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# Linking Forest Fire Regimes and Climate—A Historical Analysis in a Dry Inner Alpine Valley

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## Abstract

Forest fire regimes are likely to experience considerable changes in the European Alps due to climatic changes. However, little is known about the recent regional fire history and the impact of local climate on the fire regime during the 20th century. We therefore reconstructed the fire history in a dry continental valley of the Swiss Alps (Valais) over the past 100 years based on documentary evidence, and investigated the relationship between the reconstructed fire regime and the local climatic variability. We compared the impact of temperature, precipitation, drought and dry foehn winds on fire frequency, extent of burnt area, and fire seasonality on various spatial and temporal scales. In the subalpine zone, the fire regime appears to have been mainly driven by temperature and precipitation, whereas these variables seem to have played only a secondary role in the colline–montane zones. Here, foehn winds and, probably, non-climatic factors seem to have been more important. Temperature and precipitation played a major role in shaping fire frequency and burnt area in the first half of the 20th century, but lost their importance during the second half. Our case study illustrates the occurrence of different fire regime patterns and their driving forces on small spatial scales (a few hundred square kilometers). We conclude that the strong rise in temperature over the past century has not profoundly changed the fire regime in Valais, but in the second half of the 20th century temperature was no longer a strong determinant for forest fires as compared to human activities or biomass availability in forests.

**Key words:** Fire history; Climate; Continentality; Documentary evidence; Central Alps; Switzerland.

## Introduction

Forest fires are a major disturbance agent in many forests worldwide, shaping species composition as well as the spatial pattern of vegetation cover (Patterson and Backman 1988; Frelich 2002). At the same time, they are an important natural hazard for many human populations, for example, in Mediterranean regions, regardless of whether they have natural or anthropogenic causes (Pyne and others 1996).

Climate is one of the major drivers of fire regimes and has a multi-faceted effect on fire activity. It can act indirectly by enhancing biomass production and therefore increasing fuel supplies (Kitzberger and

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others 1997; Clark and others 2002). It can be a predisposing agent if it causes water stress and dries out fuel (Renkin and Despain 1992; Kunkel 2001), or acts directly by igniting fires, for example, through lightning, or modulating fire behavior, for example, through wind (Cesti 1990; Pyne and others 1996). Climate influences fire activity on very different spatial scales: from the global, when phenomena such as the El Niño-Southern Oscillation affect the occurrence of large fires on subcontinental scales (Swetnam and Betancourt 1990) to the local, when winds influence fine-scale fire activity patterns (Agee 1993).

Spatially, the relative importance of climatic variables varies greatly according to geographical region and ecosystem type. Lightning has been found to be an important cause of ignition in most boreal forests (Granström 1993; Nash and Johnson 1996; Larjavaara and others 2005), in some subalpine coniferous stands (Nash and Johnson 1996; Conedera and others 2006) and in Mediterranean forests in northern Baja California (Minnich and others 1993). However, this type of ignition is less common in regions with a Mediterranean climate in Europe or Chile (Susmel 1973; Montenegro and others 2004). In boreal forests in eastern Canada and in *Sequoiadendron giganteum* forests in the Californian Sierra Nevada, climate—especially drought—has been found to have a strong impact on fire frequency (Swetnam 1993; Carcaillet and others 2001). Fry and Stephens (2006), however, found no correlation between drought periods and fire frequency in *Pinus ponderosa* forests in the southeastern Klamath Mountains (California). The relative importance of weather versus fuel load as driving factors for forest fires is also disputed (Cumming 2001). For instance, Keeley and Fotheringham (2001) asserted that the fire regime in southern Californian shrublands is mainly wind-driven, whereas Minnich (2001) claimed it is mostly due to fuel build-up. There are also intense discussions as to the prevalence of either climate/weather or human activities as a driving force for the shaping of fire regimes, for example, in the Swedish boreal forests (Niklasson and Granström 2000; Carcaillet and others 2007) as well as on a global scale (Chuvieco and others 2008). Thus, region-specific analyses of the driving forces of fire regimes are required to understand local fire regimes better and to enable projections of the future fire regimes under changed environmental conditions.

In regions where the fire regime is climate-driven, climate change may have already provoked changes in fire activity. In the western USA, for instance, an extension of the fire season and an increase in the frequency of large fires has already been observed (Westerling and others 2006). In contrast, some authors suggested a decrease in fire frequency and burnt area in some regions of North America and northern Europe in a warmer climate because of the increase in precipitation and/or relative humidity (Bergeron and Archambault 1993; Flannigan and others 1998, 2001). Little is known, however, on possible recent changes in the fire regime in central Europe.

In this article, we analyze the fire regime in Valais (Switzerland), a central Alpine valley with a continental climate similar to that of Briançonnais in France and the Val d'Aoste and Vinschgau in Italy. Although the Valais is characterized by a rather modest fire activity in comparison to other regions in Europe, such as the Mediterranean basin, considerable changes in the fire regime have been forecast in association with a projected future climate (Schumacher and Bugmann 2006). However, apart from two previous rather descriptive studies (Bochatay and Moulin 2000; Gimmi and others 2004), a detailed reconstruction of the fire regime of Valais during the past century and an empirical understanding of the relationships between this regime and climatic variables are still largely lacking. Furthermore, only a few studies about the fire history of entire regions in the European Alps have been published so far (for example, Buresti and Sulli 1983; Stefani 1989; Cesti and Cerise 1992; Conedera and others 1996), and most of them cover only short study periods (two to three decades).

Thus, the main goals of our study are: (1) to reconstruct the forest fire history of Valais during the 20th century using documentary evidence (forest service reports); (2) to determine the relationship between the fire regime and the local climatic variability; and (3) to evaluate whether past climatic changes resulted in corresponding changes in the fire regime. Specifically, we want to assess if the fire regime reflects the spatial, seasonal, and temporal (1904–2006) changes in the patterns of rainfall, temperature, and the dry wind system (foehn).

## Material and Methods

### Study Area

The canton of Valais is a mountainous region located in the western Swiss Alps, bordering Italy in the south and France in the west (Figure 1). It covers an area of 5200 km$^2$, of which about half is

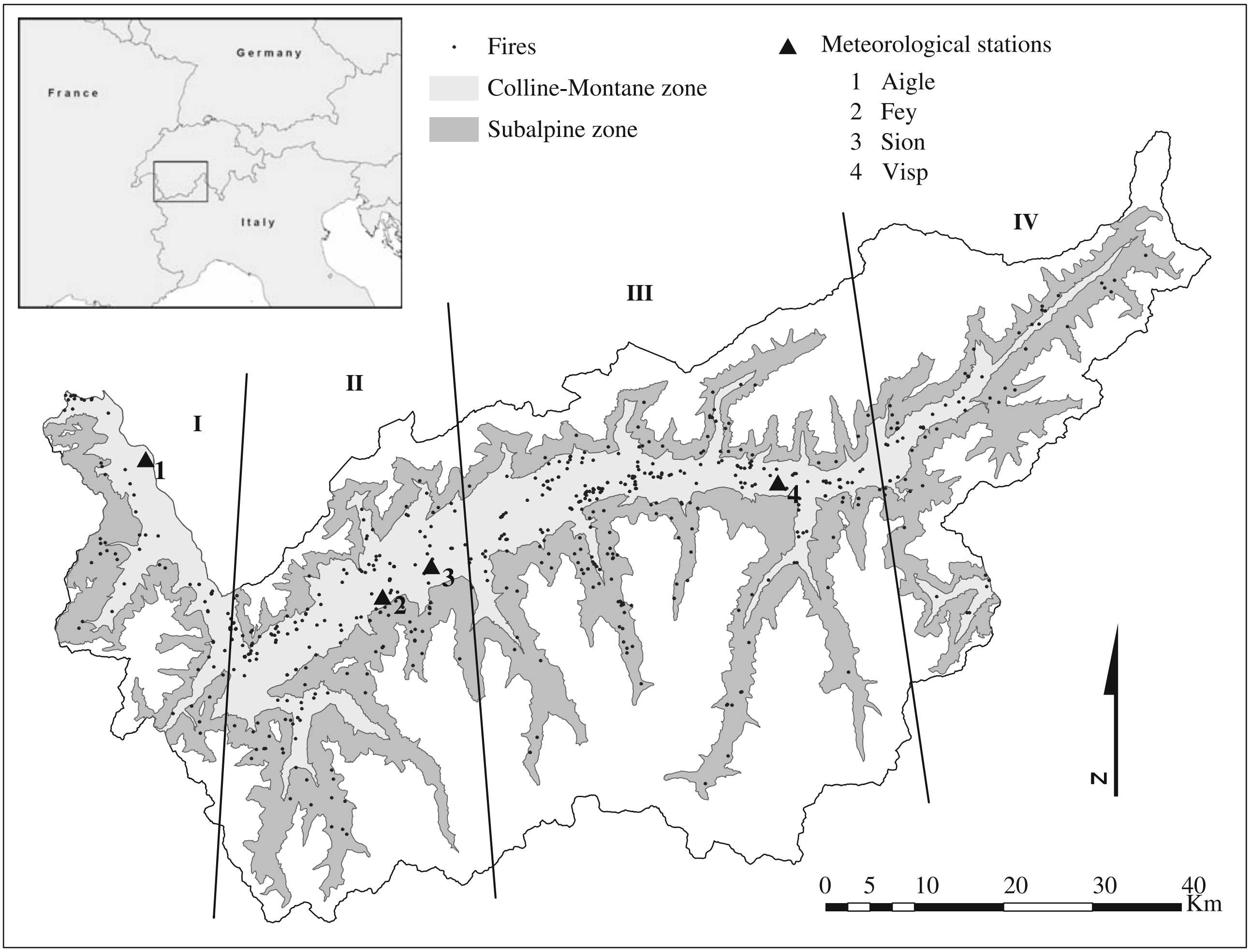


**Figure 1.** Study region (Valais) with the meteorological stations used in the study, altitudinal levels and ignition points of all documented fires with location information (1904–2006). The *Roman numbers* indicate the regions with foehn occurrence (I and III), and without foehn occurrence (II and IV) according to Bouët (1972) (*Source of administrative boundaries*: Bundesamt für Landestopographie).

unproductive (mainly rocks and glaciers) (Gutersohn 1961). Valais consists of a main valley (Rhône river valley) oriented east–west, bordered by smaller side valleys, and is characterized by strong climatic gradients.

Most of Valais has a continental climate (Braun-Blanquet 1961), that is, relatively low annual rainfall (for example, 598 mm in Sion, 482 m a.s.l.), cold winters, high insolation, and high daily and annual temperature fluctuations. The western part, however, (region I in Figure 1) is characterized by more oceanic climatic conditions with higher rainfall (for example, 1032 mm in Aigle, 381 m a.s.l.), with a peak in summer, and smaller temperature variations (MeteoSwiss 2005). During the 20th century, an increase in annual mean temperature of 1.3°C was observed in Valais (Bader and Bantle 2004), and climatic projections suggest further warming and increased summer drought for this area (for example, Schär and others 2004).

The study region is regularly affected by the foehn, a dry katabatic wind with strong gusts, which typically causes the relative humidity to drop to very low values (<30%) and the temperature to rise markedly (Ficker and De Rudder 1943; Kuhn 1989). According to Bouët (1972), the foehn blows in two distinct regions in Valais (I and III)—mainly in the Rhône valley and its southern side valleys—and is nearly absent from regions II and IV (Figure 1). Its occurrence is thus restricted to certain areas, but its desiccating and warming effects are also perceptible in the neighboring regions (Baeriswyl 1994). The main foehn seasons are from late February to mid-June (peak in April) and from mid-September to mid-November (Bouët 1972).

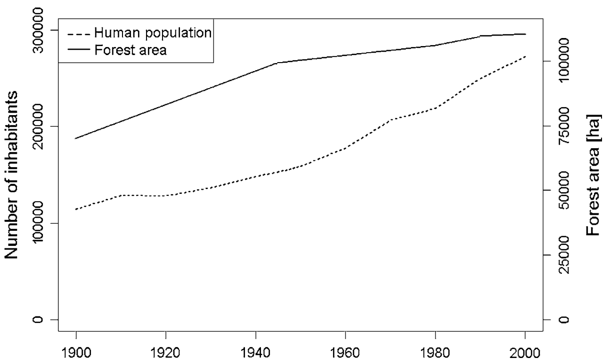


**Figure 2.** Changes in human population (Bundesamt für Statistik 2008) and in forest area (Ritzmann-Blickenstorfer 1996; Bundesamt für Statistik 2000) during the 20th century in the study region.

Today, forests in Valais cover an area of approximately 1100 $km^2$ (Bundesamt für Statistik 2000). Due to conservation measures and the decline in agricultural activities in less productive and/or less accessible areas (Walther and Julen 1986; Kuonen 1993), the forest area has strongly increased over the 20th century in the study region (Figure 2). The distribution of forest types reflects topographic and climatic patterns. At lower elevations in the oceanic region (colline zone, ~400–800 m a.s.l.), broadleaved deciduous forests dominated by *Quercus petrea* and *Quercus robur* prevail, whereas in the continental region *Quercus pubescens* is the dominant late-successional species. At medium elevations (montane zone, ~800–1400 m a.s.l.), forests in the oceanic region are dominated by *Fagus sylvatica* and *Abies alba* and in the continental region by *Pinus sylvestris* (*Picea abies* in the upper parts). At the subalpine level (~1400–2300 m a.s.l.) in the oceanic region, *P. abies* predominates, whereas in the continental region forests are dominated by *P. abies* in the lower parts and *Larix decidua* and *P. cembra* at higher altitudes (Hainard 1969; Werner 1994). Most deciduous forests are located in the oceanic part, whereas coniferous species dominate in the continental part (Werlen 1994).

Today, the population in Valais is about 300,000 inhabitants. The number of inhabitants has more than doubled over the past 100 years (Figure 2). Valais underwent important population movements from its more mountainous parts to the lowlands and from the side valleys to the main valley during the 20th century (Kempf 1985). At present, a large proportion of the population lives in the few urban centers of the main valley (Bundesamt für Statistik 2002, 2005).

## Reconstruction of the Fire Regime

Based on documentary evidence from the archives of the forest service of the canton Valais, we built a database of forest fire events covering the period 1904–2006. This database integrates data from previous inventories covering the periods 1973–2000 (Bochatay and Moulin 2000) and 1904–2003 (Gimmi and others 2004).

For some fire events, no information on the size of the burnt area was given in the historical sources. We assumed that these events were mostly small, and allocated them to the class of ''very small fires,'' that is, those with an area less than 0.1 ha. The resulting forest fire statistics are always presented in two forms, one including and the other excluding events whose size is not known.

To compare the median fire sizes of three different time periods (1904–1940/1941–1970/1971–2006), we performed a one-sided Wilcoxon rank-sum test. We wanted to test the null hypothesis that the median fire size of the 1904–1940 period was the same as that of the 1941–1970 period versus the alternative hypothesis that the median fire size of the 1941–1970 period was greater than that of the 1904–1940 period. We applied the same procedure to test whether the median fire size of the 1941–1970 period was equal to or greater than the median fire size of the 1971–2006 period. This test was calculated twice, once including and once excluding the fires of unknown size (see above).

Unfortunately, no information on fire intensity is available. Our analysis of the fire regime is therefore limited to frequency, season of occurrence, and extent of the burnt area.

## Determination of Climatic Controls on the Fire Regime

The relationship between fire frequency and climatic variables was analyzed by cross-correlating the number of fires with the sum of precipitation (mm) and mean temperature (°C) for every fire season (March–October) of the study period. As we observed that several time series (temperature and fire frequency according to elevation zones) were autocorrelated, we pre-whitened them by detrending the series using kernel smoothing. We then calculated the cross-correlations (Pearson coefficient) between fire frequency and temperature/precipitation time series at various lags.

The effect of drought on the fire regime was evaluated by comparing the changes in fire regime with changes in a drought index, calculated according to Thornthwaite (1948), over the study period. We selected the Thornthwaite index because its computation only requires monthly precipitation and temperature values (the only meteorological data available over the entire study period in the study area). We are aware that in other regions other indices fulfilling that requirement have been used successfully, such as the Palmer Drought Severity Index (Palmer 1965), for example, in Fry and Stephens (2006) and Heyerdahl and others (2008). However, we decided to work with the Thornthwaite index firstly because the Palmer Index was developed for regions with relatively homogeneous topographies, whereas it does not perform well in mountain areas (Shafer and Dezman 1982), and secondly because the Thornthwaite index was used in a previous study on drought-related forest dynamics in Valais (Bigler and others 2006), where it produced reliable results.

The Thornthwaite index ($DRI = P - PET$) requires monthly mean temperatures and precipitation sums, with $P$ equal to the precipitation sum from March to October, and PET equal to the sum of estimated potential evapotranspiration from March to October. The potential evapotranspiration was calculated based on the temperature data by taking into account day length and the sun angle (compare Thornthwaite and Mather 1957). We calculated the index values for all fire seasons (March–October) and the average monthly values during the fire seasons. The seasons with more than 12 fires and a burnt area larger than 19 ha (corresponding to the 75 percentile of the fire frequency distribution and the annual burnt area, respectively) were then highlighted, as were the monthly values for those months with fire events larger than 10 and 50 ha.

Meteorological data were available from the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss). Monthly data from the meteorological station in Sion (46°13′50″ N, 7°21′50″ E; compare Figure 1) for the entire study period (temperature and precipitation) were used to calculate monthly and annual water deficit values (Thornthwaite drought index) and for the cross-correlation analysis.

To determine the impact of foehn winds on fire activity, we superimposed the geographical distribution of fire size classes on Bouët's (1972) map of foehn occurrence and the areas affected by the foehn according to Schreiber and others (1977). We also compared fire seasonality with the corresponding mean monthly wind speed and mean monthly water deficit (compare Thornthwaite index) in the areas with different foehn occurrence.

To determine an altitudinal limit for selecting the fire events to be included in the analysis, we opted for the boundaries suggested by Schreiber and others (1977). The meteorological variables (mean wind speed, temperature, and precipitation) were calculated using data from the MeteoSwiss meteorological stations in Aigle (46°19′00″ N, 6°57′50″ E), Fey (46°11′00″ N, 7°16′00″ E) and Visp (46°17′50″ N, 7°53′00″ E) for the period 1981–2006 (compare Figure 1).

## Results

### The Fire Regime in Valais (1904–2006)

#### *Fire Distribution*

There were 906 fires (100 fires/100 $km^2_{forest}$) in the study area between 1904 and 2006 (Figure 1). Most fires occurred in the central and eastern parts of the study region. There was a higher fire frequency (129 fires/100 $km^2_{forest}$) at the colline–montane level (elevation $<1400$ m a.s.l.) than at the subalpine level (40 fires/100 $km^2_{forest}$).

#### *Fire Frequency and Annual Burnt Area*

The mean fire frequency amounted to nine fires per year (SD = 8). Two periods of change are conspicuous: a slight increase during the 1940–1950s and a stronger peak during the 1990s (Figure 3A). Fire frequency evolved differently in the two elevation zones, that is, the colline–montane versus the subalpine zone (Figure 3A). Until the end of the 1940s, they had approximately the same fire frequency per unit of forest area. Subsequently, fire frequency increased at lower elevations, whereas it remained almost constant and increased only slightly toward the end of the 20th century at the subalpine level.

During the study period, forest fires burned about 2700 ha in Valais, corresponding to an annual mean value of 26 ha, with a high interannual variability (SD = 65; compare Figure 3B). For instance, more than half of the total area burned in only 6 years (1906, 1921, 1979, 1981, 1996, and 2003), and this was mainly due to very few large events. These 6 years were all within the first or last third of the study period. In other words, the first (1904–1940) and last (1971–2006) decades were characterized by a few years with a large area being burnt, whereas in most years the area burnt was very small or none was burnt at all. The intermediate period (1941–1970) was characterized by a relatively small but regularly distributed annual burnt area.

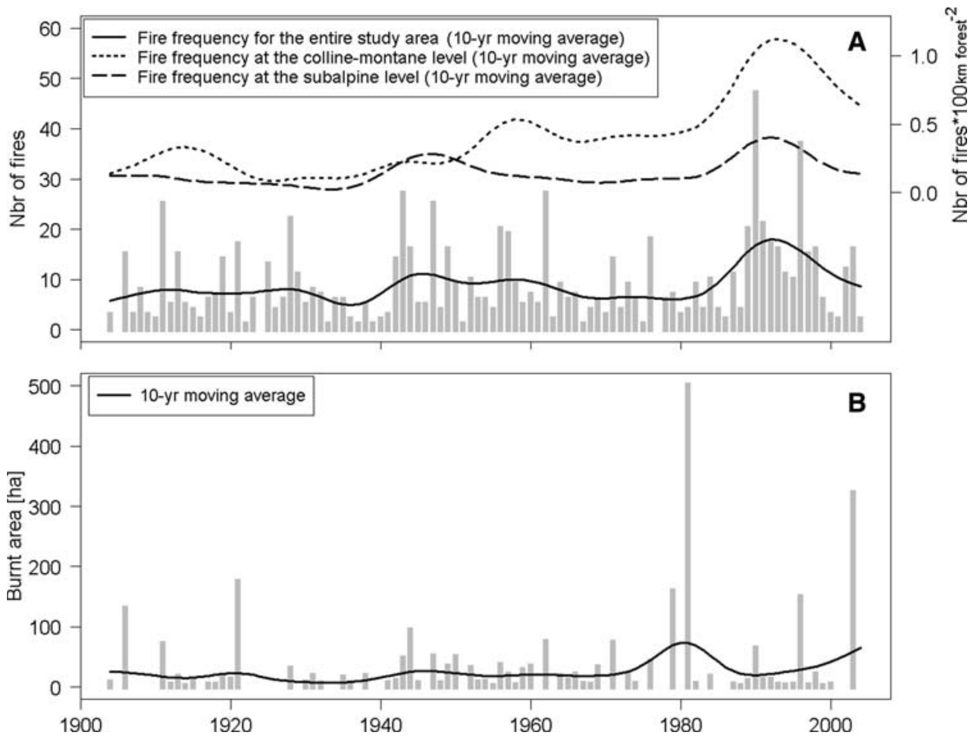


**Figure 3.** (**A**) Fire frequency for the entire study region, and fire frequency according to altitudinal levels; (**B**) annual burnt area for the entire study region.

*Fire Sizes*

If the events assumed to be smaller than 0.1 ha are included, then more than half of the fires were smaller than 0.1 ha and almost 80% were smaller than 1.0 ha (Figure 4A). Five large events also occurred (fire size >100 ha). Approximately 6% of all fires were responsible for 80% of the total burnt area. The fire size distribution fluctuated over the study period (Figure 4B). If we exclude the fires of unknown size (Figure 4B, dark grey), the Wilcoxon rank-sum test provides strong evidence for the null hypothesis of identical medians for the 1904–1940 and 1941–1970 periods ($P = 0.112$), but it suggests that the median of the 1941–1970 period was greater than that of the 1971–2006 period ($P < 0.0001$). Yet, if we assume that the fire events of unknown size were rather small and add them to the smaller than 0.1 ha class (Figure 4B, light grey), the test provides strong evidence for the alternative hypothesis, that is, that the median was greater in the 1941–1970 period than in the 1904–1940 ($P < 0.0001$) and 1971–2006 ($P = 0.004$) periods. However, in both cases, that is, regardless of whether fires of unknown size are included or not, the last two periods saw a decrease of the median fire size. In both cases, maximum size de-

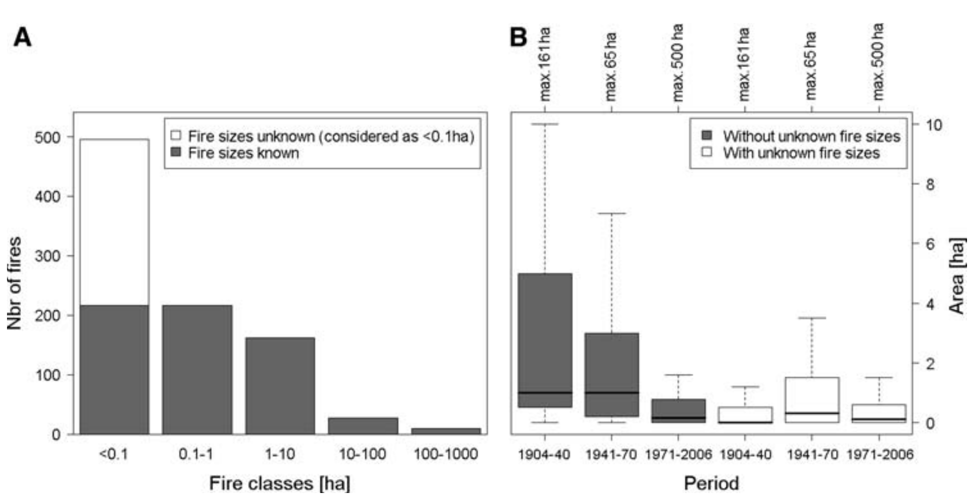


**Figure 4.** (**A**) Fire size distribution ($n = 906$) and (**B**) temporal changes in fire size distribution for all the fires documented (1904–2006). In (**A**), the *light-grey coloration* indicates the fires whose size is unknown (considered as <0.1 ha); in (**B**) the *light-grey coloration* indicates the distribution when taking into account the unknown fire sizes.

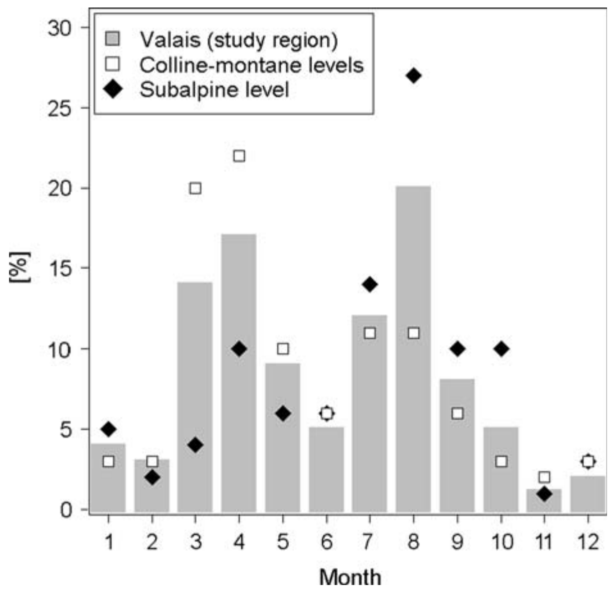


**Figure 5.** Fire seasonality for the entire study region and according to altitudinal levels (1904–2006).

creased during the second period, and then increased again during the last period.

*Fire Seasonality*

The fire season in Valais lasts from March to October (90% of all fires), with two major peaks in March–April and in July–August (Figure 5). Fires in winter are very rare. This ''double-peak'' pattern results from the combination of the seasonal fire distribution in the colline–montane versus the subalpine level, that is, a high fire activity in March–April at low elevations and in August at higher elevations (Figure 5).

*Causes of Fire*

For 42% of the fire events, the causes of ignition are known. According to forest service reports, about 85% of these fires were caused by humans (negligence, accident, or arson), which suggests that the fire regime in the study area is dominated by anthropogenic influences. The relevance of lightning as an ignition cause (15% of the fires with known causes) is spatially and temporally limited. Indeed, lightning-caused fires were restricted mainly to July–August and to high elevations (mean altitude 1700 m a.s.l.). Furthermore, the mean size of the fires caused by lightning was about 0.2 ha compared to 5 ha for fires of human origin.

## Climatic Controls on the Fire Regime

*Relationship Between Temperature/Precipitation and Fire Frequency*

The cross-correlation analysis between the time lines of temperature/precipitation and the fire frequency revealed different patterns according to area (entire study area, low elevation, high elevation) and to whether the period before or after 1950 is considered (Table 1). In most cases, fire frequency was positively correlated with temperature and negatively with precipitation of the same year, but there was no correlation with either temperature or precipitation for the period 1951–2006 and in the colline–montane zones. In addition, a positive correlation between fire frequency and precipitation was evident with a negative time lag of 3 years for almost all regions and periods considered.

**Table 1.** Cross-Correlation Between Fire Frequency (1904–2006) and Temperature/Precipitation During the Fire Season (March–October) for the Entire Study Region and Spatial/Temporal Subsets

| Space/time | Climatic variables | Lag (years prior to fire) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 |
| Valais (study area) | *T* | **0.27*** | −0.06 | 0.09 | 0.02 | −0.02 |
| | *P* | **−0.26*** | 0.12 | −0.07 | **0.34*** | 0.04 |
| Colline–montane levels | *T* | −0.09 | −0.03 | 0.06 | 0.04 | 0.07 |
| | *P* | −0.17 | 0.02 | −0.10 | **0.24*** | 0.04 |
| Subalpine level | *T* | **0.40*** | −0.09 | 0.06 | −0.03 | −0.03 |
| | *P* | **−0.20*** | −0.05 | −0.15 | **0.24*** | −0.01 |
| 1904–1950 | *T* | **0.59*** | −0.17 | 0.18 | 0.00 | −0.01 |
| | *P* | **−0.48*** | 0.24 | −0.15 | 0.22 | −0.03 |
| 1951–2006 | *T* | 0.01 | 0.04 | 0.03 | 0.01 | 0.03 |
| | *P* | −0.09 | −0.02 | −0.03 | **0.42*** | 0.13 |

*The numbers in bold with asterisks indicate significant correlations (P < 0.05).*

### *Fire Activity and Drought*

With one exception (1914), there was a water deficit (Thornthwaite index <0 mm) every year during the fire season, that is, March–October (Figure 6A). The 1940s and 1950s were the driest decades, whereas the driest single years occurred during the first part of the 20th century (1906, 1911, 1921, and 1943). Despite a strong rise in temperature since the end of the 1970s in Valais (Bader and Bantle 2004), the fire season has not become markedly drier. The fire seasons with more than 12 fires and a burnt area greater than 19 ha were clearly drier during the first half of the 20th century than during the second. Although most of the seasons with a high number of fires were relatively dry, the season with the highest number of fires, 1990, was one of the wetter seasons in the study period. The seasons with a high burnt area corresponded mostly, but not always, to dry periods. For instance, the fire season 1979 with 160 ha burnt was wetter than average (Figure 6A).

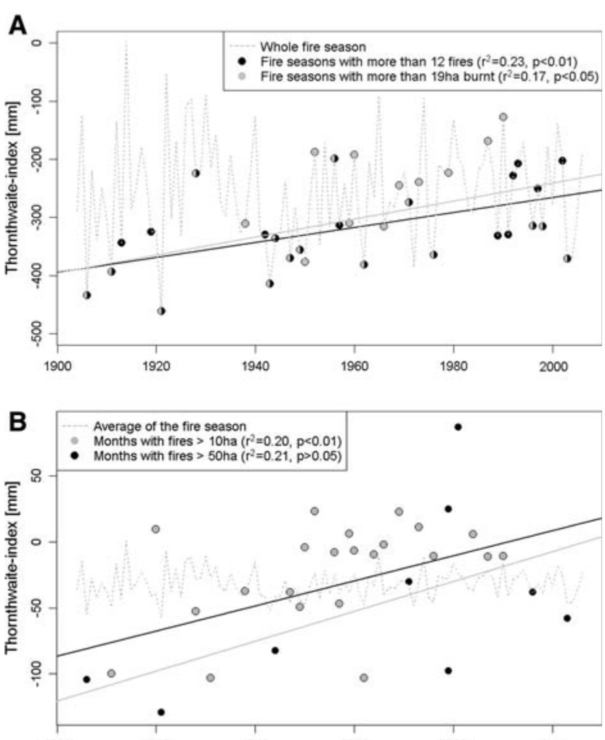


**Figure 6.** (**A**) Thornthwaite drought index (sum March–October) for all fire seasons (1904–2006) and fire seasons with a number of fires larger than 12 and a burnt area larger than 19 ha. (**B**) Thornthwaite drought index for all fire seasons (1904–2006; average March–October) and for months with occurrence of fires larger than 10 and larger than 50 ha.

Since the 1950s, large fires (>10 ha, >50 ha) have tended to occur in months that were wetter than the seasonal average, whereas prior to 1950 they tended to occur in months that were drier than average (Figure 6B). Furthermore, the frequency of these ''large'' events increased noticeably in the period 1950–1980 even though climatic conditions were less favorable for fires than they had been during the preceding decades (Figure 6A, B).

### *Fire Size Classes and Foehn Occurrence*

The geographical distribution of the fire events according to size class was found to follow a distinct pattern (Figure 7): fire events resulting in larger burnt areas tended to occur more often in approximately the center of region III. Indeed, 96% of the fires larger than 4 ha in size occurred in the regions II, III, and in the easternmost part of the study area, that is, in that part of Valais where continental climatic conditions prevail. About 80% of the fires larger than 10 ha, more than 70% of the events larger than 40 ha and 60% of the fires larger than 100 ha were located within region III. Furthermore, 80% of the fires larger than 40 ha and 60% of the fires larger than 100 ha occurred in those areas (or in their immediate proximity) where foehn tends to increase temperature and reduce relative humidity.

### *Fire, Wind, and Drought Seasonality*

Regions I and III tended to have a major peak in fire frequency in spring and a minor peak in summer, whereas in region II there was a small peak in spring and a large one in summer (Figure 8). Fire seasonality in region I matched well with wind speed seasonality, that is, the fire peak coincided with maximum mean wind speed, but not with the seasonality of water deficit (Thornthwaite index). Indeed, no obvious increase in fire frequency was discernible for the driest months. In region III, there were more fires during the summer months. In spite of a clear water deficit during this period, the corresponding increase in fire frequency was much smaller than the maximum in April that coincided with the period of maximum wind speed. The increase in fire frequency in region II in summer corresponded well with the drought conditions of the season. As in regions I and III, region II had a peak in fire frequency in spring. This March peak was considerably lower than that in summer and occurred despite the rather moist conditions and the absence of foehn.

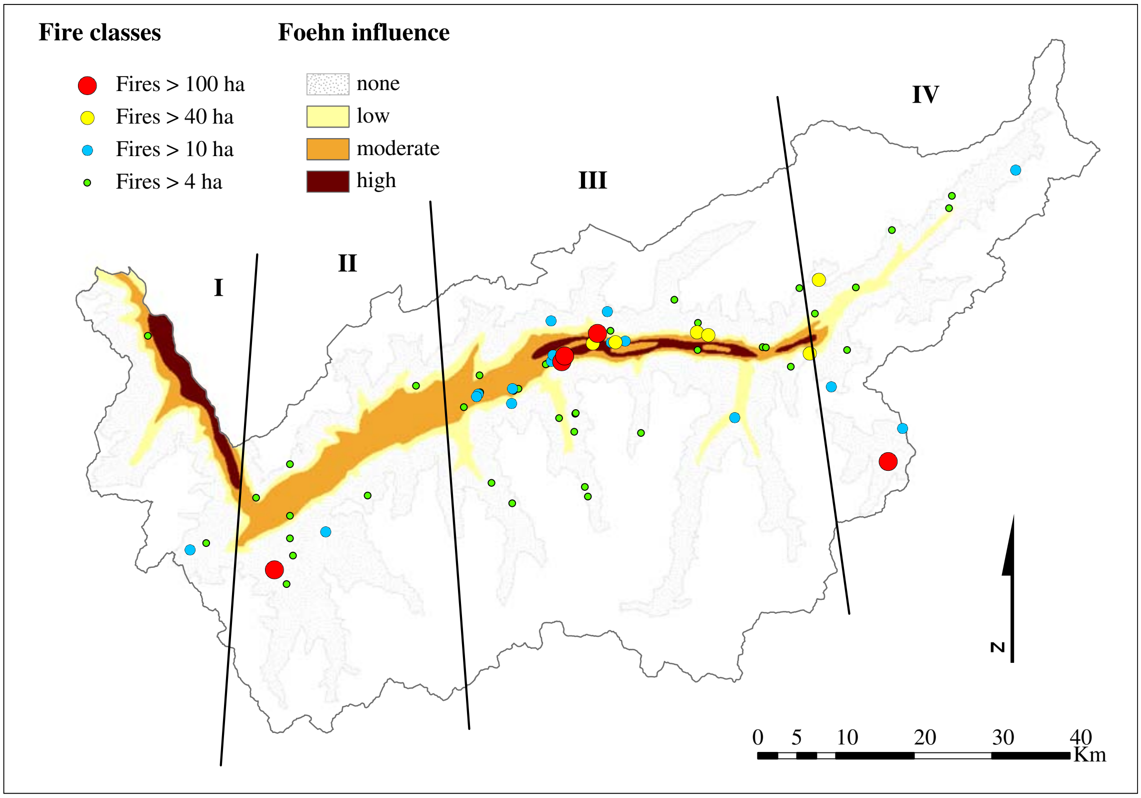


**Figure 7.** Geographical distribution of fire size classes; regions with foehn occurrence (I and III), and no foehn occurrence (II and IV) according to Bouët (1972); areas characterized by an increase in the temperature level due to foehn effects (Schreiber and others 1977, modified). The region IV was excluded from the analysis, as very few fires are located within foehn boundaries (*Source of administrative boundaries*: Bundesamt für Landestopographie).

# Discussion

## Fire Frequency

Most years with a large number of fires were dry to very dry, such as 1911, 1962, or 1996. Nevertheless, there are some exceptions and 1990, the year with the highest number of fire events, was actually quite wet. The reason for this exceptional number of fires remains unclear. One non-climatic cause could be the occurrence of a devastating foehn storm that blew down about 600,000 $m^3$ of wood in Valais during the winter preceding the 1990 fire season (Etat du Valais 2000). This led to an increase in fine fuels and coarse woody debris in the forests, coupled with more insolation of the forest floor due to the absence of a canopy in the affected areas. Frelich (2002) and Kulakowski and Veblen (2007) have pointed out possible interactions between blowdowns and fire activity.

The overall impact of temperature and precipitation on fire frequency was confirmed by the cross-correlation analysis (Table 1). However, there was a distinct significant correlation between fire frequency and temperature ($r = 0.59$)/precipitation ($r = -0.48$) in the same year during the first half of the study period (1904–1950), whereas no such correlation ($T$, $r = 0.01$/$P$, $r = -0.09$) was found during the second half (1951–2006). This change could be due to new factors that interfered with the climatic signal. The economy of the study area changed greatly from being mainly agriculture-oriented (during the 19th and the first half of the 20th century) to becoming more industry and service oriented. As a consequence, many traditional forms of forest use (for example, pasture in forests, collecting of litter and dead wood) have been abandoned or reduced in intensity and extent (Kempf 1985; Kuonen 1993; Gimmi and Bürgi 2007). Among others, these changes in forest use have contributed to an increase in coarse woody debris in the forests. Also, a significant fraction of felled logs is often left in stands to provide protection against rockfall, and so is wood that has become unmarketable because of economic rationalization (Bugmann 2005). Living and dead biomass have thus increased (Gimmi and others 2008), which may have influenced fire frequency and fire intensity, causing a relative decline in the

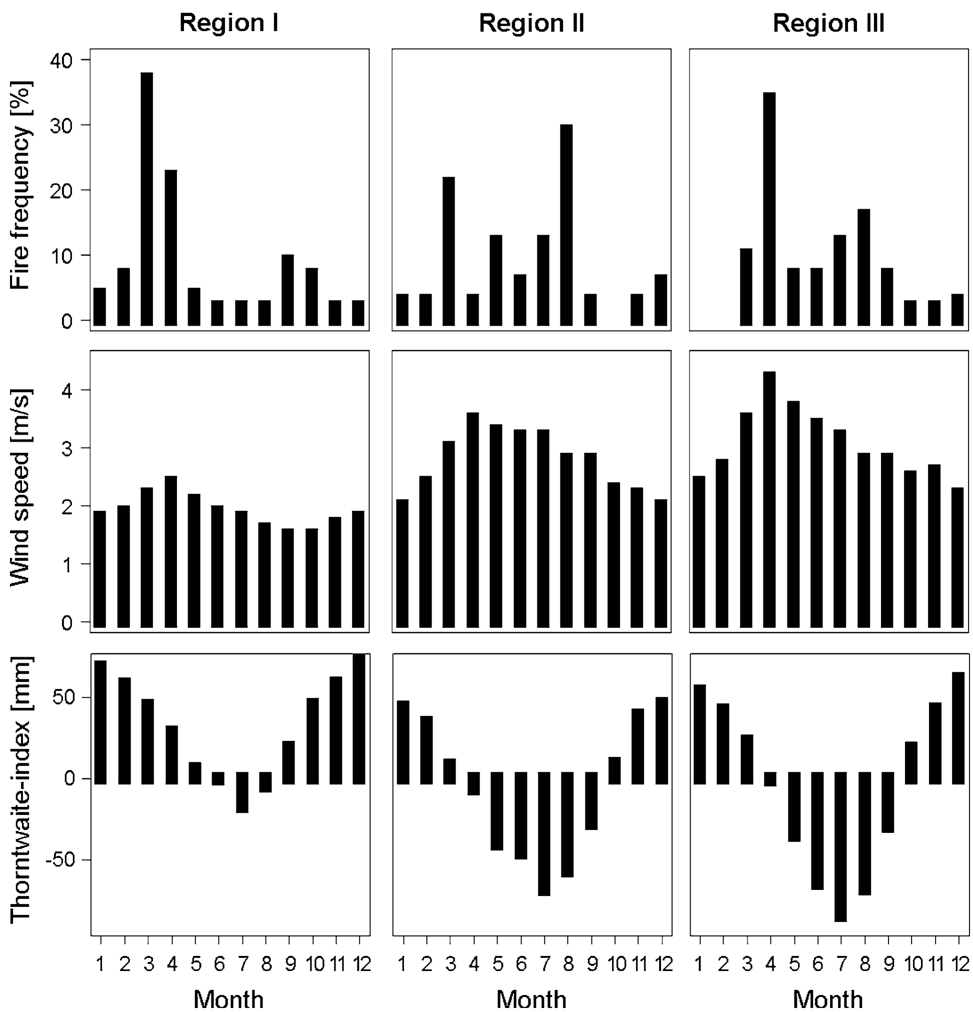


**Figure 8.** Seasonality of fire occurrence, mean wind speed, and mean monthly Thornthwaite drought index for the period 1981–2006 (*source of meteorological data*: MeteoSwiss) and foehn regions. Data exclude events outside foehn areas (compare Figure 7).

importance of climatic factors such as temperature and precipitation. The fact that there have been several years since the middle of the 20th century with a high number of fires despite moister conditions supports this hypothesis (Figure 6A). Moreover, fuel load clearly also plays an important role in the fire regime because fire frequency was found to be significantly and positively correlated with precipitation with a time lag of 3 years (compare Table 1). This indicates that rainfall tends to boost the production of fine fuels. A comparable delayed positive effect of rainfall on fire activity has also been observed, for example, by Swetnam and Betancourt (1998) in the southwestern United States, Pausas (2004) in eastern Spain, and Fry and Stephens (2006) in California.

Fire frequency varies with altitude in Valais and was considerably higher at the colline–montane than at the subalpine level. This reflects the more fire-prone climatic conditions and the higher ignition potential at lower elevations due to denser human settlements (Bundesamt für Statistik 2005). Although at the beginning of the 20th century fire frequency at these two altitudinal levels was fairly similar, the frequencies started to differ strongly after the end of the 1940s (Figure 3A).

These dichotomous trends are probably caused by human populations shifting toward the lowlands (abandonment of high-elevation agricultural land, urbanization at low elevations) and by a concomitant relative decrease in ignition sources at higher altitudes (for example, less forestry and agriculture). Fire activity at the subalpine level has not noticeably increased, although the forested area and fuel load have increased greatly since the 1950s, mainly at high elevations (Kempf 1985; Julen 1988; Gimmi and others 2008). This suggests either that fuel load is not very relevant as a controlling factor of the fire regime at higher elevations, or that the fuel build-up has been counterbalanced by a decrease in human population. Fire frequency at the subalpine level was found to correlate well with temperature and precipitation in the same year, although there was no correlation at the colline–montane level. This implies that temperature and precipitation have lost their relevance as factors influencing the fire regime over time at low elevations. This is probably because the progressively much more favorable fire weather has allowed other fire drivers to gain importance, such as the presence of anthropogenic ignition sources. Thus, climate as a key driver of fire frequency still seems to predominate at the subalpine level, whereas several other drivers operate in combination at the colline–montane level.

Similar altitudinal patterns have been observed in the Colorado Front Range, whose mountain forests are structurally comparable with those of the Swiss Alps (Bugmann 2001). Baker (2003) showed that the fire regime in this mountain range at the subalpine level was primarily climate-driven and that fuel had no limiting influence. Veblen and others (2000) demonstrated that at the montane level in contrast, climate and fuel build-up (due to fire suppression) had a strong impact on fire activity.

## Fire Size and Burnt Area

We assumed that fires of unknown sizes were smaller than 0.1 ha because very small fires are less likely to be reported in detail. Excluding the fires of unknown sizes, the fire sizes decreased during the study period (compare Figure 4B, dark grey). This could be due to fire reporting becoming more accurate over time. However, the decrease in fire size over the study period could also be caused by improvements in fire fighting techniques.

Ultimately, we propose that the temporal development of fire sizes can be explained by the simultaneous and opposite effects of two processes: first, the continuous increase in fuel load and the expansion of the forested area since the 1950s (see above) has enhanced fire risk as well as the connectivity of potentially burnable areas. This could be the reason for the increase in median fire size during the period 1941–1970 and the more frequent occurrence of extreme events since the end of the 1970s. Second, fire-fighting techniques and equipment have improved, and previously unreachable areas have become more accessible due to the use of helicopters and the strong expansion of the road network. These certainly allowed large fire events during the period 1941–1970 to be better contained (there were no fires >65 ha during this period). These measures have also reduced median fire size, but since the end of the 1970s the fuel build-up has led to more very large fires. This interpretation is supported by the fact that seasonal weather conditions for burnt areas larger than 19 ha and monthly conditions for fires larger than 10 and larger than 50 ha were wetter during the second part of the study period (Figure 6A, B). This implies that other factors besides temperature and/or precipitation must have influenced the annual burnt area during this second period.

Fire size classes were also characterized by clear differences in spatial distribution (Figure 7). A majority of the fires larger than 4 ha were concentrated in the continental part of Valais, and most of the fires larger than 10 ha were concentrated in a region affected by strong foehn winds (Bouët 1972). This geographical distribution emphasizes the role of foehn in explaining the occurrence of ''large'' fire events in certain areas, although the effect of drought periods may overlap with the foehn effect.

## Fire Seasonality

In Valais, the main fire season lasts from March to October (Figure 5). The almost complete absence of fires from November to February is due to the moist and cold winter climate. Fire seasonality is characterized by peaks in spring (March–April) at the colline–montane level and in summer (August) at the subalpine level. This latter peak arises because the weather tends to be favorable for fires only in summer at these elevations. The spring peak at low elevations is consistent with observations made in neighboring regions, for example, in the Aoste Valley (Cesti and Cerise 1992) and Ticino (Conedera and others 1996).

The March–April peak could be explained by two factors. First, the presence of large amounts of not yet decomposed litter at the end of winter provides an ideal fuel bed that can become very dry in deciduous stands because there are no green leaves in the canopy cover at this time and insolation at the forest floor is subsequently enhanced. The dominant deciduous species at the colline–montane level in continental Valais is *Q. pubescens* (Werlen 1994), which is particularly prone to fire (Cesti and Cerise 1992; Dimitrakopoulos and Papaioannou 2001). But this fuel hypothesis cannot be the only explanation, because the area covered by deciduous stands is very small compared to that covered by coniferous species (Werlen 1994). Moreover, the temperature and the precipitation levels in spring are less favorable for fire than in summer. A second reason could therefore be the occurrence of foehn at low to moderate altitudes. According to Bouët (1972), the main foehn season takes place in spring (March–May). It might then explain the fire peaks in spring in regions I and III as well as the relatively low percentage of summer fires in region III. Moreover, in region II, where there is little foehn, fire activity does not clearly increase in spring although the mean wind speed (of all types of winds, not only of the foehn) is at a maximum in spring. This last point emphasizes how important foehn winds are for the fire regime in Valais in comparison to other types of winds.

It seems, then, that fire seasonality at low elevations is mainly conditioned by the foehn in areas where it blows, whereas drought is the decisive factor in areas without foehn. In areas where both phenomena are relevant, such as in region III (compare Figure 7), spring foehn seems to play a much more important role than summer drought.

## Conclusions

On the basis of the reconstructed fire history of Valais in the 20th century, we were able to distinguish sub-regions with different fire regimes depending on altitudinal or geographical location, even though Valais is rather small. The altitudinal gradient was mainly reflected by fire frequency and seasonality, whereas the geographical location showed differences in fire seasonality and in the distribution of fire size classes.

Our study demonstrated the occurrence of different fire regime patterns and driving forces on small spatial scales. The occurrence of large fire events seems to be favored by the limited amount of precipitation due to continentality in combination with foehn winds, which are regionally constrained. The diversity in fire activity was additionally influenced by the local climatic variability along altitudinal gradients. In the subalpine zone, the fire regime appeared to be mainly driven by temperature and precipitation, but these two variables played only a secondary role in the colline–montane zone. Here, the influence of the foehn and, probably, other non-climatic factors, such as fuel load and human population density (ignition sources), were more important. Thus, this local complexity of fire activity requires locally differentiated approaches, for example, for the implementation of prevention measures.

During the 20th century, the fire regime has also changed. The annual burnt area has noticeably changed and there has been an increase in large fires in recent decades. Our study suggests that temperature and precipitation played a major role in shaping both fire frequency and burnt area in the first half of the study period, but they lost their importance after the mid-20th century. Thus, it appears that the temperature change clearly evident from the meteorological records in Valais has not caused an increase in fire frequency and burnt area. Temperature was no longer a limiting factor for forest fires in this dry valley in the second half of the 20th century.

These findings have practical implications. For example, because other factors than climate change are shaping today's fire regime, these have to be considered carefully in the development of effective fire prevention and management measures. Additional analyses will help to further pinpoint the crucial factors affecting the fire regime in Valais in the second half of the 20th and the early 21st century. In particular, special attention should be given to (1) the increase in fuel availability due to changes in forest use and management, (2) improvements in fire suppression techniques, and (3) the increased potential for humans to start fires.

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