infrastructure overcome by fire behaviour in the Riotinto Fire (Huelva) in 2004.** Source: Ferrer.

As a conclusion from this section on the working concepts and methods of anticipation as a premise for prevention and suppression of large wildfires, the importance of looking into the past, i.e. analysing historical wildfires from different points of view should be highlighted: meteorological situation, spread patterns and operational records.

In this handbook it is not possible to go into more detail, but the working concepts presented here are considered a necessary process for bringing forward appropriate prevention and suppression methods for current and future fires.

The classification of Fire Types explained as an example for a region like Catalonia can only be a mere attempt to demonstrate a possible typification of wildfires that allows to derive different fields of application when it comes to suppression and prevention of wildfires. This classification serves as a tool for structuring and organising both suppression operations as well as forest management and planning.

3. The Fire Types Concept as a support tool

Implementing the Fire Types Concept as a landscape management support tool

Most of the European prevention and suppression systems originated from a time characterised by wildfires affecting large areas in a landscape with a lower proportion of tree vegetation, fewer prevention infrastructures (accessability, firebreaks, detection and alarm systems, risk prevention etc.) and fewer suppression facilities than currently exist.

The landscape evolution mentioned above made large wildfires evolve towards a scenario with crown fires, effects on the wildland-urban interface (WUI) and simultaneous fires, plus a considerable limitation of suppression opportunities even for well-equipped and well-organised suppression services.

This development in the conception of large wildfires must be accompanied by changes in the approach to the problem to move:

from prevention based on...

- linear infrastructures and water points to facilitate anchoring
- tracks and lookouts for fast and hard-hitting intervention

... to prevention based on...

- making use of the fire´s strategic opportunities
- adapting land use and forestry practices to expected wildfires
- orienting forest management towards reducing vulnerability of forests to large wildfires

Radical fire exclusion policies have not been very efficient in large wildfire scenarios. Climate, vegetation and traditional fire use are good indicators that in many ecosystems fire is an element that sooner or later will affect some parts of an area. The role of forest management is to determine the degree of intensity and severity at which fire occurrence is accepted, and to carry out extensive forest management over an entire region to create stand structures that tolerate fire occurrence. In this context the prevention objective moves:

from...

eliminating fire from an ecosystem

... to...

reducing vulnerability of vegetation structure and infrastructures to wildfire and limiting the range of large wildfires

3.1. The Fire Types Concept as a planning element. Planning levels and fields of application

The spread of a potential wildfire is still not entirely predictable but there is a series of tools that helps to reduce uncertainty, to understand the fire when observing it and to anticipate the most likely fire behaviour. Among these tools the knowledge transfer of operational experience accumulated by the suppression system using the Fire Types Concept should be highlighted. This is a key tool for the field of prevention in the conceptual design, planning and placement of infrastructure that are essential for tackling wildfires (firebreaks, fuelbreaks, auxiliary strips, tracks, etc.).

The implementation of the Fire Types Concept in the planning process is an attempt to take this line of work further, paying more attention to the main characteristics of a large wildfire most likely to affect a more specific area, based on the model of anticipating its expected movement and its spread pattern.

For forestry policy and public administration planning bodies, different fields of application of the Fire Types Concept were derived for different planning and organisational levels *see table 4*:

Table 4. **Planning levels of preventive actions.**

Level	Allows to...	Applications
Regional planning	Determine the degree of vulnerability of an area to large wildfires and identify risk levels.	○ Evaluation of appropriateness and self-protection measures of landscape and land use types ○ Determination of the **expected fire type** in each **Homogeneous Fire Regime Zone**, and set out of general criteria for limiting spread potential.
Landscape planning	Determine a series of basic guidelines to limit the range of a large wildfire and reduce the vulnerability of an area on the level of a wildfire prevention plan.	○ Determination of **Strategic Management Points (SMPs)** to prepare suppression opportunities during potential large wildfires for the suppression systems. ○ Determination of **Management Priority Areas (MPA)** to reduce the spread potential of large wildfires. ○ Determination of the **respective model fire for a landscape unit** by specifying conspicuous landscape features in addition to the general fire type to adjust criteria for placing and dimensioning wildfire prevention and pre-suppression measures: SMPs, MPAs, sensitive points, access, water points, etc.
Forest planning	Manage forests according to the vulnerability of individual stands to the movement of large wildfires in an area.	

3.2. Contributions to pre-suppression; Model Fires and Strategic Management Points (SMPs)

The Model Fires Concept

The specification of a region through the Fire Types Concept with adjustments to particular landscape features is translated into the concept of model fires. A model fire serves as a reference and describes the maximal potential of a fire to become a large wildfire in a particular landscape unit. It provides information and criteria for discussing and placing measures that need to be implemented to provide support to fire management and suppression operations[5]. The particular landscape features of a region can be grouped into *(appendix 3a):*

- depending on relief
- depending on the development of a weather episode
- depending on availability of fuels

Strategic Management Points (SMPs).

The model fires concept allows to understand the main characteristics that describe the expected movement of a large wildfire in a particular area, pointing out its spread scheme. Accumulated operational experience and the working system of each suppression force make it possible to determine the most suitable opportunity for each fuel type and relief.

It is therefore not necessary to wait for a potential fire to occur to look for suppression opportunities, when the fire front will constrain capacity for analysis. Instead, it is possible to plan in advance, identifying the potential opportunities and adapting them to the requirements of the suppression service.

Figure 10. **Ravine junction.** In yellow, the potential area and, in red, the ravine bottom. Source: Bombers de la Generalitat de Catalunya.

This advance in planning allows to identify the Strategic Management Points (SMPs) - locations throughout a region where the modification of fuel and/or preparation of infrastructures enables the suppression service to carry out safe operations to attack and limit the range of a large wildfire.

For each Fire Type, distinct suppression opportunities with common features and consequently SMPs with similar locations, objectives and characteristics are developed, see *appendix 3b*.

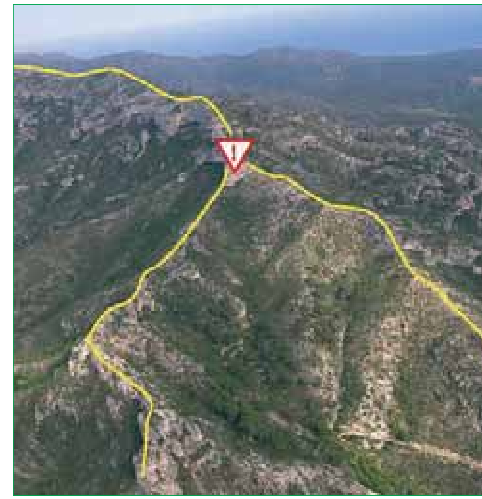


Figure 11. **Picture of a crest line junction. S**ource: Bombers de la Generalitat de Catalunya.

SMPs can have different objectives:

- Specific points limiting the multiplying effect of frontal fire spread: points where fire behaviour changes[i] because of the interaction of topography and fire movement, extending the range of a wildfire. These can be crest line junctions, *Figure 11*, in wind-driven fires or ravine junctions in topographic fires, *see Figure 10*.

- Points where ignition can be confined:
  - to facilitate anchoring of flanks and back of the fire: opening up of paths and tracks, agricultural areas or rocky terrain, forestry roads and areas with low fuel loads to facilitate the anchoring of an attack.
  - to facilitate accessibility: opening of tracks for access to very long flanks *see Figure 12*.

Figure 12. **St. Boi de Llobregat Fire, Catalonia (11/07/2005).** In red, tracks used for access and for anchoring long flanks. Source: Bombers de la Generalitat de Catalunya.

3.3. Contributions to prevention. Limiting the extent of large wildfires

Implementing the Fire Types Concept at the regional planning level allows to understand the basic variables of the spread pattern that helps to evaluate the contribution to the final extension of a fire within a Homogeneous Fire Regime Zone of each landscape unit by taking into account its morphology, location and type of fuel.

Limiting the extent of a wildfire

The suggested methods are not necessarily directly linked to specific suppression operations but they are intended to deactivate the spread mechanisms that fuel large wildfires. Actions must be planned in a way to reduce vegetation structures with vertical and horizontal fuel continuity that are considered hazardous in specific areas of the region, considering the spread type of the reference large wildfire for the zone.

As an example may serve landscapes sensitive to convection fires during southerly winds, like in Central Catalonia, that produce large wildfires with a clear south-north movement and massive spotting activity. The spread pattern indicates that south-facing (sunny) slopes are the generators of the most intense convection nuclei, causing massive spotting in a northerly direction, *see figures 13 and 14.*

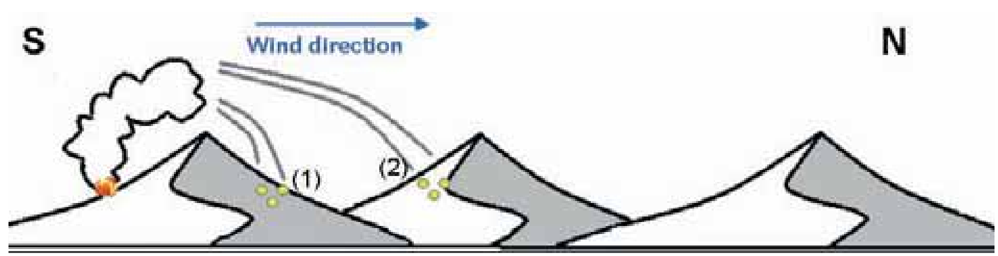


Figure 13. **Possible scenario of wind entering from the south in central Catalonia, resulting in the movement of a large wildfire in south-north direction.** The massive spot fires can reach slope (1) or/and (2). In situation (1), the spot fires will move up the favourable slope, but with the wind and aspect against it. A spot fire starting in situation (2) would be the most unfavourable situation since the slope is in full sun, with the wind and the slope in favour for the fire. Source: Bombers de la Generalitat de Catalunya.

Figure 14. **Castellnou de Bages Fire, 18/07/2005. Convection dominated fire: note the spotting activity of the fire front.** Source: Bombers de la Generalitat de Catalunya.

For such a scenario, the maintenance of stand structures with low fuel loads on south-facing slopes is recommended, particularly in the upper parts, in order to limit spotting activity and distance. The underlying concept is to transform an extremely fast moving spread dynamic with almost immediate spotting to hot slopes, into fires which may be intense but more local in extent, affecting only two slopes (hot and cold). In short, it means to turn an out-of-control convection dominated fire into a more controllable topographic fire, see *appendix 3b and Figure 15*.

In this sense, areas where forest management guidelines give priority to the reduction of fuel load and distribution can be determined by considering the spread pattern of a large wildfire.

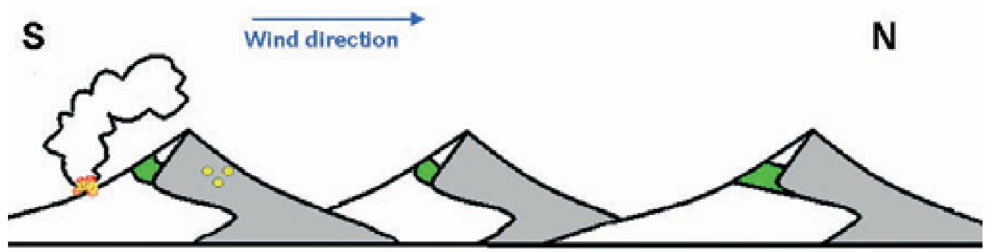


Figure 15. **Possible scenario of wind entering from the south in central Catalonia, resulting in the movement of a large wildfire in south-north direction.** In this case, the treatment zones with modified stand structure (in green) would limit spotting activity and distance. Source: Bombers de la Generalitat de Catalunya.

Fire cause management

The management of fire causes aims primarily at modifying fuel structure in zones with regular ignitions to limit fire spread and minimise the need for suppression forces, particularly in peri-urban and industrial areas.

Protection of vulnerable points

Vulnerable points (rural settlements, farmhouses, campsites, residential areas, farms, etc.) must be protected through creating infrastructure to maximise the suppression service's effectiveness in defending these points, *see Figure 16*.

Figure 16. **Low-fuel-load strip protecting a residential area.** Source: Bombers de la Generalitat de Catalunya.

3.4. Contributions to forest management

The establishment of Homogeneous Fire Regime Zones (HRZs) allows to determine the fire return interval and therefore recognize the importance of fire disturbances within them. Based on that forest managers can assess the importance they must attribute to forestry activities aimed at protecting forest stands against fire occurrence or improving their resistance to fire spread, along with other factors that determine the management of a specific area (other disturbances, seasonal conditions, protected fauna, etc.). As such, forestry schemes aimed at creating stand structures that are less vulnerable and more resistant to fire occurrence can be commenced.

Consequently, it is not only a question of working in specific areas to confine wildfires (such as SMPs) or defining zones with the priority objective of controlling fuel loads to limit the extent of any large wildfire, but also of creating stand structures that increase resistance to the spread of high-intensity fires, which consequently facilitates the task of controlling such wildfires.

4. Final considerations

This handbook aims to present a suite of methods and tools for tackling or minimising the effects of large wildfires in modern wildland, rural and urban areas. The relationship between the occurrence of large wildfires and the landscape is highlighted as a basic pairing that governs the other elements forming part of the system (fire generations, suppression and prevention services, regional planning policies, types of forest management, etc.).

Advances in knowledge about fire allow to develop strategies to cope with it, but also show that, as in other elements of nature, there are still scenarios which have not yet been experienced, yet will occur in the future. This uncertainty makes it necessary to maintain a spirit of constant adaptation in which it must be possible to review and expand any step forward taken.

All this means that this version of the handbook may not be final, and that it must remain open to the contributions and experiences of the entire community of experts that are working on fire.

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Appendices

Appendix 1
Fire as a landscape management tool

1.a. Ecology of fire

Fire is an integral disturbance factor in many natural ecosystems. Traditionally natural disturbance was perceived as a catastrophic event and as exogenous agent of vegetation change originating in the physical environment. This had severe consequences for the planning of long-term goals in forest ecosystems. Since more recently the more endogenous nature of fire as a disturbance factor with a gradient from minor to major is now widely accepted, fire has to be taken into account for the management of forest ecosystems, especially in long-term planning. While fire as a disturbance factor may be required to maintain some natural ecosystems and wildlife habitat it may wreak havoc with specific management goals such as timber production or soil conservation. Fire effects can therefore be integrated into land management planning through an understanding of how fire affects forest stand structure and landscape evolution(1).

The fire regime is an important term to characterise the different aspects of ecosystem functioning. Understanding the fire regime(3) allows to determine the response of all vegetation layers (herbaceous plants, shrubs and trees) to fire occurrence for each type of forest structure. Knowledge of these processes is fundamental for determining the basis for integrated management, which considers disturbance as an additional element in ecosystem dynamics.

Integrated practices to conserve these ecosystems must consider that fire in itself is an object of management and not only a means for obtaining other goals, such as reduction of fuel load or an improvement of animal and plant populations. Fire management includes a wide range of options: from avoiding any fire and suppressing it as soon as it starts, to doing nothing and allowing the fire regime to follow its own dynamic. Another alternative is active application of ignition processes: carrying out controlled burns to mimic the natural fire regime or simply to reduce the probability of large wildfires. Any of these activities affects the fire regime and is therefore involved in managing it. The important thing is to be clear about the objectives being pursued(1).

The integration of fire into the ecosystem allows to establish management goals that are adapted to the fire regime, determining objectives and silvicultural treatments to create and maintain a stand structure that is resistant to fire, to minimize the potential for the occurrence of Large Wildfires, and to maximize direct and indirect benefits.

The term **wildland fire**, understood as an ecological process as an integral part of ecosystem functioning, both being controlled or not, is differentiated here from the term **wildfire**, understood as an uncontrolled fire perceived by humans as a threat to life and property.

1.a.1. Characterisation of fire regimes

A fire regime is a generalized description of the role fire plays in an ecosystem. It is typically a statistical concept and can be characterized best through the following parameters[(2)]: **Intensity, Severity, Extent, Frequency, Fire Return Interval and Seasonality**.

Forest types develop a distinct structure under the influence of a specific fire regime as a result of the interaction between the different parameters and the ecosystem.

Considering the purpose of this document, the parameters characterising fire regimes can be described as follows:

Intensity

Fire intensity measures the physical extent of fire disturbances. It specifies the power of a fire in terms of energy release and is strongly dependent on stand structure, defined by the available fuel load and its horizontal and vertical distribution. The energy release (kW) is expressed per unit of length (m) of a linear fire front. As this is difficult to measure, observed flame length can be related to fire intensity and can serve as a rough estimate of fire line intensity. Examples of different fire intensities are shown in *Figures 17, 18 and 19*.

Severity

Severity is a qualitative measure of the immediate effects of a fire on an ecosystem. It refers to the degree of loss of organic material, mortality, effect (% of crown scorch in trees) and survival of both above- and below-ground biomass. It is determined by the heat released both above and below ground. Examples of different fire severities are shown in *Figures 20, 21 and 22*.

Extent

Extent refers to the area affected by fire. A clear distinction is made between outbreaks (fires smaller than one hectare), wildfires (fires between 1 and 500 ha) and large wildfires (associated with fires larger than 500 ha). Fires that become large in size usually reach their extent because they have exceeded suppression capacity, although this depends also on other variables such as the suppression system, the ecology and topography of the area, etc.).

Frequency

Frequency refers to the number of disturbances which occur in a specific area and over a certain period of time. It is defined as the number of fires per time unit in a particular area. Examples of different disturbance frequencies are shown in *Figures 23, 24 and 25*.

Fire Return Interval

The return interval is the time needed until an area may again be affected by the same disturbance. It can be calculated as the inverse of the frequency in years between the disturbance events.

Seasonality

Seasonality refers to the physiological state of the vegetation at the time a disturbance occurs. The effects of a disturbance and also its development are depending on the processes of plant development, dormancy, reproductive control, and stress physiology that create a structural heterogeneity in vegetation.

Intensity

Figure 17. **High intensity fire** Source: Bombers de la Generalitat de Catalunya.

Figure 18. **Medium intensity fire.** Source: Bombers de la Generalitat de Catalunya.

Figure 19. **Low intensity fire.** Source: Bombers de la Generalitat de Catalunya.

Severity

Figure 20. **High severity.** Source: Bombers de la Generalitat de Catalunya.

Figure 21. **Medium severity.** Source: Bombers de la Generalitat de Catalunya.

Figure 22. **Low severity.** Source: Bombers de la Generalitat de Catalunya.

Frequency

Figure 23. **High disturbance frequency.** Source: Bombers de la Generalitat de Catalunya.

Figure 24. **Medium disturbance frequency.** *Pinus pinea* in Cap de Creus. Source: Míriam Piqué.

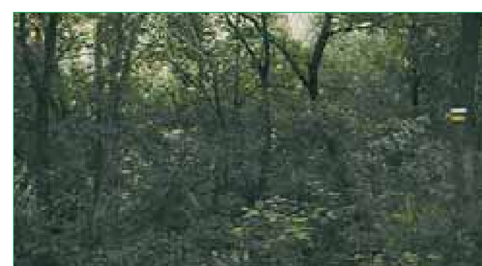


Figure 25. **Low disturbance frequency.** Source: Bombers de la Generalitat de Catalunya.

Fire can act as a disturbance factor resulting in a **stand replacement** or in a **maintenance** fire regime, depending on the intensity with which it affects a forest stand.

Stand replacement results from high intensity fires and causes high mortality in all structural layers, implicating a substitution of the major part of the individuals through regeneration or resprouting, *see Figures 26 and 27*. Stand structure disappears, forest resources are lost and the mid- and long-term management objectives will have to be totally reconsidered.

Figures 26 and 27. **Fire as a stand replacing disturbance factor in *Pinus halepensis* after fires of high intensity (left).** The disturbance results in a structural change of the forest stand and in the occurrence of new light demanding species (right), Zuera (Zaragoza/ Spain). August 2008. Source: Bombers de la Generalitat de Catalunya.

Maintenance is a process associated with low and medium intensity fires. The herbaceous and shrub layers may be partially or fully affected, and the tree layer partially. The stand structure does not completely disappear, *Figure 28*.

The fire resistance of the stand is increased, *Figure 29*, timber capital is maintained and the basic management goals will not need to be modified

Figure 28. **Fire acting as a maintenance factor in a *Quercus suber* stand affected by a rapid surface fire, destroying the herbaceous and shrub layers.** The tree layer is not severely damaged, and shade conditions are preserved (left). ***Figure 29.*** ***Pinus nigra*** **regeneration in canopy gaps opened up by fire disturbance (right).** Source: Bombers de la Generalitat de Catalunya.

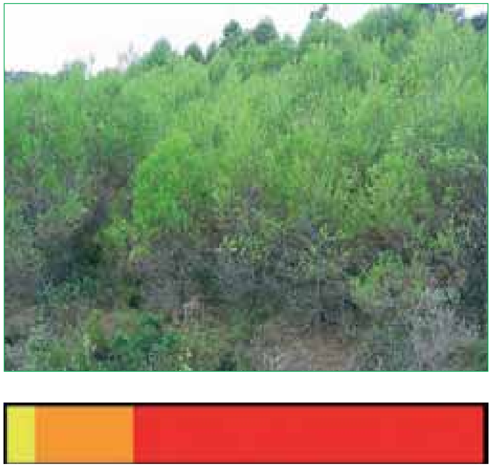
1.a. 2. Vulnerability depending on stand structure

Generally, a fire regime can be directly linked to vulnerability of vegetation structure. However, since a wide range of fire intensities, from crown fires to surface fires, can result in the mortality or survival of individuals, depending on the ecology of the species and other factors, it is not easy to see the link. Different stand structures, when affected by the same fire, will show different degrees of vulnerability to fire occurrence.

Silvicultural treatments may modify a fire regime that is linked to a forest stand through altering stand structure, i.e. accelerating processes at the most vulnerable development stages and maintaining those structures least vulnerable to fire over time. The frequency and type of silvicultural treatments in any stand structure may mitigate its vulnerability or maintain its resistance, depending on the characteristics it shares with the fire regime that defines it.

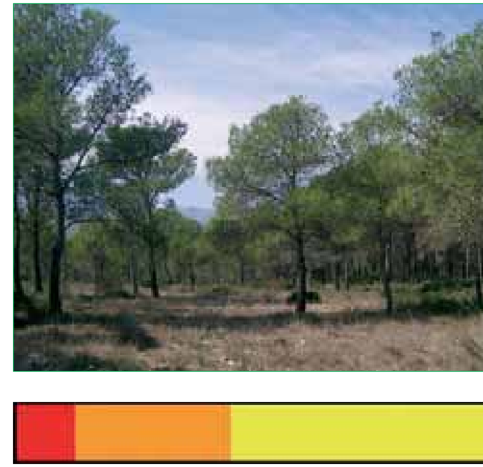
Vulnerability depends on type of stand structure (referring to stand characteristics, dominant species, spatial distribution of individuals and succession cycles), terrain and weather conditions. Below *(Figures 30, 31 and 32)* a qualitative approach is used to illustrate vulnerabilities on a relative scale, where the colour code indicates that vulnerability is high (red), medium (orange) or low (yellow).

Relation between stand structure, fire intensity and severity in a *Pinus halepensis* stand based on the relative importance of vulnerability and the effects of different types of fire on a forest stand.



Dense structure with vertical continuity from ground to crown, *Figure 30*. No stand stagnation yet, nor general self-pruning of the lower branches. The probability that the stand becomes highly vulnerable to fire disturbance is very high; medium and low vulnerability to fire have a low proportion in this type of structure.

Dense structure but with vertical discontinuity between the pine needle bed and the live branches of the crown base, *Figure 31*. The stand dynamics have stagnated, with strong self-pruning of the lower branches. The proportion of high vulnerability to fire is medium-high, although low vulnerability is significant and contributes to stand development by clearing out individuals through heat damaging the trunk base and affecting the cambium. This is typically the phase when prescribed burning is first introduced.



Structure cleared and pruned, *Figure 32.* Vertical discontinuity and crown separation (FCC<60%) prevent surface fires from rising up to the crowns; at the same time the separation between burning fuel and the crown base decreases stand vulnerability. Only during specific weather episodes a surface fire burning with high intensity is able to renew the stand, the tree mortality being determined mainly by radiation (crown scorch).

Figures 30, 31 and 32. ***Pinus halepensis* stands in Central Catalonia.** Source: Bombers de la Generalitat.

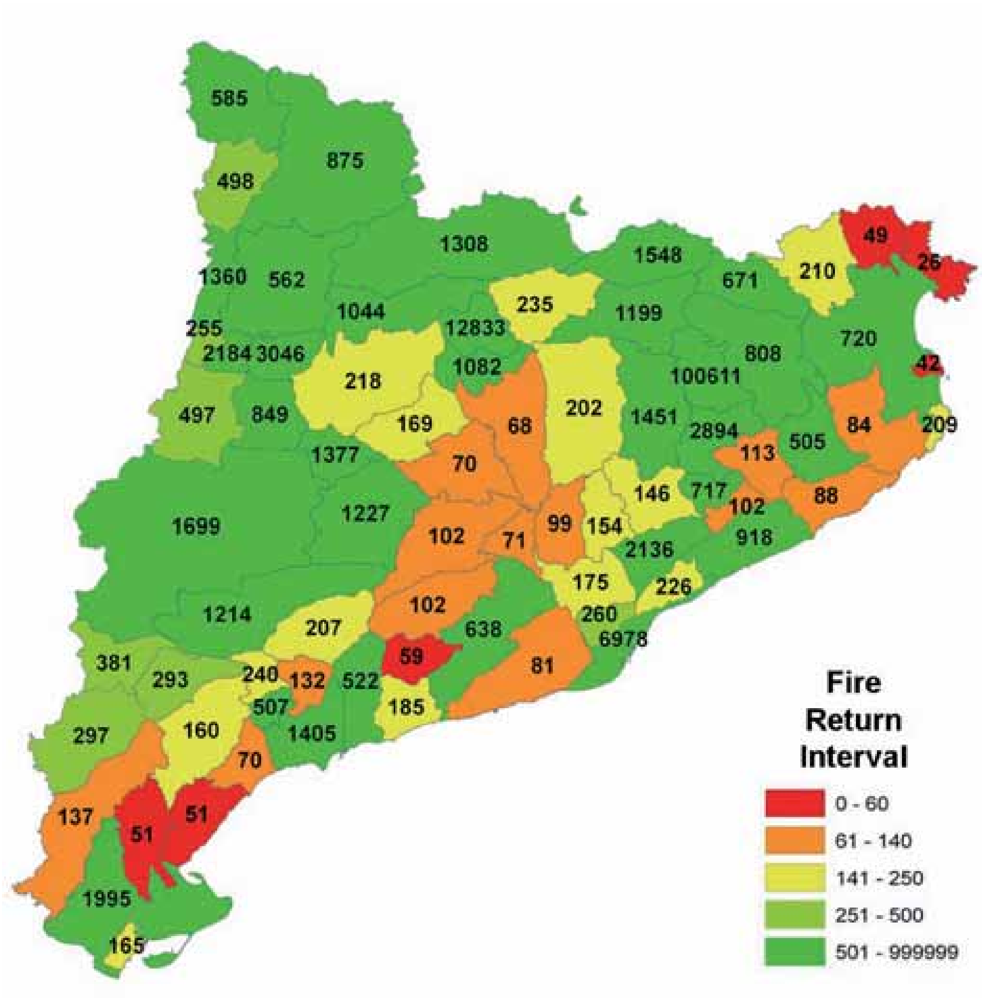
Explanation of the colour bars: The probability that a stand will burn in a certain way (and thus display low, medium or high vulnerability to fire disturbance) is directly related to its structure (owing to silvicultural treatments) and development stage. The colours indicate the vulnerability of a stand (low, medium or high vulnerability); the length of the coloured bar resembles the relative importance of the degree of vulnerability to fire impact.

1.a. 3. Natural Fire Rotation (NFR) and Homogeneous Fire Regime Zones (HRZ)

Natural fire regimes refer to the role of fire in landscapes without human intervention, however, including aboriginal fire use[(2)]. In ecosystems fire regimes can be characterised through a set of parameters (see above). Natural fire regimes, however, are modified by human activity, increasing fire occurrence (e.g. in the western Mediterranean basin) or decreasing it (e.g. in boreal forests where fire suppression has decreased fire frequency and extent). In fact, referring to a natural fire regime makes little sense in regions with strong anthropogenic influence, such as the Mediterranean basin. One has to go far back in time where climatic and vegetation conditions were different from today to find a hypothetical situation with only little impact by humans[(1)].

For Catalonia there are hardly any data on fire severity and intensity, whereas a lot more information on number of fires and burnt area is available. In this context, it appears the most viable way to characterise a fire regime through the calculation of fire frequency over a determined time period. The Natural Fire Rotation (NFR) is calculated to obtain area frequencies.

The Natural Fire Rotation (NFR) represents the time period necessary to affect the whole of a homogeneous fire regime zone, see *Appendix 3a*, under a given synoptic situation. As an example, for Catalonia the Homogeneous Fire Regime Zones were calculated, *see Figures 33 and 34*, for a period of 40 years, where existing data were extrapolated and processed.



Figures 33 and 34. Based on the analysis of fires over the past 40 years in Catalonia. Fire Return Intervals are shown for each zone. Source: Castellnou, et al, 2009[(3)].

For further information on the characterisation of fire types and homogeneous risk areas, *consult Appendix 3a* Methodology for the development and application of the Fire Types Concept.

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1.b. Traditional fire use

Fire represents a force that, once deployed, may destroy everything in its path. Mastery of it provides power and the capacity to transform the earth. The domestication of fire is considered one of the most important achievements of mankind, the only species that has mastered that step[(1)].

Throughout the history of land use in Europe, fire has been an important element of grazing, agriculture and forestry and an important process in forming landscape patterns in terms of ecological and cultural diversity [(2)].

1.b.1. Living with fires as a model for current landscapes

The crisis of the rural world at the beginning of the 20th century led to an increasing rural exodus and the associated abandonment of traditional land management practices, including fire use. Industrialisation began to affect both urban and rural environments.

In central and northern Europe, the socioeconomic changes after WW II brought a change in land use systems (increasing use of technology) and landscape patterns, resulting in the elimination of traditional burning practices. Meanwhile, these recent trends, air quality standards and the prevailing general opinion that fire is detrimental for ecosystem stability and biodiversity led to a complete ban on fire use in most European countries[(3)].

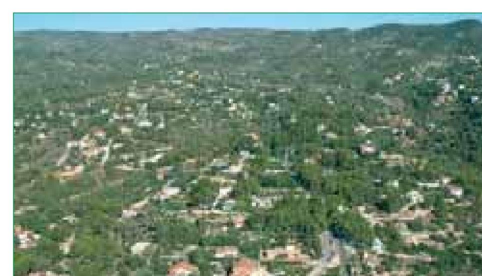
Since early humans roamed the earth, fire has provided not only resources for subsistence and improvement of living conditions but also created habitats which humans are part of. With time, human perception of and relationship to landscapes have changed, and with this, ecosystems have changed[(4)]:

Fig.35. Coexistence: Throughout early human history, the relationship between man and nature was a direct and dependent one. Low population densities and low degrees of technification made mankind aware of being a part of nature, vulnerable to environmental changes, and discovering new ways of survival.

Fig.36. Utilisation:The mere coexistence changed with increasing populations and the associated extraction of resources, particularly in the form of extensive agriculture and livestock farming, and later oversea trade on a large scale. Domestic herbivores, fire and iron tools significantly altered disturbance regimes of many landscapes. Nature produced a multitude of resources for mankind's use and pleasure.

Fig.37. Engineering: With the emerging industrialisation, the degree of technification in land use systems increased. The German Black Forest model was imported to a Mediterranean environment, eliminating redundancy to optimise the use of resources. Suddenly, the entire ancestral forest culture (including fire) was considered bad, and a struggle went on against it to the point of almost eliminating it, replacing it with Central European forestry.

Fig.38. Religion: An urban perception of woodlands as autonomous ecosystems emerged where humans no longer belong to, and where human intervention diverges from natural succession. This created the perception of forests as an ideal, static and incombustible system and agro-forestry practices were condemned as productivist systems. The forest is an untouchable god and fire, as well as chainsaws, are devils to be fought.



Figures 35, 36, 37 and 38. Source: Castellnou and Nebot, 2007[(4)].

1.b. 2. Current situation

It seems obvious that conservation and environmental management have inherited such traditional practices and that they are used for various reasons: removing slash after thinning and harvesting; improving grazing conditions for forage and habitat for domestic livestock, game or other wildlife with conservation status; eliminating of moribund plant material that could become fuel for uncontrolled wildfires, or improving the regeneration of plant species that need open environments[1].

The current situation of fire use in Europe as a tool for different practices is described in the following, from traditional fire use to prescribed burning as tools to fight wildfires[5].

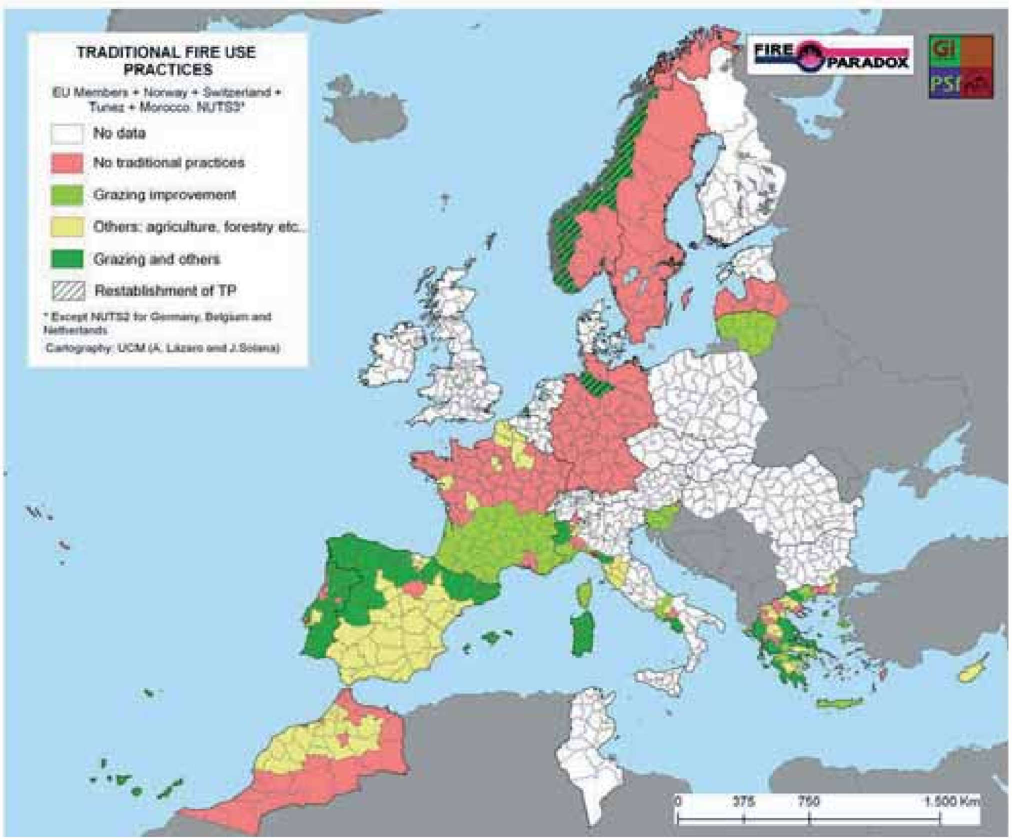


Figure 39. Distribution of the traditional use of fire in Europe and North African countries. Source: Lázaro and Montiel, 2009[5].

Traditional fire use

Although the use of fire has been recognised as a general tool in rural Europe, the current state shows a diverse situation:

1) Central and northern Europe

Gradual abandonment of traditional fire use practices.

2) Mediterranean basin

Maintenance of the use of fire as a traditional tool, deeply rooted in agriculture and livestock farming. Current socioeconomic dynamics are fundamental in ensuring the maintenance or eradication of these traditional practices.

3) Eastern Europe

Countries where agricultural activities are an important part of the local economy, and where the use of fire as a traditional practice, like in the countries of the Mediterranean basin, continues to be a practice rooted in rural life. *See Figure 39.*

Prescribed burning

1) As a replacement tool for traditional fire use in Europe

The introduction of prescribed burning in Europe was not aimed at mimicking natural processes or at reconstructing natural fire regimes. It was presented as a tool to replace traditional burning practices or management systems which have now been abandoned.

2) Development of prescribed burning

The incipient development of prescribed burning practices in Europe has taken place in different regions with different objectives. The results obtained to date show how this technique has largely been introduced in the Mediterranean countries in order to prevent wildfires, while in northern Europe the main objectives are aimed at forestry and nature conservation activities.

These trends are still developing, as some countries, e.g. Portugal and some regions of Spain, have begun to expand their objectives of prescribed burning to include forest and biodiversity management. Meanwhile, some countries in northern and central Europe might develop prescribed burning programmes for wildfire prevention, due to potentially increasing fire risk.

3) Wildfire prevention

This practice is concentrated in southern Europe and has seen a strong increase at the beginning of the 21st century.

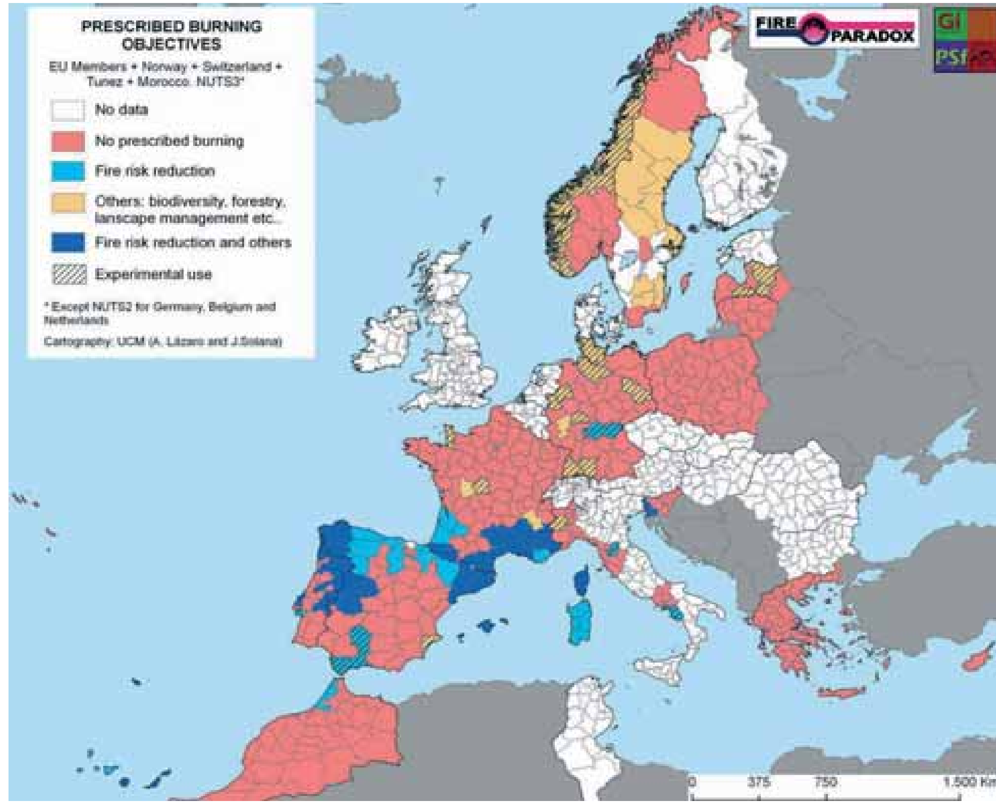


Figure 40. Distribution of prescribed burning practices and objectives in Europe and North African countries. Source: Lázaro and Montiel, 2010[5].

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1.C. The use of fire as a management tool

1.C.1. The role of fire for stand structure

The use of low-intensity fires is a very effective silvicultural tool in fire prone areas to improve the structural resistance of forest stands to fire. This treatment can be applied where species are naturally adapted to fire regimes of low intensity, maximizing the benefits of prescribed burning*(1)*.

The most important effects of low-intensity fires are:

- Reduction of dead fine fuels in the herbaceous and shrub layers, reducing the total fuel load and the vertical and horizontal continuity of fuels.
- Creation of breaks in the vertical structure through burning the lower tree branches and thinning out the crowns through radiation and convection, which accelerates the elimination of old leaves of evergreen species*(2)*.

The benefits of low intensity fires for stand structure can be applied in two ways:

- Through planned prescribed burning*(c)* in terms of passive*(d)* and active*(e)* suppression.
- Through the follow-up and monitoring of wildfires and their behaviour, allowing to integrate the experiences with low-intensity fires into prescribed burning (fire management).

This may significantly reduce the vulnerability of a stand structure to wildfires as can be seen in some fires ignited by lightning strikes. *See Figures 41, 42 and 43.*

Figures 41, 42 and 43. **Lightning-ignited fires burning with low intensity.** The effects produced are similar to the ones that can be achieved through prescribed burning: surface fuel elimination, thermal pruning of low branches and thinning of crown foliage. Depending on the return interval, these fires can create stand structures resistant to fire. Source: Bombers de la Generalitat de Catalunya.

1.c.2. Integration of fire into forest management - prescribed burning

The controlled application of fire as a management tool is based on the idea of benefitting from fire effects on stand structure under well planned and defined conditions. This also known as technical fire use in prescribed burning.

Fire as a dynamic disturbance factor in ecosystems causes a change in stand structure depending on its intensity and return interval(1). Understanding these changes allows the manager to control and regulate the development of a stand.

These precepts are determined by silvicultural objectives laid out in management plans that are mostly based on empirical experience (cause and effect).

The regulation of competition between individuals of a forest stand is achieved through treatments that eliminate some individuals to improve stand structure, mimicking succession stages that can be observed in natural processes following disturbances such as wind throw, avalanches, or low-intensity fires. In that sense, silvicultural treatments like thinnings can be understood as controlled and directed applications of a disturbance that affects individual trees of a stand. However, this requires knowledge and experience to evaluate the intensity, frequency, as well as the form of the application of a treatment.

In summary, the use of technical fire only intends to replicate natural processes aiming to improve a stand in an ecologically, technically, socially and economically acceptable frame.

Prescribed burning

Prescribed burning is the careful application of fire under specified fuel and weather conditions to meet specific resource management objectives and long-term management goals. It is used as a tool in active and passive fire suppression where prescribed burning operations are based on the use of low-intensity fires that aim at reducing fuel loads and therefore reducing the risks of high-intensity fires.

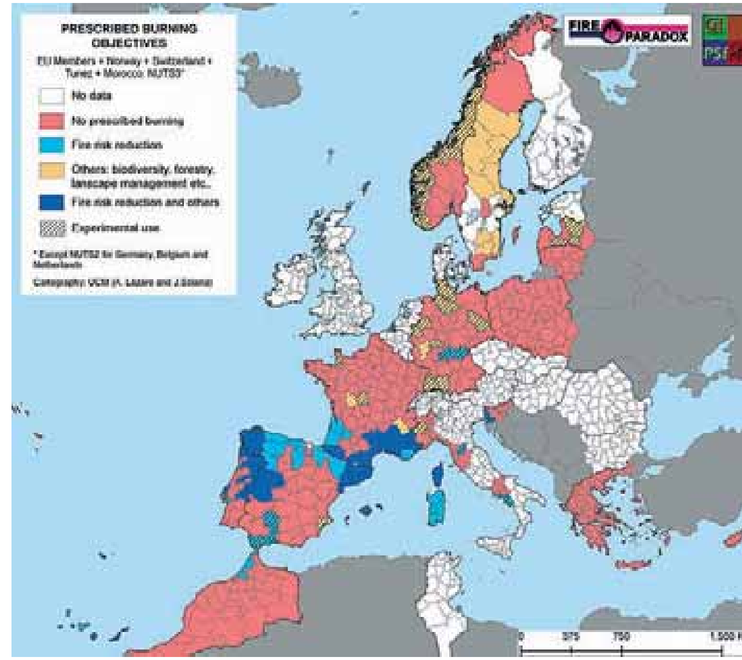


Figure 44: Objectives of the use of prescribed fire. Source: Lázaro, A. & Montiel, C. (2009)(2).

These treatments use fire to achieve a predefined management objective for a forest stand through the interaction of fire with a specific ecosystem, according to a technical plan.

At European level, prescribed burning practices can be classified according to the management objectives pursued, *see Figure 44*.The introduction of prescribed burning to southern Europe was primarily aimed at risk reduction. The experience gained in these practices later on allowed to expand the aims towards other management objectives (nature conservation, forest management or habitat management). This is the case in France, Portugal and some regions of Spain, such as Catalonia, Galicia and the Canary Islands(3).

Types of prescribed burning

Depending on the main goals that prescribed burning is applied for, it can be classified into four major groups: Wildfire risk reduction, and prescribed burning in silviculture, rangeland management and wetland management.

1) Wildfire risk reduction

This practice is concentrated mainly in southern Europe, with a strong increase in the beginning of the 21st century.

Objectives:

a) Improvement of pre-fire stand structure and increase of resistance to fire through semi-regular and irregular stand structure, *see Figure 45*.

Figure 45. **Irregular stand structure with tree individuals of different ages.** Location: Font de la Pólvora (Girona). Source: Bombers de la Generalitat de Catalunya.

- Elimination of undergrowth vegetation thus reducing fuel loads. In case of a fire this stand will burn with less intensity.
- Breaking up vertical and horizontal continuity, thermal pruning (*see Fig. 46 and 47*) and reduction of the tree cover. In case of a fire, there will only be surface fire spread and a minimised risk of crown fires.
- Decrease of density (number of trees/ha), clearing of undergrowth and elimination of advanced regeneration through radiation affecting the cambium at the base of the trunk, *see Figures 48 and 49*.

Figures 46 and 47. **Prescribed underburning eliminating undergrowth and the lower branches through thermal pruning.** The distance between the first live branches and the ground surface is increased, thus creating breaks in the vertical continuity. Location: Ports Tortosa-Beceit; Horta Sant Joan, Catalonia. Date: January 2004. Source: Bombers de la Generalitat de Catalunya.

Figures 48 and 49. **Elimination of advanced regeneration as potential ladder fuels.** Location: Ports Tortosa-Beceit; Horta Sant Joan, Catalonia. Date: January 2004. Source: Bombers de la Generalitat de Catalunya.

b) Maintaining pre-suppression infrastructures.

- Maintenance burning in areas of low fuel loads, see *Figures 50 and 51.*

Figures 50 and 51. **Creation of an area of low fuel load.** Location: Road between Balsareny – Avinyó, Catalonia. Date: February 2004. Source: Bombers de la Generalitat de Catalunya.

2) Silvicultural treatments

Objectives:

a) Competition control in regular stand structure, *see Figure 52*.

- Clearing of undergrowth (elimination of dying, dominated and suppressed trees).
- Opening up the canopy in regular structured young stands in order to control competition and water stress, *see Figures 53, 54, 55 and 56*.

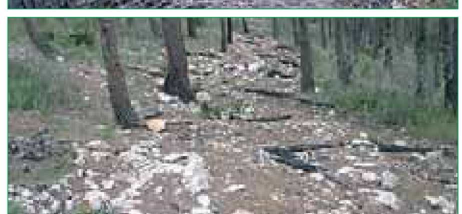
Figure 52. **Regular stand showing a homogeneous and dense layer of trees of the same age.** Source: Bombers de la Generalitat de Catalunya.

Figures 53 and 54. **Reintroduction of fire as a natural disturbance to restore fire prone stand structure in a boreal forest.** The low intensity surface fire is selecting for fire resistant Pinus sylvestris individuals and eliminating Picea abies in the undergrowth. Location: Fagerasen, Västernorrland, Sweden. Date: June 2007.

Figures 55 and 56. **Competition control in a *Pinus halepensis* stand.** Location: Sant Quirze, Catalonia. Date: Figure 55, February 2006. Figure 56, May 2006. Source: Bombers de la Generalitat de Catalunya.

b) Removal of forest slash resulting from silvicultural treatments.

- Extensive in situ burning of forest residues / slash resulting from thinning, pruning, timber harvesting or the creation of firebreaks to eliminate dead fuels and to favor a rapid and efficient recycling of nutrients, *see Figures 57, 58 and 59*.



Figures 57, 58 and 59. **Slash burning after thinning.** Location Figures 57 and 58: Rasquera; Catalonia. Date: February 2004. Location Fig. 59: Meranges, Catalonia. Date: October 2006. Source: Bombers de la Generalitat de Catalunya.

c) Treatments to restore vegetation structure

- Species selection, favouring and/ or eliminating target species of the ecosystem according to management objectives, taking into account ecological aspects, *see Figures 60-65*.

- Habitat diversification, creating a mosaic of open and closed patches depending on the fauna one wishes to promote, *see Figures 66-68*.

Figures 60, 61 and 62. **Management of critical points and species selection.** The use of prescribed fire as a tool for species management: elimination of *Ulex parviflorus* through repeated burning (aiming at the elimination of the seed bank), creating large flame lengths; restoration of *Brachypodium sp*. grassland as pasture land. Location:Tivissa, Catalonia. Date: Fig. 60 and 61 May 2002, Fig. 62 June 2002. Source: Bombers de la Generalitat de Catalunya.

Figures 63, 64 and 65. **The use of prescribed burning to control succession of woody vegetation in former military training sites:** elimination of *Betula pendula* through high intensity burning with large flame lengths has relatively little impact on the soil fauna and the seed bank of *Calluna vulgaris* due to short residence times of the fire front. Location: Drover Heide, Düren, Germany. Date: April 2007 (Figures 63 and 64), June 2007 (Figure 65). Source: Daniel Kraus, Fire Ecology Research Group, MPI Chemistry, Germany.

Figures 66 and 67. **Prescribed burning to maintain open and diverse stand structure of *Pinus sylvestris* in a landscape mosaic for habitat management of Capercaillie *(Tetrao urogallus)*.** Location: Abernethy Forest Reserve, Scotland. Source: Mark Hancock, Abernethy Forest Reserve, Royal Society for the Protection of Birds (RSPB), Scotland.

Figure 68. **Heathland burning *(Calluna vulgaris)*.** Created mosaic improves the habitat of Black Grouse *(Tetrao tetrix)* and Red Grouse *(Lagopus lagopus scoticus)*. Location: Scotland. Date: April 2004. Source: Bombers de la Generalitat de Catalunya.

3) Prescribed burning for rangeland management

Objectives:

a) Pasture renovation in areas of extensive grazing.

- Brush elimination to create grazing areas, *see Figures 69 and 70.*

b) Maintenance and improvement of pastures.

- Renovation of the seed bank to increase the quality and quantity of seeds.
- Brush control to maintain grazing areas, *see Figures 71, 72 and 73*.

Figures 69 and 70. **Burning of pastures in high mountain areas.** Elimination of *Juniperus communis* and *Genista balansae*. Location: Dòrria, Catalonia. Date: March 2007. Source: Bombers de la Generalitat de Catalunya.

Figures 71, 72 and 73. **Traditional patch mosaic burning of coastal heathland to maintain optimal grazing conditions throughout the year.** Location: Lygra, Western Norway. Date: April 2005. Source: Mons Kvamme, Heathland Centre, Lygra, Norway.

4) Prescribed burning in wetlands

Objectives:

a) Reed bed renovation.

- Reed bed burning to create open areas favouring specific avifauna species, *see Figures 74 and 75*.

Figures 74 and 75. **Reed bed burning.** Location: Ebro Delta, Catalonia. Date: February 2002. Source: Bombers de la Generalitat de Catalunya.

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Appendix 2
Generations of large wildfires

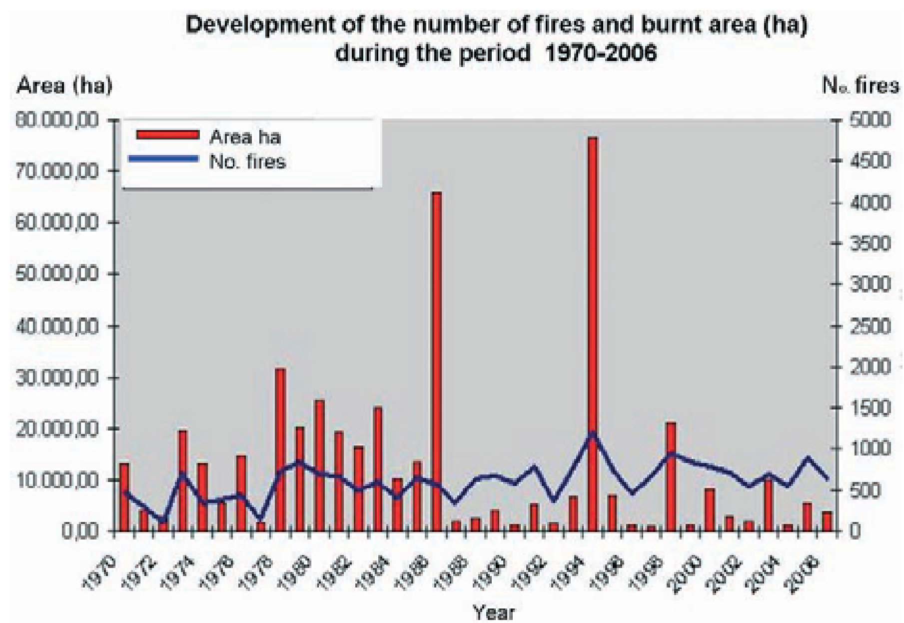
Interaction of landscape, land use, prevention/suppression systems and types of wildfires. The Catalonian example

The socio-economic changes of the 20th century can be characterized by factors that have affected all European countries on a large scale but only in a short-term period.

The main landscape changes of the last centuries include(1) :

- Industrialization and urban sprawl.
- Migration (from rural to urban areas).
- Land abandonment.
- Changing agricultural and forestry practices.
- Transition from the use of biomass to fossil fuels.
- Effective suppression of all wildfires with low and moderate intensity.
- High intensity wildfires which exceed suppression capacity, being responsible of the major part of the burnt area.

The evolution of wildland fires in Catalonia *is shown in graph 4*:



Graph 4. **Development of the number of wildfires and burnt area in Catalonia during the period 1970 – 2006.** Source: Bombers de la Generalitat de Catalunya.

European landscapes have evolved at the pace of the socio-economic changes following the patterns of re-colonization of the cultivated land by wildland vegetation and responding to land use changes with their vegetation structure. Naturally, the behaviour of wildfires has adapted to every evolutionary phase of the landscape, resulting in different **generations of wildfires**.

Fire generations can be defined by a scenario where a specific factor limits suppression capacity and thus leads to the development of a large wildfire. This factor is typically extrinsic to the suppression systems and intrinsic to the landscape and its different phases of evolution which may coincide in time and space.

1st Generation ➛ Large Wildfires caused by Fuel Continuity

Fire spread	Determined by the availability of a continuous fuel layer, especially scrubs and grasses. The cultivated land is abandoned and vegetation cover reaches continuity. The lack of opportunities for anchor points allows large perimeters.
Fuel accumulation period	From 2 to 15 years.
Period	Began in Catalonia during the late 1950s to 1960s.
Fire behaviour	Surface fires of medium intensities with very large perimeters, burning between 1,000 and 5,000 ha, predominantly by wind-driven fires.
Preventive measures	Creation of linear preventive infrastructure and water points to facilitate anchor points and to grant better access to the area.
Suppression measures	The local response is reinforced with seasonal firefighters.
Development	High intensity fires can overcome the linear preventive infrastructures.

Figure 76. **Large fire front without discontinuity, characteristic of first generation fires.** Source: Bombers de la Generalitat de Catalunya.

2nd Generation ➛ Large Wildfires caused by a high Rate of Spread

Fire spread	Fuel accumulation caused by abandonment of land and traditional land management allows fires that spread with high intensities and a fast rate of spread, advancing with spot fires.
Fuel accumulation period	From 10 to 30 years.
Period	Started to occur in Catalonia in the 1970s – 1980s.
Fire behaviour	Fires of high intensity and rate of spread, consuming 5.000 to 10.000 hectares in wind and topography driven fires. The rate of spread overruns the control lines.
Preventive measures	Reduction of the time needed for the suppression forces to arrive on scene (detection, distribution of fire stations).
Suppression measures	Increase of water-based resources and aerial means for a more forceful attack.
Development	Spot fires can overcome linear infrastructure and rapid interventions. Crown fires overcome the suppression efforts of aerial means.

Figure 77. **High intensity fire exceeding the capability of conventional water-based resources.** Source: Bombers de la Generalitat de Catalunya.

3rd Generation ➛ Large Wildfires caused by intensive crown fires

Fire spread	Through high intensity crown fires because of vertical continuity of forest fuels and forest homogeneity due to neglected forest management and the suppression of all fires of low and moderate intensity.
Fuel accumulation period	From 30 to 50 years.
Period	Began in the years 1990 to 2000.
Fire behaviour	Occurring during heat waves and generating fires from 10,000 to 20,000 ha, with crown fires, convective columns, and massive spot fires at large distances. This results in very little suppression opportunities and an easily changing fire behaviour, surpassing the capacity of the chain of command to react to information.
Preventive measures	Risk modelling to adapt the availability of resources to the probability of a large wildfire. Switching from a preventive strategy for fire elimination to a preventive strategy to have tolerable fire regimes.
Suppression measures	Analysis of similar fires to anticipate fire behaviour instead of only reacting to it. Confinement strategies. Amplifying fire suppression techniques: reintroducing fire as a tool, power and hand tools, heavy machinery, reinforcing aerial attacks and improving the efficiency combining these measures. Logistics units are installed and the level of decision making is lowered for a quicker response to changes in fire behaviour.
Development	Large wildfires with massive spotting potential affecting the Wildland-Urban Interface (WUI). Simultaneity of large wildfires

Figure 78. **Crown fire which overcomes the suppression capacity.** Source: Bombers de la Generalitat de Catalunya.

4th Generation ➛ Large Wildfires crossing the wildland-urban interface (WUI)

Fire spread	Large fires which spread through forests, residential areas and houses without any differences because of the density of backyard and garden vegetation and the resulting fuel load continuity between forests and urbanized areas. Episodes with simultaneity of Large Wildfires in one zone
Fuel accumulation period	--
Period	Began approximately in the year 2000.
Fire behaviour	Fires that can start and end in the WUI, and burn more than 1,000 ha. Independent crown fires during heat waves.
Preventive measures	Pyro-gardening, promoting fuel treatments within inhabited zones, fire resistant buildings.
Suppression measures	Attacking the fire while defending houses and people in a new defensive situation. GPS and GIS technologies to trace resources in real time. High importance of fire analysis as a tool. Strike forces to prioritise defensive measures.
Development	Simultaneous large wildfires crossing the wildland-urban interface (WUI).

Figure 79. **High intensity fire moving through a residential area.** Source: Bombers de la Generalitat de Catalunya.

5th Generation ➢ Simultaneous Large Wildfires crossing the wildland-urban interface (WUI). Megafires

Fire spread	Simultaneous large wildfires in high risk areas with extremely rapid, virulent fire behaviour, crossing urban and peri-urban areas.
Fuel accumulation period	--
Period	--
Fire behaviour	Simultaneous crown fires affecting also the wildland-urban interface (WUI).
Preventive measures	Necessity to incorporate fire into forest management directives and guidelines.
Suppression measures	Necessity of cooperation and exchange of resources, information and experiences. Coordination between regions. Continuous learning and exchange platforms.
Development	--

Figure 80. **High intensity fire front overcoming conventional water-based resources from San Diego (USA).** Source: Dave Christenson.

Starting from this experience, some conclusions can be drawn for the best tools and measures available to face Large Wildfires:

- Integrate fire into the basic directives of forest management, adapted to the fire regimes of a zone, helping to reduce the intensity of expected fires.
- Incorporate analysis tools to anticipate the behaviour of Large Wildfires, and to be more efficient in their prevention and suppression.
- Assure access, safety and opportunities for anchor points (LACES) in zones where a change in fire behaviour can be expected allowing an efficient suppression (pre-suppression infrastructures).
- Incorporate all existing suppression tools (water, heavy machinery, hand tools, fire). This implies the integration of prescribed burning into fire management as well as the creation of pre-suppression infrastructures and the recognition of fire as a forest management tool.
- Ensure an appropriate distribution of suppression resources to an expected fire on a daily basis. This includes resources for surveillance (routes, lookouts, individuals with mobile phones) and for suppression (fire stations, water points).

In order to implement these measures one has to understand the fire regime (fire ecology) and the expected fire (model fire concept), and needs a profound knowledge of the tools to be incorporated (prescribed burning, strategic management zones).

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Appendix 3
Proposed treatments for each fire spread type

3.a Methodology for the development and application of the Fire Types Concept. The Catalonian example

3.a.1 Methodology

The main phases of the methodology are(1):

- Creation of a Geodatabase of historical fire perimeters.
    - Reconstruction of perimeters.
    - Back dating and characterisation.
    - Breaking down and synthesis of initial information.

- Identification of meteorological situations at synoptic level for the back dated fires.

- Reconstruction of fire spread.
    - Examination of spread schemes and meteorological situations:
        - Cataloguing of perimeters according to spread pattern.
        - Determining the Fire Type.
        - Classifying the fires in terms of the Fire Types concept.
    - Characterisation of fire spread for each landscape unit.

- Location and characterisation of zones with homogeneous fire regimes.

Reconstruction of perimeters, back dating and characterisation

The basic information sources used in Catalonia for analysing historical fire perimeters are described in *Table 5* and *Figure 81*.

Table 5. **Information sources for compiling historical fire perimeters, weather conditions and spread patterns in Catalonia.** Source: Bombers de la Generalitat de Catalunya.

	Data	
Geodatabase of historical fire perimeters	**Reconstructing perimeters** For all fires since 2000 perimeters have been established by GPS readings (in some fires larger than 100 ha or in inaccessible terrain, the perimeter has been recorded from aircraft). In fires before 2000: ▪ Photo-interpretation of orthophoto maps and aerial photographs ▪ Reconstruction from the difference in age of present vegetation structure ▪ Private archives ▪ Eye witness interviews with firefighters, shepherds, local people and personal observations	**Back dating and characterising of wildfires.** ▪ Wildfire database (Catalan Department of the Environment and Housing and Spanish Ministry of the Environment) since 1968 ▪ Newspaper archives of *La Vanguardia* since 1899, *Diari de Tarragona* and others ▪ Private archives ▪ Perimeter reconstruction from satellite images by the Cartographical Institute of Catalonia (ICC) since 1992 ▪ Wildfire reconstruction projects by the University of Lleida (UdL), coordinated by the Fire Service (Castellnou, 1997; Martínez, 2001; Galán, 2001; Pellisa, 2004; Martínez, 2004; Rodriguez,2006; Moyano *et al*, 2007.)
Identification of weather conditions	**At synoptic level:** ▪ Synoptic situation: (http://www.wetterzentrale.de)	**At site level:** ▪ Weather readings. ▪ Weather conditions: Meteorological Service of Catalonia
Reconstruction of fire spread	**Direct observation during fire:** ▪ Observations of development of fire fronts at fires larger than 30 ha from ground and air ▪ Individual observations from ground personnel ▪ Analysis of the shape of the perimeter compared to the topography, from ground and air ▪ Evaluation of fire severity in all fires greater than 30 ha through the commander in charge from helicopter during the fire and months afterwards ▪ Photos, videos, GPS positions of vehicles, interviews with firefighters, local people and shepherds	**Post-fire evaluation, no direct observation:** ▪ Analysis of perimeter shape with respect to topography and through consultation ▪ Evaluation of fire severity on orthophoto maps or during overflights. Often this happens more than 10 years after the wildfire ▪ Interviews with firefighters, shepherds and local people, review of photos and videos ▪ Fire reports (Bombers de la Generalitat de Catalunya) ▪ UdL projects, see above
Locating zones with homogeneous regimes	▪ Land use map of Catalonia 2002 from the ICC, based on LANDSAT-TM images ▪ Habitat map of Catalonia, 2002, from the ICC	▪ PPP (Priority Protection Perimeters) map from the DMAiH ▪ DTM (Digital Terrain Model) for elevations

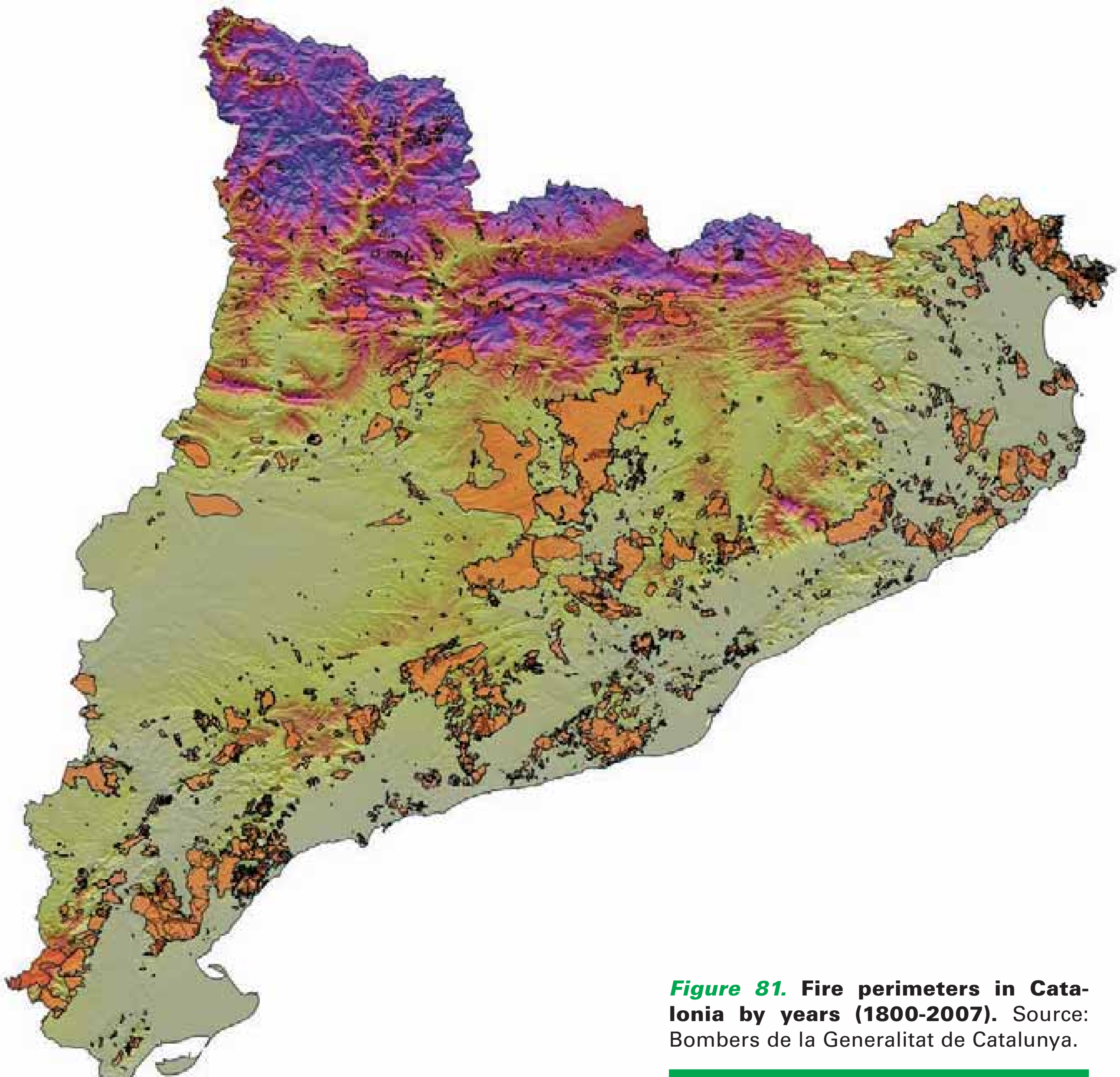


Figure 81. **Fire perimeters in Catalonia by years (1800-2007).** Source: Bombers de la Generalitat de Catalunya.

Characterisation of the Fire Types

Knowledge of the variables from *Table 6* allows to relate each historical fire to a Fire Type and compare its fire behaviour *(Table 2)*.

Table 6. **Spread patterns with description of the dominant factor to identify Fire Type and spread scheme and**
Source: Castellnou et al., 2009[(1)].

Spread pattern	Dominant factor	Fire Type	Spread scheme and strategies (or control opportunities)
Topographic	Topographic slope winds	Standard topographic fires	Follows the slopes with the steepest gradient and highest insolation at daytime. Forms of the perimeter: slopes and hydrographic basins. The critical points are ravines, intersections of ravines, and the position of back and flanks of the fire at a point with the potential for new runs.
	Sea breeze	Coastal topographic fires	Follows the steepest slope and the defined and predictible turn of the sea breeze. Opening of the flanks dominated by sea breeze.
	Topographic winds of the main valleys	Topographic fires in main valleys and canyons	The main direction of the perimeter is in direction of the main valley. A suction of the fire toward the main valley is generated by the venturi effect. Change of the ascending daytime suction to a descent at night.
Wind-driven	In level terrain	Wind-driven fires in level terrain	Follows the wind direction and opens in an angle of 30 to 60°, depending on the strength of the wind.
	In mountainous terrain	Wind-driven fires in mountainous terrain	In mountain ranges aligned with the wind direction it follows the ridge lines. In mountain ranges perpendicular to wind direction, counterwinds occur that facilitate the ascending spread because of turbulences on the slope of the opposite site that is not directly exposed to the wind. Opportunities: at the end of the water divide, or when the divide changes the direction, at bifurcations, or when counterwinds occur.
	In subsidence zones with descending winds. With general winds along the surface at night and rising up during daytime.	Wind-driven with subsidence	Phenomenon of coastal ranges in front of a large plateau that falls abruptly (central eastern coast of the Iberian peninsula, coast of California, Greek Peloponnese), when the diurnal topographic winds are able to compensate the northerly winds at altitude. When this happens, the topographic winds are descending at night while the northerly winds descend along the surface and are reinforced by the topographic winds. Therefore, the fire behaves like a topographic fire during the day and like a wind driven fire during the night. This dynamic implies that the back of the day-time fire is transformed into its head at night and vice versa. This imposes difficulties to the incident management.
Convection dominated	Without significant winds	Standard convection dominated fires	Follows the macro-topography and the wind. Opportunities: confining the head or measures to reduce spotting activity.
	With significant wind. In Catalonia in situations with hot west winds and very occasionally with intrusions of hot Saharan air masses from the south	Convection dominated fires with wind	Convective behaviour plus the wind affecting fire spread. The wind increases the spotting distance, creating new ignition points outside of the influence zone of the convective column and accelerating the general spread of the fire. The column and the spots follow the wind direction. However, the fire ends up burning large topographical basins.
	With the collapse of a pyrocumulus cloud	Convection dominated fires producing pyrocumulus clouds	The pyrocumulus collapses once it condensates and gains weight. This collapse of the convective column generates winds that can tear out trees. Massive spotting and extention of the fire in all directions.

Wildfires with storm-dominated spread patterns are not included in this table as well as in the whole document because at present there is no knowledge about their management.

Characterisation of homogeneous risk areas. The Catalonian example

The analysis of historical fires, together with the topographical information and the delimitation of priority protection perimeters have allowed to identify Homogeneous Fire Regime Zones (HRZ), following the methodology in Agee (1993) [2].

Homogeneous Fire Regime Zones (HRZ) represent regions where fire rotation and type of a potential large wildfire are homogeneous, i.e. where Fire Type, model fire (reference fire for planning) and synoptic situation that are predicted to cause the most problematic wildfire for a zone can be specified[1].

For the adaptation of the methodology in Agee[2] to the localisation and characterisation of Homogeneous Fire Regime Zones in a territory that is widely affected by human influence, the whole territory was divided into relative small and homogeneous zones for the basic calculations, and then adjacent zones were grouped:

- for the establishment of homogeneous fire regime zones a DTM (Digital Terrain Model) is used to calculate basins of approximately 450 ha in size.
- the different hydrological basins are grouped according to:

· existing landscape units identified by the Department of Environment (Departament de Medi Ambient).
· different fires occurring that are classified within the same group of Fire Types.
· different fires occurring with the same axis of main fire spread (SE-NW, N-S). The spread direction depends on the interaction between wind and topography, and the same spread axis indicates zones where this interaction appears homogeneous [1].

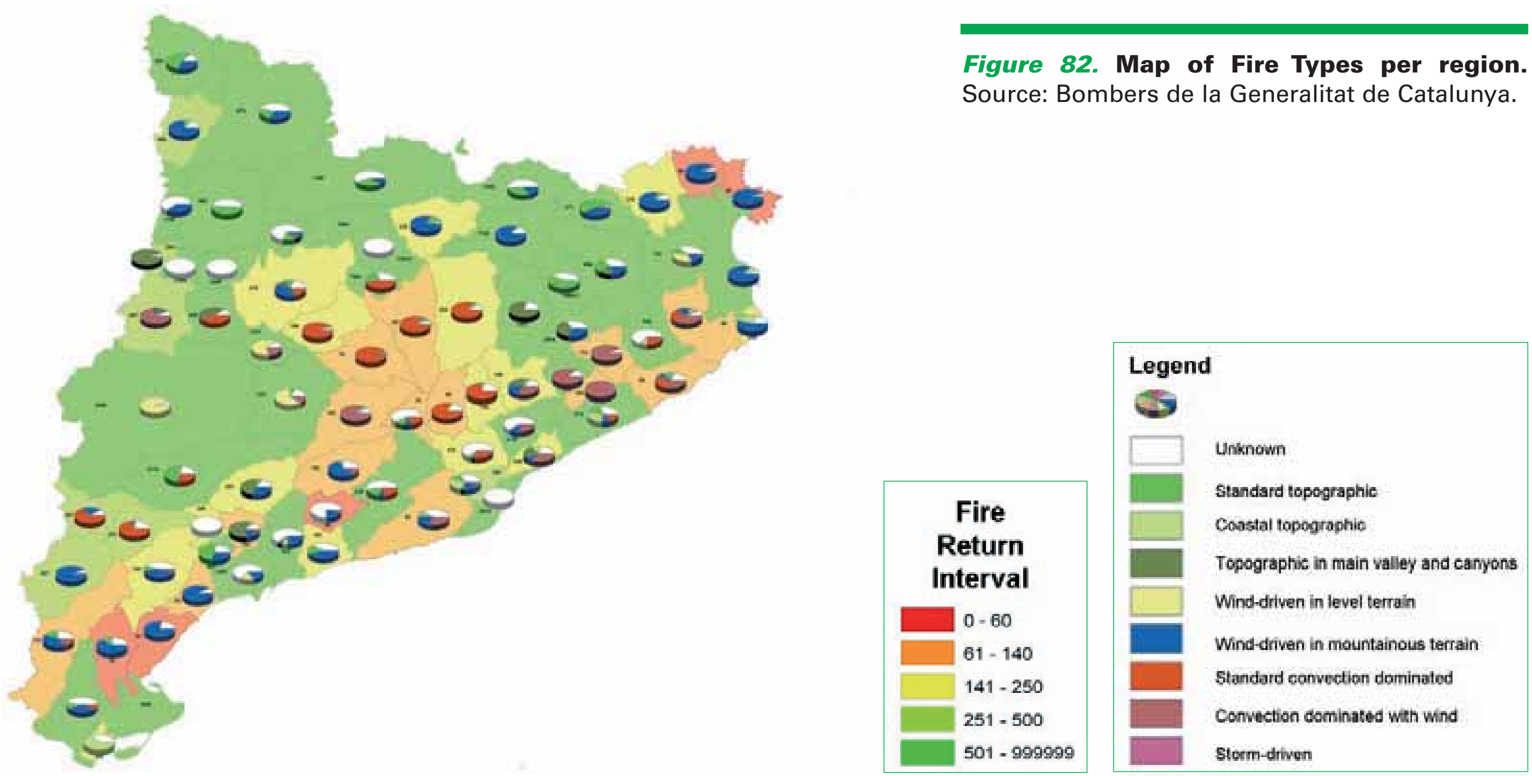


Figure 82. **Map of Fire Types per region.** Source: Bombers de la Generalitat de Catalunya.

3.a.2 Basic factors for fire spread

The entire methodology for the characterisation of the spread of each Fire Type is based on the Campbell Prediction System (CPS) [(3)] and on observed fire behaviour.

Introduction to basic fire analysis

There are various factors affecting and determining fire behaviour and spread. The basic fire triangle (heat, air and fuel) can be amended to the fire behaviour triangle: weather, topography and fuel. In this context, fuel is understood as wildland vegetation.

The factors in this triangle can be broken down into different components, *as shown in Figure 83*:

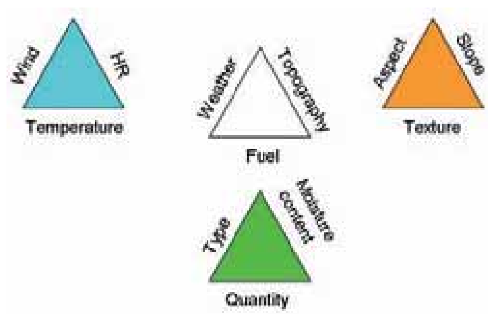


Figure. 83. **Breakdown of the main factors affecting the development of a wildfire.** Source**:** Bombers de la Generalitat de Catalunya

Defining the basic spread factor and CPS field logic

The **basic factors** affecting fire behaviour are too complex to be considered when making real time and on site fire behaviour predictions. The most important factors in *Figure 83* have to be reduced to three basic ones to come to a practical analysis approach:

Aspect: determines fuel surface temperature and flammability through solar radiation. The higher the fuel temperature, the shorter is the preheating process, and thus the intensity and speed of the combustion process is increased. The impact of solar radiation on fuel flammability changes during the course of the day and can be classified sequentially: east, south and west, or, by order of intensity, south, west and east (in the case of the northern hemisphere). Temperature differences of 40ºC in dead fine fuels can easily occur on sunny days, see *Figure 84*.

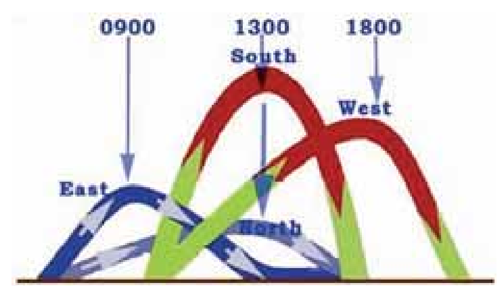
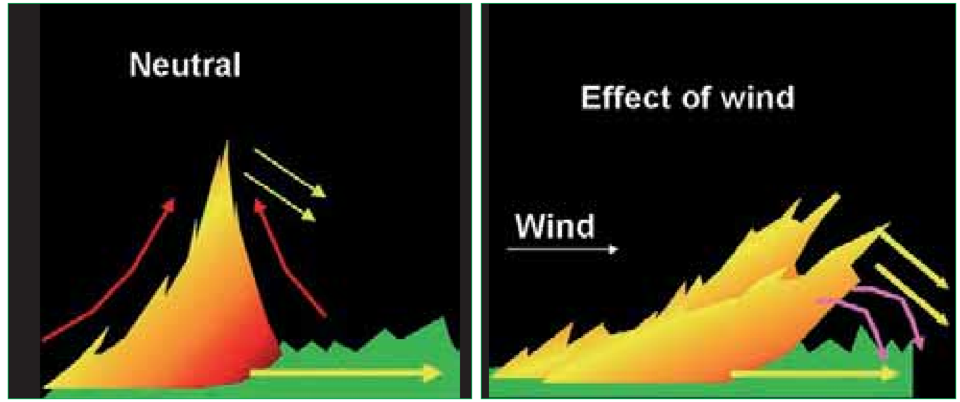


Figure 84. **Fuel flammability through solar radiation by time of day and aspect.** Source: Campbell, 1995.[(3)].

Slope: upslope fire spread is faster and more intense due to the fact that distance and angle between the inclined flame and the fuel is shorter, which facilitates the preheating of the combustible material ahead of the fire front. Downslope fire spread produces less preheating and is slower, due to greater distance between flame and fuel.

Wind: just like slope, wind accelerates fire spread due to its effects on predrying and reinforcing radiative heat transfer on fuels, and impelling and oxygenating the combustion:

- Flames are inclined in a narrow angle to the ground due to wind effect, *see Figure 85 and 86.* This implies:
  - larger flame lengths and therefore a larger quantity of fuel that is readily burning and interacting.
  - pyrolysis rates are increased when more fuel is exposed to flames.



Figures 85 and 86. **Left: Neutral flame development without wind effect.** Heat transfer through convection and radiation affects the fuel near the flame less intensely, convection is dissipated vertically and radiation is emitted above fuel height. Right: the effect of the wind inclines the flames in a lower angle, so there is less distance between flames and the fuel, and the fuels ahead of the flames receive more heat through convection (purple arrow) and radiation (yellow arrow). Source: Bombers de la Generalitat de Catalunya.

CPS field logic: The Campbell Prediction System (CPS) can be defined as a simple operational tool using the basic fire spread factors - aspect, wind and slope – as input variables to provide a logic and brief analysis for suggesting tactics based on predicted fire behaviour that are limited in space and time (time tags). The logic of the system is based on the **alignment of forces, a concept that describes how the three basic fire spread factors coincide in favour for or against the fire and how they affect the fire front**.

*Example: A fire occurring at the bottom of a south-facing slope at 12:00 hrs with a southerly wind is burning in **full alignment**: the fire can run upslope, with the wind and in hot fuel.*

*The same situation at 08:00 hrs a.m. is burning only in **2/3 alignment** (wind and slope), since at this time of day the hot slopes are the east-facing ones. When in this situation the wind changes from the north, the fire burns in 1/3 alignment (slope).*

*When the fire starts at the top of the slope, the fire is burning **out of alignment** as it has to **spread downslope against the wind** on a slope with **cold fuel**.*

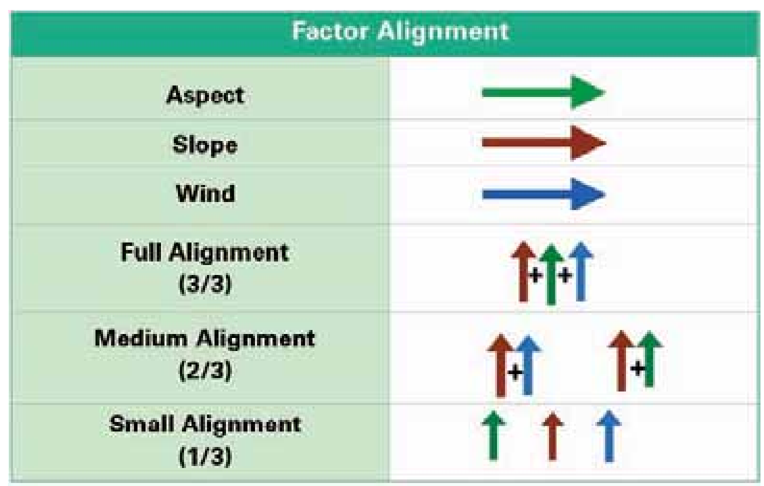
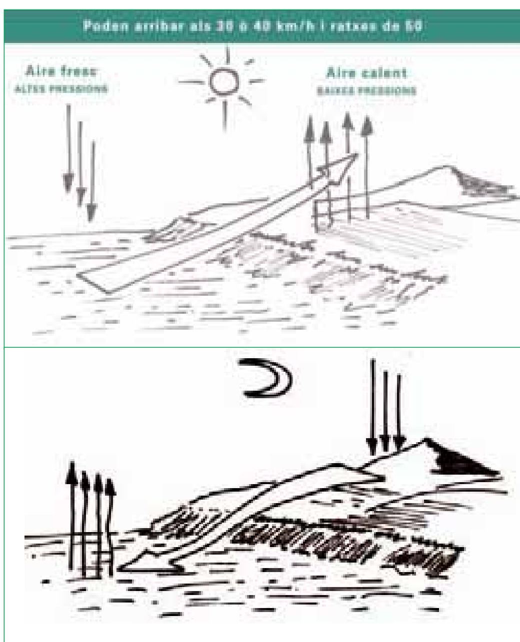


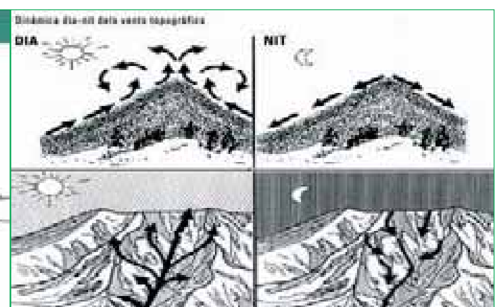
Figure 87. **Example of CPS language.** Source: Campbell, 1995[(3)].

3.a.3 Spread schemes for each Fire Type

TOPOGRAPHY FIRES

Topography fires	The potential spread of these fires is following hydrological basins along the main valley and secondary ravines. Topography fires are distinguished in **diurnal** and **nocturnal** fires, depending on when they spread.
Factors	The fire movement is dominated by three main factors: slope, local winds (sea breeze, land breeze, and valley and slope winds) and the insolation of the adjacent slopes with their specific aspect. Local winds *(figures 88, 89 and 90)* are determined by air movements generated by the solar radiation effect within the course of a day. They vary in intensity and direction in the course of a day in a routine model and are therefore predictable.
Spread pattern	This type of spread pattern is very dynamic and varies according to the disposition of the three basic spread factors, meaning that the identified position of the back, the flank and the head of a fire can vary with changes of the slope, insolation or wind direction (*figures 91 and 92*).





Figures 88, 89 and 90. **Sea breeze blows onshore along the day from the sea to inland (left).** Land breeze blows offshore at night from land to sea (centre). Valley and slope winds blow during the day from the lower to upper elevations and at night the other way (right). Source: Fire Weather. A Guide for application of meteorological information to forest fire control operations. Mark J. Schroeder.

Figures 91 and 92. **Horta Fire of 2005 (above) and Roda de Barà Fire of 2004 (below).** Examples of fires with topographic spread pattern. Source: Bombers de la Generalitat de Catalunya.

Types of Topography Fires

Standard topography fires (diurnal)
These are the most common fires because they coincide with the time period of highest risk and therefore, with the highest number of ignitions. The local winds are in this case upward winds (both valley and slope winds). Fires starting at lower parts of a basin have the biggest spread potential since they have wind and slope in favour, *see Figures 93 and 94*. On the contrary, when a fire is burning in the upper parts of a basin its spread potential is lower because of downslope and counter winds. If a fire spreads in the bottom of a ravine it develops a head on each slope with the respective flanks. The fire spread in this case is determined by the progression of the flanks upstream which give each slope the opportunity for new runs.

Figure 93. **Montmell Fire, 06/06/2006, Catalonia.** Source: Bombers de la Generalitat de Catalunya.

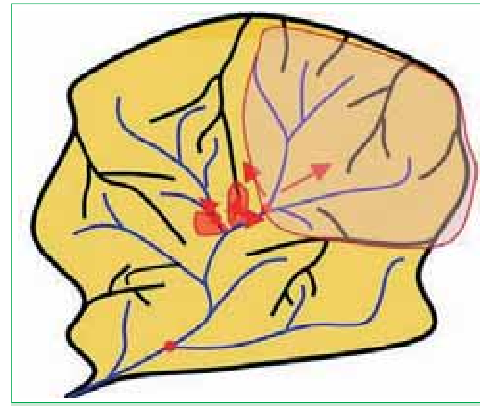


Figure 94. **The spread pattern of this diagram is designated as a spread through ravine bottom(g) and is repeated until the fire reaches the head of the valley or hydrological basin.** In case of a complex valley with lateral ramifications, this pattern is multiplied in each junction of ravines and in secondary valley confluences, extending the surface affected by the fire. Source: Bombers de la Generalitat de Catalunya.

Standard topography fires (nocturnal)
By night the wind flow is downvalley and downslope and solar radiation is not a factor. The balance between the downward wind and the topography determines the direction of the fire spread. This is the biggest difference to the diurnal topography fires where fires spread along the upper parts of the crest lines and are dissociated in two heads every time they arrive at the junction of two crest lines.

Coastal Topography Fires (Diurnal)
In the course of a day wind direction associated with the sea breeze changes. A sea breeze is a wind caused by thermal compensation between sea and land surface. Its direction changes during the day with the influence of solar radiation when the sun moves along the slopes. This phenomenon occurs whenever there is direct influence from the sea, i.e. when the land relief is not a significant barrier, *see Figures 95 and 96*.

In Catalonia, for example, the direction of the sea breeze changes from an easterly direction at the beginning of the day towards the west at the end of the afternoon, breezing from the south during noon. It is important to understand the defined and previsible rotation of the sea breeze in connection to the total local wind flow and its effects on the area burning.

Coastal Topography Fires (Nocturnal)
The spread pattern of these fires at night is similar to the one of the nocturnal standard topography fires: the flow of valley and slope winds is descending and solar radiation is not a factor.

The balance of forces between the descending wind and the topography determines the direction of fire spread.

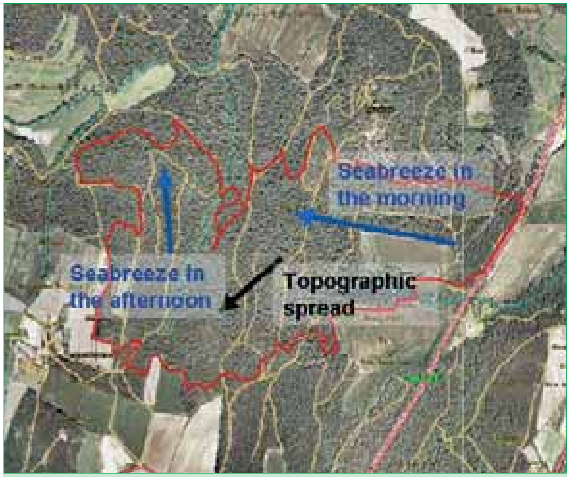


Figure 95. **Banyoles Fire 2003.** The fire was driven by the rotation of the seabreeze that produced different runs. Source: Bombers de la Generalitat de Catalunya.

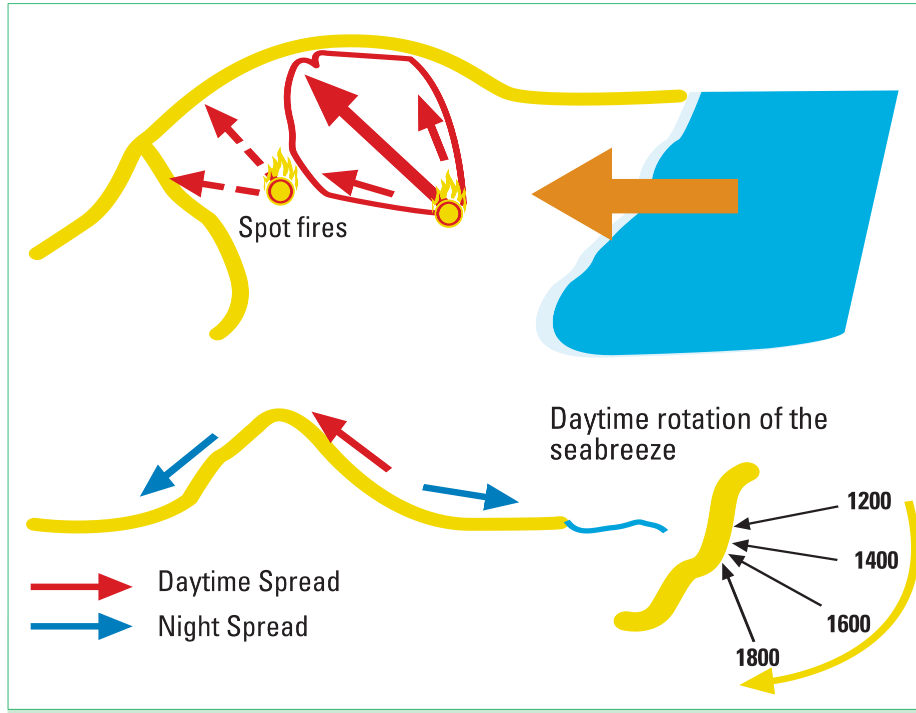


Figure 96. **Spread scheme of a topography fire on slopes in coastal areas.** Source: Bombers de la Generalitat de Catalunya.

Topographic fires in main valleys and canyons (Diurnal)

The main valleys of important hydrographical basins have a more intense local wind regime and a greater air volume flow than in secondary valleys. The phenomenon of the movement of large air volumes with greater intensity than the surrounding air where valleys are narrowing, generates underpressure and the suction of surrounding air towards this area (venturi effect). Therefore, fires burning in secondary valleys close to a main valley tend to converge towards the air flow of the main valley. Fires occurring on slopes in narrow valleys typically have a spread scheme similar to the one of main valleys. The wind speed in canyons increases and can suck the fire into its interior, thereby creating fire runs in the canyon and an extention of the front at the opposed exit of the canyon. The zones not influenced by the canyon winds are affected by general and topographic wind, thereby increasing the perimeter of the fire, see *Figures 97-100.*

Topographic fires in main valleys and canyons (Nocturnal)

The flow of valley and slope winds is decreasing and insolation is not a factor by night. The balance between the downward wind and the topography will determine the direction of the fire spread. The descending valley winds dominate the descending slope winds.

Consequently, the perimeters of nocturnal topography fires tend to spread their flanks following the direction of the main valley.

In extreme cases (e.g. near canyons close to main valleys), the descending valley wind is the only factor dominating the fire spread and head fires are running in the direction of the canyon or in parallel direction to the main valley without respecting the topography.

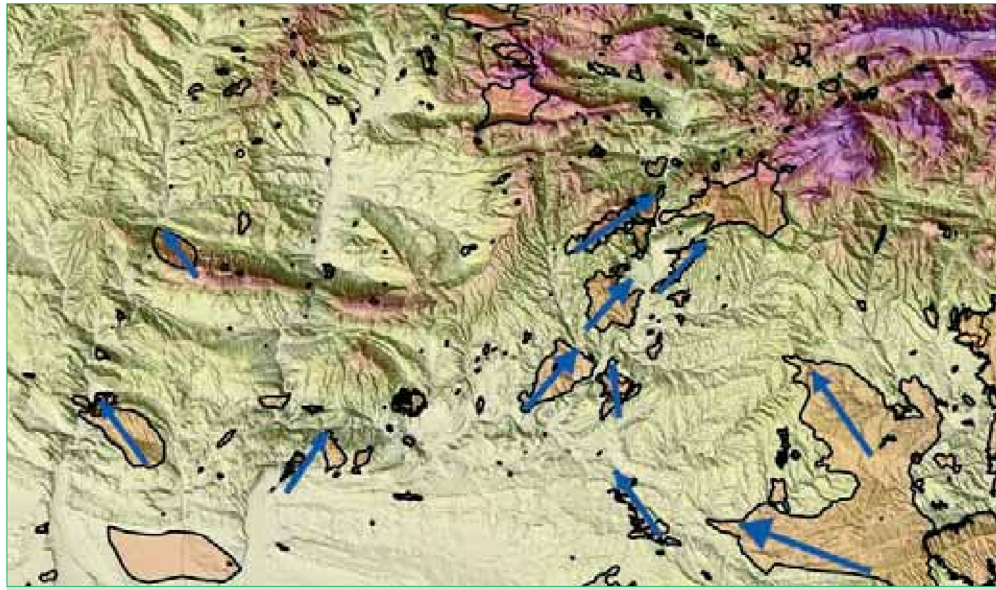


Figure 97. **Fire perimeters affected by air suction through the main valley of the Segre River, Catalonia.** Source: Bombers de la Generalitat de Catalunya.

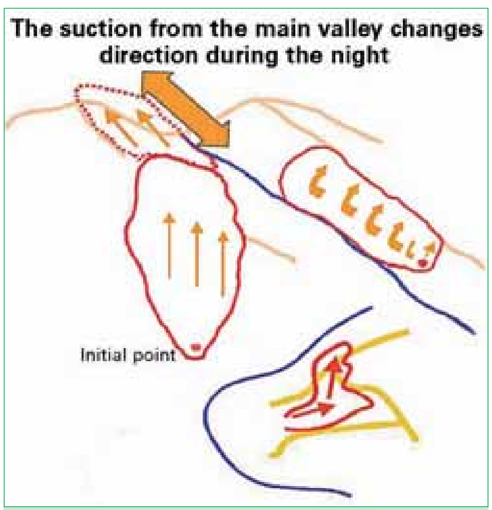


Figure 98. **Spread scheme of a topography fire with air suction through the main valley.** Source: Bombers de la Generalitat de Catalunya.

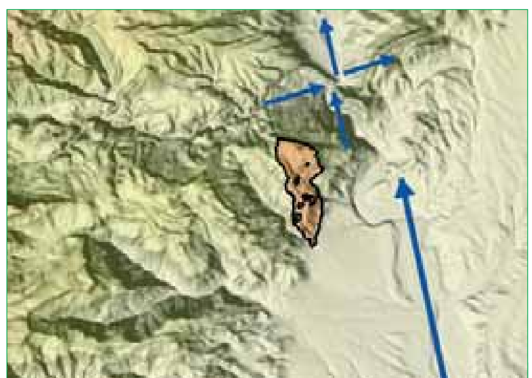


Figure 99. **Alcover Fire 2003.** The image of the perimeter shows the tendency of the fire to be sucked towards the interior of the canyon. Source: Bombers de la Generalitat de Catalunya.

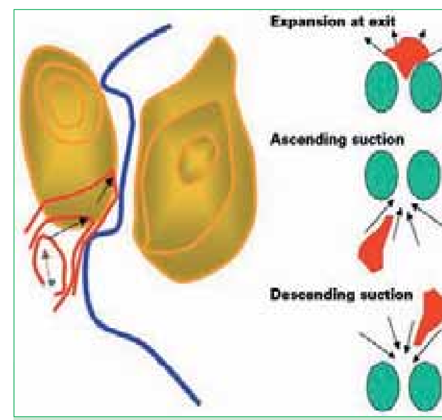


Figure 100. **Spread scheme of a topography fire typical for canyons.** Source: Bombers de la Generalitat de Catalunya.

WIND-DRIVEN FIRES

Wind-driven fires	The potential of wind-driven fires is determined by the interaction of wind with the relief and by availability of fuels. A fire front driven by wind always is spreading in the areas with maximum wind speed, following the behaviour of a continuous fluid. When wind is in favour of the fire runs, the fire easily overcomes the suppression capacity.
Factors	The fire spread is dominated by two principal factors: wind speed, *figure 102*, and rate of flame spread, which is higher than the rate of suppression progress through hose lines. The spread pattern of wind-driven fires is predictable when the wind spread over the relief is known. Smoke is the main indicator of this interaction and gives evidence of strength and direction of the wind and where wind breaks promote a fast rate of spread, *see figure 101*.
Spread pattern	A fire spread pattern with long distance spotting frequently happens when the burning fuel is coarse and maintains an extended flaming phase during a few minutes. Spotting distances from 500 to 1,000 meters are common with wind speeds of 60 km/h burning in mature tree stands, *see figures 103, 104 and 105*.

Figure 101. **Escala Fire 2001.** The zone where the smoke column comes down is affected by spot fires. Source: Bombers de la Generalitat de Catalunya.

Figure 102. **Bonastre Fire 2009.** Fire with wind speed of 140 Km/h. Flames are inclined to the surface. Source: Bombers de la Generalitat de Catalunya.

Figure 103. **Wind-driven fire in Espluga de Francolí 24/06/2006.** The red star indicates the starting point of the main fire run and the yellow points the spot fires. Source: Cos d'Agents Rurals.

Figures 104 and 105. **Example of two wind-driven fires.** Typical for these fires are smoke columns inclined towards the surface and long and outstretched perimeters. Ventalló Fire, 04/08/2006 (left) and Capmany Fire, 06/08/2006 (right). Source: Bombers de la Generalitat de Catalunya.

Types of wind-driven fires

Wind-driven fires in level terrain

In level terrain and plains wind-driven fires follow the wind direction and are opening with an angle between 30° and 60° depending on the strength of the wind, *see Figures 106 and 107*. In the initial phase of a fire the flanks are opening and generate new runs while at the same time the wind prevents the back of the fire from spreading.

Figure 106. **Ossó i Selvanera Fire 2003.** The red arrow indicates the spread direction of the fire. Source: Bombers de la Generalitat de Catalunya.

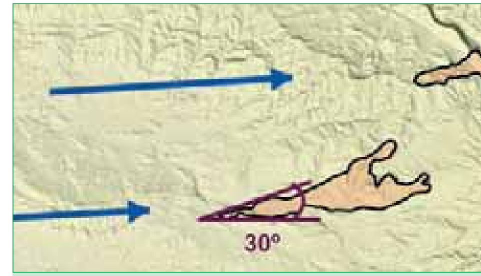


Figure 107. **Ossó i Selvanera Fire.** Perimeter opening at 30° and main runs following the direction of the wind. Source: Bombers de la Generalitat de Catalunya.

Wind driven fires in mountainous terrain

Mountain ranges parallel to wind direction

The head fire is spreading along the ridges of the mountain ranges in alignment with the wind direction, usually affecting both slopes, *see Figure 108*.

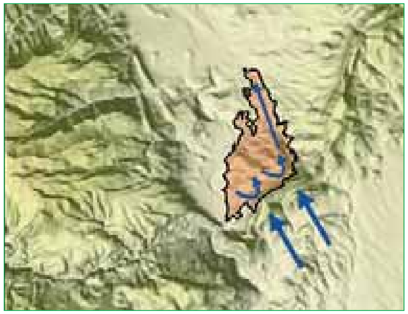
Opportunities are at the end of the water divide, or where the mountain ranges have a change in aspect, at a bifurcation or when backwinds occur.

Figure 108. **Cap de Creus Fire 2000.** The perimeter follows the mountain ranges parallel to the prevailing winds. Source: Bombers de la Generalitat de Catalunya.

Mountain ranges perpendicular to wind direction

A mountain range perpendicular to the main wind direction produces turbulent winds. Since the wind takes the shortest way to overcome the mountain range, these zones can produce sudden changes of the wind flux, remaining almost without wind (leeward) or even generating local fluxes against the dominant direction (backwinds). The occurrence of leeward or counter winds depends on the height of the mountain range which is perpendicular to the wind, the wind speed and the main wind channels on macro scale. In high relief the wind escapes along the lower elevations while in inverted and complex relief the wind escapes over the upper elevations, *see Figures 109-112.*

Figures 109 and 110. **Coll de Nargó Fire, 29/12/2004.** Left: Point of origin (red star), direction of the general wind (blue arrow), ridge axes perpendicular to main wind direction (black arrow), backwinds (blue circles). Right: Fire affected by backwinds at night. Source: Bombers de la Generalitat de Catalunya.



Figures 111 and 112. **La Riba Fire 2002.** Left: Spread pattern and perimeter of the fire. Right: smoke column pushed upward by the general wind and then broken by backwind effects. Source: Bombers de la Generalitat de Catalunya**.**

Mountain ranges diagonal to wind direction

The interaction of mountain ranges diagonal to the main wind direction produces a distinct spread scheme, burning either with the main wind in favour (direct) or against it (indirect). Diagonal mountain ranges and turbulent wind zones produce fire runs that spread differently from the main wind direction and create difficult situations for specific direct attack operations, *see Figures 113, 114 and 115*.

Figures 113 and 114. **Montgrí Fire 26/09/2008.** Left: Point of origin (red star), main wind direction (blue arrow), fire perimeter (red line), mountain range diagonal to the wind direction (purple line). Right: The general wind restrains the left flank and prevents it from descending downslope (green line). Source: Bombers de la Generalitat de Catalunya.

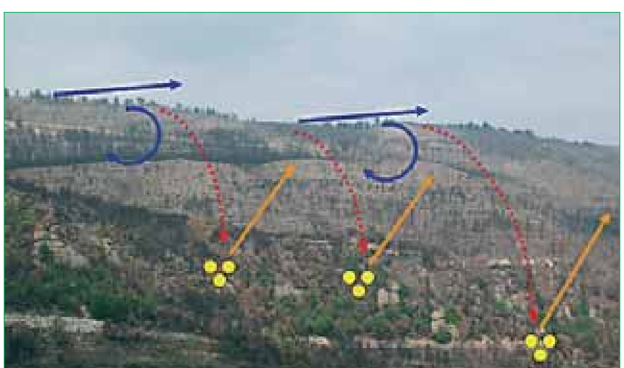
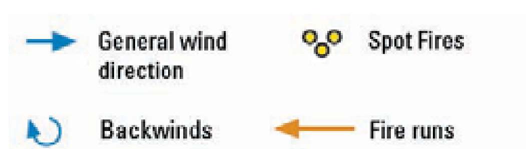


Figure 115. **Fire spread through backwinds.** Fire runs are generated through backwinds and arrive on top of the mountain range where the general wind launches spot fires downwards, generating new runs upwards by the backwinds. Source: Bombers de la Generalitat de Catalunya.



Wind-driven fires with subsidence

This phenomenon occurs in coastal mountain ranges in the extreme south of Catalonia when diurnal topographic winds have the capacity to compensate high altitude northerly wind. At night the northerly winds are descending on the surface being reinforced by the also descending topographic winds. During daytime the fire behaves like a standard topographic fire and like a wind-driven fire at night time. This dynamic fire behaviour implies that the back of the fire during the day can transform into the head of the fire at night and vice versa. *See Figures 116, 117 and 118*.

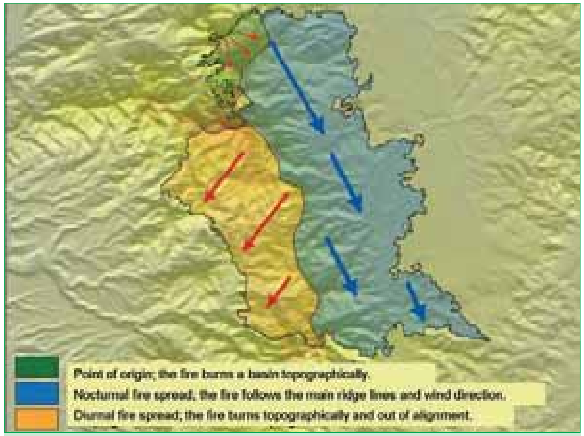


Figure 116. **Cardó Fire, 1995.** When the fire started (green) it followed a topographic spread pattern during the day. After that the fire burned the whole night (blue) until the afternoon of the following day with its spread totally dominated by the subsidence winds, when it arrived at an area that had burned before in 1993. The following days, the fire burned out of alignment, spreading topographically (orange) into a zone with difficult access where the use of hand tools was restricted. Source: Bombers Generalitat.

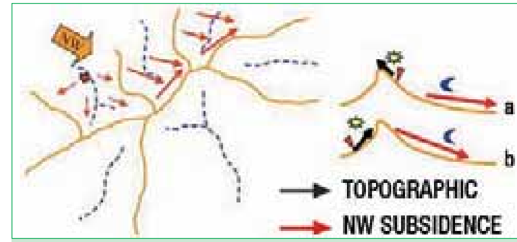


Figure 117. **Spread scheme with subsidence winds.** Extention of the back fire (a). Extention of the head fire (b). Source: Bombers de la Generalitat de Catalunya.

Figure 118. **Xert Fire, 2001.** Wind-driven fire with subsidence. Source: Bombers de la Generalitat de Catalunya.

CONVECTION DOMINATED FIRES

Convection dominated fires	These are fires associated to synoptic weather episodes characterized by low relative humidity without overnight recovery and high temperatures. The wind has little direct impact on the fire spread, however, it determines the direction of spot fires and therefore the spread direction, *see figures 119 and 120*.
Factors	The fires are characterized by two main factors: spot fires, *figure 121*, and the fire environment [a]. The availability of fuels is high and allows the head fire to advance by massive spotting. The spot fires are interacting amongst themselves and with the main fire front, thereby creating new combustion zones that again generate new spot fires in the direction of the general wind. This spread pattern causes the fire front to advance in pulses. The spotting distance is determined by the convective capacity of the combustion and the intensity of the general wind. Fire environment: Environmental conditions created and directly influenced by the fire. When a fire has built up sufficiently in extension and intensity, it creates its own fire environment by modifying its environmental conditions (rise of air temperature, decrease of relative humidity and, above all, the formation of convective winds generated through suction). The fire environment and its fire behaviour are closely correlated, *see figure 122*. Not all fires are able to create their own fire environment, only those with high intensities.
Spread pattern	The spread area of these fires is determined by the macro-topography (basins of first order and main mountain ranges), general south or west winds, wind channels along river valleys of first order, or exit channels in the case of west winds.

Figures 119 and 120. **Cardona Fire, 08/07/2005.** Source: Bombers de la Generalitat de Catalunya.

Figure 121. **Margalef Fire 2005.** Interaction between spot fires and their suction by the main fire front. Source: Bombers de la Generalitat de Catalunya.

Figure 122. **Castellnou de Bages Fire 18/07/2005.** High intensity fire creating its own fire environment. Source: Bombers de la Generalitat de Catalunya.

TYPES OF CONVECTION DOMINATED FIRES

Standard Convection Dominated Fires

Fires with an extreme fire behaviour and headfires overcoming the suppression capacity because of:

- high rates of spread (rate of linear fire spread up to 6 km/ hr).
- high fire intensity (flame lengths more than 60 mtrs).
- the surface affected (fires can consume 500 ha/ hr).

The spotting distance can range from 500 to 2000 meters, even though larger distances may have been unregistered. In this context topography does not directly produce changes in the fire behaviour (like in the case of topographic fires) because the fire is able to jump from one valley to another without having to cross valleys and slopes to keep spreading. General meteorological conditions have little impact once the fire environment is established.

The smoke column often shows the tendency to go in north direction and can only be influenced by air masses following the main river valleys. *See Topography Fires in Main Valleys and Canyons, p. 67.*

Convection dominated fires with wind

This Fire Type displays a convection dominated fire behaviour, but with the wind affecting its spread velocity. The wind increases the spotting distance, creating new ignition points out of the influence zone of the convective column and accelerating the general spread of the fire. The tendency of the smoke column follows the main wind direction while the fire is burning big topographic basins and spotting is determining the main direction of the fire spread. *See Figures 123 and 124.*

Convection dominated fires producing pyrocumulus clouds

Some convection dominated fires allow the formation of pyrocumulus clouds in the upper parts of the convective column. This phenomenon is only possible when stable and cold air masses dominate the high altitudes. These act like a tap for the vertical development of the column, which condensates once it reaches these air masses forming the typical mushroom form of a pyrocumulus cloud, *Figures 125 and 126*. Once the pyrocumulus condensates it starts gaining weight until it collapses. This happens when the fuels are almost entirely consumed and the temperatures of the convective column start sinking, or when the air masses acquired by the pyrocumulus exceed their sustaining capacity. The collapse of the pyrocumulus as a cold and condensed cloud leads to the descent of cold air along the exterior of the column, thereby generating massive spotting and an extention of the fire in all directions. This is a dangerous phenomenon because of the possibility of trappings during the collapse due to the sudden extention of the fire. By knowing and identifying the evolution of a pyrocumulus cloud those situations can be avoided.

Figure 123. **Gualba Fire 1994.** The perimeter shows the general tendency of the fire, dominated by the general west winds. Source: Bombers de la Generalitat de Catalunya.

Figure 124. **Castellnou de Bages Fire 2005.** The inclination of the convective column indicates the wind direction. Source: Bombers de la Generalitat de Catalunya.

Figure 125. **Cardona Fire 2005.** Convective column. Source: Bombers de la Generalitat de Catalunya.

Figure 126. **Cardona Fire 2005.** *Pyrocumulus plume* in high altitudes during its formation process. Source: Bombers de la Generalitat de Catalunya.

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2. *AGEE, J. K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press. 493 p.*
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3.b Proposed treatments for each fire spread type

Characterising the Fire Types of a region allows to identify the operational opportunities for the suppression systems during a large wildfire in a specific mountain range through identifying the key points where infrastructures need to be created or maintained to limit the extent of large wildfires.

These points may resemble suppression opportunities, and are called **Strategic Management Points (SMPs)**.

3.b.1 Identification of Strategic Management Points (SMPs)

Identifying where fire behaviour will change in favour of or against the suppression service is the basis for determining the priority areas for fuel treatments and for preparing preventive infrastructures.

The priority SMPs to be identified and treated are those where fire behaviour not only overcomes suppression capacity but also pushes the organisation of suppression systems to the limit.

Fire simulators and GIS tools as support

The identification of SMPs can be backed up in some cases by the use of Geographic Information Systems (GIS) tools and fire simulators, particularly those based on minimum travel time to locate opportunities[(1)].

There are mainly 3 objectives for which simulators can be used as a tool to support this methodology:

- modelling fire behaviour in backwind zones.
- modelling fire behaviour with spotting activity.
- modelling changes in fire spread dynamics.

3.b.2 Creating Strategic Management Points

A series of management activities is associated with each SMP: fuel treatments to influence fire behaviour or to ensure safe operations, as well as creation of infrastructures, such as control or defence lines, and passing points on forest roads.

The proposed forest management and prevention measures can be used to achieve the objectives set for a SMP in terms of managing and suppresing large wildfires.

Objectives of Strategic Management Points:

The planning of strategic zones for fuel treatments is based on different objectives:

- Limit wildfire activity.
  - Limit the multiplying effect of frontal fire spread.
  - Limit the intensity of fire spread through spotting.
  - Prevent crown fires in stratified mature tree stands.
  - Reduce continuity of shrub layers to reduce flame lengths.

- Confine ignition.
  - Facilitate anchor points at back and flanks.
  - Facilitate the anchoring of technical firing operations.
  - Management of fire causes.
  - Protection of vulnerable points.

- Facilitate access.
  - Ensure vehicle access and placement in safe areas.
  - Ensure access to very long flanks.

To meet these objectives it is necessary to know the type of fire behaviour that can maintain the forest structure of an SMP, e.g. *Figure 128*, depending on the respective Fire Type for planning. It is therefore necessary to categorise fire behaviour, *Figure 127*, and relate it to stand structure.

Figure 127. **Example of a qualitative classification of fire behaviour according to the Catalan Fire Service in a series of five images:** low-, medium- and high-intensity surface fires, passive crown fire with torching, and active crown fire. Source: Bombers de la Generalitat de Catalunya.

Active forest management allows to increase or reduce fuel loads, and to control spatial arrangement and fuel availability through changes in stand structure. Forest management therefore significantly contributes to change fire behaviour to the desired level (below the limit of suppression capacity) according to the established model fire and the determined fuel availability scenario.

Figure 128. **Example of a SMP in the northeastern foothills of the Prades mountains.** Location: Municipality of Montblanc, Catalonia. Arrangement and re-opening of the road to improve access to the mountain range (1). Zones with reduced fuel load at ravine intersections to avoid the opening and bifurcation of fires towards surrounding valleys (2 and 4).Creation of a supporting control line along the road to confine possible ignitions and as anchoring zone for operations of suppression resources (3). Source: Bombers de la Generalitat de Catalunya.

3.b.3 Proposed treatments for each fire spread type

The Fire Types concept is broadly based on the main types of fire spread patterns (wind-driven, topographic and convection dominated fires). For every spread type there are common recommendations as well as specific ones for the respective Fire Types such as wind-driven fires with subsidence or coastal topographic fires.

In the following, the most usual general guidelines are described that are essential for an optimal forest management and the prevention and suppression of fires.

Topography fires	
Strategy to limit fire spread	1. Direct[j] or parallel[k] attack to the back and the flanks to avoid unfavourable alignment (at the bottom or junction of ravines). The back and the flanks often remain within the suppression capacity.
	2. Indirect[l] attack at the head fire to limit the spread potential through spotting under conditions of unfavourable alignment.
	3. Wait until there is favourable alignment to attack the head fire, back or flanks. When a fire is spreading inside a ravine and affects both slopes, two heads and four flanks are the result, with the bottom of the ravine as the common denominator. This is the place from where back and flanks spread, allowing repeated runs from the head. In this case a new strategic factor is established.
	4. Limit the spread from the bottom of the ravine through a direct or parallel attack to the flanks (upstream). When the spread from the bottom of the ravine is near the junction of different secondary ravines (called node of ravines), the fire has the opportunity to increase its potential enormously repeating the same spread pattern in more than one ravine at the same time.
Access	<u>Access roads for operations</u>: - at least secondary tracks[m] from the bottom of ravines that preferably cross the bottom of the valley with safety zones every 1,000 m and the zones of ravine intersections.- at least secondary tracks at the bottom of ravines that preferably transit the north and east slopes with safety zones every 700 m.
	<u>Transit roads</u>: - at least secondary roads with security zones every 1,000 m that allow the transit of resources, following more or less parallel to the crest lines and avoiding the most exposed slopes.
Operations	- <u>Critical points with multiplying effects on fire spread or Trigger pints</u> [i]: fuel treatment in zones located in the nodes of ravines in order to avoid that fires burn new slopes and basins. This operation guarantees that fire spreads on the surface and can be attacked with hose lines or contained with hand tools. The zone must allow safe position of the ground crews.
	- <u>Limit fire intensity:</u> reduce spotting distance along the upper parts of ridges through reduction of coarse dry fuel classes (10 and 100 hr).
	<u>- Confine ignition:</u> Facilitate anchor points along the flanks: fuel treatments in zones located between the bottom of the ravine and the ridge approaching the flank in a positive diagonal angle to facilitate its suppression. To assure effectiveness this treatment must be completed in a zone at the ravine intersection. Facilitate access: create trails to enable ground crews to move between the hydrological basins with safety zones every 700 meters; preferably avoiding south and west ridges to prevent the tracks from being situated in areas where the fire can spread in full alignment. Trails parallel to the ridge should keep a certain distance to the ridge to minimize the effects of radiation and convection by a fire burning in the adjacent basin.

Wind-driven fires	
Strategy to limit fire spread	1. Direct attack from the back to the head fire. The back and the flanks often remain within suppression capacity.
	2. Stop or confine the head when it burns with the wind in favour and attack it when it loses alignment.
	3. A parallel attack approach (burning out operation) is useful for fire behaviour on flanks and back of the fire where the wind facilitates this operation. It is essential to burn from the head to the back, or, in any case, against the prevailing wind direction, *see figure 131.*
	4. Fire use in indirect attack (backfiring) is a complicated task because the wind as the driving factor determines the operational window (time and location) and limits the intensity of the backfire aimed to straighten up the smoke column. It is also difficult to redirect the head of a fire since the interaction of the fire fronts is limited by the wind.
Access	• <u>Access roads for operations:</u> - at least secondary tracks from the end of ridge lines, along the lower limits of the influence zone of counterwinds. - tracks parallel to the main ridge line and converging towards the end of the ridge line for access to the flanks from the lower part or, from the head (end of the ridge line) to move towards the back, slowly descending and with distance from the flanks, with safety zones every 700m.
Operations	1. <u>Direction of progress and access</u>: - Direct attack from the back to the head, flanking operations. - Parallel attack from the head to the back, against the wind direction.
	- <u>Critical points with multiplying effects on fire spread</u>: keep opportunities for operations in leeward and counterwind zones, at the end of crest lines or before they junction, *See Figure 129.*
	- <u>Limit fire intensity:</u> reduce spotting distance along the upper parts of ridges through reduction of coarse dry fuel classes (10 and 100 hr).
	- <u>Confine ignition:</u> facilitate anchoring along the flanks in a positive diagonal angle to wind direction along the slope.

Figure 129. **Prescribed burn at Coll de Valleta, 17/03/2005, to create zones of reduced fuel loads in the upper parts of the slopes, susceptible to sending or receiving spot fires.** Source: Bombers de la Generalitat de Catalunya.

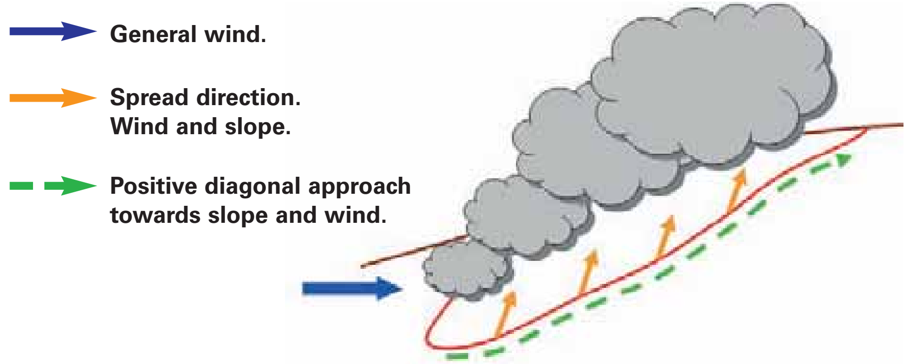


Figure 130. **Positive diagonal approach towards slope and wind.** Smoke and flames do not pass the advancing fire line. Source: Bombers de la Generalitat de Catalunya.

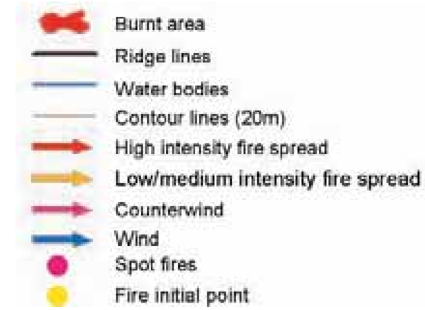
Convection dominated fires	
Strategy to limit fire spread	1. Direct or parallel attack at the back and the flanks to limit opening and to prevent new runs in direction of the head, thereby avoiding that the width of the fire front increases.
	2. Break the dynamics of the advancing head through spotting by indirect attack, wait for or generate discontinuities in the front line wider than the spotting distance with parallel attack.
	3. Attack the head to stabilize it where it loses alignment or is becoming a flank due to the effect of indirect attack.
	4. Wait for a change in weather conditions.
Access	Access roads for operations: - at least secondary tracks at leeward sides of fire front that cross perpendicular to main spread axis for indirect attack operations and at leeward sides of a ridge with sufficient distance to enable effective backfiring operations (generally north and east slopes). A supporting control line of 10 m is required on both sides as well as safety zones every 500 m. - at least secondary tracks at leeward sides of fire front that cross perpendicular to main spread axis for indirect attack operations and at leeward sides of a ridge with sufficient distance to enable effective backfiring operations (generally north and east slopes). A supporting control line of 10 m is required on both sides as well as safety zones every 500 m.
	Transit roads: tracks that enable movement of ground crews in south-north and west-east direction with safety zones every 1,000 m; avoiding preferably south and west slopes to prevent full alignment of forces[n]. Tracks parallel to ridge line should maintain a certain distance to ridge top to minimize the effects of radiation and convection of fires burning in the adjacent basin.
Operations	- Critical points with multiplying effects on fire spread: fuel treatments in zones located in the nodes of ravines in order to avoid that fires burn new slopes and basins. This operation guarantees that fire spreads on the surface and can be attacked with hose lines or contained with hand tools. The zone must allow safe position of the ground crews. Give priority to treatments at ravine junctions of major order as well as zones located at the bottom of ravines perpendicular to the main spread axis to contain spot fires and descending fronts.
	Limit fire intensity: reduce spotting distance along the upper parts of ridges through reduction of coarse dry fuel classes (10 and 100 hr); give priority to slopes in full alignment with the winds dominating this type of fire. In the case of Catalonia these are slopes with south and west aspect.
	Confine ignition: facilitate anchor points along the flanks: fuel treatments in zones located between the bottom of the ravine and the ridge approaching the flank in a positive diagonal angle to facilitate its suppression. To assure effectiveness this treatment must be completed in a zone at the ravine intersection. *See figure 130.*

Figure 131. **Alcover Fire 5/08/2003.** Use of the road (red) as anchoring line for parallel attack (yellow) to confine and define the flank. Safety zones in blue. Source: Bombers de la Generalitat de Catalunya.

Figure 132. **Prades mountains.** Secondary track parallel to the ridge line and strip of low fuel load along the ridge line. Source: Bombers de la Generalitat de Catalunya.

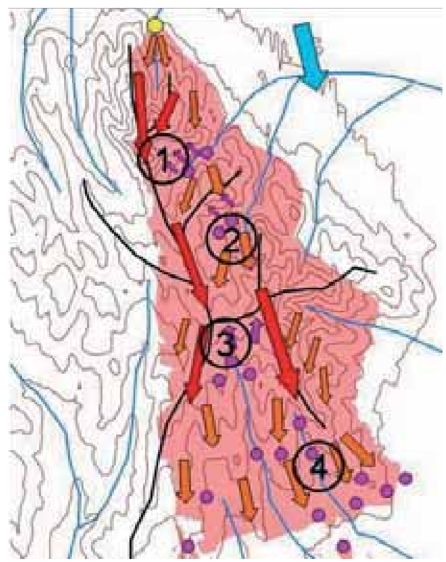
3.b.4 Validation of pre-defined opportunities

In the following remarkable operational aspects, fire behaviour observations and principal suppression opportunities are described, both success stories as well as failures, as a necessary process to validate opportunities during large wildfires.



VALIDATION OF PREDEFINED OPPORTUNITIES IN WIND-DRIVEN FIRES IN LEVEL TERRAIN

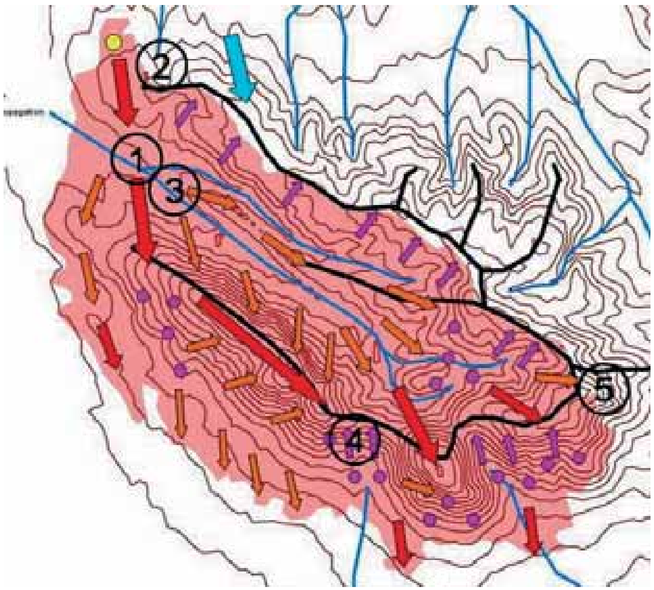
Ventalló Fire, 1011 ha, 04/08/2006



Initial strategy: **KEEP FLANKS CLOSED** to prevent them from opening.
Opportunity 1: BACKWIND: the head of the fire reaches the narrowing main ridge lines, with a local backwind effect on the slope. This opportunity allows to constrict the fire front, but spot fires escape the influence zone of the back-wind onto the other slope, burning now with the general wind in favour.
Opportunity 2: BACKWIND: similar to 1 but with a less pronounced backwind effect; the width of the valley allows to work on the descending flank, but the lack of access and visibility hamper the action.
Opportunity 3: CHANGE OF ALIGNMENT OF RIDGE LINE: a ridge line junction opens the front when arriving on the least aligned ridge line. From there the fire begins to slow down, but spotting activity and the opening head along several ridge lines widen the front.
Opportunity 4: END OF RIDGE LINE: a break in fuel continuity in the forest-farmland mosaic allows to attack the various spot fires and limit their spread.

VALIDATION OF PREDEFINED OPPORTUNITIES IN WIND-DRIVEN FIRES IN MOUNTAINOUS TERRAIN

Montgrí Fire, 671 ha, 26/09/2004



Initial strategy: **KEEP FLANKS CLOSED** to prevent them from opening and **CONFINE** the fire to the two mountain ridges.

Opportunity 1: CLOSE OFF THE HEAD BEFORE IT REACHES THE SECOND RIDGE LINE: there is an opportunity - although a very slight one because of fuel continuity - to stop the head before it enters the wind dynamic of the ridge. The flanks can be closed, but the head escapes and affects the ascending slope with the wind in favour. The other flank also opens rapidly.

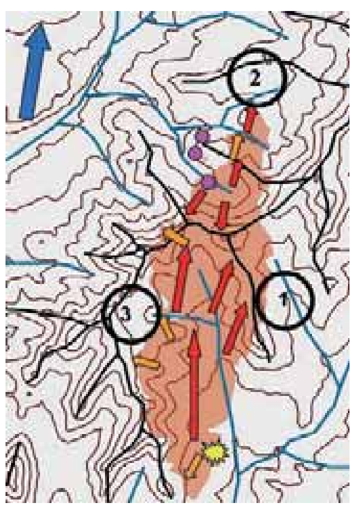
Opportunity 2: CLOSE THE LEFT FLANK BEFORE IT REACHES THE OPPOSITE SLOPE: operation to prevent the left flank from reforming and making new runs in alignment with the secondary ridge line.

Opportunity 3: BACKWIND: The left flank opens because of the effect of the valley diagonal to wind direction, which channels part of the wind. Small backwinds are generated, pushing the flank inside.

Opportunity 4: BACKWIND: a pass between two aligned ridge lines; the slowing down of the fire spread and the backwinds have the effect that the progress of the suppression teams is equal to fire spread, but terrain, fuel continuity and smoke hamper the operation.

Opportunity 5: RIDGE LINE JUNCTION: Ridge line junction: bifurcation of the secondary ridge line; the fire arrives there with the backwind from the main ridge and its further spread is limited at the point where its rate of spread is lowest.

VALIDATION OF PREDEFINED OPPORTUNITIES IN TOPOGRAPHIC FIRES



Sallent Fire, 134 ha, 12/07/2007

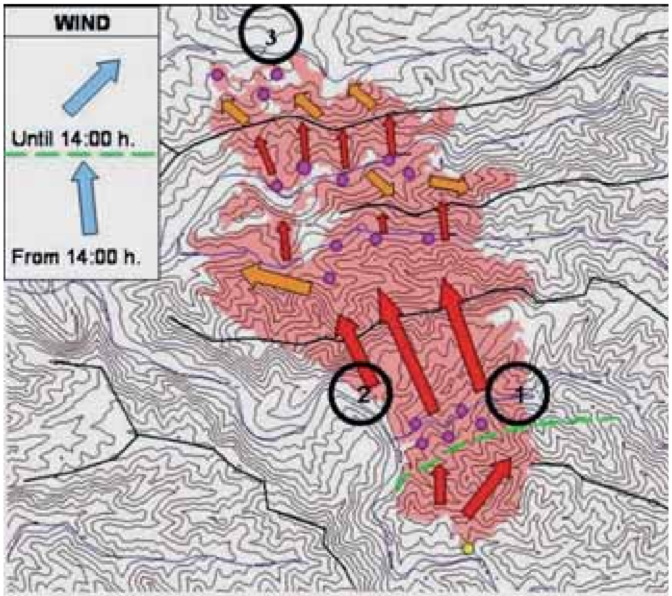
Initial strategy: **CLOSE FLANKS** particularly the **RIGHT FLANK** before it reaches the torrent to the east.

Opportunity 1: PLOUGHED FIELDS. A torrent to the east with ploughed fields in the valley bottom. This opportunity is taken to close 2/3 of the right flank in these fields, preventing it from opening up on the fully aligned slopes.

Opportunity 2: LOSS OF ALIGNMENT AND PLOUGHED FIELDS TO STABILISE THE HEAD. Spotting occurs to the north from runs from the upper part of the first basin. An increasing proportion of fields allows to narrow the head between ploughed fields and a burning out operation that is anchored at a forest road.

Opportunity 3: PLOUGHED FIELDS AND LOSS OF ALIGNMENT TO CLOSE THE LEFT FLANK. The water-based resources progress rapidly with the support of aerial means to zones with small alignment and anchor points in ploughed fields.

VALIDATION OF PREDEFINED OPPORTUNITIES IN CONVECTION DOMINATED FIRES WITHOUT WIND



Rocafort Fire, 869 ha, 19/07/2005

Initial strategy: **ANCHOR BACK AND CLOSE LEFT FLANK** to prevent it from opening.

Opportunity 1: LEFT FLANK MOVES OUT OF ALIGNMENT and begins descent towards the ravine to the north. A change in general wind direction affects fire behaviour, although wind speed remains low, with spot fires crossing a ravine and runs in full alignment.

Opportunity 2: THE NEW LEFT FLANK LOSES ALIGNMENT and can be anchored in discontinuities in the main ravine bottom, preventing it from opening up on the next slope. A quarry and small fields reaching from the back to the most northerly part can be used to anchor the flank.

Opportunity 3: A PATCH-MOSAIC OF FIELDS allows to confine the spot fires with burning out operations, stabilising the head. Up to there the fire was capable of crossing all ravine bottoms with spot fires, offering no opportunities for burn outs or backfires. On the previous ridge a backfire is used to slow down fire spread for 1 hour and limit the fire's spotting potential.

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FORESTRY SUPPLIERS, INC

Glossary

- **a** Fire environment
- **b** Time Lag
- **c** Prescribed Burning
- **d** Passive suppression
- **e** Active suppression
- **f** Preheating process
- **g** Spread through ravine bottom
- **h** Backwinds or leewinds
- **i** Trigger points
- **j** Direct attack
- **k** Parallel attack
- **l** Indirect attack
- **m** Classification of forest roads and tracks
- **n** Alignment of forces

Glossary

a) Fire environment

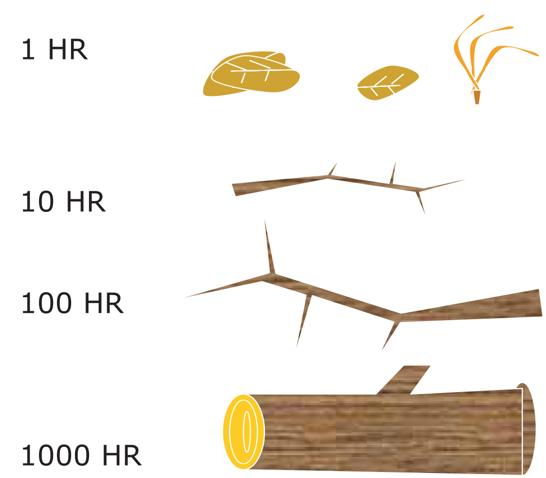
Environmental conditions generated through the fire itself and directly influenced by it. When a fire has built up sufficiently in extension and intensity, it creates its own fire environment, thereby modifying the meteorological components (rise of temperature, decrease of relative humidity and, above all, the formation of a convective column through fire suction). The fire environment and its behaviour are closely related parameters. However, not every fire is able to create its own fire environment, only those with high intensities.

b) Time Lag

Time lag is the time dead fuels need to reach equilibrium of their moisture content with the surrounding relative humidity. This parameter is measured in hours and depends mostly on the form and size of the fuel.

There exist fuels of:

- *1 hr (diameter < 6 mm), e.g. herbs, needles and leaves;*
- *10 hr (6 mm – 2.5 cm), like small branches;*
- *100 hr (2.5 – 7.5 cm), thicker branches;*
- *1000 hr (7.5 –20 cm) like logs and tree trunks.*



c) Prescribed Burning

Careful and planned application of fire under specified fuel and weather conditions to meet specific resource management objectives and long-term management goals.

d) Passive suppression

Treatment of defined points/zones in the landscape, be it with prescribed fire, silvicultural treatments or other methods with the objective of preparing the suppression of fires based on the capacities of the suppression system.

e) Active suppression

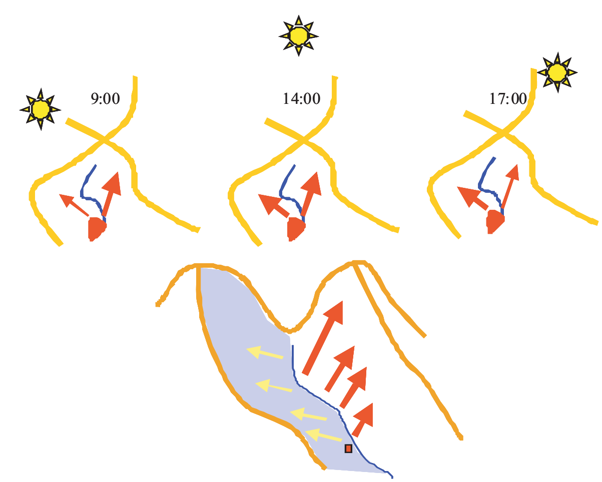
Operations carried out in the instant of a fire, with the objective of suppressing the fire or modifying fire behaviour. These include direct, parallel and indirect attack.

f) Preheating process

Phase in the combustion process. The temperature rise, close to the water boiling point, leads to predrying of the fuel, releasing gases of low flammability like water steam. With continuous increase of the temperature the drying process advances to the interior of the fuel particle.

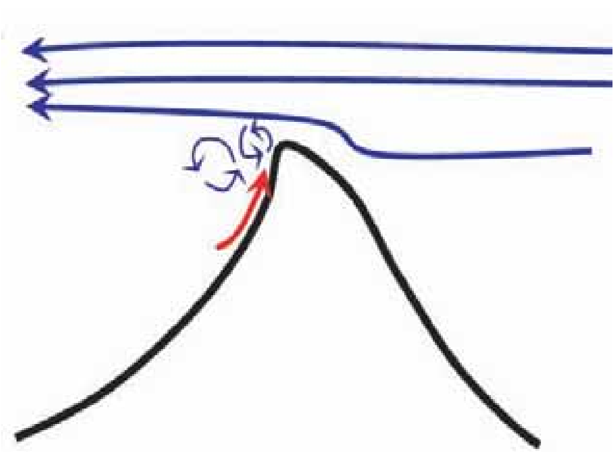
g) Spread through ravine bottom

Fires that spread topographically following the hottest slopes. The most important spread variable is the time of day which determines the heating of the slopes and therefore where the fire can reach the highest intensity. The dynamic of local and sea/ terrestrial winds will affect the fire behaviour being able to convert the back of a fire into its head.



h) Backwinds

Backwinds or leewinds are wind currents contrary to the direction of the general wind, originating in the turbulences developing in leeward slopes through friction of the general wind at abrupt mountain ranges perpendicular to it.



i) Trigger points

Points in the landscape where fire behaviour and fire potential will change. From this point fire behavior can become better or worse from a suppression point of view.

j) Direct attack

Strategy in the frame of active suppression. Direct attack on the flames and surrounding fuel with water, hand tools, heavy machinery or retardants.

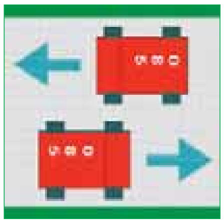
k) Parallel attack

Strategy in the frame of active suppression. Fire attack from the distance, advancing parallel to the fire, basing the actions on a fire line and eliminating the fuel among the line.

l) Indirect attack

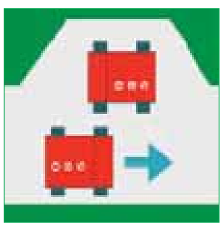
Strategy in the frame of active suppression, creating another fire front with equal or superior intensity and with the capacity to suck in the original fire. The starting point for such operations is a critical point to the front of the fire with the objective of stopping its advance or decreasing its spread.

m) Classification of forest roads and tracks



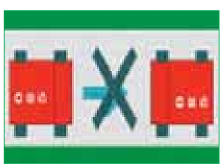
PRIMARY ROADS

Roads or tracks where two type I fire engines (dimensions: 2.45 m wide, 3.05 m high and 6.7 m long) can pass each other on the whole or almost whole route.



SECONDARY ROADS

Roads or tracks where two type I fire engines can pass each other at passing points. The distance between the passing points must not exceed 200 m.

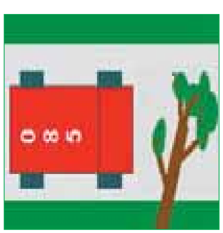


TERTIARY ROADS

Roads or tracks that only allow the traffic of type I fire engines in one direction.

NOT ACCESSIBLE

Road or track where no vehicles can pass.



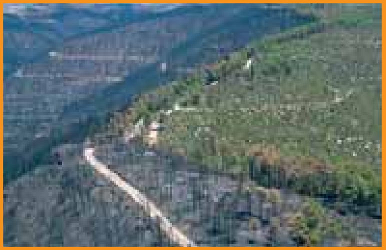
CLOSED

Road or track where fire engines temporarily cannot pass, but current state can be easily mended to allow traffic.

n) Alignment of forces

Degree of coincidence of the three basic factors determining fire spread (slope, aspect and wind), indicating favourable or unfavourable behaviour of the fire front. In can be expressed as in full, medium or small alignment, or out of alignment.

In the last few decades several European regions, particularly in Mediterranean countries, have been characterised by dramatic land use changes. The abandonment of farmland and reduced grazing have led to an increase in wildland areas. These changes in the landscape have contributed to a more aggressive spread of large wildfires all over Europe. Over the last few years, the occurrence of large wildfire episodes with extreme fire behaviour has affected different regions of Europe: Portugal (2003 and 2005), south-eastern France (2003), Spain (2006 and 2009), and Greece (2000, 2007 and 2009).



In this context, the aim of this handbook is to introduce the methodology of the Fire Types Concept as a prevention and pre-suppression tool. This handbook includes the integration of fire use into forest planning in order to prevent large wildfires. It can be used as a tool to complement and support forest policies.

The handbook consists of two parts. The first part of the document gives an overview on the current state and the development of European forests over the last 50 years. The causes of the increase of large wildfire events are discussed, with a focus on land use changes and policies that aimed to increase fire suppression capacity. The fire type concept, and the analysis of spread patterns are presented and described for forest and landscape planning to identify strategic management points.

The second part of the handbook consists of three annexes: (1) the use of fire as a forest and landscape management tool, (2) prevention strategies depending on fire generation and (3) management activities for each type of fire spread.