

# FOREST FIRES IN THE ALPS

**State of knowledge, future challenges and  
options for an integrated fire management**

**White Paper for policy makers**

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80 million people, 7 countries, 48 regions,  
mountains and plains addressing together  
common challenges and opportunities



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## Executive Summary

The International Association of Wildland Fire recently stated that *“Climate change has already had significant consequences in the global wildfire reality, affecting citizens as well as the global wildland fire community.”* They also emphasized that *“There is already evidence of climate-driven fire regime change in the Northern Hemisphere with fire risk increasing in non-traditional fire-prone countries”*. One of these regions are the European Alps. Wildfires are an emerging issue that can lead to high damages in protection forests, increasing the risk of natural hazards and resulting in threats for people and high costs up to millions of euros for fire suppression and restoration measures. The recent extremely dry and hot summers in different parts of the Alpine space, e.g. 2013, 2015, 2017 and 2018, evidenced the need to be better prepared in order to face the changing fire regime with more intense and frequent fires. In this context, experts in integrated fire management at the 4th European Climate Change Adaptation Conference (ECCA) in Lisbon, Portugal, in May 2019 emphasized the importance to *“include the social dimension of fire in land management approaches by focusing on fire as not just an ecological problem, but an economic and social one”*.

### DEFINITION AND CAUSES

In the Alpine context, forest fires are defined as uncontrolled fires in forested area, independent of cause, size and fire type, including fires on clear-cuts, in young forest, coppice and vegetation at the alpine forest border. The most important factors that determine fire ignition are the presence of an ignition source and the moisture content of the fuel (burnable material). About 90% of fires in the Alpine region are ignited directly or indirectly by humans. Main causes are cigarettes, fires getting out of control, flying sparks from trains or during work, arson, hot ashes and power lines. Around 10% of forest fires in the Alps are caused by lightning strikes. Fire behavior, including propagation and intensity, depends on fuel moisture content, vegetation structure and continuity, topography and wind.

### FIRE DRIVERS AND IMPACTS OF FIRES

Forest fire activity in the Alpine region will probably increase in the near future, due to the increasing intensity of drought periods and heat waves and the increasing fire hazard resulting from rural abandonment and more recreational activities. The mountain forests in the Alps provide numerous ecosystem services to the population and fulfil an important protection function against natural hazards. Forest fires can lead to new avalanche-prone slopes, a higher risk of rockfall, mudslides, soil erosion and a local change of hydraulic regimes. Especially forests on steep, southern slopes are at risk, which play an important protective role against different kinds of natural hazards. Firefighting is generally difficult in the Alps due to the rugged topography and low accessibility. Given the expected change in fire regime, it is likely that costs of firefighting, civil protection measures, post-fire restoration and necessary protective measures will strongly rise. The negative impacts of forest fires in the Alps can be summarized as:

- Reduction of the protection function of mountain forests
- Increased vulnerability to natural hazards
- Loss of natural resources and decreased productivity through increased soil erosion
- High costs from firefighting and post-fire management
- Increased danger for humans and infrastructure at the Wildland-Urban-Interface (WUI)
- Increased air pollution and carbon release

Total direct costs for firefighting and post-fire management (excluding prevention measures) associated with forest fires in the Alpine region are estimated to be currently around **75 Mio. Euro per year**.

Current efforts to manage forest fires in the Alpine region are unable to prevent the occurrence of extreme forest fire events. The implementation of a foresighted and integrated forest fire management is highly needed and includes measures on fire prevention, fire suppression and post-fire management.

### PROPOSAL FOR SOLUTIONS

We propose a framework for an integrated fire management, which addresses the drivers of the current and future fire regime in mountain forests, considers the needs of people living in and visiting the Alpine region and aims to mitigate the negative impacts of fires. The framework includes several recommendations and proposed actions to cope with the changing fire regime in the Alpine region. The costs for these integrated forest fire management measures are estimated to be **around 10 Mio. € per year**:

#### **Recommendation: Design and implement short- and long-term prevention measures**

- Improve early warning systems considering topography and specific site conditions in the Alpine region
- Increase resistance and resilience of forests by promoting site adapted tree species
- Anticipate the effects of natural hazards by promoting an adapted forest fuel management
- Improve forest management planning by considering fire behavior and dynamics
- Adapt forest management, including use of prescribed burning, and establish protection measures at the WUI
- Foster awareness-raising activities for stakeholders and the population to establish a fire awareness culture
- Compile dynamic fire risk maps on a local and national scale to identify current and future fire hotspots, as well as low fire intensity areas, to guarantee firefighters safety and tactical suppression actions

*Estimated direct costs for these measures per year and for the whole Alpine region: 5 - 7 Mio. €*

#### **Recommendation: Adapt suppression measures to the specific conditions of the Alpine region**

- Improve the knowledge about suppression measures and build an adequate forest infrastructure
- Promote the deployment of specialized action forces
- Adapt firefighting techniques and use technical (controlled) fires as part of suppression strategies
- Ensure quick and efficient air support by helicopters

*Estimated direct costs for these measures per year and for the whole Alpine region: 1.5 - 2.5 Mio. €*

#### **Recommendation: Improve the understanding and measures on post-fire management**

- Restore forest cover using technical measures and improve post-fire ecological-based restoration activities
- Minimize risks of fire effects and natural hazards
- Intensify research on fuel modeling and fire behavior
- Establish continuous monitoring and case studies on burned sites to monitor mortality and regeneration

*Estimated direct costs for these measures per year and for the whole Alpine region: 1 - 2 Mio. €*

#### **Recommendation: Support knowledge transfer and exchange of experiences**

- Establish a multi-stakeholder approach among authorities, action forces and scientists
- Conduct transnational trainings and specific forest fire scenarios for fire brigades and action forces
- Continue the collaboration in forest fire research in the Alpine countries
- Address negative effects of rural abandonment and recreational activities
- Organize international workshops
- Use joint terminology

*Estimated direct costs for these measures per year and for the whole Alpine region: 0.5 Mio. €*

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## Motivation for this study

In the last years, intensity of wildfires and sizes of burned areas have increased around the world due to the anthropogenic climate change. Recent forest fire events proved quite well that forest fires are also an urgent issue in the Alpine region. They lead to an endangerment of protection forests, increased vulnerability to natural hazards and may result in high costs up to millions of euros for one fire. Forest fire frequency and severity will likely increase in the future due to climate change, more recreational use of forests and changing forest management. Especially protection forests dominated by coniferous tree species on southern slopes are at risk. The impacts of forest fires can lead to new avalanche-prone slopes, a higher risk of rockfall, mudslides or soil erosion. Furthermore, costs of firefighting, restoration of forests and necessary protective measures can seriously rise.

In the context of the EUSALP - EU Strategy for the Alpine Region, the Action Group 8 is aiming to improve risk management and adapting governance mechanisms by enhancing and valorizing existing cooperation structures. The identification of good practice solutions in tackling climate change is one of the major activities. In this context, the Austrian Federal Ministry of Agriculture, Regions and Tourism (BMLRT) has launched the project “Forest fires in the Alps: State of knowledge and future challenges” in cooperation with the University of Natural Resources and Life Sciences, Vienna (BOKU), and the members of Action Group 8.

A panel on forest fires experts was established, followed by the design and implementation of a multi-lingual online survey. Scientists, authorities and members of action forces of all EUSALP member states (Austria, France, Germany, Italy, Liechtenstein, Slovenia and Switzerland) contributed to the survey. Based on the results of the survey, the processes, legal bases and major challenges in forest fire prevention, suppression and post-fire management in the Alpine region were identified. In June 2019, a forest fire workshop was held in Vienna in order to identify success stories on fire management and to discuss the major elements of an integrated fire management for the Alpine region. The present white paper for policy makers was finalized in February 2020.

# 1. State of knowledge

## 1.1. Introduction

In the last years devastating forest fires around the world pointed to the fact that a further increase in the threat of wildfires is likely due to the anthropogenic climate change (e.g. Jolly et al. 2015; Westerling et al. 2011). Higher temperatures in combination with longer drought periods, the change in forest management, rural abandonment, or more intense recreational use of forests are generally known causes that increase the probability of more frequent and more intense wildfires (e.g. Dupire et al. 2019; Vacchiano et al. 2018; Pezzatti et al. 2013).

**Wildfires are an emerging issue in the Alpine region** that can lead to high damages in protection forests, increasing vulnerability to natural hazards and resulting in high costs up to millions of euros for fire suppression and required restoration measures. Due to the increasing trend of constructing homes near or in the vegetation zone, the wildland-urban-interface (WUI) is currently in the spotlight, as wildfires affect these urban areas more easily. Critical infrastructure and technical facilities (e.g. cell towers) built in the forest may also experience a higher risk of destruction in the future. Recent studies showed that forest fire frequency and severity will likely increase in the Alpine region in the future (Arndt et al. 2013; Barriopedro et al. 2011; Moreira et al. 2011; Seidl et al. 2014; Valese et al. 2014; Wastl et al. 2012; Zumbrunnen et al. 2012).

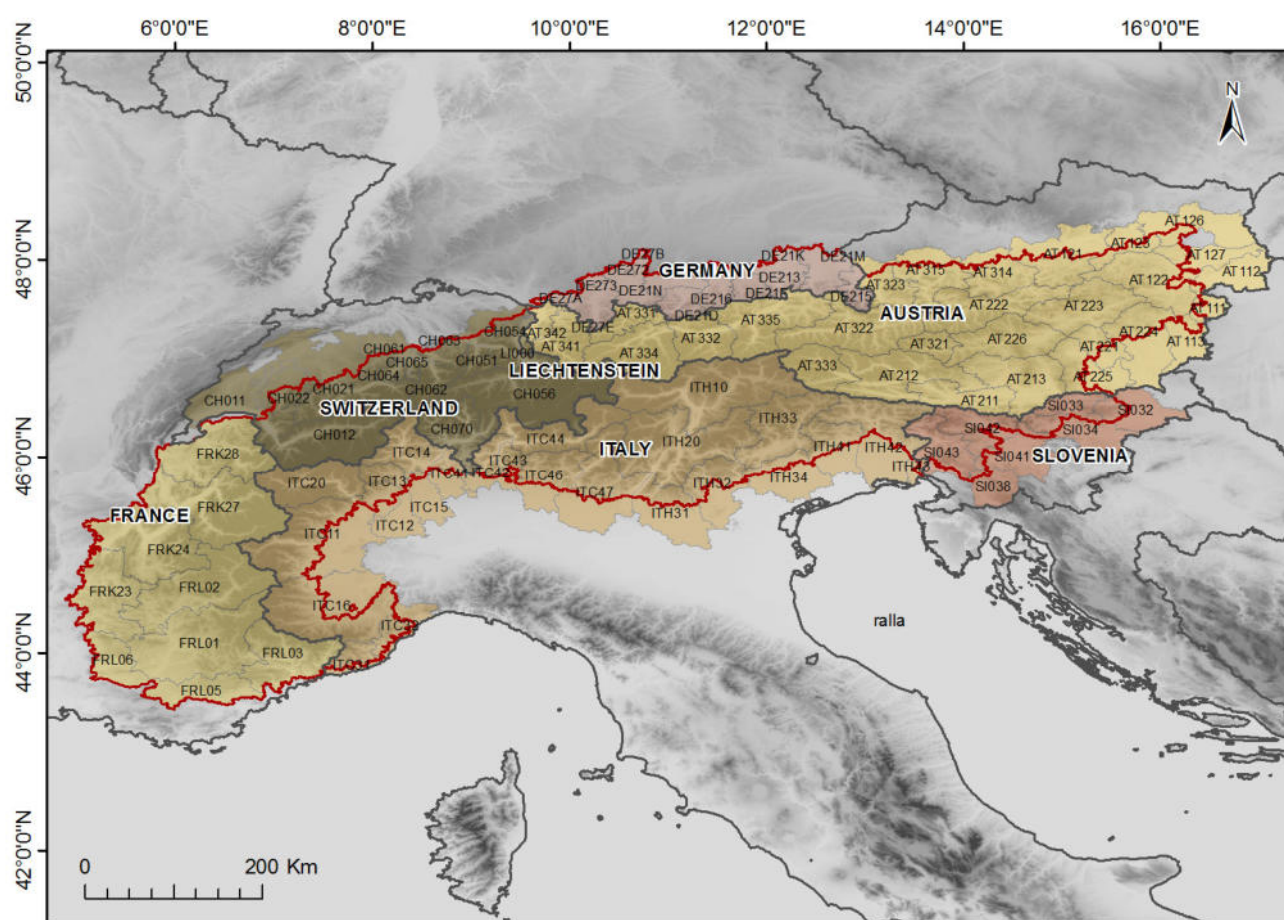
**Especially forests dominated by coniferous tree species on southern slopes are at risk, which often play an important protective role against natural hazards.** The impacts of forest fires can lead to new avalanche-prone slopes, a higher risk of rockfall, mudslides or soil erosion, which cause several threats to infrastructure and the population living in the Alpine region. Firefighting is generally difficult in the Alpine region due to the rugged topography and many remote areas. Forest fire related costs are likely to strongly increase due to firefighting conditions, civil protection measures, carbon and pollutant emissions, restoration of forests and necessary protective measures.

A great share of the Alpine forests consists of Norway spruce (*Picea abies*) or Scots pine (*Pinus sylvestris*). Especially Spruce dominated forests at lower altitudes are already suffering from climate change and will become even more affected if temperature and dryness rise as expected. In addition, under altered climatic conditions, historically less fire-prone forests could be affected by large fires as well, as it was the case for the Central-European beech mountain forests in particularly dry years of last decades (Ascoli et al. 2013a; Maringer et al. 2016a). At higher elevations, open grasslands and shrub stands of mountain pine (*Pinus mugo*) adjacent to forests provide easy burnable fuel. Additionally, the pressure of invasive neophytes has increased in the last years and can locally take over forest recolonization after fire to the detriment of indigenous tree species (Maringer et al. 2012).

Windstorms and bark beetle outbreaks can lead to **fuel accumulation** increasing fire hazard. In the future, a more intense use of forests as recreational areas may increase the likelihood of fire ignitions through negligence and carelessness, causes that are already frequent today. Rural abandonment leads to increased fuel quantity and continuity, which can lead to a more aggressive fire behavior and higher fire intensity. Simultaneous large anthropogenic fires are already increasing (e.g. 11 simultaneous large fires in October 2017 with almost 10000 ha burned in a week in **Italy**). In addition, the number of lightning induced forest fires is expected to increase in the future

(Conedera et al. 2006). Lightning fires are an issue especially in the central and eastern Alps, since they often affect remote areas and can produce large fires (e.g. “Monte Jovet fire” in 2013 with 946 hectares burned, **Italy**).

The term **Alpine region** used in this paper is the geographically defined mountainous region in Central Europe according to the 48 NUTS2-regions mentioned for the EUSALP group (<https://www.alpine-region.eu/7-countries-and-48-regions>). For our analysis we used a more precise match of the Alpine border defined by the Alpine convention by aggregating available data on NUTS3-level (**Figure 1**).



**Figure 1:** Map of the Alpine regions at NUTS 3 level. In red, outline of the Alps according to the Alpine Convention.

## 1.2. Definition of a forest fire and related terms

The commonly used term **wildfire** includes all uncontrolled vegetation fires igniting away from built-up areas. For the Alpine region and in this report we focus on **forest fires**, which are defined as uncontrolled fires in (partly) forested area (including clear-cuts, young forest, coppice and vegetation at the alpine forest border), independent of fire type (smoldering fire, surface fire, crown fire), size and cause (e.g. also single burning tree from lightning).

When the term “forest fire” is used in this paper, we address only forest fires, otherwise all wildfires are meant. In the graphs and statistics we generally refer to forest fires. In **Italy** and **France** there is no differentiation between wildfires and forest fires. Statistics on these countries always show the **total number of wildfires**, including fires in shrub- and grassland. However, Italy and France distinguish between total burned area and burned area on forest land, therefore statistics on burned area are synonymous with forested area for all Alpine countries.

The definition of a **small forest fire** is not uniform in the Alpine country. Sometimes *ignitions* are separated from *real fires*, whereby *real fires* may only be events beyond five hectares in size. In **France**, small forest fires below one hectare are only sparsely documented. In **Switzerland, Germany, Austria** and **Slovenia** each uncontrolled fire in the forest – even just some square meters or a burning tree from lightning – counts as a forest fire and is therefore included into the statistics. In **Italy**, national statistics on forest fire consider 100 m<sup>2</sup> as minimum burned surface.

There is no uniform definition of an **extreme forest fire** event in the Alpine region or worldwide, due to the different fire regimes, fire frequencies and intensities. In more fire prone areas such as the Mediterranean region, an extreme wildfire burns thousands of hectares and leads to the destruction of houses, infrastructure, injuries and even deaths. Such fires are often **characterized by a stop of the fire front because of fuel absence or weather change rather than because of firefighter’s efforts. In other words: They are beyond suppression capacity limit.** In fire prone regions, such as the southern part of the **French Alps**, the definition of an *extreme fire* encompasses a holistic approach, including the social consequences, as defined by Tedim et al. (2018). In the Alpine region, even relatively small forest fires can be *extreme*, if they have a high severity and are undermining the protective function of the forest over a settlement. They can lead to a significant, long-term change in vegetation composition or following natural hazards and erosion. Forest fires in the Alps can also be *extreme* regarding the scope of suppression measures, when several hundreds of action forces fight a forest fire of some hectares in difficult, steep terrain that burns for several days. Fighting forest fires in the Alps and following post-fire measures are expensive – in this context, a fire might be *extreme* regarding the costs, when an area of only some dozens hectares is burned, but total costs are high. As an example, a forest fire in Tyrol, **Austria**, in spring 2014 with a burned area of 80 hectares led to direct and social costs of about three million euro.

### FIRE DANGER VS. FIRE RISK

Regarding **fire risk assessment** a differentiation between the terms *fire danger*, *fire hazard*, *fire vulnerability* and *fire risk* has to be done (Goldammer et al. 2017; Hardy 2005; Pausas 2017). **Fire danger** refers to the dynamic change of factors affecting the initiation, spread and difficulty to fight a fire. It largely depends on meteorological conditions, including moisture, wind and sometimes lightning activity, and may change quickly during time. Currently, fire danger assessments are the most widely used national early-warning systems in the Alpine region. **Fire hazard** is related to the degree of fire propagation potential and the expected fire intensity according to the quantity and continuity of the vegetation (i.e. fuel) and topography. It is therefore of *static nature* and does not include weather conditions. **Fire**



**vulnerability** refers to the probability of fire damage, taking into account ecological effects (e.g. risk of natural hazards), (critical) infrastructure, settlements and potential human losses. **Fire risk** includes potential causes of fires (direct/indirect influence of human and lightnings) but also *fire hazard* and *fire vulnerability*. *Fire risk maps* are used to identify particularly endangered regions for long-term fire management planning. **Integrated Fire Danger assessment Systems (IFDS)** aim to integrate all mentioned aspects of fire danger and fire risk to generate a complex and dynamic risk assessment (e.g. San-Miguel-Ayanz et al. 2018).

### FIRE IGNITION VS. FIRE BEHAVIOR

A distinction has to be made between factors that determine the ignition potential of forest fires and those parameters that are decisive for the spread and intensity of a fire. The **probability of fire occurrence**, or ignition potential, is mainly determined by two factors. On the one hand, there is the soil or **litter moisture**, i.e. the moisture content of the combustible material on the forest surface, such as needles, leaves or grass. Moisture content is determined by micro- and macroclimatic conditions – specifically precipitation, temperature, relative humidity and wind. In the Alps, special weather circumstances leading to dry conditions such as foehn winds or long-lasting thermal inversion are of importance, especially in the winter term. On the other hand, a fire can only occur if a **source of ignition** is present. This means that either a lightning strike acts as a natural source of ignition or, much more frequently, an (in)direct human influence must take place (e.g. discarded smoldering cigarettes, hot ashes, flying sparks from trains, fires that went out of control, or arson). Due to the high human presence for recreation activities in the Alps, more forest fires are recorded at weekends and on holidays. In addition, forests near settlements and roads are statistically more frequently affected by fires than remote forests (Arndt et al. 2013; Conedera et al. 2015).

The **intensity and spreading potential** of a forest fire depend on several other factors. **Type of vegetation** highly influences fire behavior. Coniferous forests in the northern Alpine region burn more frequently and intensively than broadleaf dominated forests (Fréjaville et al. 2016; Girardin and Terrier 2015), while fires in the southern continental valleys or Maritime Alps are also frequent in broadleaf forests dominated by European beech (*Fagus sylvatica*) or chestnut (*Castanea sativa*) (Pezzatti et al. 2009). The **forest structure and continuity** determine whether a crown fire can develop or whether the flames remain on the ground. Low hanging branches or high shrubs can serve as fire ladders, leading to crown fires. Dead wood accumulation (e.g. due to extensive forest management, or natural disturbances like wind storms or bark beetle infestations) may increase fire residence time and fire severity and makes firefighting and mop-up more dangerous. In addition to vegetation, **topography** plays a decisive role (Conedera and Tinner 2010). Fires usually spread more rapidly uphill because hot air rises upslope and preheats the fuel particles (e.g. Boboulos and Purvis 2009). Steep terrain can also be prone to extremely dangerous fire behavior for both firefighters and civilians (Lahaye et al. 2018). Canyons in mountainous regions may lead to an unexpected increase of fire intensity, even without accompanying strong winds (Viegas and Pita 2004). On south-facing slopes vegetation is drier, resulting in a higher spreading potential. Pieces of glowing trees and stumps rolling down steep slopes can ignite new fires, as has been documented in several parts of the Alpine region. Finally, **wind** is decisive for propagation speed. During strong foehn events combined with **drought** and steep slopes, large-area and intensive forest fires are recorded more often. Local and large-scale wind systems can lead to a dangerous change in the propagation direction and speed of the fire front.

The differentiation between **fire propagation** and **fire ignition** depends on local conditions and requirements. Authorities, action forces and media in **Austria** and **Slovenia** mainly use and communicate only the ignition danger of forest fires. In **France** and **Switzerland**, experts combine propagation and ignition danger and disseminate a

cumulative index. In **Germany**, the used WBI combines ignition and propagation danger but is disseminated as “forest fire danger” in general. In **Italy**, there is no uniform way of how to deal with the issue of fire ignition vs. propagation.

### 1.3. Documentation of forest fires in the Alpine region

There exists no standardized way on how to collect forest fire data at Alpine level. One option may be the documentation via the MODIS active fire or VIIRS product, two automated satellite detection systems, which are currently done by the European Forest Fire Information System (EFFIS). However, fire coordinates are missing here and smaller fires (below 30 hectares) cannot be detected. The most frequent size of an Alpine forest fire is below one hectare (Conedera et al. 2018; EUSALP survey). Even if there is a ground fire of several hectares but below a dense canopy, it will be difficult to detect with current satellite products. EFFIS provides yearly reports and statistics at country level, for some countries back to 1980. The reports include data separated by region that allows to reconstruct statistics for the Alpine area. However, as all these statistics mainly include large fires, they are only relevant for **France** and **Italy**.

Each Alpine country has its own forest fire documentation system with different attributes, criteria and accuracies. In most datasets some fires are still missing, especially small ones. The reliability and survey period since forest fire data is being collected varies in each country (**Table 1**). This makes it difficult to compare statistics and results for the Alpine region. During the **MANFRED project** (<http://www.manfredproject.eu>), which aimed at defining management strategies to adapt Alpine Space forests to climate change risks, forest fire data for the whole Alpine region was collected until 2009. However, data from some countries covered a short period or were incomplete (e.g. from **Austria** and **Germany**). It may be useful to find common (historical) fire patterns for different Alpine countries to create transnational fire severity maps (Fox and Carrega 2006).

In 2008, the **Austrian Forest Fire Research Initiative (AFFRI)** was launched at the Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna, **Austria**. Within the framework of the project and various follow-up projects, current and historical forest fires in Austria have been processed and imported into an online database, which now comprises more than 6000 data records. Via a public Web GIS interface, interested persons can access the information collected over the past 25 years (1993-present), compile graphics and statistics and report forest fires independently (<http://fire.boku.ac.at>). The database provides information on all major fire events in **Austria** that have taken place in the last 25 years (Eastaugh and Vacik 2012). Collected data include date, time and duration, location, coordinates (WGS 84), burned area, cause of the fire, affected vegetation and tree species, fire type, fire behavior, number of action forces, helicopters and fire brigades involved.

In **France**, the Prométhée database (<http://www.promethee.com>) was implemented by forest and fire agencies in 1973. However, the database suffers three main limitations: Firstly, it compiles and maps mainly wildfires larger than 10 hectares. Secondly, it covers only the Mediterranean parts of France, therefore the Southern extent of the French Alps. And thirdly, the accuracy of the database has constantly evolved, so that the oldest statistics may not be considered as comprehensive.

In **Germany**, forest fires are documented by the respective state forestry commissions and then aggregated to the federal scale by the Federal Office for Food and Agriculture (BLE). For example, the Bavarian State Ministry of

Agriculture and Forestry reports the number of forest fires, area affected, ignition date, type of forest property and fire causes of its 47 regions, of which six have an Alpine proportion. Records of forest fires have been made at least since the 1950s, however, most of the fire data before 2006 was lost due to a restructuring of the forestry commission. Data did not include a precise fire location and perimeter, but since 2015 local foresters may report single fire events via a GIS-Interface of the Bavarian Forestry Administration (Bavarian Forest Information System BayWIS). There is no separate report focusing on forest fires in the German (Bavarian) part of the Alps.

In **Italy**, every region has its own database on forest fires. The series length can vary depending on the region, but in all cases, it encompasses several decades (e.g., for Veneto Region from 1981). Burned areas are collected at national level, until 2016 by the former “Corpo Forestale dello Stato” and nowadays by “Carabinieri Forestali”. The database is included in the SIAN (National Information System for Agriculture). Usually fire related measures are taken on the ground.

In **Slovenia**, a complete forest fire database at national level exists since 1995. The database was drafted within the framework of forestry profession and refers exclusively to forest fires. Data are gathered by the Slovenia Forest Service (SFS), public forestry service. Collected data include date, time, location, coordinates (D48), burned area, cause of the fire, fire type, affected vegetation and tree species, relief features, weather conditions, damage (EUR), date of forest fire report and forest fire hazard level. Since 2013, the SFS Fire Database and a database from Information System for Reporting Interventions and Accidents (ISRIA), ruled by the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief (ACPDR), have been linked in an application called “Varstvo gozdov” (eng. *Forest protection*) made by the Slovenian Forest Service (SFI). This application connects forest fire data with data about the action forces and fire brigades involved during a fire event. For the Karst area, the mostly endangered region in Slovenia, a complete forest fire database exists since 1991.

In **Switzerland**, a complete forest fire database at national level exists since 2008. However, this database contains records starting from 1900, which were retrieved either from cantonal and local databases or through archive searches in newspapers (Pezzatti et al 2019; <https://www.wsl.ch/swissfire>), thus making it a unique dataset at an international level. The dataset currently comprises more than 10000 events and is directly accessible to the federal and cantonal authorities via a web interface for inserting new data or downloading fire statistics.

**Table 1:** Length of the national/regional databases available for this study for the Alpine region by country.

	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	
Austria																																																
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#### 1.4. Characterization of current fire regime

The definition of *fire regime* lacks a clear definition but may include factors such as fire pattern, frequency, intensity, cause, burned area, seasonality and type of fire (Whelan 1995; Krebs et al. 2010). In the Alpine region, the yearly distribution of these factors greatly depends on regional weather conditions. These conditions are highly variable within the Alps, locally and temporally (Böhm et al. 2001; Hiebl et al. 2009). We concentrate on those parameters of the fire regime, where data is available for the whole Alpine region.

##### FIRE PATTERN AND OCCURRENCE

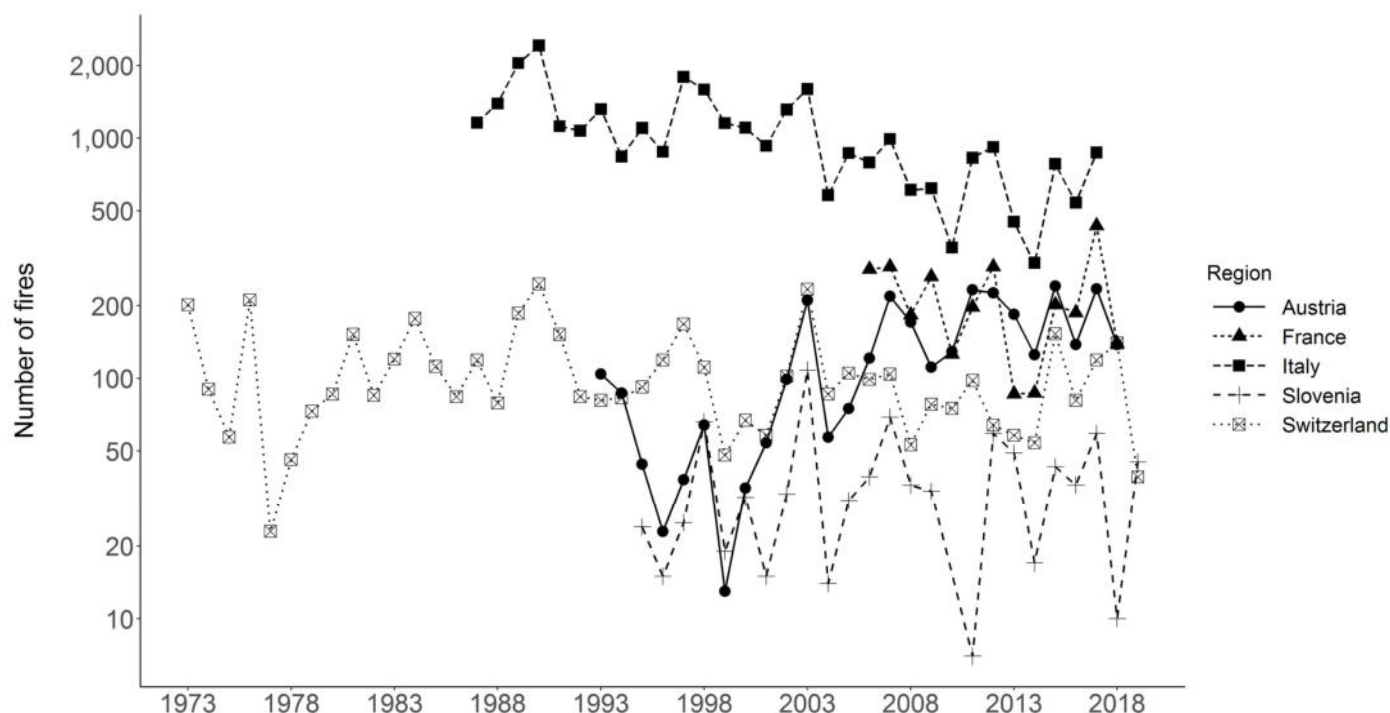
According to the current situation, the highest numbers of forest fires and the largest burned areas can be found in the southern parts of the Alps (Conedera et al. 2018; **Figure 3**). Inner alpine dry valleys are generally at greater risk than slopes in the Northern Alps or areas which are wet during the whole year. Wastl et al. (2012) analyzed the long-term trend of forest fire danger in the Alpine region from 1950 to 2010. They found a significant increase of yearly average fire danger in the Western Alps and an even stronger increase in the Southern Alps, while both in the Northern Alps and inner valleys the increase was rather weak. Yet, an increasing trend of fire danger must not correlate with more forest fires. In the mountainous Alpes-Maritimes department in the south-east of **France** there is a clear decrease in the number of forest fires due to new politics of firefighters since the 1990s (with 2003 as exception). In the canton Ticino, **Switzerland**, there are now less fire days than before 1990. However, in past years there are more forest fires observed on the northern side of the Swiss Alps.

Conifer forests on southern slopes and on limestone bedrock were found to be at highest risk in the Northern Alps (Sass et al. 2012). In the Southern Alps, also beech and chestnut coppice are often affected by fires (Pezzatti et al. 2009; Bajocco et al. 2011). Grassland or shrubland that derive from abandoned agricultural land close to forests are one of the main ignition points in the south of the Alps. In the surrounding of villages and settlements, but also along roadsides and railway tracks, fires are started more often than in remote areas. This applies to the entire Alpine region. In some countries (e.g. **Austria** and **Germany**) there is both an increased probability of ignition and fire spread on forest areas after clear cuts. This is a result of lower fuel moisture combined with dry grass dominated fine fuel. Specialized recreational areas are also problematic, e.g. climbing or bouldering places. Here, a greater risk of fire ignition is present, often coming from campfires or discarded cigarettes. Several recent forest fires were found in such areas (e.g. Forest fire 2018 in Hallstatt, Upper Austria). Fire intensity is altered by vegetation, topography and local weather conditions.

##### FIRE SEASONALITY AND FREQUENCY

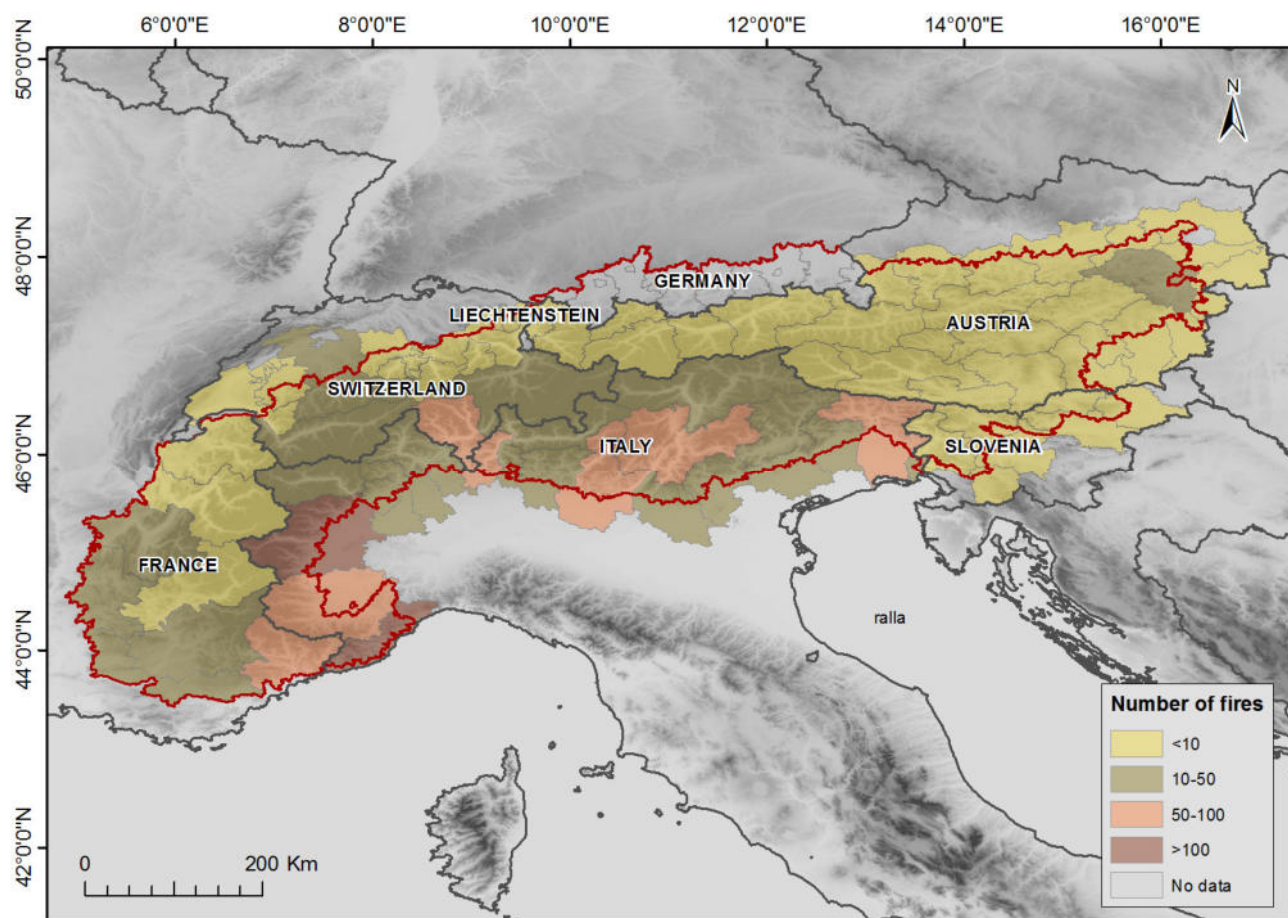
In the Alpine region, there are two main fire seasons during the year. The first starts, depending on the local weather conditions, in early spring and peaks in March or April before new grass is growing, due to dryness linked to frost and stable springtime weather conditions. The second peak correlates with the summer months July and August. Especially in the foehn regions north or south of the Alps, also winter fires are an issue, due to the temperature inversion-caused thermal belt above the fog line with very sunny conditions (Schunk et al. 2013). The year 2003 is generally known to have been one of the most extreme fire years in the Alps. However, several authors have identified large forest fire events or other extraordinary fire seasons in the Alpine region in recent years (**Figure 2**). They are often associated with heat waves and dry foehn winds, which is generally seen as an indication of a changing climate that will lead to a new fire regime in the Alps (Ascoli et al. 2013a; Conedera et al. 2006; Müller et al. 2015; Pezzatti et al. 2013; Schär et al. 2004; Schunk et al. 2013; Wohlgemuth et al. 2010).





**Figure 2:** Distribution of the annual number of forest fires by country (within the Alpine region).  
No data available for Germany and Liechtenstein. Source: National/Regional databases.

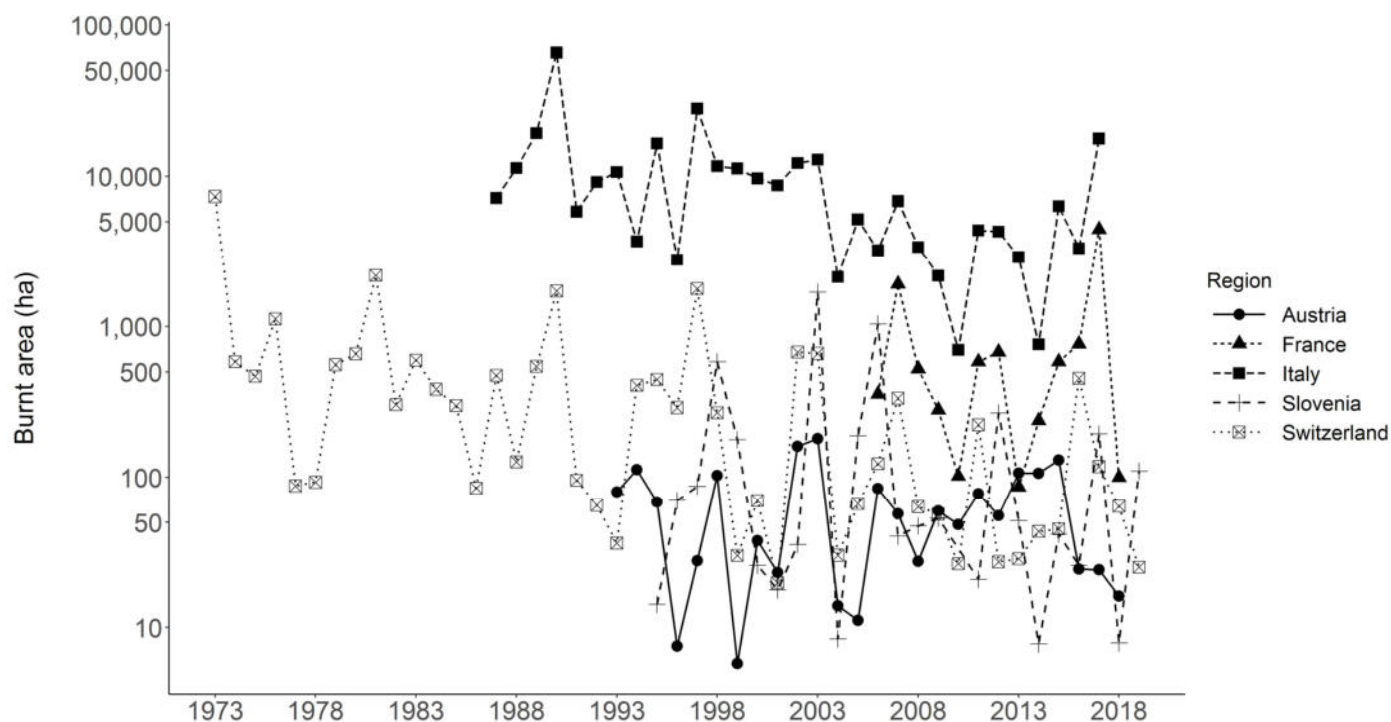
In autumn 2011, **Austria** experienced a new record in number of forest fires and burned area. In spring 2012, the north of **Italy** reported a never seen before lightning fire very early in the year that burned 300 hectares close to the southern border of **Austria** (Valese et al. 2014). Likewise, in 2012, **Slovenia** had a new record in terms of number of forest fires and burned area. In summer 2013, a new record in the number of forest fires was documented in **Austria**. The northeast of **Italy** experienced above-average number of fires and burned areas, especially in the region Friuli-Venezia Giulia that borders Carinthia in **Austria**. In spring 2014 and 2015, the two largest forest fires in **Austria** since more than 30 years burned an area of 100 hectares each. In the end of October 2017, 11 simultaneous large fires in the Piemonte Region, **Italy**, burned almost 10000 ha in a week, mainly in broadleaved forests. These fires were not typical as the precipitation usually peaks at the end of October in this area; however, in 2017 a long-term spring-summer drought lasted until the end of October, causing a very high fire danger. It was the largest fire outbreak regarding simultaneous fires of the last 30 years in the Alpine region. In October 2018, one of the largest forest fires ever recorded occurred in Veneto region, **Italy** (Monte San Lucano, 632 ha).



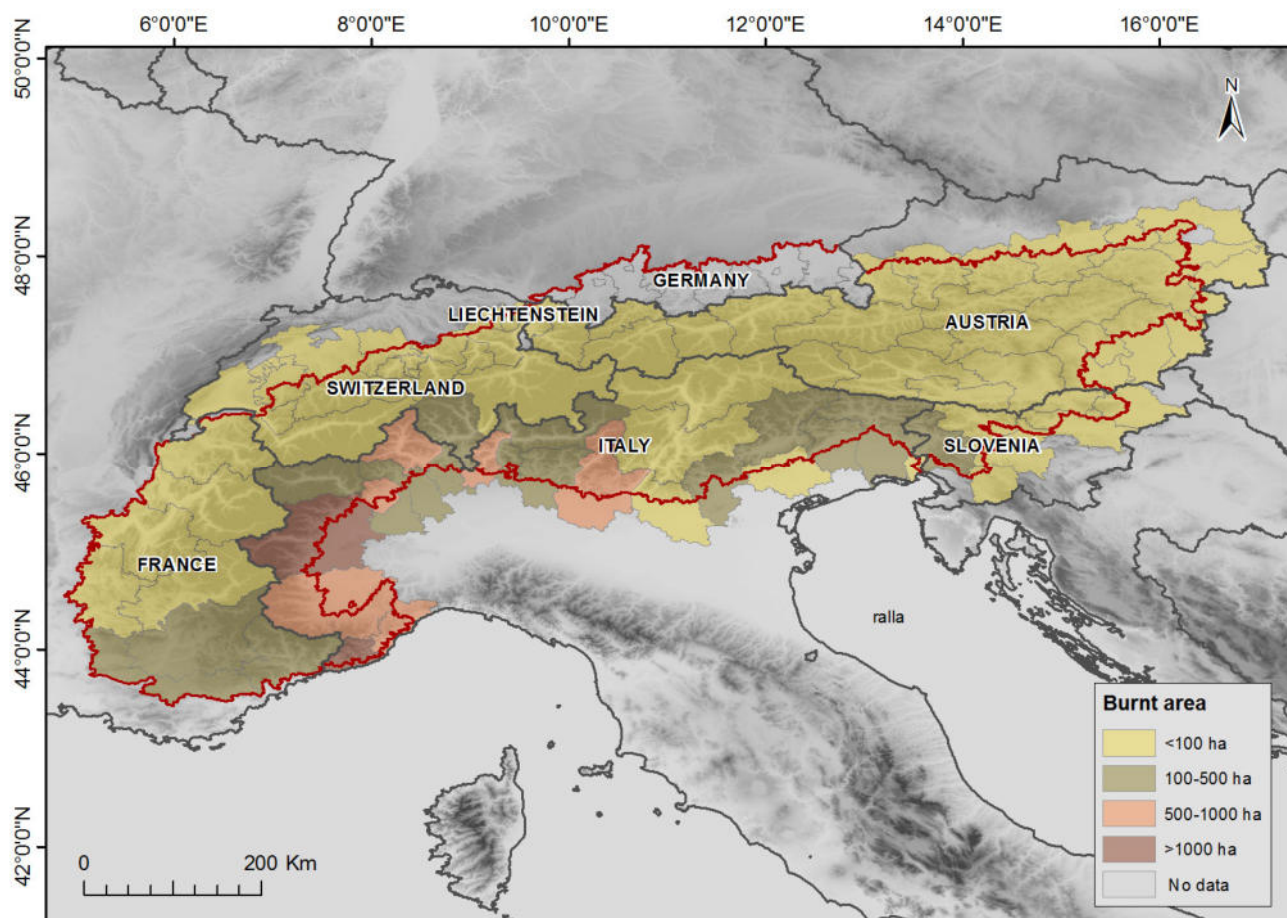
**Figure 3:** Average number of fires per year by region. No data available for Germany and Liechtenstein.  
 Source: National/Regional databases

## BURNED AREA

Most forest fires (around 80%) in the Alpine region are small (below one hectare in size). There are strong differences in number of fires and fire size between the Alpine countries per year (**Figure 4**).



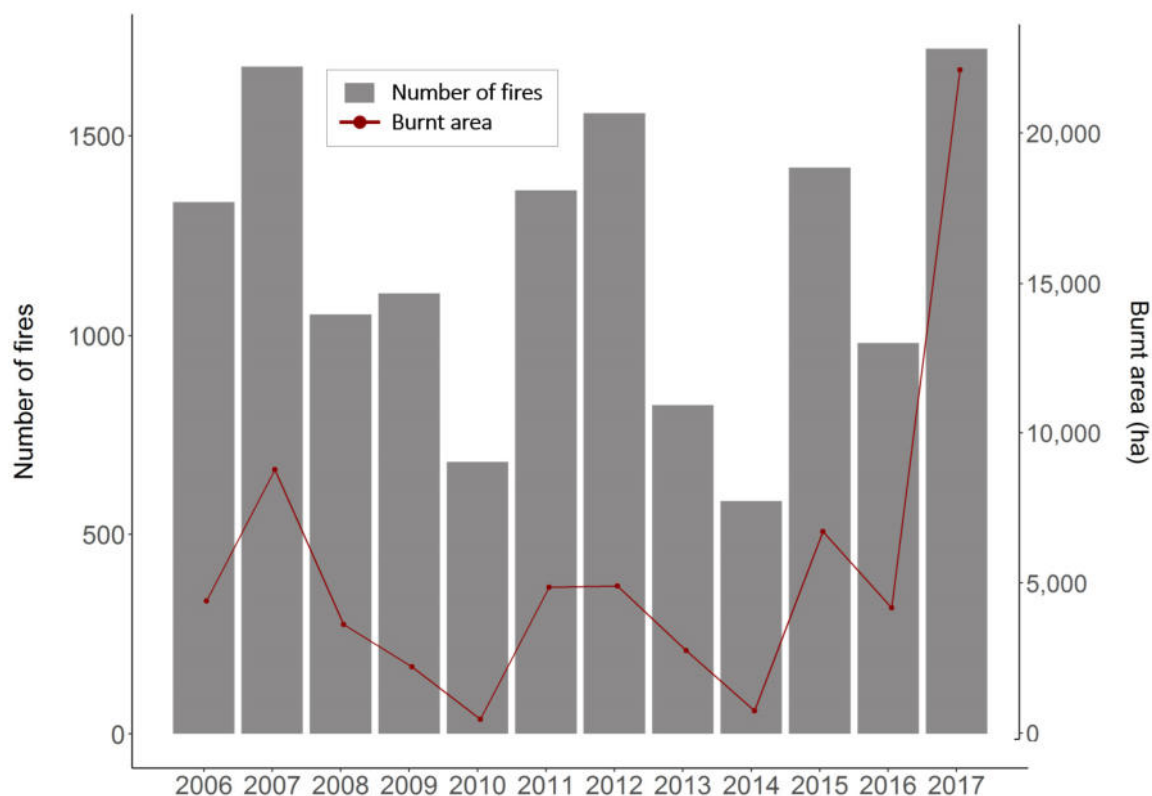
**Figure 4:** Total burned area per year by country (within the Alpine region). No data available for Germany and Liechtenstein.  
Source: National/Regional databases.



**Figure 5:** Average burned area (ha) per year by region. No data available for Germany and Liechtenstein.  
Source: National/Regional databases

The Southern Alps encounter more and bigger fires than the Northern Alps (**Figure 3, Figure 5**). A mean Alpine forest fire in **France** and **Italy** covers an area of about a hectare, but 10% of fires are larger than 10 hectares and cause 85% of the total burned area. In **Slovenia**, two thirds of the fires are below one hectare in size while most forest fires in **Austria, Germany** and **Switzerland** are below 0,1 ha. The total burned area and number of fires for the Alpine region in the last years is shown in **Figure 6**.





**Figure 6:** Mean annual number of fires and burned area in the Alpine region (Austria, France, Italy, Slovenia and Switzerland) from 2006 to 2017. No data available for Germany and Liechtenstein. Source: National/Regional databases

**Table 2** gives an overview of the fire situation in the Alpine countries. While **Austria** has the largest amount of forest area in the Alpine region, most fires and the largest burned areas occur in **Italy**, followed by **France**. The median size of a forest fire in the Alps is generally low, with about 0.1 hectares in **Austria**, **Germany** and **Switzerland**, 0.5 ha in **Slovenia** and around 1 hectare in **France** and **Italy**. The average burned area per year differs strongly between the countries and ranges from 0.22 ha to 44 ha per 10000 ha of forest area.

**Table 2:** Fire situation in the Alpine countries according to number of fires, burned area, fire size and yearly ratio of burned forest. No data available for Liechtenstein. Sources: National/Regional databases, EFFIS reports, Forest fire workshop Vienna.

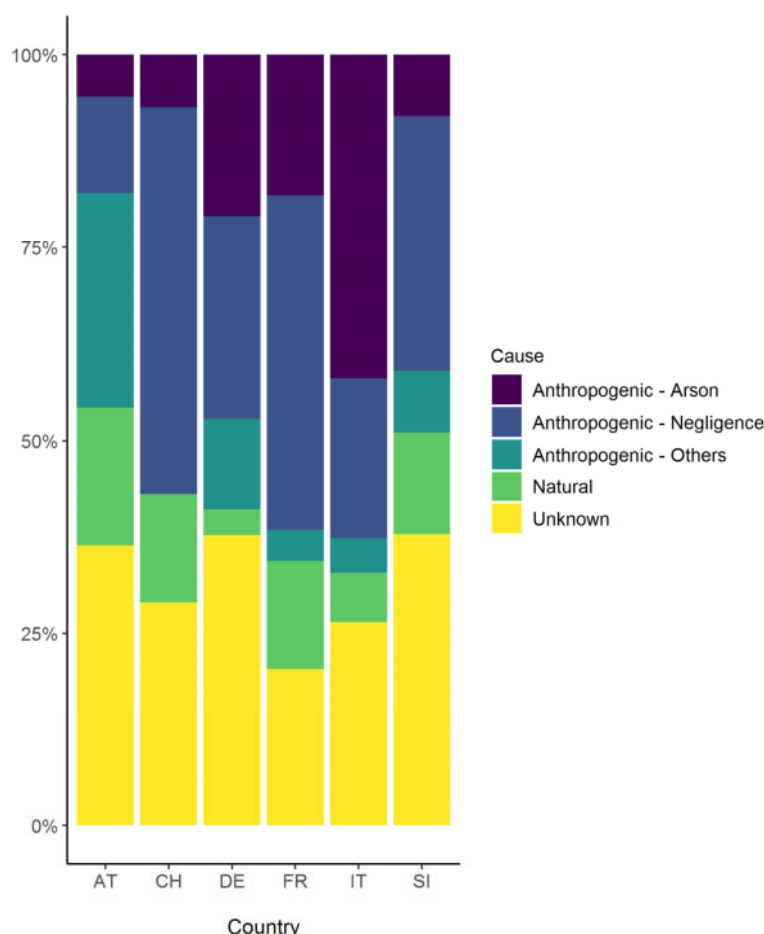
	Austria	France	Germany	Italy	Slovenia	Switzerland
Total area in the Alpine region (km <sup>2</sup> )	69 277	40 786	11 197	<b>73 386</b>	13 763	33 360
Forest area in the Alpine region (km <sup>2</sup> )	<b>28 921</b>	14 099	4 036	22 623	7 238	9 929
Mean annual number of forest fires in the Alpine region	122	213	no data	<b>1 043**</b>	37	105
Mean annual burned forest area (ha) in the Alpine region	64	818	no data	<b>9 984</b>	201	515
Median size of a forest fire in the Alpine region	< 0.1 ha	1 ha	< 0.1 ha	1 ha	0.5 ha	< 0.1 ha
Yearly ratio of burned area (ha) in the Alpine region*	0.22	5.80	no data	<b>44.13</b>	2.77	5.19
Largest wildfire (total burned area) after 2000 in the Alpine region	Tyrol 2014 Absam (100 ha)	Var 2003 Vidauban (6744 ha)	Bavaria 2017 Jochberg (27 ha)	Piemonte 2017 Val Susa (3974 ha)	Bovec 2005 Ognjišče (126 ha)	Wallis 2003 Leuk (300 ha)

\* Average burned area per year per 10 000 ha of forest area

\*\* For Italy mean annual number of fires is related to all documented wildfires

## FIRE CAUSES

A large part of forest fires in the Alpine region is directly or indirectly caused by humans. The most important causes are negligence, intentional and accidental fires, e.g. cigarettes, fires out of control, arson, hot ashes, flying sparks and power lines. Humans are responsible for more than 90% of all fires in the Alpine region (**Figure 7**). Especially in the southern and eastern central Alps also natural fires caused by lightning strikes are an issue. A study compared lightning occurrence with the occurrence of forest fires in **Austria** (Müller et al. 2013). Lightning is the only relevant natural cause and triggers 15% of all fires, while humans account for 85%. In the summer months, lightning-induced forest fires can have a share of up to 50% in **Austria** and parts of **Switzerland**.



**Figure 7:** Causes of fire ignitions in the Alpine region by country. No data available for Liechtenstein. Forest fires in Austria shown as “Unknown” have been identified to likely be anthropogenic caused. Source: National/Regional databases.

**Arson** is mainly an issue in the Mediterranean areas e.g. of **France** and **Italy**. In the **Italian** Alps, 40% of all forest fires are intentionally caused (Italian regional fire databases). In **France**, arson accounts for 40% (Prométhée database). But also in other Alpine countries arson can be an issue. In **Germany**, it accounts for around 15% of all fires, in **Switzerland** and **Austria**, less than 10% are intentional (Austrian fire database; National databases). Arson may increase in the future, due to complex land use changes and accompanying conflicts that trigger intentional fires.

### TRADITIONAL USES OF FIRES

There are different kinds of traditional uses of fire in the Alpine region. Easter and solstice fires are practiced each year in some parts of **Austria**, **Germany**, **Slovenia** and **Switzerland**. In **Switzerland**, Easter fires combined with fireworks represent the traditional way to celebrate the National day on August 1<sup>st</sup>. This commemorative use of fire turns sometimes to uncontrolled fires in open areas or even forests. In **Slovenia**, bonfires are lighted for carnival and on May 1<sup>st</sup>. In **Germany**, there has recently been an increased contact between people carrying out solstice fires and

forest authorities. In some areas, permissions are issued, which include restrictions in case of high fire danger. Today fires are also used as political statements, e.g. from the initiative “Feuer in den Alpen” (<http://www.feuerindenalpen.com>).

Land and forest owners used to burn their land regularly in the past for different purposes. Fire has been extensively used to clear and maintain pastures or to fertilize non-arable land by fostering the grass palatability and fresh sprouts after the fire (Conedera and Krebs 2010, Valese et al. 2014). The burning of brush fuels to promote herbaceous regrowth on pasture lands has also been common in many Alpine regions. This issue is known in almost all Alpine countries under different names: e.g. *strokeburning* in **Austria**; *Brüsada* in southern **Switzerland** and northern **Italy**; *Schwendi* in the German speaking part of **Switzerland**; *Essart* and *brulis* in **France**; *Rüttibrennen* as part of the traditional Black Forest Reutbergwirtschaft in **Germany** (Conedera et al. 2007). Today, these measures are often forbidden due to civil protection concerns, nature conservation or air pollution control laws. Although the traditional use of fire may lead to dangerous situations when it is not under control, the decline of the traditional use of fires can have a negative impact on the long term. Herbaceous pasture lands are abandoned and turn to continuous brush lands, which are highly endangered regarding fire ignition. This phenomenon is known as the “Fire Paradox” (Sande Silva et al. 2010).

The illegal use of fire is a problem especially in the Southern Alps since it is applied surreptitiously in high fire danger seasons, resulting in unclear effects on the ecosystem and ultimately higher costs for fire control systems (Ascoli and Bovio 2013). Burning agricultural or forest residues is a regulated traditional activity in **Italy**. That means, farmers need a permit and have to follow safety rules to do the burns according to regional laws. The **Slovenian** decree on fire protection in the natural environment also describes special measures to be applied when burning residues. Traditional fires include also the maintenance of blueberry stands (*Vaccinium myrtillus*) and the removal of litter in chestnut grove. A regulation that considers the interests of various stakeholder groups in the traditional use of fires in the Alps is strongly needed to avoid illegal behaviors and surreptitious use of fire.

### 1.5. Effects of forest fires

Forest fires can have several effects on the forest, environment, infrastructure and human settlements. Besides the reduction of the protection function of forests, increased natural hazards, loss of natural resources and soil erosion may follow high intensity fires. Moreover, high firefighting and post-fire measures costs have been reported all over the Alpine region. Air pollution and carbon release can be an issue and may become more important in the future.

Forest fires may also have positive effects on the environment, depending on the fire regime (e.g. DeBano 2000, González-Pérez et al. 2004, Moretti et al. 2004, Neary et al. 1999, Turner et al. 1997). As an example, nearly all fires create patches in the forest where vegetation can regenerate, resulting in an increased landscape heterogeneity that will likely limit the extent of a subsequent disturbance in the forest (Seidl et al. 2006).

### NATURAL HAZARDS

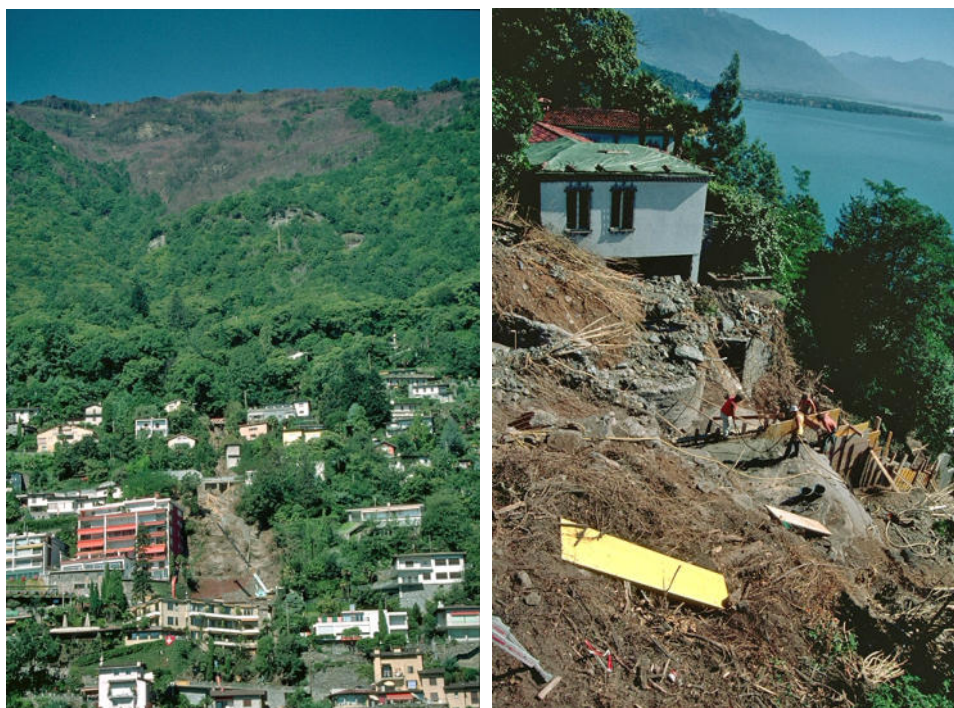
Natural hazard events in the Alpine region may result as a direct consequence of forest fires and include new avalanche prone slopes, mudslides, increased run-off, rockfall and erosion of the soil. In **Switzerland**, several studies were accomplished on this topic. Providoli et al. (2002) showed that splash erosion can occur after fires in the common



chestnut (*Castanea sativa*) coppice stands in southern Switzerland. Maringer et al. (2016a) analyzed the protection function of burned European beech forests (*Fagus sylvatica*) against rockfall. Gehring et al. (2019) found out that there is a shallow landslide disposition in burned European beech forests. There are also some studies on fires and debris flows in **Italy** and in the Mediterranean region, e.g. the “Piano straordinario incendi della Regione Piemonte” (Regione Piemonte 2018).

The potential risk and occurrence of natural hazards depend on several factors. Besides the size and severity of the fire, vegetation structure and composition before the fire, topography, climate conditions, soil and bedrock are key elements for the development of natural hazard at the slope. In case of a stand replacing crown fire, the protection function of the forest is at risk, which is of high importance in many regions of the Alps. According to Sass et al. (2012), steep slopes of the subalpine level with a low humus layer on limestone are particularly unfavorable for regeneration. Here, a complete erosion of the soil may occur, leading to an increased danger of several natural hazards. Even with surface fire of low intensity the natural regeneration may be damaged. A fire in an area recently afforested with high costs to increase the protection function can be seen as “worst case scenario”.

Debris flow occurred in Ronco sopra Ascona (Southern Switzerland) in summer 1997, five months after a forest fire burned the whole catchment of the torrent (**Figure 8**). The effects of the fire on the hydrological soil properties turned a 10 years precipitation event into a 200 years debris flow, which transported 3500 m<sup>3</sup> of material into the village (Conedera et al. 2003).



**Figure 8:** Severe debris flow in Ascona, Switzerland, in summer 1997, five months after a forest fire.  
Photo: Lorenza Re, Forest Service Canton Ticino

## ECOLOGICAL EFFECTS OF FIRES ON ECOSYSTEMS

Conedera et al. (2003) demonstrated how forest fires can alter the hydrogeological responses of mountain catchments in **Switzerland**. Vergani et al. (2017) investigated the root reinforcement decay after a forest fire in a Scots pine (*Pinus sylvestris*) protection forest. They found a reduction of root reinforcement by a factor of 3.6 due to degradation of the root mechanical properties. Several studies in the Alpine region have investigated the effect of forest fires on tree mortality and regeneration (e.g. Bär et al. 2018; Bär et al. 2019; Conedera et al. 2010; Fox et al. 2008; Maringer et al. 2016b). Gehring et al. (2009) and Vergani et al. (2017) analyzed the stability of roots after fires, as roots help to prevent erosion years after the fire and the death of the corresponding trees. Large forest fires can also change the runoff and thus modify local hydraulic regimes. Forest fires may also increase the vulnerability to windthrow and to bark beetle outbreaks and other pests.

Regarding biodiversity, the effects of forest fires highly depend on the fire regime (frequency and intensity of the fires) and the main tree or woody species concerned. Some species like pines or other pioneer ones (e.g. European larch (*Larix decidua*), silver birch (*Betula pendula*)) need open environments to grow and take advantage from the passage of a fire reopening the mountain environment (e.g. Ascoli et al. 2013b). However, this will only be true as long as the fire regime does not result in a high fire recurrence at the same place. Other resprouting species like the chestnut tree also react immediately after fire (Hofmann et al. 1998), whereas non-fire adapted species like the European beech developed their surviving strategy based on delayed mortality and favorable regeneration conditions (Maringer et al. 2016). Other species will be strongly impacted by the fire, especially if the number of very large and high intensity fires increases. In general, changes in the forest communities are likely to open up new ecological niches, compensating for the possible loss of species (Moretti and Barbalat 2004; Moretti et al. 2006). Yet, there is also the risk of a spread of invasive neophyte species (Lonati et al. 2009; Maringer et al. 2012).

## SMOKE

Smoke from forest fires in the Alpine region is especially an issue during firefighting, because of possible smoke intoxication and visual restrictions. The use of breathing apparatus, especially regarding self-contained breathing protection with additional oxygen bottles, is impossible to be used. Smoke may also be problematic near settlements or traffic routes and can prevent the possibility of orienting oneself near an intense fire. In **France**, a project is under development in the region Provence-Alpes-Côte d'Azur to model smoke propagation and dispersion during both wildfires and prescribed burnings.

## COSTS

Forest fires in the Alpine region are associated with high costs for stakeholders, communities and the federal states. Currently the main direct costs are caused by suppression measures and post-fire management. According to a recent investigation done at the Institute of Silviculture, University of Natural Resources and Life Sciences Vienna, annual mean direct costs for firefighting and post-fire management are around 650,000 Euro per year in **Austria**. Assuming, that the equipment and the means for fire suppression as well as the framing conditions like topography and environmental conditions can be extrapolated to other alpine countries, it is possible to come up with a rough estimation about the direct costs related to forest fires. Using the yearly burned area in the Alpine region, it is assumed that current mean direct costs resulting from forest fires are around **75 Mio. Euro** per year (fire prevention measures not included). However, the costs will vary between the Alpine regions. Highest costs are in **Italy** and **France**. The **social costs** associated with forest fires, e.g. on the side of voluntary firefighting, are difficult to estimate on an Alpine scale

but are assumed to be **at least twice as high** as the direct costs. In **Slovenia**, costs of firefighting interventions are reported centrally by voluntary and professional firefighters through the platform “Spin” (<https://spin3.sos112.si>).

## 1.6. Fire management

Fire management includes long and short-term fire prevention, fire suppression and post-fire management. All activities from authorities, scientists and action forces concerning fire are part of fire management. The following measures can be distinguished:

### FIRE PREVENTION

- Long-term fire prevention
- Short-term fire prevention

### FIRE SUPPRESSION

- Pre-suppression of fires
- Detection of fires
- Suppression of fires

### POST-FIRE MANAGEMENT

All measures are linked and should be integrated for a comprehensive fire management. **Long-term fire prevention** includes scientific research on fire dynamics, awareness-raising, identifying forest fire hotspots and fuel treatments (e.g. prescribed burning, grazing or forest management). Forest management is not only an issue for authorities, but also for forest and land owners, who, even if their property is situated in a high fire danger area, are often not aware that they should care about forest fires (EUSALP Survey). **Short-term fire prevention** is associated with periodic fire danger assessment, the dissemination of a daily fire danger bulletin and related fire restrictions. The **pre-suppression of fires** is linked to the work of action forces and includes all activities on planning, recruitment and training, but also the maintenance of firefighting equipment and the improvement of a system of fuelbreaks, roads and water supplies. The (early) **detection of fires** is crucial for effective firefighting. It can be achieved by automated smoke detection systems, surveillance flights, video control system (a video surveillance system), monitoring service or by counting on the reports by the local population or tourists. During **fire suppression**, firefighters, helicopter teams and other action forces actively fight a fire with different techniques and equipment. **Post-fire management** includes securing forest cover and settlement areas, avoiding natural hazards, restoration of the forest area and monitoring of burned sites. The state of the art in fire management will be described in the following chapters.

### 1.6.1. Long-term fire prevention

Fire prevention measures can have various aspects. On the long term, the improvement of forest management planning and the establishment of forest fire risk maps are key issues to prevent devastating fires in the future. Besides, anticipation of fire effects on other natural hazards, awareness-raising, regulation of traditional fire uses, scientific fire research and prescribed burns can also be appropriate to prevent large forest fires in the Alpine region.

## FOREST MANAGEMENT

Research on forest management effects on forest fires in the Alpine region started several years ago, e.g. in **Switzerland** (Berli 1996; Conedera et al. 1996; Gimmi et al. 2004; Weibel et al. 2009), **France** (Gatheron 1950; Meyer 2005; Genries et al. 2009), **Italy** (Tiller 1988; Bovio 1996; Kuntner 2001), **Germany** (Goldammer et al. 1997; Badeck et al. 2003; Thonicke and Cramer 2006) and **Austria** (Gossow et al. 2009; Vacik et al. 2011).

In some Alpine regions, **fuelbreaks** are created in order to improve suppression capacity and safety of firefighters, and hamper forest fire growth (e.g. Maritime Alps in **France**, Piemonte region in **Italy**). Preventive silviculture measures, like variable retention, thinning and species substitution towards less flammable compositions, are effective actions for long-term fire prevention. However, the selection of tree species is mostly driven by the preferences of the forest land owner and by the requested need to maintain forest ecosystem functions in the mountains. A change in tree species composition to reduce forest vulnerability to fire is seldomly applied. The restoration of former conifer afforestations by thinning and natural regeneration or advanced planting is recommended by the forest fire prevention plans in **Italy** for instance. In **France**, there is a national forest fire protection strategy. Planning is mostly done at the departmental level. These departmental plans of PFCI (fire prevention plans for forests) are an obligation in those departments most exposed to fire risk. In all other departments (including parts of the Alpine departments), the realization is not imposed and is done voluntarily on the initiative of the local services of the state. Several – but not all – Alpine departments have made such voluntary PFCI plans. In Brandenburg, **Germany**, they observed multiple benefits of establishing strips of broadleaves to sub-divide large coniferous areas or to buffer roads and railway lines with high ignition potential (König 2007). However, this measure was applied in dry lowland areas and is difficult to be established in the rugged Alpine terrain. In **Slovenia**, a system of firefighting infrastructure (firebreaks, firewalls, fire trails, fire warning boards, fire-fighting infrastructure sign boards) is built and maintained in areas with highest fire danger. The Slovenian Forest Service, in cooperation with the forest owner, ensures the regeneration of burned areas and forests damaged by natural disturbances. A close-to-nature forest management system is used in Slovenia, which is also suitable for the Alpine region. Characteristics of this close-to-nature forest management are:

- Preservation of the natural environment and an ecological balance of the landscape;
- Sustainability of all forest functions;
- Integrated approach regarding the whole forest ecosystem;
- Imitation of natural processes and forms;
- Using tree species suitable for specific site conditions;
- Management based on a cognitive approach – constant monitoring and learning;
- Management based on long-term economic efficiency;
- Plans designed at a broader and more detailed level.

## FOREST FIRE RESEARCH

In July 2008, the UNISDR Wildland Fire Advisory Group (WFAG) followed the suggestions of the European Alpine countries to address the specific forest fire problems in the high-altitude regions of the Alps, and to establish a Sub-Regional Wildland Fire Network. With the launch of the Alpine Forest Fire Warning System (ALPFFIRS) project in 2009, consensus was reached that such initiatives play an important role in advancing research and development in the Euro-Alpine region.

Currently, many research groups work on forest fire research in the alpine context. At the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), in **Switzerland**, factors increasing forest fire risk are explored and tools



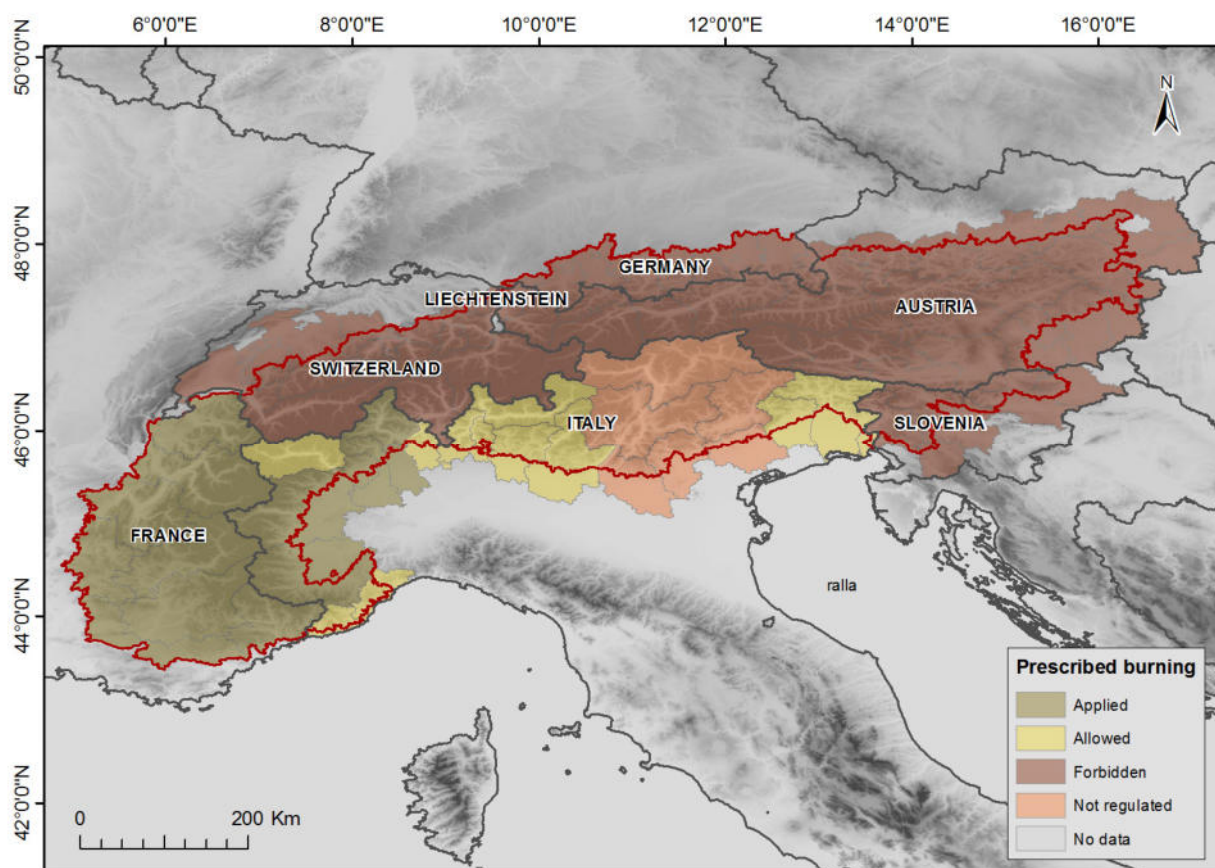
to predict forest fire hazards are developed. The group has developed the early warning systems FireLessII and FireNiche, which help forest authorities to assess the danger situation. The nationwide forest fire database Swissfire serves as the basis for medium-term forecasting methods and forest fire risk maps. With the **Austrian** Forest Fire Research Initiative (AFFRI) at the Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna, forest fires are nowadays documented homogeneously, those factors influencing fire ignition are being studied, and the elements of an integrated fire danger system are being explored to identify fire hotspots in the eastern Alps. In **Italy**, the Lombardia, Piemonte and Veneto regions in collaboration with Universities from Milano, Padua and Torino are working at characterizing forest fuel types and fuel models (Ascoli et al. 2015a; Rizzolo 2016) and at assessing forest fire risk based on fire behavior (Veneto Region 2018).

### **PRESCRIBED BURNING**

Prescribed burning is the use of controlled fires to achieve clearly defined land management goals. In the Alpine region, the main objectives of prescribed burns are fire hazard reduction in forests and shrublands, grazing management, habitat maintenance and firefighting training (Ascoli and Bovio 2013). Under certain conditions, this fire prevention measure is the most cost effective to mitigate high intensity fires in adverse conditions, and therefore a good method to prevent destructive crown fires and following natural hazards.

In the Alpine space, prescribed burning is mainly used in **France** where it is regularly planned and executed, particularly in the Alpes-Maritimes department (1000 to 3000 ha every year) – but not in the Alpine region. There are two main reasons for prescribed burns in the south-eastern parts of France: firstly, to diminish fire hazard by burning grass and bush under the tree canopy layer, and secondly, to burn small trees because of excessive growing of forest that decreases pasture possibilities. Prescribed burning practitioners in France are forest or fire technicians with a common training. They form a homogeneous community and share their experiences every year during meetings and publish the results online. In **Slovenia**, prescribed burning is part of a specialized forest fire training for firefighters (Jereb and Turk 2014). In **Italy**, there is no national law about prescribed burning. Instead, it is regulated by regional laws and regional fire management plans. Currently, it is only applied occasionally in Piemonte region (Ascoli et al. 2013b; Ascoli and Bovio 2013), while e.g. in Veneto region, it is not regulated. Encouraging experiences to promote prescribed burning were carried out in Friuli-Venezia Giulia region in 2008, involving the mayor of Taipana municipality, at the border with **Slovenia** (Valese et al. 2011).

In all other Alpine countries, prescribed burning is mostly not used and/or forbidden, e.g. for risk avoiding policies, lack of expertise, nature conservation concerns, forest law or air pollution control (**Figure 9**). Some regional exceptions can be found, e.g. in the southern parts of Lower **Austria** and **Slovenia**, where railway embankments are burned each spring to prevent forest fires from flying train sparks.



**Figure 9:** Prescribed burning regulations by countries and regions. No data available for Liechtenstein.

## AWARENESS-RAISING

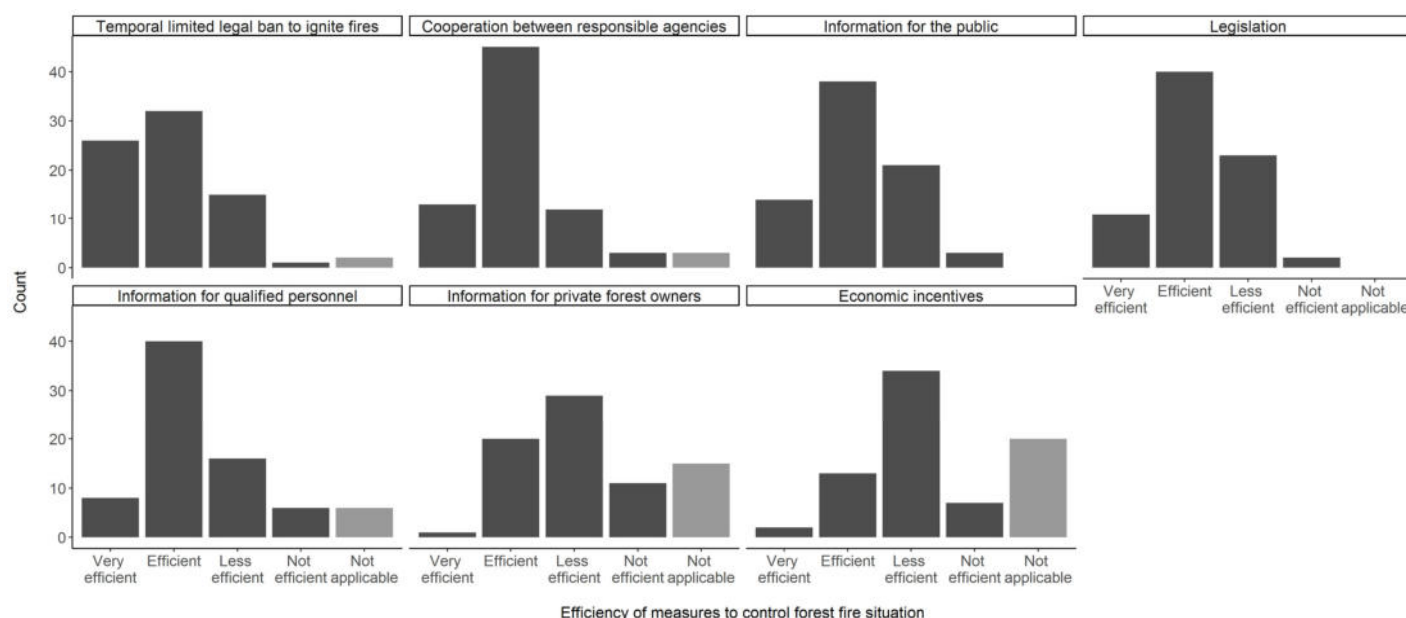
Currently, few measures are taken in the Alpine region to raise public's awareness of and knowledge about forest fires. In Upper **Austria**, the voluntary fire brigades teach the basics on forest fires prevention during school visits. After large fires in the **Italian** Alps in October 2017, awareness of the local population has raised, and new initiatives have evolved to manage forests on both private and public lands. The Piemonte region started a campaign to inform citizens about forest fire prevention, as well as to communicate the post-fire restoration measures set by the "Piano Straordinario Incendio 2017" (Regione Piemonte 2018). The ministry of interior in Bavaria, **Germany**, recently presented a new flyer about forest fire fighting to inform the general public. In **Switzerland**, many initiatives are taken at both federal and cantonal level to improve the communication about the current fire danger to the population and to inform about the importance of preventing large forest fires (e.g. Ghiringhelli et al. 2019; Reinhard et al. 2019; Roosli et al. 2019). In **Slovenia**, a campaign to inform citizens about forest fire prevention is especially conducted in periods of high fire danger.

The general awareness of forest fires and the knowledge about fire prevention measures, hazardous behavior and self-protection is low among the population in the Alpine region (EUSALP Survey). This results in incorrect behavior in

the forest (e.g. carelessly discarded cigarettes) or improper security measures during work (e.g. burning activities despite local drought). Inappropriate leisure activities can lead to forest fires, e.g. when campfires are ignited or fireworks are lit in the danger zone of the forest.

## FOREST LAWS

Forest laws in the Alpine region can be at national or federal state level. They generally include a section on forest fires and establish how to proceed in case of high fire danger. In **Italy**, the main law on forest fire is the n. 353 of 21 November 2000. Since forest management is a regional competence, the 353/2000 is a framework law. It gives the main guidelines for forest fire prevention and suppression. Every region and autonomous province has its own forest fire regional law, which regulates in detail the matter. The 353/2000 declares for every region to have a compulsory forest fire prevention plan. Concerning **Austria**, the forest act includes regulations regarding organization of suppression measures, planning suppression tactics, restoration efforts after forest fires and cost allocation for suppressing forest fires (ForstG - Forstgesetz 1975, §42, Ermächtigung der Landesgesetzgebung). Forest and forest protection laws are the subject of federal legislation in **Germany**. The Free State of Bavaria is responsible for the Alpine region (Bayerisches Waldgesetz (BayWaldG) of 22 July 2005 (GVBl. S. 313, BayRS 7902-1-L), last modified on 24 July 2019 (§8, GVBl. S. 408). Different laws are regulating the forest fire issue in **Switzerland** both at federal and cantonal level. The Swiss federal forest law (Lfo, SR 921.0) and the related Ordonnance (Ofo SR 921.01) define the prevention and restoration measures, whereas the Ordonnance on alarm (OAIIRS, SR 20.12) aims at protecting the population through a timely alarm when fire danger is high (cf. Reinhard et al. 2019). All these principles and rules are punctuated and detailed in the correspondent cantonal laws. In **Slovenia**, Fire Protection Act, Forest Act and Decree on fire protection in the natural environment regulate the field of forest fires at national level. The efficiency of the legal measures to prevent forest fires in the Alps is shown in **Figure 10**.



**Figure 10:** Degree of efficiency of the measures in place to control the forest fire situation in the Alpine region (shown are the values for all countries). Source: EUSALP Survey

## RESTRICTIONS AND LEGAL FIRE BANS

In **Austria**, the national forest law allows the district authorities to issue legal forest fire bans in case of high fire danger. These bans include prohibition of lighting a fire and smoking in the forest and its danger zone. Theoretically, it is possible to impose bans on access to endangered forests, but this is not issued in practice. In some regions forest fire bans are issued on a certain date (e.g. beginning of March) and are in force until late of autumn, independent of actual weather conditions.

Forest fire regulations in **Germany** are subject to the state forest laws. Each state has its own implementation measures and distributes the competencies to the different levels of administration. Often the authorities at the district level have the possibility to issue legal regulations to prevent forest fires (e.g. prohibition of visiting forest areas with high forest fire risk or ban of lighting fires in the forest and its vicinity). These regulations are not uniform among states, e.g. the possibility to ban visitors' access to the forest only exists in some states. In Bavaria, permissions are needed to use fire in a 100 m buffer from the forest border. Smoking and controlled fires in forests are not allowed from 1 March to 31 October (some exceptions apply for forest owners, hunters and rescue services). There are no additional fire bans used.

In **Italy**, fire bans are regulated at regional level and sometimes at municipal level. In general, land burning is always forbidden. Burning activities from agricultural and forest residues is allowed under permission, except during periods of high fire danger. Touristic fires (e.g. campfires) are allowed in picnic areas outside the high fire risk season. Fire bans can also be issued at municipal level to reduce air pollution. The closure of forests under high fire danger conditions is possible if this measure is included in local fire prevention plans.

In **Slovenia**, the decree on fire protection in the natural environment allows the municipalities to issue legal forest fire bans in case of high or very high fire danger for the municipality's area. The decree also foresees special measures to be taken during periods when high or very high fire danger is declared. The forest act prescribes that fires may not be lit in forests except at designated fire sites and only for the purpose of eradication of overpopulated insects and forest tree diseases posing a threat to forests. Grassland and fallow land burning in areas where fire could threaten a forest is prohibited. Stubble burning in fields is only permitted in the presence of an adult who has the fire under control.

In **Switzerland**, fire bans are regulated by the cantonal forest laws and the related ordonnances or decrees of application. No other limitations are foreseen by the law.

### 1.6.2. Short-term fire prevention

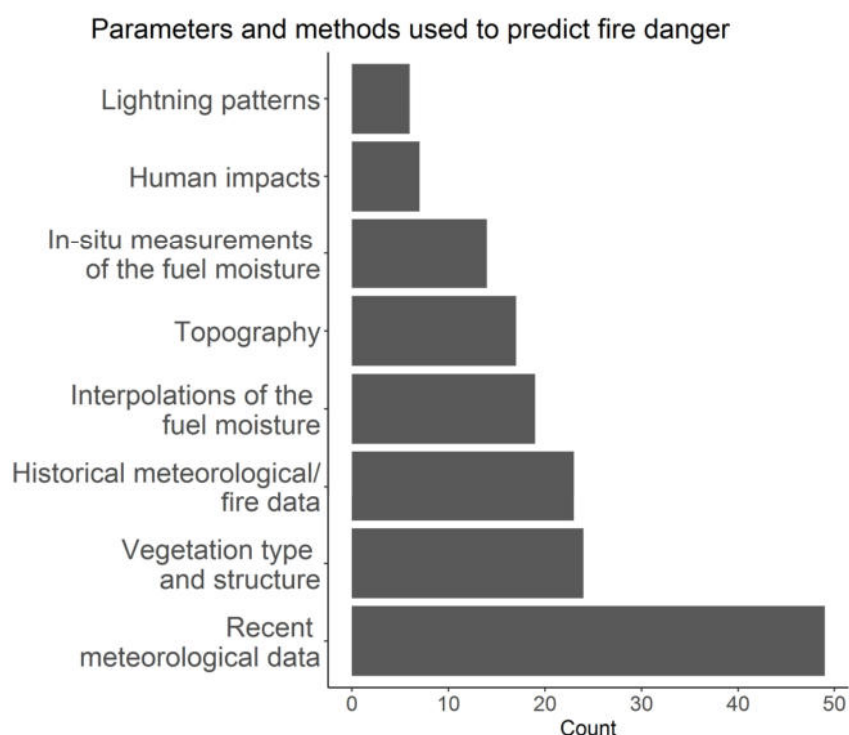
Fire danger monitoring and assessment (and related measures in case of fire danger) are short-term key issues to prevent devastating forest fires. Fire danger assessment should give a comprehensive overview on the current fire danger (potential of fire ignition, expected fire behavior) in a specific region based on high-resolution data.

## FIRE DANGER ASSESSMENT SYSTEMS IN THE ALPS AND EUROPE

In most European countries national or regional weather services or authorities provide an assessment of forest fire danger on a national level (e.g. German Weather Service (DWD) in **Germany**, Central Institute of Meteorology and Geodynamics (ZAMG) in **Austria**, ARSO Meteo and SFS portal *Varstvo gozdov Slovenije* (<https://www.zdravgozd.si>, Ogris 2018) in **Slovenia**, National Civil Protection Department (DPC) in **Italy**). In **Switzerland** and **Liechtenstein**, the



Federal office for the environment (BAFU) coordinates and harmonizes the information provided by the single Cantons and the Principality publishing in a nationwide overview map (Reinhard et al. 2019). In the Alpine region, the most used system is the (adapted) **Canadian FWI** with actual meteorological data (e.g. from ALADIN in **Slovenia** and INCA in **Austria**), sometimes combined with vegetation information (**Figure 11**).



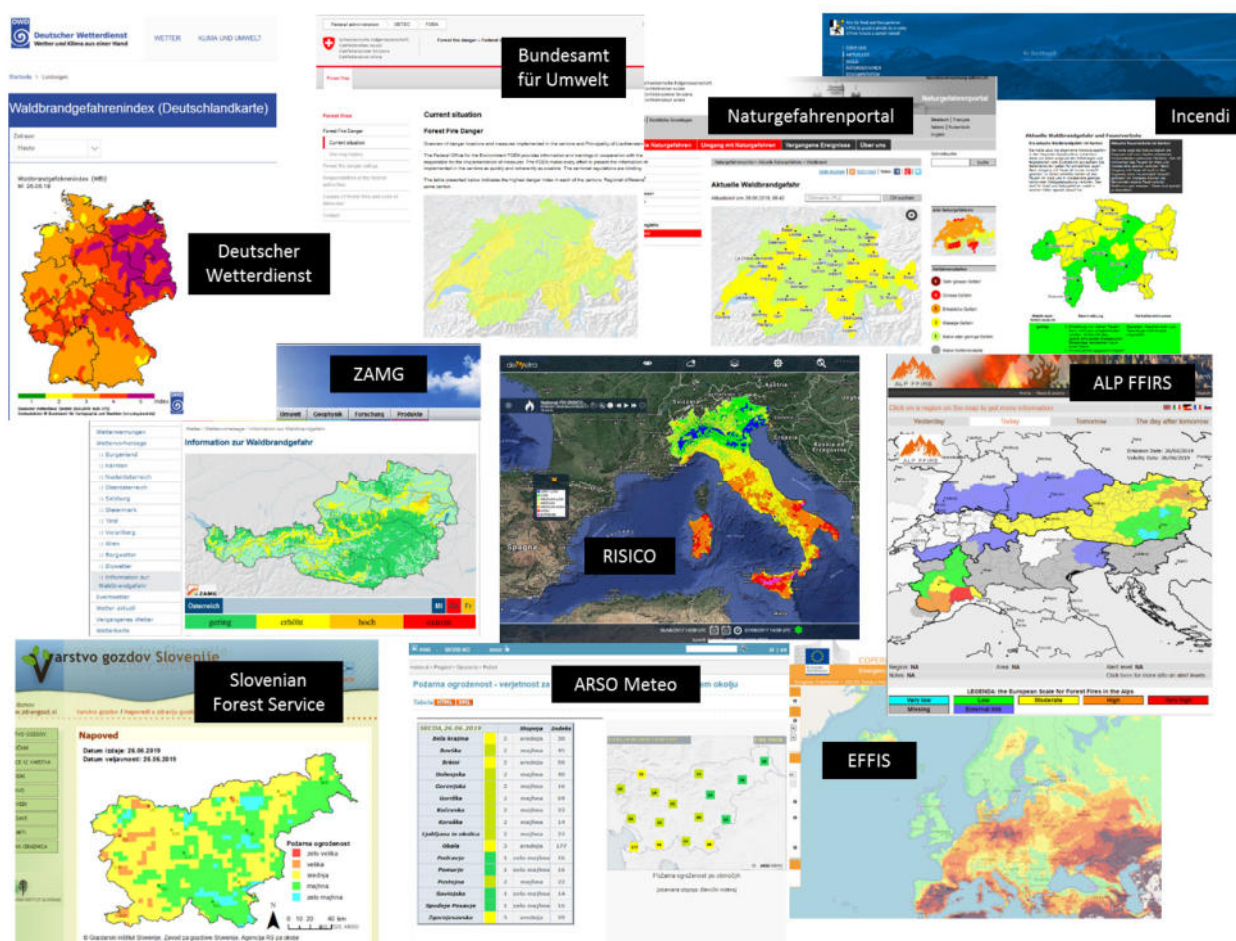
**Figure 11:** Parameters and methods used to predict fire danger in the Alpine region (shown are the results for all countries). Source: EUSALP Survey

The **Joint Research Center (JRC)** of the European Commission hosts the European Forest Fire Information System (**EFFIS**), which is part of the Emergency Management Services in the EU Copernicus program. EFFIS offers a trans-European and area-wide forest fire danger assessment with an operative spatial resolution of 8 x 8 km<sup>2</sup>. Especially in the Alpine region this rough scale is not very meaningful. National forest fire danger assessments use regional meteorological models that lead to a spatial resolution up to 1 x 1 km<sup>2</sup> (e.g. from ZAMG in **Austria**).

In **Switzerland**, two additional approaches for the regional daily fire danger assessment have been developed: The statistical approach **FireNiche**, that models the local fire-enhancing meteorological niche by combining best fitting meteorological variables and indices (De Angelis et al. 2015), and the **FireLessII**, a wireless sensor system that provides hourly fuel moisture values of selected representative forest stands (Conedera et al. 2014). In **Germany**, the WBI (for high forest), an adapted Canadian FWI, and the grassland fire index (for open areas) are used in summer together with expert assessments. In winter, the fire indices are adapted by including alpine stations data, alpine climate monitoring

and input from a group of district foresters delivering special information from their region. In **Slovenia**, the developmental stage of the vegetation is included in the danger assessment on forest fires. Currently, a new fire danger assessment model is being developed, based on the occurrence of past fires (Šturm 2013). In **Italy** and **France**, a modified Canadian FWI together with expert knowledge is used for danger assessment. In **Italy**, the RISICO system is centralized and managed by the Civil Protection. At the regional administrative level in Italy, departments of Environmental Protection (ARPA) (and Regional Forestry Corps in autonomous regions) prepare daily bulletins of fire danger forecast. This fire danger forecast considers weather conditions and climate, and, in some regions, it also includes vegetation, physical state and land use, morphology and organization of the territory, thus making it a more complex index than currently used in Austria, Germany or Switzerland. In **France**, an expert team of meteorologists is dedicated to fire weather forecasts during the summer season. They produce predictions on areas of 668 km<sup>2</sup> on average, i.e. with homogeneous fire weather regime (Lahaye 2018) (**Figure 12**).

In most Alpine countries, the model output data is validated and may be edited by an expert based assessment (known from Austria, France, Germany, Italy and Switzerland).



**Figure 12:** Screenshots of the national/regional forest fire danger assessment systems in the Alpine region.

## DISSEMINATION OF THE FIRE DANGER SITUATION

Awareness-raising of the population is essential for fire prevention in times of high meteorological fire danger. In **Switzerland** and in **Slovenia**, when the degree of danger becomes remarkable, fire danger is communicated via internet and traditional media (newspaper, radio, television) to the public. In **Austria**, up-to-date information on forest fire danger is disseminated via the central meteorological service in Austria (Zentralanstalt für Meteorologie und Geodynamik - ZAMG) and a forest fire blog operated by the Austrian Forest Fire Research Initiative (<http://fireblog.boku.ac.at>). High fire danger is also disseminated over the media by forest authorities or state fire brigades. In **France**, a forest fire smartphone application is available and used for awareness-raising. In **Germany**, there are official warning broadcasts via road traffic information on radio as well as by the German Weather Service (Deutscher Wetterdienst, DWD). A similar nationwide app as in France is planned. Aerial observation flights are featured by the media and thus contribute to public awareness as well. In **Italy**, Mediterranean fires steal the spotlight in the news, making it more difficult to justify and fund fire prevention measures for the Alpine region. Dissemination about fire danger is given mainly by the regional administrations. However, media are usually more interested in fires in summer, when extreme conditions are present, rather than during winter, when also large fires can occur if dry and windy conditions are present.

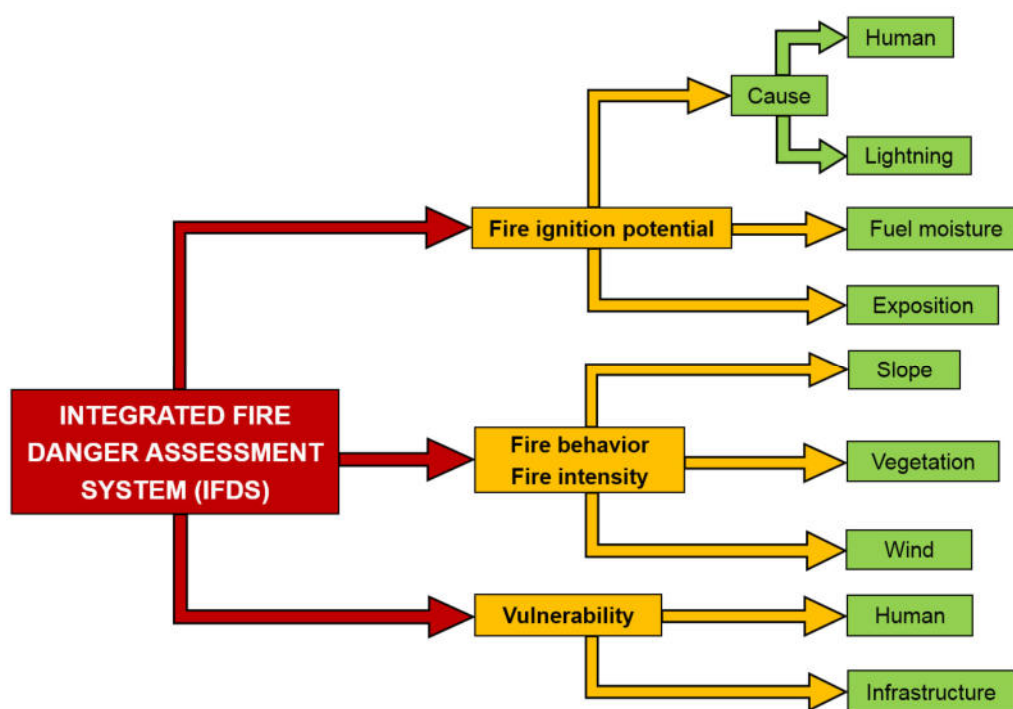
**Visitor information** in the forests indicating the current and local fire danger in the Alpine region is rare or of static nature, i.e. it is permanently attached, irrespective of the actual forest fire danger. Therefore, an effective visitor guidance appears questionable. A widely known example of a dynamic visitor information is “Smokey the Bear” in the USA. This system is present at all main forest entrances and informs the public about the current forest fire danger in a specific region. A summary of fire prevention measures applied in the Alpine region is shown in **Table 3**.

**Table 3:** Fire prevention measures in the Alpine countries. No data available for Liechtenstein. The fire danger indices are explained in chapter 1.6.2. Sources: National/Regional databases, Forest fire workshop Vienna, EUSALP survey.

	Austria	France	Germany	Switzerland	Slovenia	Italy
Indices used for fire danger assessment	FWI	FWI (adapted)	WBI	FWI (adapted), Fire Niche, Fireless	FWI (adapted)	FWI and adapted FWI (RISICO)
Differentiation between ignition and propagation in fire danger assessment	No	Yes	No	No	Yes	No
Use of legal fire bans	Yes	Yes	Yes	Yes	Yes	Yes
Inclusion of fire prevention measures in forest management plans	No	Yes	Partly	Partly	Yes	Yes
Execution of prescribed burning	No	Yes	No	No	Yes (outside forests)	Partly

## INTEGRATED FIRE DANGER ASSESSMENT SYSTEMS (IFDS)

An IFDS integrates long- and short-term fire danger assessment (including estimations on fire hazard, fire vulnerability and fuel moisture content), see chapter 1.2. Most current fire danger assessment systems only rely on fire weather parameters. However, the anthropogenic influence on the fire regime can outsize climatic and natural factors and has, in some areas, the highest explanatory power for the occurrence of forest fires (Arpaci et al. 2013; Pezzati et al. 2013).



**Figure 13:** Model of an integrated fire danger assessment system (IFDS) with related components (orange) and necessary datasets (green). Adapted according to San-Miguel-Ayanz et al. 2018.

An integrated and harmonized procedure for wildfire risk assessment is needed at the pan-European level (San-Miguel-Ayanz et al. 2018). In order to generate an integrated forest fire danger assessment, the different vegetation forms/compositions and fuel quantities, topographic factors (altitude, slope inclination, exposure) as well as the regional heterogeneity of climatic conditions in the Alpine region have to be taken into account. In addition, potential fire causes (including human influence) and vulnerabilities (e.g. social impact, loss of human life, critical infrastructure) should be considered for reliable risk modeling (**Figure 13**). First attempts in this direction were done in **Switzerland** (e.g. Conedera et al. 2011; Conedera et al. 2015). In **Austria**, a prototype of an integrated fire danger assessment system was established on a spatial resolution of 100 x 100 m (Müller et al. 2020). It should be noted that even a spatial resolution of 1 x 1 km – which is quite high for meteorologically interpolated data – is not sufficient to accurately describe the conditions on mountain slopes. Snow melts sooner on southern slopes, which are drier and have a different tree species composition than northern slopes. It is the knowledge of such small-scale features of forests that is decisive for the ignition and propagation of fires.



### 1.6.3. Pre-suppression of fires

The pre-suppression of fires includes all measures associated with firefighting preparation. Adequate **equipment** and **trainings** of firefighters and action forces are crucial for quick, effective and secure firefighting operations in the highly heterogenic Alps. The trainings in some regions (e.g. **Austria**) include realistic fire scenarios and trans-national exchanges.

A well planned and maintained **forest infrastructure** is crucial when fighting fires, especially in remote areas of the Alps. In general, the density of forest roads in the Alpine region is high compared to other European regions (e.g. Mediterranean, Scandinavian countries). In 2009, the Slovenian Forest Service in cooperation with the Administration of the Republic of **Slovenia** for Civil Protection and Disaster Relief, prepared and issued an “Atlas of fire protection facilities”. The Atlas shows a cartographic map of all fire-fighting infrastructure in the Karst, Brkini, Čičarija and Slovenian Istria. In addition, it features all infrastructure facilities such as power lines, gas pipelines, hydrology, orography, settlements and a mask of the forest type. At the border to **Italy**, the Atlas is supplemented by the same content on the Italian side. Planning is done in collaboration between SFS foresters, firefighters and locally community, and in the long term with clearly defined priorities. Important elements of fire intersections include avoidance areas, turning points, entry platforms and intervention platforms. The main structural interventions in **Italy** are the construction of forest roads in high risk areas and of aboveground and underground permanent water tanks. In **Germany**, there are maps for fire service deployment available which include information on forest roads (e.g. weight of fire vehicles permitted, points for taking up water, emergency points). In some regions of **Switzerland**, forest fire-specific emergency plans are in place (on the level of communities/forest districts). In **Liechtenstein**, both emergency planning and intervention planning are being implemented throughout the country.

### 1.6.4. Detection of fires

The low awareness of forest fires among the Alpine population is countered by the **active willingness to report** them: If smoke rises in the forest or even flames can be seen, it can be assumed that a telephone call reaches the warning center within some minutes. For this reason, most forest fires in the Alpine region can be attacked shortly after they are started, especially in countries with a dense network of volunteer fire brigades, such as **Austria** or **Switzerland**. In **Italy**, during the high fire danger season, the surveillance of forest areas has improved, particularly in high fire risk areas. Surveillance is done by the Carabinieri forestali, members of civil protection, the local police, or volunteers from forest firefighters. In **Germany**, air observers in small fixed-wing aircraft fly to spot smoke/fires and usually consist of a specially trained firefighter and a forester.

In the future, **drone systems** may help to early detect forest fires in remote terrain. In **Switzerland**, drones are occasionally used to identify existing hotspot during firefighting operations (especially in case of smoldering fires below the ground). Tests have shown that drones (even professional devices) are very sensitive to wind. Together with a corresponding dense canopy, its use seems to be limited. In **Austria** and **Germany**, there are also attempts with drones to discover hotspots and new fire sources. At the Department of Mechanical Engineering at the Technical University of Munich (TUM), scientists and TUM's own fire service have developed a drone system to gain real-time images during firefighting operations (<https://www.mw.tum.de/aktuelles/news-singleview/article/multicopter-projekt-copka-echtzeitbilder-fuer-den-feuerwehreinsatz>). A similar approach may be also be used for forest firefighting in the Alps.

Systems to **automatically detect forest fires or smoke** from fires are currently implemented and used in the northern and central parts of **Germany** and in a southern region of **Slovenia**, but not in the Alpine region. In the particularly forest fire endangered regions of **Germany**, a partially automated camera surveillance system has been developed and installed in recent decades, which helps to detect fires at an early stage and to quickly guide firefighters to the fire. It would be worth considering whether such a system could also be installed in the most forest-endangered areas within the EUSALP region. The German system is called AWFS („Automatisches-Waldbrand-Früherkennungs-System“). Analyses show that such systems can reduce the burned area significantly (Chtioui and Kaulfuß 2019). However, currently installed sensors mostly monitor flat areas. Therefore, relatively few cameras mounted on towers can observe large areas to pinpoint smoke. This may be much more difficult in complex terrain like the Alps.

#### 1.6.5. *Suppression of fires*

Fire suppression in the Alpine region needs specific **equipment** and **tactics** due to the mountainous terrain. Where possible, tank tenders in combination with water tanks, ponds, hydrants and/or long fire hose lines are used. Independent fire pumps are utilized in case of large differences in height. In remote terrain, initial firefighting is often carried out with fire rakes and fire beaters to prevent ground fires from further spreading. Firefighting backpacks or high-pressure lances are common to reach glowing hot spots beneath the surface. Sprinkler systems to wet the vegetation are sometimes used in the southern parts of the Alps, especially during night hours and at firebreaks. Off-road firefighting vehicles and quads are only sporadically available. In **Italy**, all units specialized in forest fires have all-wheel drive pickups equipped with firefighting modules that are able to move on narrow alpine forest roads. There are also a smaller number of 4wd water tanks available, used mainly for supporting pickup operations. In **France**, ground suppression is mainly based on all-wheel drive water tanks working in groups. **Helicopters** and/or fixed wing air support are essential for an effective fire suppression in the heterogenic and small-scaled environment of the Alps. In all Alpine countries there are firefighter units, which are specially trained to work with helicopters, water buckets, winch operations, etc. In **Austria** and Bavaria, **Germany**, helicopters are increasingly used to transport water to mobile basins placed near the fire, from which ground troops lay hoses, especially in the mop-up phase.

Ground and surface fires can be attacked directly at the fire front or at the fire flanks with ground troops. In case of steep or inaccessible terrain aerial support is essential to prevent fires from spreading. Because of the mountainous area, several **safety** issues have to be considered in the Alpine region, e.g. the danger of rockfall, risk of falling or new fires through burning tree parts that roll down the slope. If the terrain is steep, mountain rescue teams are often part of the action forces to secure firefighters. In areas of special interest during the First or Second World War, also the explosion of buried munition and bombs can be an issue for firefighter's safety.

While prescribed burns are a measure for long-term fire prevention, they have to be distinguished from **tactical burns**, which are used to control large fires, e.g. when igniting a counterfire to stop a head fire. Tactical fires are mostly used in **France** and **Italy** in case of large fires. They are uncommon or not executed in the other Alpine countries.

#### 1.6.6. *Post-fire management*

All measures executed after the extinguishing of a fire are part of post-fire management. Measures may be necessary to restore forest cover, protect against natural hazards, manage game density and monitor the burned sites. Post-fire management is case-specific, as each fire burns in a different manner and affects different elements of the landscape.

In the **Italian** Alps, the state of knowledge on post-fire management interventions advanced markedly in recent decades in both coniferous (e.g. Marzano et al. 2013) and broadleaves forests (e.g. Ascoli et al. 2015), and research findings helped in designing one of the largest post-fire restoration programs after large forest fires in October 2017 in the south-western Alps (Regione Piemonte 2018). In **Switzerland**, post-fire management aims at minimizing natural hazards (erosion, debris flows, shallow landslides) and may consist in aiding the reforestation of burned area by planting site and fire adapted species that increase future forest resilience to fires (Ghiringhelli et al. 2019). This same system of post-fire management is also applied in **Slovenia**.

### PROTECTION AGAINST NATURAL HAZARDS

Standing deadwood after forest fires protects against **gravitational natural hazards** for several years. Weakened trees, however, (e.g. needles scorched, xylem damages) may be infested by pests such as bark beetles and can die some years after the fire (Bär et al. 2018; Michaletz and Johnson 2007). At present, there is no uniform procedure in the Alpine region for dealing with trees that have died as a result of forest fires. If access to the burned site is practicable, sometimes nearly all trees are harvested in order to achieve the highest possible proceeds, regardless of whether this is the best approach from a forestry point of view.

Even after intense forest fires, the first green usually sprouts within a few days on sites where sufficient seed and living rhizomes remain in the unburned topsoil and weather conditions are favorable. Especially in mountainous regions and in protection forests, the sowing of fast-growing grass is applied to support this development, like it was done at the largest recent forest fire site in **Austria** (Absam in Tyrol 2014, cf. **Table 2**). Heavy rainfall events within the first weeks after a fire may lead to significant erosion or **mudslide** events (e.g. Gehring et al. 2019). It is possible to calculate the rain intensity and potential damage in a given burned area. In some Alpine countries, alarm and safety precautions are issued (e.g. the closing of endangered roads when large amounts of rainfall are predicted). In **France**, the most disturbed areas are the forests established a little more than a century ago to stabilize soils (RTM Forests), which are mostly difficult to treat after a fire and are often subject to erosion recoveries today.

### RESTORATION OF FOREST COVER

Natural reforestation can be expected on areas without extreme topographical, climatic or pedological aspects. However, depending on the location, this process can take a long time, that is why supporting measures such as planting trees and preparing the ground vegetation may be necessary. In unfavorable locations, extensive efforts must be made to secure or restore the forest stand. In the western Alps research programs identified effective post-fire measures to restore Scots pine (Beghin et al. 2010) and beech forests (Ascoli et al. 2013a) after large fires.

### MONITORING AND CASE STUDIES

There are several monitoring sites and case studies regarding forest fires in the Alpine region, especially in the Southern Alps. For example, after the forest fire in 2003 in Leuk, **Switzerland**, researchers established a comprehensive monitoring program, which brought new knowledge on fire behavior and on vegetation regrowth and reforestation. Some tree species such as European larch (*Larix decidua*), Swiss stone pine (*Pinus cembra*) or black pine (*Pinus nigra*) are highly resilient to ground fires because their thick bark protects the living cambium from high temperatures. After a forest fire in Jochberg, **Germany** (cf. **Table 2**), a restoration plan was set up, which included the construction of a system of paths and the planting of Scots pine trees. The costs were charged to the people who caused the fire and to their liability insurances. On a fire site in Lower **Austria** it was observed that black pines still show a good survival rate even with 60-70% of their crowns scorched. At the forest fire site in Absam, **Austria** (cf. **Table 2**), trunks of surviving

Norway spruce (*Picea abies*) were found to be more damaged than Scots pine (*Pinus sylvestris*). Therefore, higher mortality rates are expected with spruce trees (Bär et al. 2019).

### INVASIVE NEOPHYTES

Neophytes are an issue in the European and Alpine forests as several studies have already shown (e.g. Pötzelsberger et al. 2018). In **Italy** and **Switzerland**, some studies have focused on the spread of invasive neophytes after fires (Lonati et al. 2009; Maringer et al. 2012). One example of an invasive species common in the Alpine region is the tree of heaven (*Ailanthus altissima*). This species can cope with unfavorable conditions and displaces other species by the release of toxins (Lawrence et al. 1991).

### 1.7. Legal bases, processes and governance

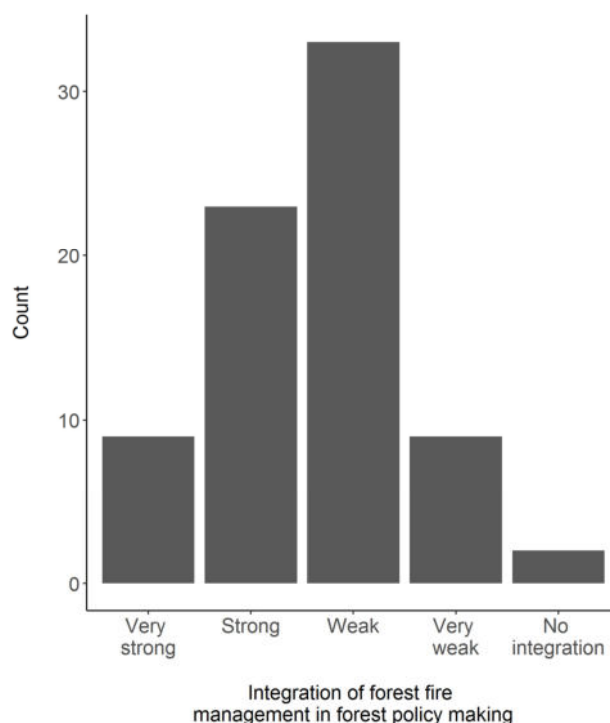
A common forest policy at EU level does not exist. The instrument in place is the **European Forest Strategy**, which serves as a holistic framework for national forest policy development. Forest fires are not tackled directly by a single policy but are influenced by other forest-related policies at EU level. The Member States rely on the European Agricultural Fund for Rural Development to financially support national forest fire prevention activities and forest restoration, and on the EU Solidarity Fund to receive financial aid after a major natural disaster (European Commission 2019). In 2018, the European Commission decided to upgrade the rescEU mechanism to help member states to face natural disasters. Part of the mechanism consists of providing support for firefighting planes. The Commission Expert Group on Forest Fires is also established within the European Commission.

It is assumed that transnational fire management plans are not realistic and that it is more expedient to establish them on a local level, as they sometimes do not exist at all (e.g. in **Austria**). In the northern Alps, there are often no specific programs or subsidies for fire prevention. From the Mediterranean regions of **France** and **Italy**, it is known that banning fires is a necessary and useful tool in dry seasons to reduce unintentional fires but is not enough under extreme conditions, as fires ignite anyway (e.g. from arsonists or hazardous behavior of farmers and shepherds). In **France**, a large number of preventive measures are financed and implemented by local authorities regardless of the nature of the land, with possible state and EU subsidies on Rural Development Plans. These measures may include public awareness, fire detection, warning and patrols. Funding for technical equipment can be directly granted to landowners (local authorities and private owners). In **Slovenia**, the rules on financing and co-financing investments in forests define the funding for fire measures in fire-endangered forests, e.g. fire protection infrastructure, installation of warning signs or forest protection works. Most fire protection measures are covered by a subsidy from the state budget. In **Italy**, regional forest fires prevention plans include measures for fire prevention and often include also a budget for measures implementation. Usually the main part of the budget comes from measures of the Rural Development Plan dedicated to risk reduction interventions, to which both privates and public organizations have access. In **Switzerland**, the financial subvention of agriculture helps maintaining the rural and forest landscape. Special aid payments are also devoted to the restauration of agricultural land, such as meadows or pastures, and of chestnut orchards. These latter are often situated in the neighborhood of settlements, playing a role at the wildland-urban-interface (WUI) and lowering the danger of ignitions spreading to the forest.

It is not only forest policy that is relevant to prevent forest fires, but also the **rural policy**. Farmers, forest landowners and the public have to be included to foster comprehensive fire management plans. Since fire causes are tightly bound



to human behavior, other policies can have an impact on forest fires as well. In Ticino, **Switzerland**, the prohibition of burning garden debris in the open at the end of the 80's, which was done for air quality reasons, had a great impact on fire ignitions, which were halved in the following decade.



**Figure 14:** Degree of integration of forest fire management in forest policy making in the Alpine region (shown are the values for all countries). Source: EUSALP Survey

## PROGRAMS FOR FIRE PREVENTION

The “Plans de Prévention du Risque Incendie de Forêt”, in **France**, exist since about 20 years and have led to the development of fire risk maps. These maps are used to delineate areas where building or developing other activities is not allowed. In **Slovenia**, forest management plans are renewed every ten years and include a chapter about fire prevention. The Forest Service also makes plans for fire prevention annually, to get subsidies from the state budget. There are no specific fire prevention programs in **Austria** and **Germany**. In **Italy**, regional fire prevention plans were introduced from National Law 47/1975 (abrogated by National Law 353/2000). The fire prevention plans have to be updated every three years. In 2018, the new Italian Forestry Law 34/2018 was approved; it introduced relevant aspects for forest fire prevention. Both Art. 3.2c and Art. 7.1 include fuel management techniques in forested areas within silvicultural practices, with cascading effects on authorization protocols. Of particular interest is Art. 12, which states that in high fire risk areas where public safety issues are identified, regions can implement fuel management programs in accordance with land owners or, when absent, with direct replacement or assignment of the management of the land involved to companies or consortia. Small scale fire prevention plans (“operationa”) are currently being developed in the country outside the Alpine space (**Figure 14**).

## 2. Current and future challenges

One difficulty of future forest fire management is to find a good balance between actions on fire prevention, fire suppression and post-fire management. Today, greatest focus and most money is spent on fire suppression. Especially in the Alpine region, too little attention is paid to forest fire prevention and not enough measures are present. However, it will be necessary under the assumed coming intensified fire regime.

### 2.1. Changing environmental and socio-economic conditions

Two main factors influence the current and future challenges of an integrated fire management: The changing environment (especially climate change) and the changing socio-economic conditions (such as rural abandonment and intensified recreational activities).

#### CLIMATE CHANGE

The Alps are among the most affected regions by climate change (Cane et al. 2013; Dupire et al. 2019; Lindner et al. 2010; Pauli et al. 2003; Wastl et al. 2012). In recent years, several drought and temperature records occurred in the Alpine region, like the driest July ever recorded in 2013 in **Austria** or the extremely hot summer in 2015 (Müller et al. 2017). This drought led to anomalies in the current forest fire regime (cf. Chapter 1.4). Depending on the assumed climate scenario, a temperature increase of +2 to +5 °C can be expected in the coming decades. While precipitation is likely to increase in winter, longer heat waves and droughts are most likely in summer (Gobiet et al. 2014; IPCC 2014; Trnka et al. 2016). This results in more days with a high fire danger in the Alpine region. Drought, on the other hand, may induce higher tree mortality rates, thereby increasing fire hazard (Allen et al. 2010; Anderegg et al. 2015; Choat et al. 2018). At the same time, extreme precipitation events will probably increase. The fluctuations between very dry and very humid conditions are likely to increase in the future, leading to new challenges regarding equipment and operational tactics of fire brigades and action forces. Reduced snowpack (both in surface and in duration) increases the exposed areas to winter fire, which will probably become a greater problem in the future.

Within the project FIRIA (Fire Risk and vulnerability of Austrian forests under the impact of climate change) the future occurrence of forest fires in Tyrol, **Austria**, was estimated. The Canadian Build-Up Index (BUI) was applied, a sub-component of the Fire Weather Index (FWI) that correlates well with the distribution of summer forest fires in Austria (Arpaci et al. 2013). The number of days in the highest BUI classes were analyzed. The model calculations simulated by regional models (ALADIN, RegCM3 and REMO) showed that the number of days with high forest fire danger might increase regionally by more than 40 days until 2100. In the future, even areas that have not shown any relevant risk will be increasingly endangered (Sass 2014). This applies in particular to protection forests. The results of the Tyrolean study may be transferable to other Alpine regions.

The change of the fire regime in the Alpine region will probably occur within the next decades (Forest fire workshop Vienna). A rapid and disruptive change is more likely than a steady one, which means that some low fire seasons will be followed by a very intense one. Weather conditions like in 2003 will happen every two years around the years 2030/2040 (Global and European temperature report 2019; Cane et al. 2013). While it is quite clear that the Southern Alps will encounter dryer and more fire prone conditions, the tendency for the Northern Alps is still uncertain. Many

indirect effects and tipping points may be relevant worldwide but also in the Alpine region (e.g. loss of arctic ice shield together with changed atmospheric circulation pattern in the northern hemisphere).

While the number of lightning strikes in Central Europe shows a decreasing trend since several years, the number of lightning induced forest fires seems to rise in most of the Alpine countries (National fire databases; Conedera et al. 2006). A recent study showed that high lightning activity does not correlate with more lightning induced forest fires, but local drought can lead to more ignitions despite a lower amount of lightning strikes (Müller et al. 2013).

Recent years showed that current fire seasons are shifting and expanding, or even new fire seasons are developing (Müller et al. 2015). This means in particular that late autumn and winter fires may become more relevant in the future, as the years 2011 (Schunk et al. 2013), 2015 and 2018 have already shown. While fires in the cold season have a limited impact on forest communities, especially summer fires under very dry conditions lead to a high mortality rate in the Southern Alps (Dupire et al. 2019).

### **SOCIOECONOMIC DRIVERS OF THE FIRE REGIME**

In addition to climate change, the main focus regarding drivers of future fire regime has to be put on human influence. Due to the increasing recreational use of the forest and a higher number of visitors, the number of potential ignition sources is increasing. Tourists will come earlier and leave later because of changes in the vegetation season. In addition, rural abandonment and declining management measures in private forests and the associated increase in deadwood can increase the intensity of uncontrolled fires and the risk of crown fires (Agee et al. 2000).

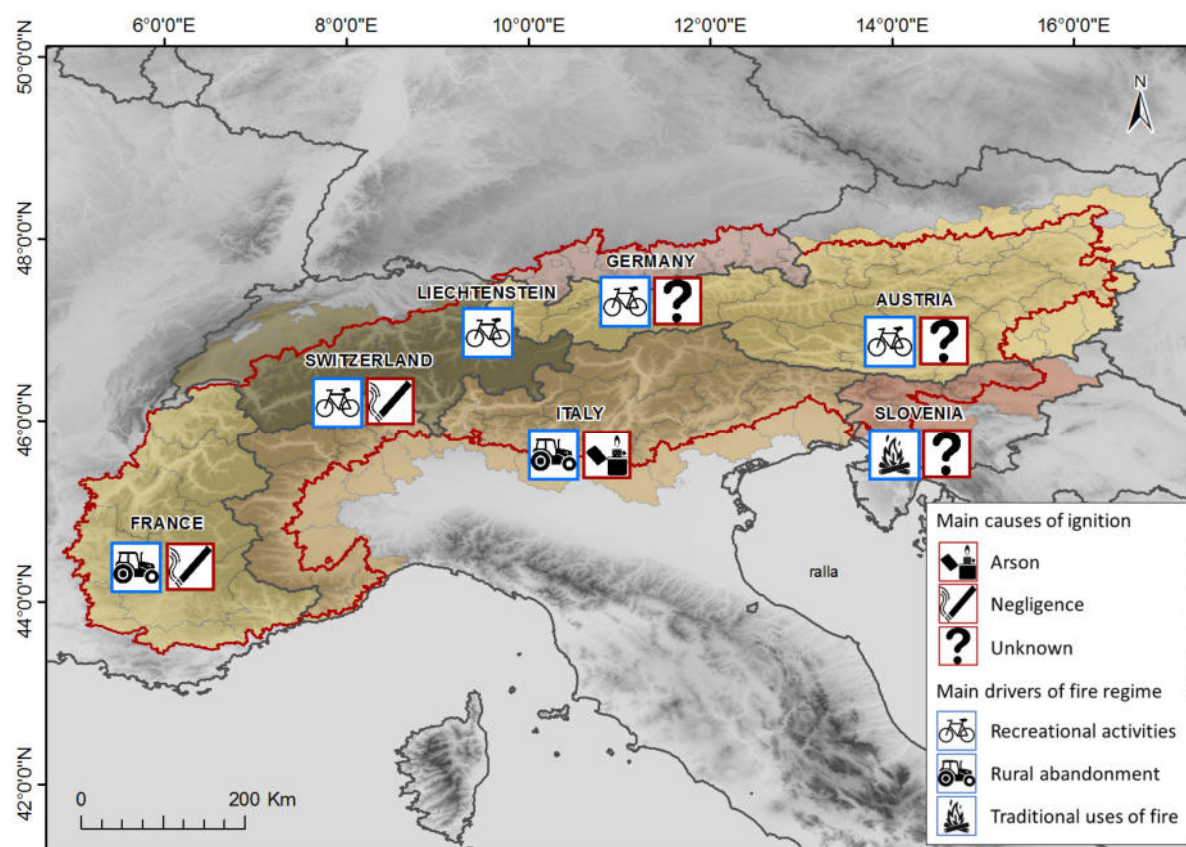
**Rural abandonment** is the most important reason for large fires in **France** and **Italy**. Beside climate, an increase in fuel quantity and connectivity is the crucial element that changes. Rural abandonment leads to the loss of pastures and the replacement of cultural firebreaks with fire prone brush lands. Also uncontrolled practices of pastoral burning are increasing (Pezzatti et al. 2013). Moreover, an aging rural population is more vulnerable to fire events. The maintenance of the forest and its infrastructure (e.g. water availability, forest accessibility, fuel amounts, road maintenance) is one key challenge in the future. This maintenance services are also needed for harvesting purposes, tourists and infrastructure. **Tourism and recreational activities** are the most important social factors for forest fires in **Austria, Germany, Liechtenstein, and Switzerland (Figure 15)**.

Another topic which is likely to become more relevant in the future is the threat to the **Wildland-Urban-Interface (WUI)**, where urban areas (settlements, businesses, detached houses and critical infrastructures) border directly on forest and open land. Such situations can often be observed near large cities or on the edge of settlements, possibly as an effect of the desire for “proximity to nature”. Expanding city areas are more affected and endangered when a nearby protection forest is hit by a fire. Most Alpine villages used to be cultivated or grazed in their surroundings. Especially in the Southern Alps most of these fields and pastures have been abandoned. Flammable vegetation encroached this area, leading to an increased fire hazard. In countries like France, USA or Australia, the problem of this phenomenon is well known. Many forest fire catastrophes with numerous deaths, also in southern Europe, resulted from the flames spreading to populated areas or hitting traffic routes.

In the Alpine region, the issue of the WUI is still hardly discussed. Recent fire incidents (e.g. Absam 2014 and Lurnfeld 2015, in **Austria**) showed that crown fires under the influence of strong wind can hardly be controlled and that the high propagation speed is dangerous for people, infrastructure and property. Considering the habit of some

homeowners to build their homes directly on the edge of the forest or even in the forest, this means an underestimated risk, especially in fire-prone forests. A recent example of such a scenario dates back to August 2018 in Eastern **Germany**, when a fire on the embankment along the railway tracks near Siegburg was triggered by flying sparks, seriously damaging eight houses and injuring 32 people (Extra-Blatt 2018).

Given the mentioned changes of the primary drivers of forest fires in the Alpine **forest fire frequency, size and intensity are expected to increase in the future**. This results in rising costs for combating forest fires, for example through more helicopter operations. In the case of several major fire events at the same time, there could be a bottleneck in the **availability of helicopters** in the future, making effective firefighting in the Alps more difficult. More fire events also result in higher restoration costs for the affected forest areas and lead to cost-intensive safety measures against consequential hazards such as erosion, rockfall, avalanches or mudslides.



**Figure 15:** Main causes of fire ignition and main drivers of fire regime in the Alpine countries.  
Source: National/Regional databases, EUSALP Survey.



## 2.2. Fire prevention

Key challenges in fire prevention lie in the preparation of fire risk maps, an adapted forest management planning, awareness-raising and improved fire danger assessments.

### LONG-TERM FIRE PREVENTION

It is necessary to identify fire “hot spots” in order to develop proper fire management activities. **Fire risk maps** that include fire hazard (endangered vegetation), fire triggers (human and lightning) and fire vulnerability (e.g. endangered infrastructure, settlements and potential damage) are only available in some regions of the Alps, e.g. in **Switzerland**. To generate such maps on a local scale, fire hazard modeling is necessary to identify endangered forest types in combination with topographic effects. In **Austria**, first attempts to include vegetation, topography and potential fire triggers (but not vulnerability) for a nationwide risk assessment were recently started. At the moment no vulnerability analysis is done to extend fire hazard to fire risk. In **Italy**, each region must produce fire risk maps in regional fire management plans; however, a national standard for fire risk assessment at regional level is not in place. The methodology varies greatly from region to region. The oldest maps were mainly based on empirical approaches. The new generation of risk maps are based on fire behavior simulations to assess fire hazard, on forest ecosystem services provision and on exposed people and infrastructure to assess fire vulnerability. In **Slovenia**, each region must produce fire risk maps in regional and national forest plans which include fire risk and fire triggers mainly based on empirical approaches. The methodology to define the forest fire hazard level is prescribed in the Forest Protection Regulations.

It is essential to integrate actual scientific knowledge in **forest management** planning. A shift of tree species composition in forests with high fire risk is a good practice to adapt forests to fire. However, site conditions limit tree species choice, as there is no “free” choice. Also, some species are more adapted to fire than others (Dupire et al. 2019). On the Jochberg fire site in **Germany** (cf. **Table 2**) Scots pine was chosen again as main tree species, as it is well adapted to the local site conditions and as the existing trees proved a surprisingly high fire tolerance.

The lack of site maps that take into account changing precipitation and temperature conditions in the Alpine region in the future, poses a challenge for the selection of appropriate tree species. Besides tree species choice, it is also important to address small-scale forest owners, to include risk assessments in plans (e.g. climate change scenarios, invasive plants) and to manage forest works residues in order to reduce ignition possibilities in high endangered areas. In the Alpine region, silvicultural fire prevention measures are only implemented sporadically. Pure **Norway spruce** stands (*Picea abies*) exhibit a high risk of various damaging factors and, with regard to the predicted global warming, also a lower resilience (Lexer et al. 2014). In addition, spruce forests contain significantly higher amounts of fuel than pine forests, thus potential forest fires can reach higher intensities and develop more rapidly into crown fires (Arpaci et al. 2013). In **Germany**, there are successful examples of the understory replacement of pine stands by hardwood species which have led to a change in within-stand climate and reduction of flammability (Otto 1980). Yet, this study is from Lower Saxony, a lowland area far from the Alps. Transferring the results to the Alpine area may be problematic.

**Fuelbreaks** make particularly sense in fire prone areas characterized by relatively frequent forest fires or where large fires can develop, such as in broadleaves and Scots pine forests, shrublands and grasslands in the Southern Alps, or black pine forests at the eastern edge of the Alps. In mountain areas, especially on steep terrain, this measure has been poorly implemented because of high costs of realization and potential risks of erosion or windthrow. Due to extensive management and rural abandonment in mountain forests, but also with respect to nature conservation and



biodiversity increase, considerable quantities of **deadwood** can remain in the stock leading to a potential higher fire intensity. Under today's ecological conditions, more importance is attached to nature conservation than to the protection against forest fires. A large quantity of deadwood also accounts for difficulties during firefighting, e.g. leading to new ignitions when lying deadwood and stumps are burning and rolling down the slope, compromising firefighters' safety and making mop-up operations more difficult.

Biotic and abiotic **disturbances** are already an issue in the Alpine forests. For example, bark beetle outbreaks in Norway spruce stands increased in the last years and are observed at higher and higher elevations. Interactions between disturbances may also alter the fire regime. Research is needed to identify potential negative effects, e.g. more fire ignitions on clear cuts after windthrows or higher fire intensities on areas where large amounts of small deadwood debris stay in the forest after bark beetle infestations.

A problem arises from the **owner structure** of native forests in the Alpine region. About 50% of the total Alpine forest area is attributed to small forest owners with an average of less than five hectares. Some forest owners do not have the necessary expertise in forest management, leading to inappropriate maintenance measures. It is difficult to clarify the risks of forest fires to small forest owners and to convince them of the need for preventive measures. The urgency of precautions against bark beetles and clearing work to deal with storm damage is more relevant for most forest owners. Currently, only a small number of technicians, decision makers and scientists in the Alpine country are part of **multi-stakeholder panels** regarding fire prevention strategies. The causes for such infrequent transnational activities are multiple, such as lack of availability of operational staff, high costs caused by travel and language difficulties (these exchanges often take place in English).

**Awareness-raising** is a key issue regarding the long-term prevention of forest fires, as current knowledge and awareness of fires within the Alpine population are low. There is a strong need for integrated approaches, including measures designed as bottom-up approach to be started in schools. It is necessary that measures on fire prohibition and right behavior in the forest in case of high fire danger gain the status of general education in the population.

### SHORT-TERM FIRE PREVENTION

One key element for short-term fire prevention are **fire danger assessments**. However, it seems unrealistic to build up a transnational fire danger map for the whole Alpine region fitting all needs. Fire danger assessments in such small-scaled landscapes like the European Alps encounter several difficulties. While a spatial resolution of 1 x 1 km is state of the art of regional weather models, this resolution is insufficient when considering narrow valleys, mountain peaks and the corresponding effects of temperature, precipitation, wind and solar irradiation on northern and southern slopes (Carrega 1995). This leads to an inadequate picture of estimated surface fuel moisture, the crucial part in potential fire ignition (Schunk et al. 2013). For models with very high resolution, data are hard to obtain and difficult to interpret. Besides the major role that atmospheric conditions and topography play in determining fuel moisture, also **vegetation** type and structure, tree species, deadwood content and ground cover can alter fuel moisture significantly (Carrega and Geronimo 2007; Schunk et al. 2013). Currently used fire danger rating systems mostly do not include vegetation parameters. In **Germany**, the WBI uses three different forest types with nominally different soil and vegetation parameters for large areas. Yet, only one forest type is used for the Alpine part of Germany. For some **Swiss** subregions with high fire frequency the Fire Niche Index approach as proposed by De Angelis et al. (2015) has been successfully implemented. On the national level, the FWI System is the common and future forest fire danger rating system in Switzerland.

Current assessments of forest fire danger do not take into account **potential triggers of forest fires**. There are two relevant causes of forest fires in Europe: Lightning strikes and humans. San-Miguel-Ayanz et al. (2018) showed that potential social effects and spatial distribution of **critical infrastructure** (e.g. potential loss of life, damage to property, major traffic routes) should also be included in an integrated forest fire danger assessment system. Yet, having a fire index that is affected by day of week, population density, tourist numbers, distance from roads, vegetation type etc. may be too difficult to both interpret in operational conditions and to parametrize, at least under northern Alpine conditions where few fires occur.

A critical point of currently used fire danger models in the Alpine region is their **inappropriate suitability for the winter season** and early spring. South-sided slopes are snow-free earlier as a consequence of higher temperatures and stronger solar radiation. Together with dead fine organic material from the last year (grass, litter), this results in an earlier and higher risk of forest fire ignition than on northern slopes. The occurrence of inversion weather conditions with higher temperatures and dryer conditions above the fog cap and the resulting difficulty of estimating forest fire danger based on station data from the valleys are an issue in the Alpine region too. These winter phenomena can only be insufficiently described with current forest fire danger indices like the Canadian Fire Weather Index (FWI), as they are not intended to be used in the cold season (Van Wagner 1987). An improvement of the prediction accuracy of winter and spring fires may also be achieved by including a high-resolution data layer of the actual snow cover in combination with a grassland fire index, to describe the fuel moisture behavior of dead fine fuel in winter and spring. Until now, such an approach is not implemented in European national forest fire assessment systems but is tested in some countries (e.g. from the national weather service in **Germany**).

It is not enough to generate fire danger maps and disseminate them via the web – the **information must be effectively delivered**. There is a need to separate the technical parts (danger assessment) of the implementation part (translation in warning levels, practical measures, communication to all potential users). Other issues have to be considered, like how to inform people (e.g. tourists) coming from outside the country. Language difficulties can lead to uninformed, misbehaving persons. It has to be noted that there is a clear tendency in the Alpine region to indicate the greatest possible danger in a country (e.g. by media), with the **risk of overwarning** large areas.

## **COSTS**

The costs of fire prevention measures in the Alpine region are difficult to calculate because of missing area-wide data but are assumed to be currently low compared to costs associated with the suppression of fires or post-fire management. However, costs for fire prevention are likely to rise due to the required change in forest fire management and a greater focus on prevention strategies and will probably exceed expenditures on fire suppression. According to assumptions of the authors contributing to this study, necessary annual mean costs on fire prevention measures to reduce the impacts of an intensified Alpine fire regime will reach at least **5 - 7 Mio. Euro** in the future (cf. Chapter 3). This money will have to be shared differently between the Alpine countries, depending on the assumed future threats and the needs for fire prevention.

## **2.3. Fire suppression**

As the amount of days with high fire danger and the number and intensity of fires in the Alpine region will likely increase in the future, an effective fire suppression is an essential part of future fire management.

## PRE-SUPPRESSION OF FIRES

There are several challenges regarding firefighting operations. The development of forest areas is not always in the interest of fire brigades. With regard to the density of the **forest road network**, the Alpine region is in a good position compared to other parts of Europe. Yet there is the need for improvement in terms of practicability (e.g. planning width of forest roads, reversal possibilities) or accessibility for firefighting vehicles (e.g. barriers), which repeatedly cause problems during extinguishing work. Another essential part of pre-suppression is **water availability**. Water tanks, ponds or additional hydrants were already installed in some regions, but the missing area-wide implementation of risk maps in the Alpine regions leaves open gaps with little water available for firefighting, especially in remote and dry areas. Also lakes and artificial ponds of snowmaking systems may not be accessible easily and quickly. While there are regional differences regarding **firefighting trainings**, it is important that firefighters understand fire behavior. A better education strategy can save time and money and leads to a lower risk of injury during operations. Realistic fire scenarios are not easy to train but essential to prepare action forces for extreme conditions. It is necessary to identify and train possible extreme scenarios in the future, like several large fires in close proximity and eruptive fire behavior on slopes and in canyons.

## FIRE SUPPRESSION

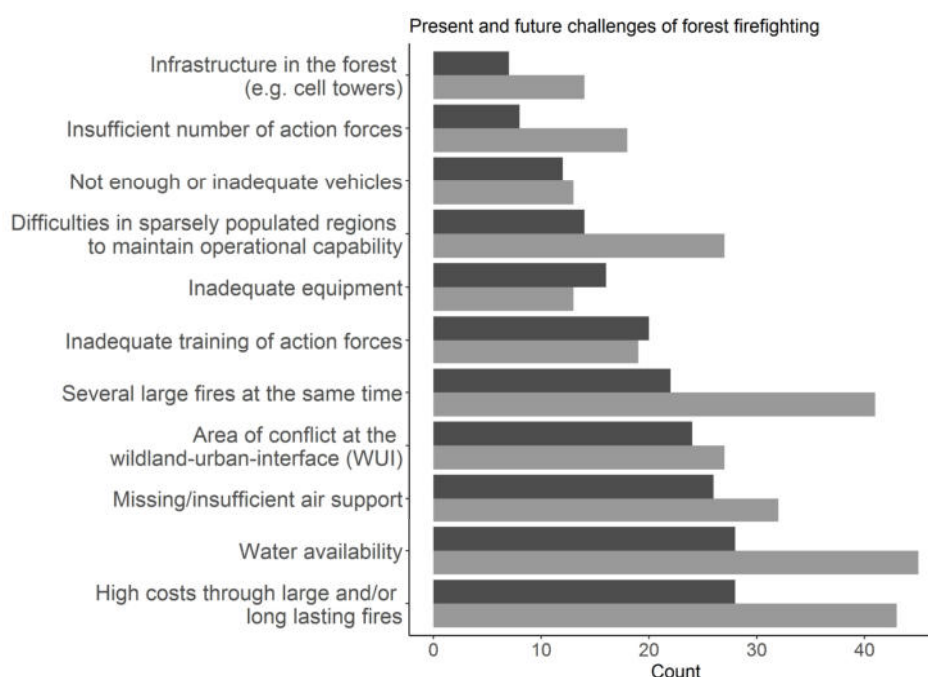
In the last years and decades fire brigade associations in the Alpine region have developed continuously. Post-event considerations of extreme fires have led to an improvement of operational tactics, operational sequences and firefighting. It can be assumed that forest fires are fought more quickly and effectively today than twenty or thirty years ago. In the Alpine region, the resources for firefighting are huge compared to other European countries and surpass available resources in most countries worldwide. This may also be reflected in recent forest fire statistics, which suggest a local increase in forest fires events but also a drop in the mean size of fires.

In **Italy**, there was a big institutional change after 2016, when the Corpo Forestale was merged into the Carabinieri and competences were shifted to fire brigades, leading to organizational and political difficulties in some regions by the loss of coordination of state aerial means and competences in firefighting operations. Another problem is that firefighters are usually equipped with ordinary multi-emergency **equipment** and trucks but not with specific equipment and vehicles for forest firefighting. This problem is also known from **Austria, Germany and Switzerland**, especially regarding the **clothing** of firefighters. The usual uniform was developed for fighting building fires. During forest fires in summer, heat accumulation sometimes leads to circulatory problems and limited mobility is a problem in difficult terrain. This may result in fire suppression in “shirts and shorts” which leads to an increased risk of injury. Special funds were distributed at national level (KRAS funds) in the past in **Slovenia** to voluntary and professional firefighting units to purchase specialized forest fire vehicles and specialize personal and common protective equipment.

**Lightning induced fires** often occur in steep, impassable terrain and can make firefighting difficult or even life threatening. Terrain features such as **canyons** or steep slopes can have an immense impact on fire behavior and firefighter safety (e.g. several multi-casualty firefighting accidents were reported from Portugal). The same applies to **strong winds** or surprising changes in wind direction – not uncommon in the Alpine area. Finally, the existing tree species and **change in vegetation composition** can pose a risk to firefighters, for instance when a ground fire suddenly turns into a crown fire or if conifers explode into flames due to their high resin content.

The efficiency and scope of **helicopter operations** in the event of a fire is often discussed. In the Alpine region, the use of helicopters for reconnaissance, containment and combating forest fires is of great importance, since planes are mostly not suitable due to narrow valleys and steep slopes. If the fire is hardly accessible for action forces on the ground, rapid deployment from the air can have a great impact on the size of the fire. In some Alpine regions **bureaucratic hurdles** in requesting air support cause difficulties. The use of helicopters for firefighting purposes can be accompanied by **high machine and personnel costs**, which are not always covered by the federal or state governments (**Figure 16**). An ongoing monitoring is needed to prohibit inadequate air strikes. Another challenge regarding aerial operations are night flight prohibitions in some countries (e.g. **Austria, Switzerland**). Also, the reimbursement for direct operational costs such as fuel, crew catering or damaged equipment is not clearly defined everywhere and needs to be improved.

More **technical expert teams** with a high education level are specially requested from fire brigades, because they are able to analyze a fire and anticipate its behavior, which is crucial in steep mountainous regions like the Alps. The potential use of **tactical fires** depends on the country and region and should only be conducted if enough experience is available. In some regions the young firefighter generation is less bound to rural activities and knowledge of the territory which leads to difficulties when fighting fires in steep, inaccessible terrain. In **sparsely populated areas** where migration and rural abandonment are an issue (e.g. parts of **France**, northern **Austria**), fire brigades struggle with securing their staff number. The number of fire brigade members is reduced due to age-related retirement and a lack of new recruits so that an effective continuation of a volunteer fire brigade is no longer possible.



**Figure 16:** Present (dark grey) and future (light grey) challenges of forest fire fighting in the Alpine region, identified by the participants of the Alpine fire survey in 2019 (shown are the values for all countries). Source: EUSALP Survey

## COSTS

Most government money in the Alpine region is put into fire suppression and firefighting operations. High expenditures can be found in **France, Italy and Austria**. Tactics with air support via helicopters are crucial because of the accompanied high costs but are common and needed in steep and inaccessible terrain. The mean annual direct fire suppression costs for the Alpine region are supposed to be currently around **45 Mio. Euro** according to calculations at the University of Natural Resources and Life Sciences Vienna. To reduce these costs and according to assumptions of the authors contributing to this study, a mean annual investment of at least **1.5 - 2.5 Mio. Euro** (equivalent to 5% of the current direct costs) is expected to be required at an Alpine scale (cf. Chapter 3). These resources will have to be covered by the Alpine countries depending on the actual and assumed future impacts of fires.

## 2.4. Post-fire management

Current and future challenges regarding post-fire management include difficulties in reforestation, tree species choice, protection against natural hazards, game management and neophytes.

### REFORESTATION AND TREE SPECIES CHOICE

In climatic or geographical unfavorable locations, reforestation measures after forest fires will get more difficult in the future due to climate change. Some tree species may be suitable for reforestation in a specific location under current conditions but may be unsuitable if temperature rises as expected and precipitation patterns change significantly. One future challenge is to anticipate and identify those species that are appropriate for a specific fire site. Also, the species composition (see Chapters 1.6.1 and 2.2) will influence the probability of future forest fires.

### PROTECTION AGAINST NATURAL HAZARDS

In the Alpine region, the protective functions of the forest must be considered in particular, since its destruction may have adverse effects on gravitational natural hazards such as erosion, rockfall, torrential floods, mudflows and avalanches (Gehring et al. 2019; Maringer et al. 2016; Sass et al. 2012). Depending on the location (e.g. the geological initial substrate, soil, slope and topography), the vegetation (e.g. tree species, vegetation type, stand structure, age classes), the fire severity and the silvicultural measures deployed, there are different succession paths and time spans until the forest is restored. If the organic soil layer is lost during intense smoldering fires (or is removed by extinguishing work), this can result in long-term damage and missing forest cover for decades to centuries. If the number and intensity of forest fires in the Alpine region raise as expected, this would challenge the function of protection forests and may lead to an increased risk of natural hazards. Also, much higher costs for a) trying to reforest areas influenced by soil loss and gravitational hazards and b) artificial structures to take over the forests' protective functions can be expected in the future.

### MONITORING AND CASE STUDIES

Currently, a detailed monitoring of fire sites or a review in form of case studies is only executed on some selected burned areas in the Alpine region. However, knowledge about fire behavior, effects of fires and post-fire regeneration is an urgent need to understand fires in the Alps and to anticipate effects under an intensified fire regime. Post-fire effects like soil water storage capability, smoke and related health issues, health of the forests and health of the surviving trees (e.g. Bär et al. 2018; Bär et al. 2019) are challenges which will likely get more important in the future especially when more fires and larger burned areas occur.



## GAME MANAGEMENT

Game browsing on tree regeneration is a big issue on burned areas, e.g. on the largest recent fire site near Absam, **Austria**, in 2014 (cf. **Table 2**). The challenge of game browsing may become more important in the future, when changing climate conditions and a higher pressure by forest visitors lead to difficulties for game in obtaining food, especially in the cold season.

## NEOPHYTES

The problem of **neophytes** on burned areas should not be underestimated, especially under a changing climate that may promote new plant species. On the one hand, neophytes can be considered as a negative element and therefore monitoring is necessary to identify and eliminate them. On the other hand, if certain neophytes do not represent a problem from a forest fire perspective, it could be considered to let them grow to quickly regain a protective function. However, this development has to be monitored and eventually actions must be taken to rebuild a balanced biodiversity.

## COSTS

The current mean annual direct costs for post-fire management and for the whole Alpine region are supposed to be around **30 Mio. Euro** according to calculations at the University of Natural Resources and Life Sciences Vienna (cf. Chapter 1.5). To reduce these costs and in line with the assumptions of the authors contributing to this study, a mean annual investment of at least **1 - 2 Mio. Euro** (equivalent to 5% of the current direct costs) is expected to be required at the Alpine scale (cf. Chapter 3). Assuming an increase in size and severity of forest fires in the future, the impacts of fires will likely increase as well. Therefore the assumptions about the expected annual costs for post-fire management are to be seen as a conservative estimate.

**Table 4:** Summary of the opinions regarding main challenges and relevant factors for the forest fire regime in the Alpine countries. No data available for Liechtenstein. Sources: Forest fire workshop Vienna, EUSALP survey.

	AT	FR	DE	IT	SI	CH
Changing environment and socio-economic conditions (relevance of factors)	<b>Natural factors influencing the fire regime</b>					
	Temperature	X	X	X	X	X
	Precipitation	X	X	X	X	X
	Wind	X	X		X	o
	Lightning ignitions	X	X	X	X	X
	<b>Socioeconomic drivers of the fire regime</b>					
	Rural abandonment	X	X	o	X	o
	Tourist activities	X	X	o	o	X
	Traditional use of fire	X	o	X	o	X
	Negligence	X	X	X	X	X
	Arson	X	o	X	X	X
	<b>Interactions between climate change and fire</b>					
	Heatwaves and droughts	X	X	X	X	X
	Disturbances	o				
	Health of the forests					
Forest fire effects	... on natural hazards	X	o	X	o	X
	... on ecosystems / biodiversity	o			X	
	... on health (e.g. smoke)	o	o	o	o	o
Fire prevention & risk assessment (importance)	Fire prevention measures in general	X	X	o	X	o
	Integration of fire management plans	o	X	X	X	o
	Awareness-raising measures	X	X	X	X	X
	Fire danger assessment	X	X	X	X	X
	Forest fire research	X	X	o	o	X
Fire suppression & post-fire management	<b>Fire suppression – importance of</b>					
	... air support	X	X	X	o	X
	... training of fire brigades	X	X	o	X	X
	... firefighting techniques	X	X	o	X	o
	<b>Post-fire management – importance of</b>					
	... restoration activities	X	o	o	o	X
	... costs	X	X	o	X	o
	... monitoring and case studies	X	o	o	o	X

**RANKING:**

	HIGH (very important/relevant)
	MEDIUM
	LOW
	UNCLEAR / INFORMATION MISSING

**QUALITY OF INFORMATION:**

X	HIGH
o	low

## SUMMARY OF THE TABLE

**Table 4** summarizes the main drivers of the fire regime and the most prevailing challenges of forest fire management in the Alpine region. Temperature and precipitation – in other words **heatwaves** and **drought** – are the most important natural factors influencing the fire regime in the Alpine region. Lightning ignitions are relevant in the central Alps.

Regarding the socioeconomic drivers of the fire regime, **rural abandonment** is more important in France and Italy, while **tourist activities** are very relevant in Austria, Germany and Switzerland. **Negligence** was identified as the most relevant cause of forest fires in the whole Alpine region.

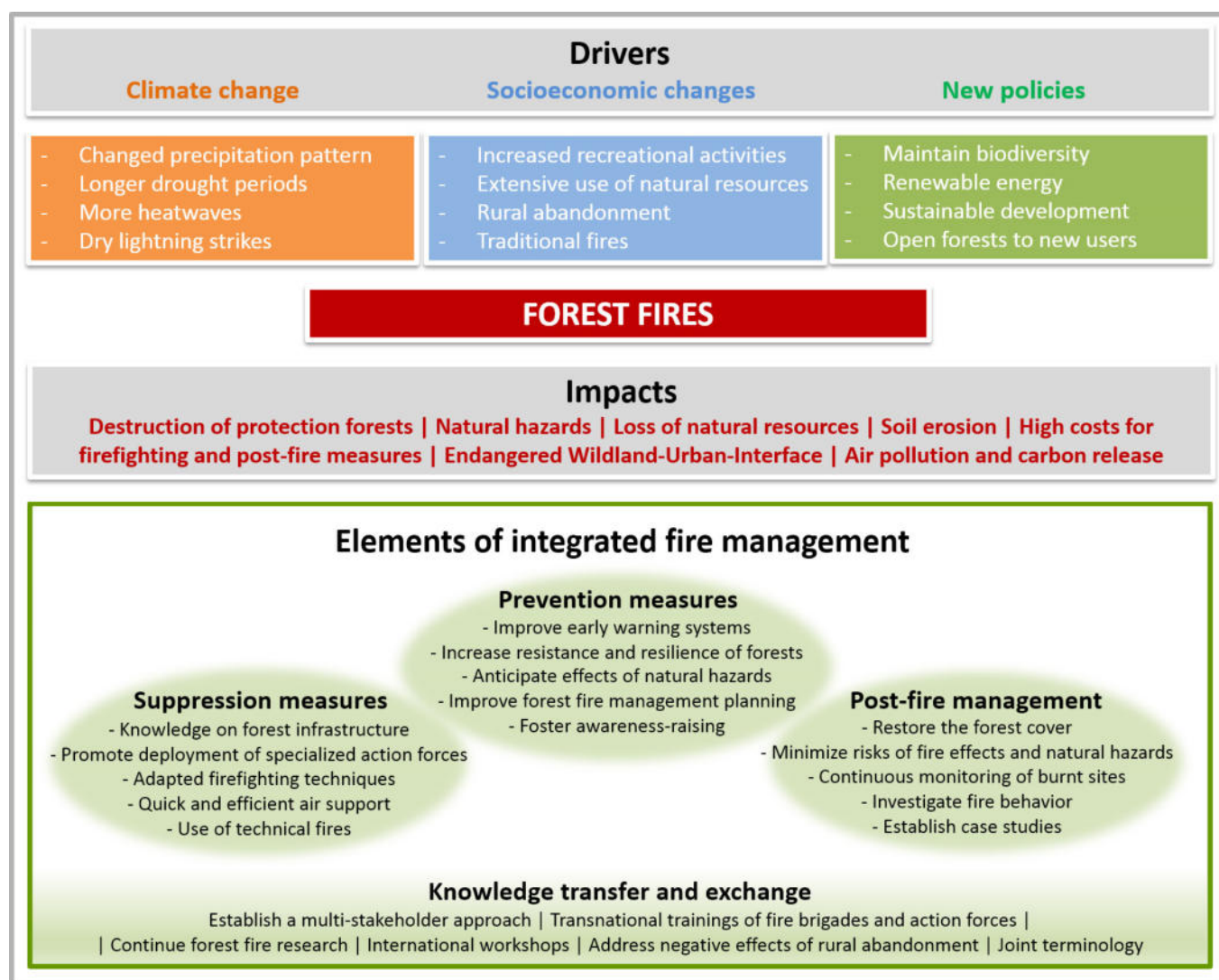
Currently, there is only few information on **disturbances** and the **health of the forests** as part of interactions between climate change and fire. In general, **forest fire effects** on natural hazards, ecosystems, biodiversity and health are not well understood. **Awareness-raising measures**, **fire danger assessment** and **forest fire research** are highly relevant for fire prevention in the whole Alpine area. Regarding the integration of fire management plans, the relevance differs between the countries.

The **training of fire brigades** and air support is very important in most Alpine countries. The importance of restoration activities as part of post-fire management is high in Austria and Switzerland, while the assessment of the importance is indifferent for all other countries. **High costs** are especially an issue in France and Italy, while **monitoring** and conducting **case studies** are more relevant in Slovenia and Switzerland.

### 3. Options for an integrated fire management

#### 3.1. Proposed IFM framework

Several **Integrated Fire Management (IFM)** approaches have been suggested aiming to achieve healthier forest ecosystems, communities that are less at risk from fire, and more cost-effective fire suppression strategies. The **Food and Agriculture Organization of the United Nations (FAO)** has proposed voluntary **Fire Management Guidelines** for authorities and stakeholder groups. These guidelines recommend that fire management should be an integral part of a coherent and balanced policy applied not only to forests but also to other land-uses in the landscape.



**Figure 17:** Drivers and impacts of forest fires and elements of an integrated fire management for the Alpine region.

Based on the characterization of the current state of knowledge on forest fires in the European Alpine Region and the identified challenges, we propose a **framework for an integrated fire management**, which addresses the drivers of the current and future fire regime in mountain forests, considers the needs of humans living in the Alpine region and aims to mitigate the negative impacts of fires (**Figure 17**).

Three main driver factors have been identified: **Climate change, socio-economic changes** and **new policies**. The Alps are among the most affected regions by climate change. Several drought and temperature records occurred in the Alpine region in recent years, which already led to anomalies in the forest fire regime. Also, climate change has and will affect the Alpine area more severely than the lowlands. Under climate change, dry lightning strikes may increase the likelihood of natural fire ignitions. Due to the increasing recreational use of the forests the human influence will grow, leading to a higher number of human-caused ignitions. Rural abandonment and declining management measures influence the fuel loads and increase the intensity of uncontrolled fires. The existing policies will lead to increased trade-offs and potential conflicts in the use of natural resources. The intensified demand to utilize existing timber resources and to stimulate the bioeconomy needs to be balanced with the maintenance of biodiversity and the protection of habitats. The mentioned drivers will not occur in all areas with same intensity but will cause several impacts on forest resources and require an integrated approach for fire management.

When applying this framework in practice, it is important to consider the specific socio-economic and ecological situation of each Alpine region. It is necessary to identify the most relevant elements in a regional context and adapt the concrete measures from these priority components. A preliminary screening of the most urgent topics has been done on a national scale (**Table 5**), which would have to be updated in a regional context. However, it seems that the collaboration among multiple levels of stakeholders is in place in most countries, while forest fire research activities and training of specialized action forces is of high relevance.

**Table 5:** Priority of actions regarding forest fire management in the Alpine countries. No data available for Liechtenstein.  
Sources: Forest fire workshop Vienna, EUSALP survey.

	AT	FR	DE	IT	SI	CH
1. Establish a multi-stakeholder approach	X	o		o	X	X
2. Training of fire brigades and specialized action forces	X	X	o	o	X	X
3. Address and minimize negative effects of rural abandonment	X	X	o	o	X	X
4. Implementation of prevention measures in forest management	X	X	X	X	X	X
5. Improve early warning systems	X	X	o	X	X	X
6. Minimize risks of natural hazards after forest fires	o	o		o	X	o
7. Awareness-raising activities	X	X	X	X	X	X
8. Forest fire research	X	o	o	o	X	X

HIGH (very important / relevant)

MEDIUM

LOW

UNCLEAR / INFORMATION MISSING

X

HIGH

o

low

In the following we present some **success stories from existing solutions in the Alpine countries**. They might serve as an example for an integrated fire management approach.




## 3.2. Prevention measures

### 3.2.1. Early warning and fire danger rating systems

In the Alpine region, there is the need to consider the specific meteorological conditions of the mountain environment, the vegetation characteristics and the topography (slope, exposition and altitude). Fire ignition depends on these factors and early warning systems will have to provide an appropriate spatial and temporal resolution. Additionally, the existing critical infrastructures and the role of human influence needs to be considered in an **integrated forest fire danger model**. There may be the need to improve or adapt meteorological fire danger indices, which are able to capture the specific conditions during early spring as well as the changing seasonal patterns. An Alpine-wide identification of forest fire hotspots could help to provide a sound database for the adaption of such integrated systems. As a basis for this, a common reporting scheme, a definition of forest fire events has to be established. A comparison of the fire regime in the past with the recent and future conditions may lead to new insights in the design of such early warning systems. In **Germany** and **France**, initiatives have been made to improve the fire danger rating in complex terrain (**Figure 18**, **Figure 19** and **Figure 20**). Additional station data have been included in the overall prediction process to overcome problems regarding inversion weather situation and low spatial resolution.

**Fire danger rating in complex terrain**



Country: Germany  
Scale: Regional (Alps)

**Problem description**

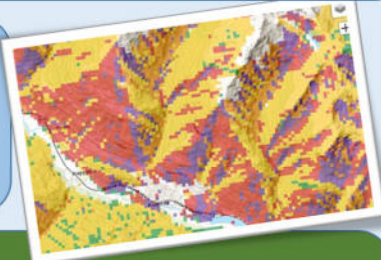
- Underestimation of fire danger at mid-elevation forests due to lack of stations, complex orography and temperature inversion in the winter term.
- The current used forest fire index (WBI) is not suitable for conditions that foster fires with characteristics like grassland fires.

**Solution**

- Use of meteorological stations of the avalanche warning service to calculate an adapted fire danger index.

**Best practices**

- Improvement did not require additional installations.
- Correct assessment of actual fire danger in mountainous areas.
- Better danger assessment increases awareness-raising and reduces the number of forest fires.



**Figure 18: Success story** regarding prevention measures: Fire danger rating in complex terrain in Germany.

## Research and implementation of new indices to predict fire danger in winter



Country: France  
Scale: Nationwide

### Problem description

- Poor efficiency of the Fire Weather Index (FWI) to predict fire danger in winter (especially in mountainous regions).
- Fires occur, even if the FWI shows a low fire danger.



### Solution

- Implementation of new indices by combining Fine Fuel Moisture Code (FFMC) and wind speed
- Increased research on the relation between snowpack and fire occurrence in mountainous areas like the Alps

### Best practices

- More accurate prediction of fire danger in the winter season
- Anticipation of the preventive/operative measures needed
- Identification of the areas more prone to winter fire and development of site-adapted measures

**Figure 19: Success story** regarding prevention measures: Implementation of new indices to predict fire danger in winter.

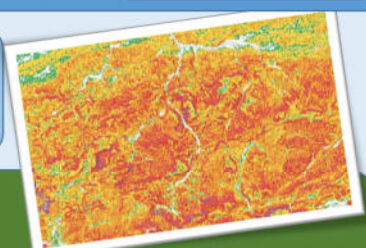
## Evaluation of spatio-temporal trends of fire weather danger



Country: France  
Scale: Regional (French Alps)

### Problem description

- Inexistent overview of fire weather danger in the French Alps, leading to a unknown situation of local fire danger.



### Solution

- Use of historical meteorological data to characterize fire weather danger and fire regime
- Evaluation of different methods and thresholds of fire weather indices (FWI, FFMC) according to fire activity

### Best practices

- Objective overview of the fire weather danger in a specific area
- Identification of hotspots of high fire weather danger
- Vulgarization of the results to the local authorities and fire brigades
- Similar method can be applied to other countries in the Alpine region, if meteorological datasets are available


**Figure 20: Success story** regarding prevention measures: Evaluation of spatio-temporal trends of fire weather.

### 3.2.2. Awareness-raising activities

It is recommended that representatives of authorities, action forces and scientists actively participate in public **awareness-raising activities** at country and regional level. It would be good to identify a team of forest fire experts, who could act as contact persons at training events, seminars, workshops and practical training sessions. Researchers should work together with stakeholders to develop forest fire prevention projects while meeting the increasing demands. The preparation of recommendations or guidelines on different topics of forest fires (e.g. correct behavior in the case of a fire event, silvicultural preventive measures) can also contribute to awareness-raising. Regular meetings between stakeholders, research institutions, action forces and state warning centers ensure better networking and an ongoing exchange. In cooperation with schools, extended awareness-raising measures are useful, such as the visit of burned areas or the creation of educational material.

Awareness-raising should address citizens, politicians and authorities in the Alpine region. Appropriate measures should be tailored for the specific target groups. For example, young people may be addressed through social media channels and older people through “classic” media (radio, television, print media). Local farmers may play an important role if they are involved in the implementation of prevention measures, such as prescribed burning activities. To tackle the problem of uncontrolled fires escaping from agricultural areas, burning of forest residues by landowners, specific awareness-raising measures such as information material about safety burning measures or incentives for using the residues to produce biomass would be useful. In this context, the question “What to say and how to say it?” rises and should be carefully handled. It is important to explain the current situation and to adapt public awareness activities to the level of fire danger in the regions also. In **Italy**, a nationwide initiative was launched to raise the awareness about the importance of prescribed burning activities (**Figure 21**).


### Bringing prescribed fire practices on the main national TV science program (3M viewers)



Country: Italy  
Scale: Nationwide

**Problem description**

- Fire prevention in Italy is still in its infancy, especially when it comes to prescribed burning.
- A large part of environmentalist people and associations strongly oppose to prescribed burning for its perceived threat to understory and soil biodiversity.



**Solution**

- Shoot a short documentary on prescribed burning for the main science program on national TV ("Superquark").
- Documentary broadcasted in 2018, with 3+ million viewers.
- First time that prescribed fire was mentioned by national media.

**Best practices**

- First step towards popularizing the importance of fire prevention and explaining the role of vegetation and climate in fire spread.
- It gave voice and relevance to fire scientists.

**Figure 21: Success story** regarding prevention measures: Prescribed burning practices on TV.

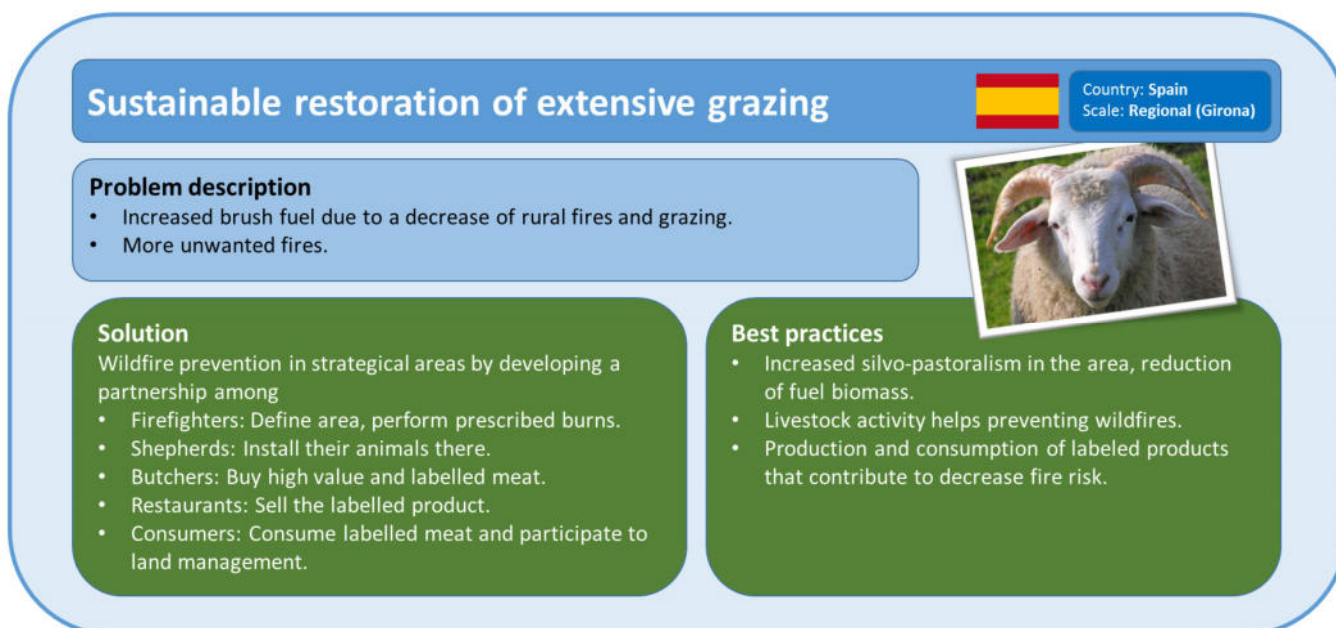


In this context, it is important to initiate **social science studies** to analyze the interactions between humans, stakeholders and fires in the Alpine region and learn about the preferences of the citizens living in the European Alps. All measures should be adapted to the **regional context** with an **early involvement of all stakeholders**. Such an integrated approach needs time and the implementation of prevention measures (e.g. building of infrastructures in the forest) is expensive, this is why there is need for subsidy programs to adapt forests to the changing climate. In regions with a higher fire danger, like the Southern Alps, governance and communities could aim for **fire smart communities**, where communities improve fire resistance of houses, infrastructure and landscapes themselves. Such initiatives have been widely promoted in Australia in the aftermath of 2009 “Black Saturday” tragedy, when fires claimed 170 fatalities (Mc Leod et al. 2009). In the US, the FIREWISE initiative, developed by the National Fire Protection Association, and the Working on Fire (WoF) initiative originating from South Africa pursues the same goal.

### *3.2.3. Measures to increase resistance against fires*

Extreme forest fire events in the Alps are not synonymous with large burned areas. A relatively small burned surface on unstable slope above a densely populated valley can generate immense damage to the valley bottom, compromising the habitability. It is therefore important to precisely **identify endangered areas and implement measures to increase the resistance of mountain forests against fires**. It is necessary to integrate measures of different nature, including silvicultural management, agricultural management in areas close to forests and infrastructure planning (e.g. buildings, roads, tourist trails). Besides, a better integration of forest fire risk assessments, prevention measures and climate change projections in forest management and planning is needed.

Local initiatives to minimize the negative effects of rural abandonment should expand and be integrated into other measures. This may be done as a bottom-up approach, however, support from the policy is needed to be successful in the long run. If existing success stories are shared and promoted, this may help to push forward. An outstanding example from Catalonia (Spain) includes sheep and their shepherds, butchers, local restaurants and consumers to create a label where the meat comes from sheep, which are used for landscape conservation (**Figure 22**).



**Figure 22: Success story** regarding prevention measures: Sustainable restoration of extensive grazing in Spain.

The **creation of fires strips** may be combined with establishment of alpine pastures or skiing slopes, optimized on their management and firefighting requirements. Protection strips can play a role in the indirect attack of a forest fire to prevent the spread of a fire.

**Power lines** represent a potential danger of igniting massive forest fires, as recently happened in Portugal or the USA, but also in **Italy** during the La Muda fire (2011) and the Monte San Lucano fire (2018). Power lines should be kept clean from ignitable biomasses and corresponding safety zones should be established and monitored (e.g. trees should be adequately cleared). The construction of new power lines should avoid protective forests and should prefer buried alternatives. In case of low intensity power lines, the use of protected cables is recommended.

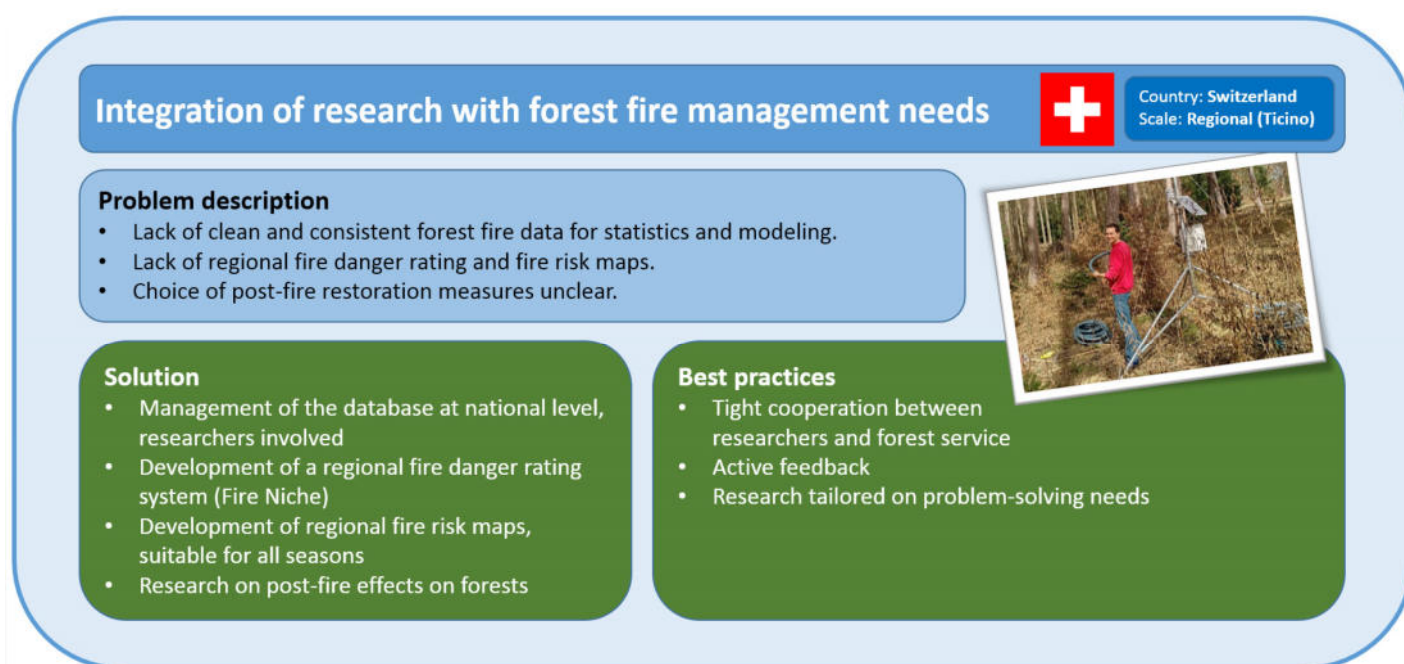
The excessive **spreading of the WUI** in mountain areas should be contained in the future. In countries with high forest fire risk, like the USA or Australia, instructions for homeowners were compiled on how to make their homes safe from forest fires – for example, by applying a fire protection strip, removing fuel from the vicinity of the building or setting up an external water intake (NFPA 2019). Such prevention measures are unusual and new to citizens in the European Alps.

**Prescribed burning is an effective tool** to control the accumulation of biomass and needs to be better analyzed and developed in the Alpine area, also taking advantage of the great experience acquired in the Pyrenees and the Maritime Alps. In regions where forest ecosystems are adapted to the occurrence of fires, such as parts of Southern Europe, prescribed burning is an often practiced and helpful way to avoid devastating forest fires.



**Deadwood removal** from the forests adds additional costs for forest owners or municipalities. It should only be carried out after a comprehensive on-site assessment of the potential fire risk and a comparison with nature conservation considerations. A possible compromise can be the removal of deadwood only in selected forests with a high fire risk. Also, the wood collected can serve as biofuel and therefore regaining of expenses may be possible.

Especially the integration of fire behavior in management plans may be a crucial part for the coming intensified fire regime. Knowledge on fire behavior helps to identify which measures have to be adopted to increase the resistance to fire. This work can only be done locally by defining and identifying the areas in which the fire has a homogeneous behavior. Being able to understand how fire develops (direction, intensity, formation of lateral tongues, formation of thermals, rolling of embers downstream, etc.) allows to better identify which measures to adopt for fire prevention. For this purpose, the collaboration and exchange of knowledge on an Alpine scale is needed to generate a homogenized fuel bed map that is also suitable for the Alpine region. Such a fuel bed map and the continuous monitoring of the fuel moisture in different environmental contexts would be essential for improving fire behavior predictions. In **Switzerland**, strong emphasis is put on fuel moisture monitoring in order to support fire management planning as part of fire prevention measures (**Figure 23**).



**Figure 23: Success story** regarding prevention measures: Integration of fire research with fire management.

Silvicultural knowledge is little used to adapt forest management in the Alps due to lack of risk awareness regarding forest fires. A change in the **choice of tree species** towards a higher proportion of deciduous trees is perhaps the most appropriate measure, since it reduces the likelihood of (severe) forest fires and increases resistance to other disturbances such as bark beetle infestations or windthrows. As the majority of forest damage in the Alpine region is currently of biotic nature or caused by storm events, the adaption of forest management towards more mixed forests

can support both strategies. In case of **conversion strategies**, the site conditions must be carefully considered when selecting tree species. Beech (*Fagus sylvatica*) is usually successful on sufficiently humid and deep sites, but maple (*Acer spp.*) and oak (*Quercus spp.*) are also suitable on drier sites. The green alder (*Alnus viridis*) and the flour and rowan berry (*Sorbus spp.*) have shown their potential in the Northern Alps.

Due to many years of **experience in the Mediterranean region**, a comprehensive portfolio of forest prevention measures already exists. The existing silvicultural recommendations have to be checked for their suitability in mountain areas and need to be communicated to authorities and forest owners in endangered areas. Possible areas of conflict must be taken into account, such as skepticism towards prescribed burning, the change in tree species composition or the possible contradiction between leaving deadwood in the forest for nature conservation purposes and fire prevention measures. In **Italy**, following the new forest law (D Lgs 34/2018), new forest planning guidelines are being drafted. The new mandatory forest management plans should include risk maps, fire management considerations and have to comply with regional fire management plans.

### 3.3. Suppression measures

#### 3.3.1. Training of specialized action forces

An effective training of action forces is the key element to successfully fighting a forest fire. This should also include safety aspects and lessons learned from other areas, e.g. northern America or the Mediterranean, as far as these results can be transferred. It is necessary to promote local protocols for joint interventions along the borders and to organize more joint trainings between firefighters of neighboring countries. It would be advantageous to have more specially equipped forest fire emergency units that could be deployed across country borders if necessary. In **Austria** and **Switzerland** specialized firefighters for mountain forest fires are trained in order to have a common standard in operational tactics at national level (**Figure 24**). There is a need to share **effective firefighting techniques** for the Alpine region (e.g. methods that need less water) and to organize trainings that are adapted to reality. Firefighter crews, especially in highly endangered areas, should be well equipped with specific firefighting equipment, and need to get trained on the correct use of these tools. Model scenarios for an improved training, better preparation for emergency and post-event evaluation should be established by defining areas with similar fire behavior. The active support of meteorologists and fire behavior analysts is helpful in case of larger fires, also to improve firefighter safety. For this purpose, trainings with all stakeholders and short time availability in case of fire events are required.

The use of **tactical fires** (e.g. backfires) is an indispensable tool in the south of the Alps that allows more effective extinction and safety for the firefighters. Its use requires good knowledge of the territory, the fire behavior and the specific tools. Trainings to improve this knowledge should be extended to other parts of the Alpine region. In this context, the role of **natural fires** has to be considered in the future by using enhanced cooperation between fire brigades, meteorological institutions and research. Discussions among experts have to take place (e.g. such as the feasibility of **letting natural fires burn** on selected sites) in the Alpine region, in order to balance the efforts in fire suppression and fire prevention measures.

## Specialized firefighters for mountain forest fires



Country: CH / AT  
Scale: Nationwide

### Problem description

- Lack of specialized firefighters for mountainous areas.
- Use of inadequate materials and techniques for mountainous areas.
- Associated high costs, prolonged activity, and greater damage to the forest.



### Solution

- Establishment of a network of specialized, trained and well equipped fire brigades in mountainous areas.

### Best practices


- Joint trainings by regional fire brigades.
- Common standard of performance, operational tactics and knowledge.
- Modern equipment and adapted firefighting techniques.

**Figure 24: Success story** regarding suppression measures: Training of specialized firefighters for mountain forest fires in Switzerland and Austria.

### 3.3.2. Providing necessary infrastructure

Detailed maps of infrastructure available for fire suppression must be easily available for firefighters and action forces, especially in high fire risk zones. One success story in this context is the new regulation in **Germany** on the preparation of special firefighting maps for highly endangered areas. Planning the **infrastructure** needed for an efficient response in case of a fire is important for pre-fire suppression and active firefighting, e.g. the building of forest roads in high risk areas, anchor and turning points, permanent fire ponds, underground tanks, or hydrants. In some parts of the Alpine region, especially in remote areas, there is a lack of infrastructure. Together with local stakeholders, like forest owners, forest authorities and firefighters, there is the need for a joint development of measures on a collaborative and scientific supported basis. In **Slovenia**, the current, ambitious plan is to build up 25 meter of forest roads per hectare in high fire risk areas (**Figure 25**).

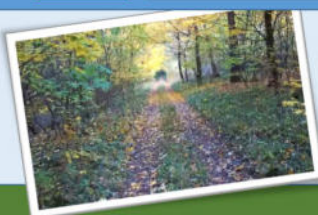
## Dense network of fire protection roads



Country: Slovenia  
Scale: Regional (South)

### Problem description

- Long time to first fighting a forest fire.
- Lack of forest roads available for firefighters in remote areas where forestry is not economically profitable.



### Solution

- Building 600 km of fire protection roads in an area of 60.000 ha.
- Reaching 25 m of forest roads per hectare in high fire risk areas.

### Best practices

- Area accessible to firefighters and their vehicles.
- Decreasing average burnt area per forest fire (below one hectare).
- Reduced damage after forest fires.
- The measure ensures forest management on non-profitable sites.

**Figure 25: Success story** regarding protection measures: Dense network of fire protection roads in Slovenia.

The most important factor in case of a fire is the **promptness of intervention**. Intervening in the first quarter of an hour from the ignition, makes it possible to turn off the outbreak and minimize damages and costs. This promptness of intervention is possible with a close collaboration and coordination between ground forces and helicopters.

The following scheme can be activated for the Alpine space as soon as a certain level of fire danger is exceeded:

- Where appropriate (e.g. remote areas): Reconnaissance flights by an expert, lookouts or automated smoke detection cameras on towers/mountain tops. In the future, the use of reconnaissance drones with long flight time equipped with high resolution cameras may be useful for fire detection in some places.
- Simultaneously readiness of a helicopter with a team of firefighters (4-5 firefighters) with manual extinguishing tools, 1-2 bags of 1000 liters of water, light pipes and pumps (cf. initial attack or smokejumper crews in the US). This intervention unit is able to intervene immediately even at difficult places (e.g. lightning fires in remote areas).
- Readiness of a light and flexible helicopter with a minimum load of 800-1000 liters of water or retardant.

In case of a detected forest fire, a helicopter with the fire team should be immediately deployed and local fire brigades should be alerted. The coordination of the helicopter and the local fire brigades via radio contact is required to succeed in the extinction.

The helicopter team is unloaded on the ground, assesses the situation and intervenes immediately. Small drones may help in this setting to a) keep an overview of the situation, b) transmit this overview to the command center and c) independently find smoldering fires without the use of an additional helicopter with the help of thermal IR-cameras. However, possible difficulties have to be considered if drones and helicopters are used in the same area and at the same time. Depending on the development of the fire, there are three scenarios:




- If the fire is extinguished or put under control, the helicopter team passes the area to the local fire brigades for final control and extinction.
- If the fire is more active, a second helicopter is requested and suppression continues.
- If the personnel or aerial means are not sufficient, further support is requested.

An intervention scheme of this type can cover an area of 1500 to 5000 km<sup>2</sup>, depending on the degree of danger. The organization of this scheme in the Alps can be implemented at regional level, but also at national and European level. In order not to waste resources for the purchase of aircrafts/drones, to optimize their use and to guarantee mutual assistance in cases of strong danger spread over a larger region, a European coordination is desirable. Such a coordination is an integral part of the Union Civil Protection Mechanism **RescEU project** to strengthen EU civil protection response to disasters that has already been activated and would need to be adapted to Alpine conditions. In this context, the framework conditions for the deployment and **cost compensations of helicopter support** should be regulated uniformly at state level. In **Germany**, all firefighting costs have to be covered by the local communities, unless a “catastrophic event” is called out, which usually is the case for all larger fires. In **Italy**, competencies are clear: Regions pay their own light helicopter fleet, while the state pays the national firefighting fleet. In Tyrol, **Austria**, a new regulation was passed to preserve communities from any costs that come with aerial firefighting support.

Another option for rapid **intervention** when fires occur is a dense network of volunteer fire brigades like it is present in **Austria**, which allows a quick first reaction even in remote areas, followed by specialized fire fighters and support from helicopters (**Figure 26**).


## Dense network of volunteer fire brigades



Country: Austria  
Scale: Nationwide

**Problem description**

A long response time for the forest fire fighters to start with the initial attack on the a forest fire is crucial especially in remote Alpine areas. Bad accessibility of these areas and a low number of fire fighters can lead to larger and uncontrolled fires, which are hard to be suppressed during the operations.



**Solution**

- Establishing a dense network of volunteer fire brigades under the control of each municipality.
- First efforts were undertaken before the year 1900. Today around 340.000 members in 4500 volunteer fire brigades cover an area of 84.000 km<sup>2</sup>.

**Best practices**

- Mean time to start with the initial attack on forest fires is reported to be 20 minutes.
- Voluntary and well trained action forces are available 24/7
- Every 25<sup>th</sup> person in Austria is member of a volunteer fire brigade, which allows to rise awareness on forest fire issues
- Costs for equipment and training are covered by joint funds from municipalities, federal provinces and the federal government.

**Figure 26: Success story** regarding suppression measures: Dense network of volunteer fire brigades in Austria.

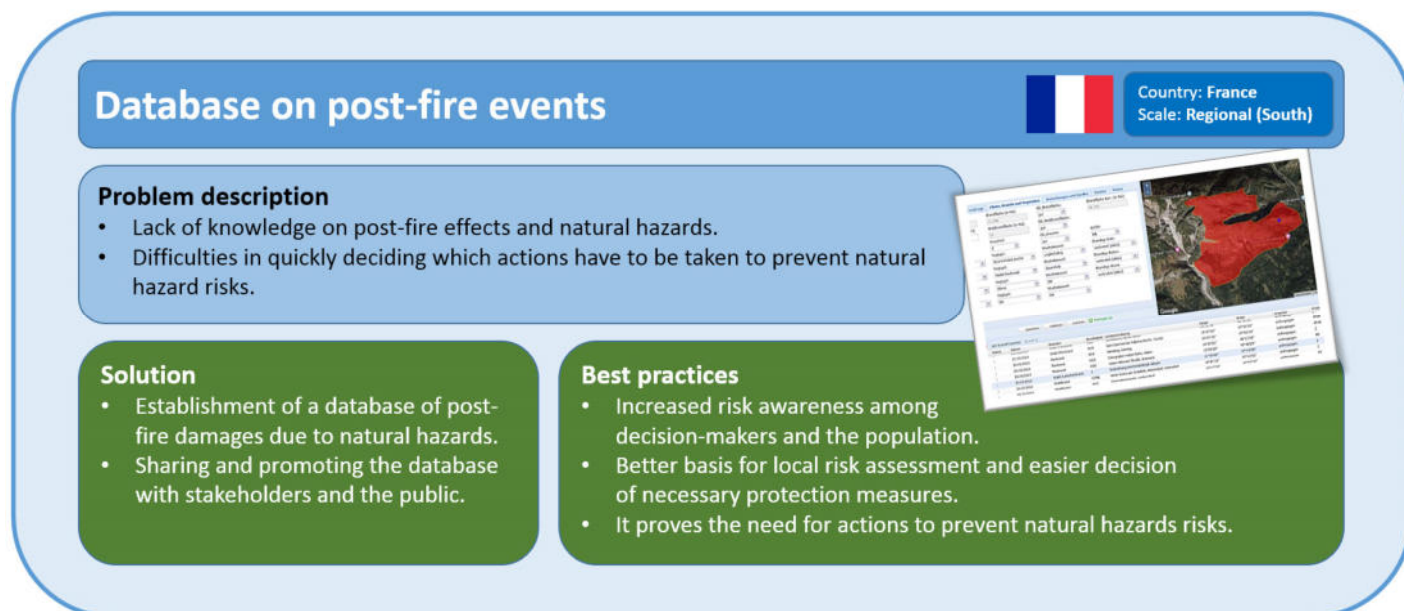


### 3.4. Post-fire management

#### 3.4.1. Monitoring

It is necessary to foster a **comprehensive monitoring program** which covers as many **regional case studies** as possible in different vegetation forms and geomorphological locations considering various types of forest fires. This monitoring should be done in collaboration with all Alpine countries. In **France**, there is a database on post-fire events established, which could serve as a prototype for such a monitoring (**Figure 27**).

Most important would be a **continuous monitoring** of the fire area, for example with regard to the survival probability of the damaged trees, the observation of the vegetation succession and the occurrence of natural hazards as a consequence of the fire event. Possible erosion phenomena and the role of biological pests (bark beetles, fungi) could be also monitored.



**Figure 27: Success story** regarding the reduction of negative forest fire effects: Database on post-fire events in France.

#### 3.4.2. Minimize the occurrence of natural hazards

First measures to minimize the occurrence of **natural hazards** might be already necessary during the **fire suppression** operations. It has to be considered the need to intervene not only at the fire front but also within the burned area in order to limit the damage to the vegetation due to persistent underground fires. Especially in very steep areas that will likely be unstable following the fire and may generate natural hazards, it is necessary to extinct all internal fires with air support or from the ground with specialized helicopter-transported teams. Firefighting techniques should consider the **sensibility of the soil**, as e.g. the use of high-pressure pipes may wash away the humus layer. A low intensity forest fire usually does not require forestry measures after the fire, as the trees will not suffer much damage.

Yet, if it is an intensive smoldering fire that burns the tree roots and humus cover or even a massive crown fire, extensive measures may be necessary to restore the forest functions (Heel 2015).

There are no technical or silvicultural measures known which make a high intensity forest fire area immediately safe from **erosion** in an acceptable time and with a reasonable amount of effort. Rapid sowing of site-adapted grass and perennial seeds is suitable for short-term stabilization of areas at risk of erosion – if an intact soil cover remained after the fire. In case of considerable damage, plantations with site-adapted tree species support natural regeneration. When trees are massively damaged or dead, a balance has to be found between removing the affected individuals and leaving them in the stand.

In order to avoid natural hazards after forest fires, it is important to leave standing deadwood in the stand if possible, as this will protect against **rockfall** and **avalanches** for several years. In addition, trees can be cut and arranged parallel to the slope between other trees or rootstocks. This measure also helps to avoid and stop dangerous rockfall.

**Post-fire regeneration** can be enhanced through an ecologically-based management that considers the timeliness at which tree stem mortality and canopy opening occur. In low to moderate fire severity areas, cutting should be delayed by a few years after a fire event (1–5 years) in order to increase the probability of a masting to occur. In case of masting, cutting should be carried out the following winter, as seed availability will be rapidly exhausted. Post-fire harvesting should not be delayed (> 5 years), as this may have an adverse impact on established saplings. Cutting should leave some fraction of temporarily surviving trees, even if they are highly damaged, to serve as seed sources and shelter for their seedlings while favoring intermediate light conditions suitable for sapling establishment. In high fire severity areas, the sudden accumulation of woody debris in unstable piles might result in log shifting, which in turn causes mechanical injuries to tree regeneration. Under these conditions, cutting aimed at stabilizing woody debris by directional log felling should be timely. When fire danger is high, salvage logging aimed at reducing hazardous fuels should extract most of the woody debris. Subsequently, once retained injured trees, they should not be extracted in order to guarantee some woody debris input within the system. In forests with biodiversity vocation, fire disturbance can be seen as an opportunity to increase stand diversity. Therefore, post-fire management should favor the establishment of other species as well.

In addition to silvicultural measures after a fire, technical protective measures may be necessary, especially in protection forests. Snow rakes and snowbucks can help to protect the young tree vegetation on the slope and the underlying infrastructure from snow movements.

### 3.5. Knowledge transfer and exchange

Since the ALP FFIRS project there was no Alpine wide approach to adopt a **transnational network**. While there exist several collaborations between stakeholders within the countries (e.g. in **Austria** between authorities, action forces, the national weather service and scientists), the transnational exchange in the Alpine region is currently weak. In addition to encouraging further transnational projects such as *Interreg*, it is worthwhile to establish a good collaboration between the various local actors, even at micro-regional level, by meetings with stakeholders from other regions who can present useful ideas and local experiences. In each case, a multi-policy approach with a high level of collaboration is needed. Relevant stakeholders in the Alpine region include authorities, action forces, helicopter

enterprises, companies for firefighting equipment, scientists, meteorological institutions, mountain rescue organizations, avalanche and torrent control agencies, state police, federal army, local and agricultural communities, tourism organizations, infrastructure facility managers (e.g. railways, roads, mobile operators), water source protection agencies and different NGOs. It would be beneficial and necessary to deploy actions to reach a greater number of participants in multi-stakeholder approaches, e.g. by the organization of local dissemination seminars in original language or simultaneous translations at major events. An example for a success story in this context is the establishment of a multi-stakeholder roundtable after extreme fires in **Italy** (Figure 28).

**Multi-stakeholder roundtable after extreme fires**



Country: Italy  
 Scale: Regional (Piemonte)

**Problem description**

- Simultaneous large forest fires as a result of an exceptional drought (2017).
- Disturbed areas include forests for wood provision, biodiversity conservation, recreation, and slope stability.
- Challenge deciding priorities for restoration with limited resources and stakeholders with contrasting interests.



**Solution**

- Establish a multi-stakeholder roundtable to discuss restoration options based on best available science, interests, and resource constraints.
- Develop guidelines for post-fire restoration, available for private forest owners. Meet local population to explain causes, solutions, and actions being undertaken.
- Slope stabilization was given the highest priority, especially along recreational roads.

**Best practices**

- Roundtable helped deciding the most urgent actions for post-fire restoration.
- Forest owners were helped with an easy-to-read guideline for restoration decisions.
- Public money was channeled to the most effective solutions.
- Public opinion was given special attention with public hearings and newspaper articles.

**Figure 28: Success story** regarding knowledge transfer and exchange: Establish a multi-stakeholder roundtable after extreme fires in Italy.

## TRANSNATIONAL TRAININGS OF FIRE BRIGADES AND SPECIALIZED ACTION FORCES

An increased involvement of **firefighting scenarios in the contact zones between forest and settlements** should be one aim of training courses for action forces. Critical infrastructures and their potentially increased risk in the future, for example mobile phone masts in the forest, must be taken into account. One possibility of specific trainings for firefighters both technically and tactically, is given by the CESIR (Centre Euro-Méditerranéen de Simulation des Risques) of the civil security school of Valabre (**France**). It allows trainings and instructions through computer simulations on the basis of fire situations in an Alpine environment in particular for the heads of intervention teams, who are coordinating the use of various technics and means including air support. The Bavarian Mountain Rescue organization in **Germany** has an indoor training center for simulating helicopter operations, which may also be used to train forest firefighting (<http://www.bw-zsa.org>).

## FOREST FIRE RESEARCH

It is necessary to **continue forest fire research in the Alpine region** in order to assess the short-, medium- and long-term effects of forest fires on the protection function of mountain forests and on the nutrient and carbon cycles after forest fires. Especially Norway spruce, the most dominant tree species in the Alpine region, and possible future natural disturbances interactions (heat waves, droughts, windthrows, bark beetles) should be investigated. Regarding fire effects, improved fire severity assessments are needed, including tree mortality and soil effects. Best practices and success stories should be passed to stakeholders and practitioners. For example, the forest fire site Absam in Tyrol, **Austria**, can serve as best practice example here. Several projects coordinated by the “Landesforstdirektion Tirol” were initiated in cooperation with research institutions (University of Natural Resources and Life Sciences Vienna, University of Innsbruck). Results on post-fire effects were/are published (e.g. Lechner et al. 2019, Vacik et al. 2019)

Future studies should also investigate the expected spread of deciduous tree species (e.g. beech, oak, chestnut) in the face of climate change and their possible vulnerability to spring fires. Alpine ecophysiology (e.g. resistance of native tree species to heat/fire, long-term damage after fires and establishment of young forests after fires) should also be a focus of future research. The anticipation of future forest fire regime would aid in the identification of new fire-related hazards and in the ability to adjust disaster management strategies. It is thus essential to secure funding from national and European sources to continue forest fire research in the future.

## JOINT TERMINOLOGY

During the EU-project ALP FFIRS a first attempt was made to prepare a manual with the most common terms on forest fires in all Alpine languages. This manual may be used as a basis for improving the country-specific understanding of the different terms related to forest fires. Thanks to the JRC project “Determination of forest fire causes and harmonization of methods for reporting them” (Savazzi 2010) a terminology of fire causes has been gathered from 24 countries and a proposal for a harmonized EU classification scheme has been made. The most important and common terms (e.g. “forest fire”) shall be clear for all stakeholders involved in an integrated forest fire management. Joint terminology has to be present during workshops, trainings and international workshops.



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**Figure 29:** Participants of the EUSALP forest fire workshop in June 2019, Vienna.  
 Photo: Institute of Silviculture, BOKU Vienna



## References

- Agee J.K., Bahro B., Finney M.A., Omi P.N., Sapsis D.B., Skinner C.N., van Wagtenonk J.W., Weatherspoon C.P., 2000. The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management*, 127, 55-66.
- Allen C.D., Macalady A.K., Chenchouni H., Bachelet D., McDowell N., Vennetier M., Kitzberger T., Rigling A., Breshears D.D., Hogg E.H., Gonzalez P., Fensham R., Zhang Z., Castro J., Demidova N., Lim J.H., Allard G., Running S.W., Semerci A., Cobb N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259, 660-684.
- Anderegg W.R.L., Hicke J.A., Fisher R.A., et al., 2015. Tree mortality from drought, insects, and their interactions in a changing climate. *New Phytologist* 208, 674-683.
- Arndt N., Vacik H., Koch V., Arpaci A., Gossow H., 2013. Modeling human-caused forest fire ignition for assessing forest fire danger in Austria. *iForest*, 201(6), S. 315–325.
- Arpaci A., Eastaugh C.S., Vacik H., 2013. Selecting the best performing fire weather indices for Austrian ecoregions. *Theoretical and Applied Climatology*, 114, S. 393–406. DOI: 10.1007/s00704-013-0839-7.
- Ascoli D., Castagneri D., Valsecchi C., Conedera M., Bovio G., 2013a. Post-fire restoration of beech stands in the Southern Alps by natural regeneration. *Ecological Engineering*, 54, 210-217.  
<https://doi.org/10.1016/j.ecoleng.2013.01.032>
- Ascoli D., Lonati M., Marzano R., Bovio G., Cavallero A., Lombardi G., 2013b. Prescribed burning and browsing to control tree encroachment in southern European heathlands. *Forest Ecology and Management* 289, pp 69-77.  
<https://doi.org/10.1016/j.foreco.2012.09.041>.
- Ascoli D., Bovio G., 2013. Prescribed burning in Italy: issues, advances and challenges. *iForest-Biogeosciences and Forestry*, 6(2), 79.
- Ascoli D., Vacchiano G., Motta R., Bovio G., 2015a. Building Rothermel fire behaviour fuel models by genetic algorithm optimisation. *International Journal of Wildland Fire*, 24(3), 317-328.
- Ascoli D., Vacchiano G., Maringer J., Bovio G., Conedera M., 2015b. The synchronicity of masting and intermediate severity fire effects favors beech recruitment. *Forest Ecology and Management*, 353, 126-135.
- Bajocco S., Pezzatti G.B., De Angelis A., Conedera M., Ricotta C., 2011. Bootstrapping wildfire selectivity for the forest types of Canton Ticino (Switzerland). *Earth Interactions*, 15, 19 (11 pp.). <https://doi.org/10.1175/2011EI387.1>
- Bär A., Nardini A., Mayr S., 2018. Post-fire effects in xylem hydraulics of *Picea abies*, *Pinus sylvestris* and *Fagus sylvatica*. *New Phytologist* 217, 1484-1493.

- Bär A., Michaletz S., Mayr S., 2019. Fire effects on tree physiology. *Tansley Review. New Phytologist*, 223, 1728-1741.
- Barriopedro D., Fischer E.M., Luterbacher J., Trigo R.M., García-Herrera R., 2011. The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Scienceexpress*. <http://dx.doi.org/10.1126/science.1201224>.
- Beghin R., Lingua E., Garbarino M., Lonati M., Bovio G., Motta R., Marzano R., 2010. *Pinus sylvestris* forest regeneration under different post-fire restoration practices in the northwestern Italian Alps. *Ecological Engineering*, 36(10), 1365-1372.
- Boboulos M., Purvis M.R.I., 2009. Wind and slope effects on ROS during the fire propagation in East-Mediterranean pine forest litter. *Fire Safety Journal*, 44, S. 764–769.
- Bundesforschungszentrum für Wald, 2012. Österreichs Wald. <http://bfw.ac.at> [12.09.2018]
- Cane D., Wastl C., Barbarino S., Renier L.A., Schunk C., Menzel A., 2013. Projection of fire potential to future climate scenarios in the Alpine area: some methodological considerations. *Climatic change*, 119, 733-746. doi: 10.1007/s10584-013-0775-7
- Carrega P., 1995. A method for the reconstruction of mountain air temperatures with automatic cartographic applications. *Theor. Appl. Climatol.* 52, 69-84.
- Carrega P., Geronimo N., 2007. Risque meteorologique d'incendie de forêt et methodes de spatialisation pour une cartographie a fine echelle. *Actes du XXeme colloque international de l'Association Internationale de Climatologie*. Tunis, September 2007.
- Choat B., Brodribb T.J., Brodersen C.R., Duursma R.A., Lopez R., Medlyn B.E., 2018. Triggers of tree mortality under drought. *Nature Plant* 558, 531-539.
- Chuvieco E., Aguado I., Yebra M., Nieto H., Salas J., Martín M.P., Vilar L., Martínez J., Martín S., Ibarra P., de la Riva J., Baeza J., Rodríguez F., Molina J.R., Herrera A., Zamora R., 2010. Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. *Ecological Modelling*, 221(1), S. 46–58.
- Conedera M., Peter L., Marxer P., Forster F., Rickenmann D., Re L., 2003. Consequences of forest fires on the hydrogeological response of mountain catchments: a case study of the Riale Buffaga, Ticino, Switzerland. *Earth Surface Processes and Landforms*, 28(2), 117-129. <https://doi.org/10.1002/esp.425>
- Conedera M., Cesti G., Pezzatti G., Zumbrennen T., Spinedi F., 2006. Lightning-induced fires in the Alpine region: An increasing problem. *Forest Ecology and Management - FOREST ECOL MANAGE*. 234. 10.1016/j.foreco.2006.08.096.
- Conedera M., Vassere S, Neff C, Meurer M, Krebs P., 2007. Using toponymy to reconstruct past land use: a case study of 'brüsáda' (burn) in southern Switzerland. *Journal of Historical Geography* 33: 729-748.

Conedera M., Krebs P., 2010. La pratica del fuoco pastorale nella Svizzera sudalpina dal tardo Medioevo ai nostri giorni. In: Proceedings of the meeting “Al fuoco! Usi, rischi e immaginari collettivi dal Medioevo al XX secolo” (Lorenzetti L, Giannò V eds). Mendrisio (Sondrio - Italy) 15-17 Nov 2007. LabiSAIp ed., Giampiero Casagrande Ed., Milan, Italy, pp. 191-215.

Conedera M., Lucini L., Valse E., Ascoli D., Pezzatti G.B., 2010. Fire resistance and vegetative recruitment ability of different deciduous trees species after low- to moderate-intensity surface fires in southern Switzerland. D. X. Viegas (Ed.), (p. (12 pp.)). Presented at the VI international conference on forest fire research. Coimbra: ADAI/CEIF University of Coimbra.

Conedera M., Tinner W., 2010. Langzeit-Feuerökologie der Schweiz. Schweizerische Zeitschrift für Forstwesen, 161(11), S. 424–432.

Conedera M., Torriani D., Neff C., Ricotta C., Bajocco S., Pezzatti G.B., 2011. Using Monte Carlo simulations to estimate relative fire ignition danger in a low-to-medium fire-prone region. Forest Ecology and Management, 261(12), 2179-2187. <https://doi.org/10.1016/j.foreco.2010.08.013>

Conedera M., Brini M., Ascoli D., Fodera G.M., 2014. FireLess II: ein innovatives, kabelloses System zur Evaluation der Waldbrandgefahr. Technik in Bayern 5: 20:21.

Conedera M., Tonini M., Oleggini L., Vega Orozco C., Leuenberger M., Pezzatti G.B., 2015. Geospatial approach for defining the Wildland-Urban Interface in the Alpine environment. Computers, Environment and Urban Systems, 52, 10-20. <https://doi.org/10.1016/j.compenvurbsys.2015.02.003>

Conedera M., Krebs P., Valse E., Cocca G., Schun, C., Menzel A., ... Pezzatti G.B., 2018. Characterizing Alpine pyrogeography from fire statistics. Applied Geography, 98, 87-99. <https://doi.org/10.1016/j.apgeog.2018.07.011>

De Angelis A., Ricotta C., Conedera M., Pezzatti G.B., 2015. Modelling the meteorological forest fire niche in heterogeneous pyrologic conditions. PLoS One, 10(2), e0116875 (17 pp.). <https://doi.org/10.1371/journal.pone.0116875>

DeBano L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology, 231-232, 195-206.

Dupire S., Curt T., Bigot S., Fréjaville T., 2019. Vulnerability of forest ecosystems to fire in the French Alps. European Journal of Forest Research, 1-18.

Eastaugh C.S., Vacik H., 2012. Fire size/frequency modelling as a means of assessing wildfire database reliability. Austrian Journal of forest Science, 129(3/4), S. 228–247.

European Commission, 2019. *Legislation on protecting the EU's forest against fire*. Available from: <https://ec.europa.eu/environment/forests/fires.htm> [06.08.2019]

EFFIS, o.J. Copernicus. Emergency Management Service.

[http://effis.jrc.ec.europa.eu/static/effis\\_current\\_situation/public/index.html](http://effis.jrc.ec.europa.eu/static/effis_current_situation/public/index.html) [16.09.2018]

European Environment Agency, 2019. *Global and European temperature Report*. Available from:

<https://www.eea.europa.eu/data-and-maps/indicators/global-and-european-temperature-9/assessment>  
[01.07.2019]

Extra-Blatt, 2018. Brand in Siegburg – Kanzlerin wünscht Verletzten schnelle Genesung. Rheinische Anzeigenblätter.

<https://www.rheinische-anzeigenblaetter.de/mein-blatt/extra-blatt/siegburg/brand-in-siegburg-kanzlerin-wuenscht-verletzten-schnelle-genesung-31078582> [12.09.2018]

Fernandes P.M., Davies G.M., Ascoli D., Fernández C., Moreira F., Rigolot E., ... Molina D., 2013. Prescribed burning in southern Europe: developing fire management in a dynamic landscape. *Frontiers in Ecology and the Environment*, 11(s1), e4-e14.

Fox D.M., Carrega P., 2006. Post forest fire erosion control: a modelling strategy to shorten response time. V International conference on Forest Fire Research, DX Viegas ED, 2006, Portugal.

Fox D.M., Maselli F., Carrega P., 2008. Using SPOT images and field sampling to map burn severity and vegetation factors affecting post forest fire erosion risk. *Catena* 75 (2008), 326-335.

Fréjaville T., Curt T., Carcaillet C., 2016. Tree cover and seasonal precipitation drive understory flammability in alpine mountain forests. *Journal of Biogeography* 43, 1869–1880.

Ganthaler A., Bauer H., Gruber A., Mayr M., Oberhuber W., Mayr S., 2014. Effects of the needle bladder rust (*Chrysomyxa rhododendri*) on Norway spruce - implications for subalpine forests. *Journal of European Forest Research* 133, 201-211.

Gehring E., Conedera M., Maringer J., Giadrossich F., Guastini E., Schwarz M., 2019. Shallow landslide disposition in burnt European beech (*Fagus sylvatica* L.) forests. *Scientific Reports*, 9(1), 8638 (11 pp.).  
<https://doi.org/10.1038/s41598-019-45073-7>

GDV, Die deutschen Versicherer, 2019. Available from: <https://www.gdv.de/de/themen/news/wie-die-folgen-von-waldbraenden-versichert-sind-10960> [08.11.2019]

Ghiringhelli A., Pezzatti G.B., Conedera M., 2019. Das Konzept „Waldbrand 2020“ des Kantons Tessin. *Schweizerische Zeitschrift für Forstwesen*, 170(5), 242-250.

Girardin M.P., Terrier A., 2015. Mitigating risks of future wildfires by management of the forest composition: an analysis of the offsetting potential through boreal Canada. *Climatic Change*, 130: 587–601

- Gobiet A., Kotlarski S., Beniston M., Heinrich G., Rajczak J., Stoffel M., 2014. 21st century climate change in the European alps – A review. *Science of the Total Environment*, 493, S. 1138–1151.  
DOI:10.1016/j.scitotenv.2013.07.050.
- Goldammer J., Mitsopoulos I., Mallinis G., Woolf M., 2017. Wildfire Hazard and Risk Assessment. Words into Action Guidelines: National Disaster Risk Assessment, Hazard Specific Risk Assessment. United Nations Office for Disaster Risk Reduction (UNISDR).
- González-Pérez J.A., González-Vila F.J., Almendros G., Knicker H., 2004. The effect of fire on soil organic matter – a review. *Environment International*, 30, 855-870
- Gossow H., Hafellner R., Vacik H., Huber T., 2009. Major Fire Issues in the Euro-Alpine Region – the Austrian Alps. *International Forest Fire News IFFN* 38, 1-10, ISSN 1029-0864
- Hardy C.C., 2005. Wildland fire hazard and risk: Problems, definitions, and context. *Forest Ecology and Management* 211 (1–2), pp 73-82. <https://doi.org/10.1016/j.foreco.2005.01.029>.
- Heel M., 2015. Waldbrände in den Nördlichen Kalkalpen – raumzeitliche Verteilung und Beispiele lokaler Auswirkungen. Dissertation, Universität Augsburg, Fakultät für Angewandte Informatik.
- Hofmann C., Conedera M., Delarze R., Carraro G., Giorgetti P., 1998. Effets des incendies de forêt sur la végétation au Sud des Alpes suisses. *Mitteilungen der Eidgenössischen Forschungsanstalt für Wald, Schnee und Landschaft: Vol. 73*. Birmensdorf: Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft.
- Jereb L., Turk B., 2014. Introduction of new preventive measures for the limiting of wildfires. *Ujma, Magazine for natural and other disasters issues*, n. 28, 2014
- Jolly W.M., Cochrane M.A., Freeborn P.H., Holden Z.A., Brown T.J., Williamson G.J., Bowman D.M.J.S., 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications* 2015 (6), 7537.
- König H.C., 2007. Waldbrandschutz : Kompendium für Forst und Feuerwehr. Fachverlag Matthias Grimm, 197 p., ISBN 978-3940286017
- Lahaye S., 2018. Comprendre les grands feux de forêt pour lutter en sécurité. Thèse de doctorat en Environnement et archéologie, l'École pratique des hautes études, Paris, et de l'Institut des sciences de l'évolution, Montpellier.  
<http://www.theses.fr/2018PSLEP042>
- Lahaye S., Curt T., Fréjaville T., Sharples J., Paradis L., Hély C., 2018. What are the drivers of dangerous fires in Mediterranean France? *International Journal of Wildland Fire*, 27, 155-163.
- Lawrence J.G., Colwell A., Sexton O.J., 1991. The ecological impact of allelopathy in *Ailanthus altissima* (Simaroubaceae). *American Journal of Botany*, 78 (7), 948-958.



- Lexer M.J., Rabitsch W., Grabherr G., Dokulil M., Dullinger S., Englisch J., Essl F., Gollmann G., Gottfried M., Graf W., Hoch G., Jandl R., Kahrer A., Kainz M., Kirisits T., Netherer S., Pauli H., Rott E., Schleper C., Schmidt-Kloiber A., Schmutz S., Schopf A., Seidl R., Vogl W., Winkler H., Zechmeister H., 2014. Der Einfluss des Klimawandels auf die Biosphäre und Ökosystemleistungen. In: Austrian Panel on Climate Change (APCC), Österreichischer Sachstandsbericht Klimawandel 2014. Verlag der Österreichischen Akademie der Wissenschaften, Wien, S. 467–556.
- Lonati M., Gorlier A., Ascoli D., Marzano R., Lombardi G., 2009. Response of the alien species *Panicum acuminatum* to disturbance in an Italian lowland heathland. *Botanica Helvetica* 119: 105-111
- Maringer J., Wohlgemuth T., Neff C., Pezzatti G.B., Conedera M., 2012. Post-fire spread of alien plant species in a mixed broad-leaved forest of the Insubric region. *Flora*, 207(1), 19-29. <https://doi.org/10.1016/j.flora.2011.07.016>
- Maringer J., Ascoli D., Dorren L., Bebi P., Conedera M., 2016a. Temporal trends in the protective capacity of burnt beech forests (*Fagus sylvatica* L.) against rockfall. *European Journal of Forest Research*, 135(4), 657-673. <https://doi.org/10.1007/s10342-016-0962-y>
- Maringer J., Ascoli D., Küffer N., Schmidtlein S., Conedera M., 2016b. What drives European beech (*Fagus sylvatica* L.) mortality after forest fires of varying severity? *Forest Ecology and Management*, 368, 81-93. <https://doi.org/10.1016/j.foreco.2016.03.008>
- Marzano R., Garbarino M., Marcolin E., Pividori M., Lingua E., 2013. Deadwood anisotropic facilitation on seedling establishment after a stand-replacing wildfire in Aosta Valley (NW Italy). *Ecological Engineering*, 51, 117-122.
- Michaletz S.T., Johnson E.A., 2007. How forest fires kill trees: a review of the fundamental biophysical processes. *Scandinavian Journal of Forest Research* 22, 500-515.
- McLeod R.N., Pascoe S.M., Teague B.G., 2009. 2009 Victorian Bushfires Royal Commission: Interim report. Government Printer for the State of Victoria, Melbourne.
- Moreira F., Viedma O., Arianoutsou M., Curt T., Koutsias N., Rigolot E., Barbati A., Corona P., Vaz P., Xanthopoulos G., Mouillot F., Bilgili E., 2011. Landscape – wildfire interactions in southern Europe: Implications for landscape management. *Journal of Environmental Management* 92: 2389–2402.
- Moretti M., Barbalat S., 2004. The effects of wildfires on wood-eating beetles in deciduous forests on the southern slope of the Swiss Alps. *Forest Ecology and Management*, 187(1), 85-103. [https://doi.org/10.1016/S0378-1127\(03\)00314-1](https://doi.org/10.1016/S0378-1127(03)00314-1)
- Moretti M., Duelli P., Obrist M.K., 2006. Biodiversity and resilience of arthropod communities after fire disturbance in temperate forests. *Oecologia*, 149(2), 312-327. <https://doi.org/10.1007/s00442-006-0450-z>
- Moretti M., Obrist M.K., Duello P., 2004. Arthropod biodiversity after forest fires: winners and losers in the winter fire regime of the southern Alps. *Ecography*, 27, 173-186.

Müller M.M., Vilà-Vilardell L., Vacik H., 2020. Towards an integrated forest fire danger assessment system for the Alpine region, submitted.

Müller M.M., Vacik H., 2017. Characteristics of lightnings igniting forest fires in Austria. *Agricultural and Forest Meteorology*, 240-241, 26-34.

Müller M.M., Vacik H., Diendorfer G., Arpaci A., Formayer H., Gossow H., 2013. Analysis of lightning-induced forest fires in Austria. *Theoretical and Applied Climatology*, 111(1/2), S. 183–193.

Müller M.M., Vacik H., Valsecchi E., 2015. Anomalies of the Austrian Forest Fire Regime in Comparison with Other Alpine Countries: A Research Note. *Forests*, 2015(6), S. 903–913.

Müller T., 2007. Wirkung von Glasscherben bei der Entzündung von Streuauflagen. Diplomarbeit, Abteilung für Bodenkunde und Bodenphysik, Institut für Geoökologie, TU Braunschweig, 92 S. (unveröffentlicht)

Neary D.G., Klopatek C.C., DeBano L.F., Ffolliott P.F., 1999. Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management*, 122, 51-71.

NFPA, National Fire Protection Association, 2019. Firewise USA – Residents reducing wildfire risks.  
<https://www.nfpa.org/Public-Education/Fire-causes-and-risks/Wildfire/Firewise-USA> [03.09.2019]

Ogris N., 2018. Daily forecast of meteorological fire risk of forests in Slovenia by model FWI-INCA. Forest health forecasts, 2018. URL: [https://www.zdravgozd.si/prognose\\_zapis.aspx?idpor=42](https://www.zdravgozd.si/prognose_zapis.aspx?idpor=42). DOI: 10.20315/NZG.42

Otto H.J., 1980. Waldbauliche Überlegungen und Maßnahmen im Gefolge der Waldbrände von 1975 und 1976 in Niedersachsen. *Forstwissenschaftliches Centralblatt*, 99(1), S. 385–388.

Pauli H., Gottfried M., Grabherr G., 2003. Effects of climate change on the alpine and nival vegetation of the Alps. *Journal of Mountain Ecology* 7.

Pausas J.G., 2017. Fire danger, fire hazard, fire risk ... <https://jgpausas.blogs.uv.es/2017/08/05/fire-danger-fire-hazard-fire-risk> [15.09.2019]

Pezzatti G.B., Bajocco S., Torriani D., Conedera M., 2009. Selective burning of forest vegetation in Canton Ticino (southern Switzerland). *Plant Biosystems*, 143(3), 609-620. <https://doi.org/10.1080/11263500903233292>

Pezzatti G.B., Zumbrennen T., Bürgi M., Ambrosetti P., Conedera M., 2013. Fire regime shifts as a consequence of fire policy and socio-economic development: an analysis based on the change point approach. *Forest Policy and Economics*, 29, 7-18. <https://doi.org/10.1016/j.forpol.2011.07.002>

Pezzatti G.B., Bertogliati M., Gache S., Reinhard M., Conedera M., 2019. Swissfire: technisch modernisiert und dank Archivrecherchen inhaltlich erweitert. *Schweizerische Zeitschrift für Forstwesen*: September 2019, Vol. 170, No. 5, pp. 234-241.

Pötzelberger E., Lapin K., Brundu G., 2018. National and subnational legal frameworks on non-native tree species in Europe. In: Pötzelberger E., Spiecker H., Hasenauer H., Konner M., Mohren G.M.J., Gazda A. (Eds.). COST Action FP1403 NNEXT – International Conference 'Non-native tree species for European forests', Vienna, Austria, 12-14 September 2018. Book of Abstracts, Universität für Bodenkultur, ISBN: 978-3-900932-59-6.

Providoli I., Elsenbeer H., Conedera M., 2002. Post-fire management and splash erosion in a chestnut coppice in southern Switzerland. *Forest Ecology and Management*, 162, 219-229. [https://doi.org/10.1016/S0378-1127\(01\)00517-5](https://doi.org/10.1016/S0378-1127(01)00517-5)

Regione Piemonte, 2018. Piano straordinario di interventi di ripristino del territorio percorso dagli incendi boschivi dell'autunno 2017. Available online:  
<https://www.regione.piemonte.it/web/sites/default/files/media/documenti/2019-04/Piano%20Straordinario%20interventi%20di%20ripristino.pdf> [30.11.2019]

Reinhard M., Beyeler S., Plüss T., Pezzatti G.B., Conedera M., 2019. La gestion des incendies de forêts en Suisse: la vision nationale de l'OFEV. *Schweizerische Zeitschrift für Forstwesen*, 170(5), 281-284.

Rizzolo R., 2016. Fuel models development to support spatially-explicit forest fire modelling in eastern Italian Alps. Regional Council deliberation n.59 of May 18<sup>th</sup> 2018.

Roosli B., Felder U., Zahner M., 2019. Waldbrandgefahr: koordinierte Warnung in der Zentralschweiz. *Schweizerische Zeitschrift für Forstwesen*, 170(5), 274-277.

Sande Silva J., Rego F., Fernandes P., Rigolot E., 2010. Towards Integrated Fire Management – Outcomes of the European Project Fire Paradox. Research Report 23. European Forest Institute. ISBN: 970-952-5453-48-5

San-Miguel-Ayán J., Costa H., de Rigo D., Libertá G., Vivancos T.A., Durrant T., Nuijten D., Löffler P., Moore P., 2018. Basic criteria to assess wildfire risk at the pan-European level. JRC Technical Reports. EUR 29500 EN, ISBN 978-92-79-98200-2, doi:10.2760/052345

Sass O. (Hrsg.), 2019. Waldbrände in den Nordtiroler Kalkalpen. Innsbrucker Geographische Studien Bd. 41.

Sass O., 2014. FIRIA – Fire Risk and Vulnerability of Austrian Forests under the Impact of Climate Change. Endbericht. APRP 3rd Call 2010. <https://www.klimafonds.gv.at/report/acrp-3rd-call-2010> [19.12.2018]

Sass O., Heel M., Leistner I., Stöger F., Wetzler K.F., Friedmann A., 2012. Disturbance, geomorphic processes and regeneration of wildfire slopes in North Tyrol. *Earth Surface Processes and Landforms*, 37(8), S. 883–889.

Savazzi R., Duché Y., Ganteaume A., Piwnicki J., Lourenço L., Bento Gonçalves A., Ferreira A., SuarezBeltran J., 2010. Analysis of fire causes classification schemes adopted in Europe and elsewhere (Final Report). Deliverable D 2.2. Contract number 384 340 “Determination of forest fire causes and harmonisation for reporting them”. European

Commission-JRC, p 71.

[http://www.uc.pt/fluc/nicif/Projetos/Internacionais/jrc/relatorio\\_final/Analyses\\_of\\_fire\\_causes.pdf](http://www.uc.pt/fluc/nicif/Projetos/Internacionais/jrc/relatorio_final/Analyses_of_fire_causes.pdf)

Schunk C., Wastl C., Leuchner M., Schuster C., Menzel A., 2013. Forest fire danger rating in complex topography – results from a case study in the Bavarian Alps in autumn 2011, *Nat. Hazards Earth Syst. Sci.*, 13, 2157-2167, <https://doi.org/10.5194/nhess-13-2157-2013>.

Seidl R., Donato D.C., Raffa K.F., Turner M.G., 2016. Spatial variability in tree regeneration after wildfire delays and dampens future bark beetle outbreaks. *Proceedings of the National Academy of Sciences*, 113 (46), 13075-13080.

Seidl R., Schelhaas M.J., Rammer W., Verkerk P.J., 2014. Increasing forest disturbances in Europe and their impact on carbon storage. *Nature Climate Change* 4: 806–810. <http://dx.doi.org/10.1038/nclimate2318>.

Šturm T., Šumrada R., Mikoš M., Jurc M., Turk G., Podobnikar T., Hladnik D., 2013. Forest fire occurrence prediction in Slovenia using GIS technology. University in Ljubljana. URN:NBN:SI:DOC-VH662VJB. <http://www.dlib.si>.

Tedim F., Leone V., Amraoui M., Bouillon C., Coughlan M.R., Delogu G.M., Fernandes P.M., Ferreira C., McCaffrey S., McGee T.K., Parente J., Paton D., Pereira M.G., Ribeiro L.M., Viegas D.X., Xanthopoulos G., 2018. Defining Extreme Wildfire Events: Difficulties, Challenges, and Impacts. *Fire* 1 (9).

Tinner W., Conedera M., Ammann B., Lotter A.F., 2005. Fire ecology north and south of the Alps since the last ice age. *Holocene*, 15(8), S. 1214–1226.

Trnka M., Balek J., Štěpánek P., Zahradníček P., Možný M., Eitzinger J., Žalud Z., Formayer H., Turňa M., Nejedlík P., Semerádová D., Hlavinka P., Brázdil R., 2016. Drought trends over part of Central Europe between 1961 and 2014. *Climate Research*, 70(2), S. 143–160. DOI: 10.3354/cr01420.

Turner M.G., Romme W.H., Gardner R.H., Hargrove W.W., 1997. Effects of fire size and pattern on early succession in Yellowstone National Park. *Ecological Monographs*, 67 (4), 411-433.

Vacchiano G., Foderi C., Berretti R., Marchi E., and Motta R., 2018. Modeling anthropogenic and natural fire ignitions in an inner-alpine valley. *Natural Hazards and Earth System Sciences*, 18, 935–948.

Vacik H., Arndt N., Arpaci A., Koch V., Müller M.M., Gossow H., 2011. Characterisation of forest fires in Austria. *Austrian Journal of Forest Science*, 128(1), S. 1–32.

Valese E., Driussi M., Held A.C., Gottardo E., Ascoli D., Anfodillo T., 2011. The pilot project Ohonj na Buonah for studying the application of prescribed burning in the Eastern Alps of Italy (Friuli-Venezia Giulia region). *Proceedings of the 5<sup>th</sup> International Wildland Fire Conference*.

Valese E., Conedera M., Held A.C., Ascoli D., 2014. Fire, humans and landscape in the European Alpine region during the Holocene. *Anthropocene*. <http://dx.doi.org/10.1016/j.ancene.2014.06.006>.

Van Wagner C.E., 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Headquarters, Ottawa. Forestry Technical Report 35, 35 p.

Vergani C., Werlen M., Conedera M., Cohen D., Schwarz M., 2017. Investigation of root reinforcement decay after a forest fire in a Scots pine (*Pinus sylvestris*) protection forest. *Forest Ecology and Management*, 400, 339-352.  
<https://doi.org/10.1016/j.foreco.2017.06.005>

Viegas D.X., Pita L.P., 2004. Fire spread in canyons. *International Journal of Wildland Fire* 13, 253-274.  
<https://doi.org/10.1071/WF03050>

Chtioui Y., Kaulfuß S., 2019. Waldbrandüberwachung. FVA Deutschland. Online available:  
[https://www.waldwissen.net/waldwirtschaft/schaden/brand/fva\\_waldbrand\\_wb3/index\\_DE](https://www.waldwissen.net/waldwirtschaft/schaden/brand/fva_waldbrand_wb3/index_DE) [08.09.2019]

Wastl C., Schunk C., Leuchner M., Pezzatti G.B., Menzel A., 2012. Recent climate change: Long-term trends in meteorological forest fire danger in the Alps. *Agricultural and Forest Meteorology* 162-163, 1-13.

Westerling A.L., Turner M.G., Smithwick E.A.H., Romme W.H., Ryan M.G., 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences* Aug 2011, 108 (32) 13165-13170; DOI: 10.1073/pnas.1110199108

ZAMG, 2018. Information zur Waldbrandgefahr. <https://www.zamg.ac.at/cms/de/wetter/wetter-oesterreich/waldbrand> [13.04.2018]

Zumbrunnen T., Bugmann H., Conedera M., Bürgi M., 2009. Linking Forest Fire Regimes and Climate - A Historical Analysis. *Ecosystems* 12: 73–86. <http://dx.doi.org/10.1007/s10021-008-9207-3>.



## NATIONAL AND REGIONAL DATABASES ON FIRE STATISTICS:

### Austria:

Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna (BOKU), Fire database Austria (<http://fire.boku.ac.at/firedb>)

### France:

Ministry of Agriculture and Food, French Forest Fire Database, BDIFF (<http://bdiff.ifn.fr/>)

### Germany:

Bundesanstalt für Landwirtschaft und Ernährung, Forest fire statistics of the federal republic of Germany ([https://www.ble.de/DE/BZL/Daten-Berichte/Wald/wald\\_node.html](https://www.ble.de/DE/BZL/Daten-Berichte/Wald/wald_node.html))

### Italy:

Civil Protection Departments of Regione Piemonte, Regione Liguria, Regione Lombardia, Regione Valle d'Aosta, Regione Friuli Venezia Giulia, Regione Veneto, Provincia Autonoma di Trento, and Provincia Autonoma di Bolzano.

### Slovenia:

Slovenian Forest Service (<http://www.zgs.si/index.html>)

### Switzerland:

Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Swissfire (<https://www.wsl.ch/en/services-and-products/data-monitoring-and-inventories/swissfire.html>)

## Annex

### Glossary of terms and definitions:

**FOREST FIRE:** Uncontrolled fire (partly) in forested area (including clear-cuts, young forest, coppice and vegetation at the alpine forest border), independent of fire type (smoldering fire, surface fire, crown fire), size and cause (e.g. also a single burning tree from lightning)

**ALPINE REGION:** Geographically defined mountainous region in Central Europe according to the 48 regions mentioned for the EUSALP group (<https://www.alpine-region.eu/7-countries-and-48-regions>). For our analysis we used a more precise match of the Alpine border defined by the Alpine convention (<http://webgis.alpconv.org>) by aggregating available data on NUTS3-level.

**AUTHORITIES:** Renowned persons in civil service responsible for or mainly engaged in forest fire precaution or aftercare measures on a transregional or nationwide basis.

**SCIENTISTS:** Renowned persons with scientific background responsible for or main research in forest fire science on a nationwide or pan-European basis.

**ACTION FORCES:** Renowned persons from fire brigades, police or national army responsible for or main focus on forest fire fighting on a transregional or nationwide basis.

### Demographics of the EUSALP survey

**Table 6:** Number of answers obtained per target group.

	Action forces	Authorities	Scientists	Total
AT	8	11	4	23
CH	2	17	3	22
DE	2	3	2	7
FR	2	2	6	10
IT	3	3	5	11
LI	-	1	-	1
SI	-	5	1	6
Total	17	42	21	80

**Table 7:** Number of answers obtained from the perspective of the country/region.

	Country	Region
<b>AT</b>	15	8
<b>CH</b>	6	16
<b>DE</b>	2	5
<b>FR</b>	5	5
<b>IT</b>	4	7
<b>LI</b>	1	-
<b>SI</b>	6	-
<b>Total</b>	<b>39</b>	<b>41</b>

**Table 8:** List of regions from where answers were provided.

Country	Regions
<b>AT</b>	Burgenland, Kärnten, Oberösterreich, Salzburg, Steiermark, Tirol, Vorarlberg
<b>CH</b>	Appenzell Ausserrhoden, Appenzell Innerrhoden, Bern, Fribourg, Graubünden, Jura, Lucerne, St. Gallen, Schwyz, Solothurn, Ticino, Vaud, Zug, Zürich
<b>DE</b>	Bavaria
<b>FR</b>	Provence-Alpes-Côte d'Azur
<b>IT</b>	Bozen, Friuli-Venezia Giulia, Liguria, Piemonte, Trento, Veneto
<b>LI</b>	-
<b>SI</b>	-