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ORIGINAL ARTICLE

Human impacts on fire occurrence: a case study of hundred years of forest fires in a dry alpine valley in Switzerland

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Abstract Forest fire regimes are sensitive to alterations of climate, fuel load, and ignition sources. We investigated the impact of human activities and climate on fire occurrence in a dry continental valley of the Swiss Alps (Valais) by relating fire occurrence to population and road density, biomass removal by livestock grazing and wood harvest, temperature and precipitation in two distinct periods (1904–1955 and 1956–2006) using generalized additive modeling. This study provides evidence for the role played by humans and temperature in shaping fire occurrence. The existence of ignition sources promotes fire occurrence to a certain extent only; for example, high road density tends to be related to fewer fires. Changes in forest uses within the study region seem to be particularly important. Fire occurrence appears to have been negatively associated with livestock pasturing in the forest and wood harvesting, in particular during the period 1904–1955. This study illustrates consistently how fire occurrence has been influenced by land use and socioeconomic conditions. It also suggests that there is no straightforward linear relationship between human factors and fire occurrence.

Keywords Fire regime · Anthropogenic fires · Climate · Valais · Central Alps · Switzerland

Introduction

Forest fires are a major natural disturbance and hazard in many parts of the world, with considerable impact on vegetation formations and human societies in fire-prone areas (Pyne et al. 1996; Bowman et al. 2009). Changes in the forest fire regime, that is, the frequency, size, seasonality, and intensity of fires within a particular area (Krebs et al. 2010), have been observed in many regions during recent decades (e.g., Moreno et al. 1998; Westerling et al. 2006). These changes have triggered interest in identifying and disentangling the driving factors of fire regime.

Fire regimes are controlled by a very wide array of factors (Krebs et al. 2010). Climate and weather are crucial drivers of fire activity, in particular through high temperatures and low precipitation that may cause fuel drying and hence an increase in fire occurrence or intensity, or wind occurrence that may cause fuel drying as well as boost fire spread (Agee 1993; Pyne et al. 1996). Moreover, temporal climate variability has been found to bring about long-term changes in fire activity (e.g., Power et al. 2008; Marlon et al. 2009; Mooney et al. 2011). Topography influences fire spread, fuel loads determine fire intensity, and human

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population density affects ignition rates (Pyne et al. 1996; Omi 2005).

Recent studies have pointed out the important impact of human demography and activities, such as land use and fire management, on fire activity in the past few centuries and at the global scale (cf. Chuvieco et al. 2008; Marlon et al. 2008). Marked changes in fire regimes have occurred in northern America during the past 100–200 years, partly induced by the settlement of Europeans (cf. Hessburg and Agee 2003; Marlon et al. 2008). Although the impact of fire suppression, that is, the measures related to the control and extinguishing of fires after their outbreak (NWCG 2006), varies depending on forest type (cf. Keeley et al. 1999; Johnson et al. 2001; Floyd et al. 2004), it has been suggested that the systematic containment of fires may have caused an extension of fire rotations and an increase in fuel loads, thus permitting higher fire intensities (Minnich 1983; Fulé et al. 1997; Minnich 2001; Cleland et al. 2004). The introduction of grazing in forests is likely to have promoted fire exclusion through fuel consumption, thus provoking changes in fire rotations and intensities as well (Murray et al. 1998; Heyerdahl et al. 2001; Hessburg et al. 2005). Lastly, substantial changes in fire frequency in the United States have been found to be associated with changes in human population densities, both before and after European settlement (Keeley and Fotheringham 2001; Guyette et al. 2002).

Signs of anthropogenic influences on fire regimes have been detected in Europe too, including indications of human control of fire frequency through agricultural activities during some periods of the Holocene, for example, in the French and Swiss Alps (Carcaillet 1998; Tinner et al. 1998; Gobet et al. 2003). For the boreal forests of northern Europe, Niklasson and Granström (2000) and Wallenius et al. (2004) were able to relate the increase in fire frequency between the sixteenth and the twentieth centuries to the expansion of human settlements and increasing population densities.

Also today, fire activity in Europe is not only affected by climate change (Moriondo et al. 2006) but also by changing land use and particularly forest conditions. The connectedness of forested areas, stand density, and fuel loads have altered with changing forest management strategies and the abandonment of former agricultural areas in rural and marginal regions (Schelhaas et al. 2003). In Mediterranean countries, for instance, these processes have contributed to the creation of a more fire-prone landscape by expanding the area covered by shrubland, homogenizing forest or shrubland areas and increasing fuel load (Moreno et al. 1998; Romero-Calcerrada and Perry 2004; Mouillot et al. 2005; Koutsias et al. 2012). This phenomenon represents a serious threat for humans and infrastructures, in particular for those located in the wildland/urban interface (Vélez 1997; Lampin-Maillet et al. 2010).

The canton (state) of Valais is a dry continental valley in the Swiss Alps (Fig. 1). This region has a rather modest fire regime compared with other areas in Europe or America. However, it is located at the fringe of the Southern Alps and the Mediterranean basin, both of which are characterized by substantial fire activity (Vélez 1997; Bovio 2000). This makes its case particularly interesting in the context of changing environmental conditions, such as global warming and land abandonment in peripheral areas.

In a recent study, (Zumbrunnen et al. 2009) the fire regime in Valais from 1904 to 2006 was reconstructed based on archival sources, and its relationships with local climatic variability were investigated under a temporal perspective. Temperature and precipitation were found to shape fire frequency during the first half of the twentieth century, but no such signal was obvious during the second half of the century. This led to the question to which extent human activities shape the fire regime in Valais. Zumbrunnen et al. (2009) suggested that fuel buildup and high population densities overlapped or blurred the signal of climate on fire frequency during the second part of the twentieth century. However, no data were available to test this hypothesis. An empirical understanding of the relationships between the fire regime and anthropogenic variables is still missing, but it would be of high interest given that Valais as well as many other regions in the European Alps have undergone substantial socioeconomic and land cover/land use changes, which are likely to continue in the future (Mather and Fairbairn 2000; Johann 2004; Schumacher and Bugmann 2006; Gellrich et al. 2007).

The goal of the present study is to identify the impact of humans on fire occurrence, that is, the number of fires in a certain area during a certain time period, in Valais. We compared the periods 1904–1955 and 1956–2006, which are characterized by distinct land use and socioeconomic contexts. Specifically, we wanted to determine what the impacts of human factors on fire occurrence were in Valais during the period 1904–2006 and whether the relationship between fire occurrence and human factors changed over this period. Based on a conceptual framework (cf. Fig. 2; Sect. 2.2), we studied the impacts on fire occurrence of (1) population and road density as proxies for ignition potential and (2) wood harvest and livestock grazing as proxies for fuel load. In addition, as fire occurrence is strongly related to climate, predictors reflecting climatic conditions in the study region, that is, precipitation and temperature, were considered to allow us to disentangle anthropogenic and climatic factors.

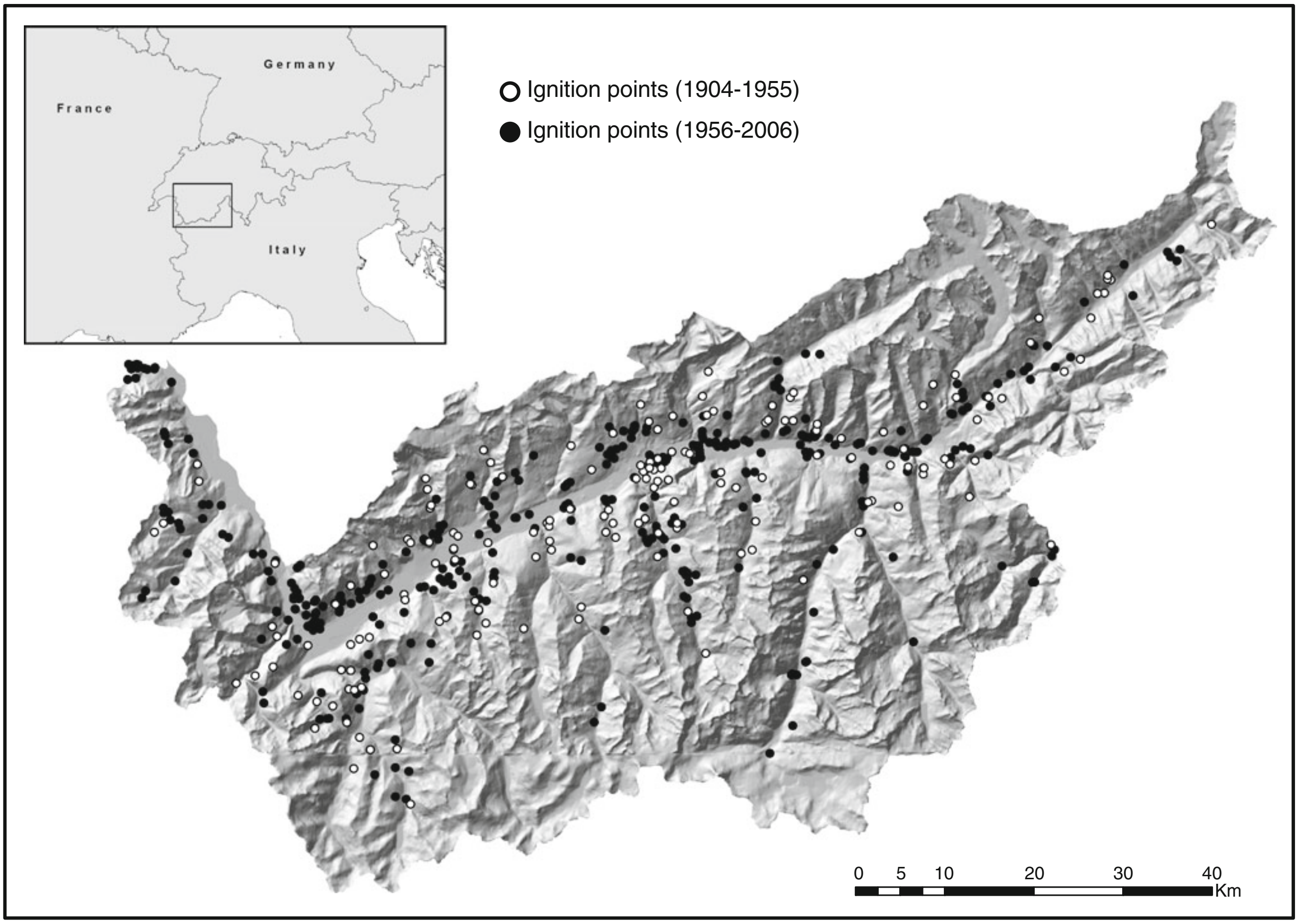


Fig. 1 Study region (Valais) with the ignition points for the periods 1904–1955 and 1956–2006 (Source of administrative boundaries: Swisstopo; source of fire data: Zumbrunnen et al. 2009)

Materials and methods

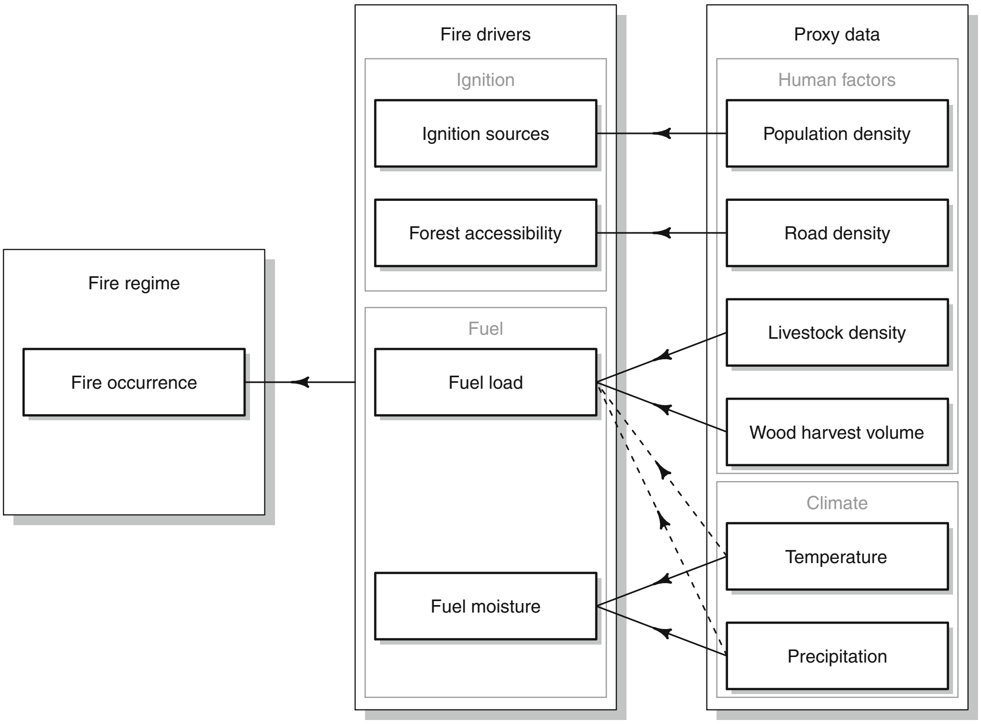
Study area

The canton of Valais is a large inner-alpine valley in the western Swiss Alps on the borders with France and Italy (Fig. 1). It consists of a main valley (the Rhône river valley), oriented along an east–west axis, bordered by side valleys. This mountain region covers an area of 5,200 km^2, of which about half is covered by glaciers and rocks (BFS 2009). It is characterized by a continental climate, that is, it has relatively low annual precipitation (e.g., 598 mm in Sion, 482 m a.s.l.), cold winters, high insolation, and high daily and annual temperature fluctuations (Braun-Blanquet 1961; MeteoSwiss 2009). As in the rest of the European Alps, climate in Valais has been subject to marked changes over the recent decades (Rebetez and Dobbertin 2004; Beniston 2006). For instance, during the twentieth century, an increase in annual mean temperature of 1.3 °C was observed (Bader and Bantle 2004). Valais is also characterized by the occurrence of the foehn, a dry katabatic wind with strong gusts (Ficker and De Rudder 1943; Bouët 1972; Kuhn 1989).

In the decade after World War II, Valais underwent considerable socioeconomic changes, and as in many other regions of the Alps, the economy changed from being mainly agriculture based to more industry- and service based. This change led to the abandonment of many traditional agricultural and forest practices, which in turn impacted forest cover (Elsasser 1984; Kempf 1985; Gimmi and Bürgi 2007).

The forest area in Valais has increased from 75,000 hectares at the beginning of the twentieth century to ca 95,000 hectares by the end of the century due the decline in agricultural activity in less productive and/or more remote areas, but also to strict conservation measures (Walther and Julen 1986; Kuonen 1993). Forests at low elevations (400–800 m a.s.l.) are dominated by broadleaved species (mainly *Quercus pubescens*), at medium elevations (800–1,400 m a.s.l.) by *Pinus sylvestris*, and at higher elevations (1,400–2,300 m a.s.l.) by other coniferous species, mostly *Picea abies* and *Larix decidua,* and by *Pinus*

Fig. 2 Conceptual model of the potential impact of human and climatic factors on fire occurrence through ignition and fuel conditions



cembra at the highest elevations (Hainard 1969; Werlen 1994; Werner 1994). At the end of the twentieth century, coniferous stands were covering 81 % of the forested area in Valais (Brassel and Brändli 1999).

The socioeconomic development mentioned above also contributed to changing numbers and distribution patterns of humans in Valais. The population has more than doubled over the past 100 years and currently amounts to about 300,000 inhabitants. Valais underwent important population shifts from high-elevation areas to the lowlands and from the side valleys to the main valley during the twentieth century (Kempf 1985). Nowadays, a large part of the population lives in the urban centers of the Rhône river valley (BFS 2005).

Conceptual framework

Our analysis was based on a conceptual framework for the impact of potential drivers on fire occurrence (Fig. 2). We postulated that the most important anthropogenic drivers shaping fire occurrence are ignition potential and fuel load. In this study, we used the density of roads and human population as proxies for ignition potential (Fig. 2). Road density is aimed to reflect forest accessibility, particularly since the terrain in Valais is mountainous and rough. Roads have been found to increase the frequency of fire ignited by humans (e.g., Franklin and Forman 1987; Cardille et al. 2001; Yang et al. 2007). Likewise, fire occurrence appears to be positively related with population density (Keeley and Fotheringham 2001; Guyette et al. 2002). For this reason and because 85 % of fires with known causes in the study region originated from human activities (Zumbrunnen et al. 2009), we used population density to quantify potential ignition sources. However, the influence of humans on the ignition of forest fires may be more complex. Some studies showed a decrease in fire occurrence where human presence was high (e.g., Syphard et al. 2007, 2009), likely due to landscape fragmentation, fuel insufficiency, or fire suppression efforts.

We used indices of biomass removal associated with human activities as proxies for fuel load (Fig. 2). First, livestock density was treated as an indicator of farmed grazing pressure in forests. Goats and sheep have been grazing in the forests for centuries and contributed to the reduction of the herb layer and the understory and hence to the reduction of fine fuel (Gimmi and Bürgi 2007; Gimmi et al. 2008). Wood pasturing was widely practiced during the first decades of the twentieth century and still widespread up to the late 1950s (Loup 1960; Kempf 1985; Kuonen 1993; Gimmi and Bürgi 2007). Although the extent and intensity of wood pasturing has diminished afterward due to laws and regulations as well as changes in agricultural practices (Stuber and Bürgi 2001), livestock was still found in forests. For instance, the Swiss National Forest Inventories conducted in the 1980s and 1990s report traces of pasturing by livestock on 13 and 11 % of the sample plots in Valais, respectively (Bachofen et al. 1988; Brassel and Brändli 1999). In our analysis, we did not

Table 1 Variables used in the models

Variable	Unit	Original spatial resolution	Original temporal resolution	Cell value	Source
Fire occurrence	Fires/ha$_{forest}$	Municipal to exact coordinates	Daily to annual	Area-weighted count	Forest service reports
Population density	Inhabitants/ha	Municipal level	Decennial	Area-weighted	Swiss federal statistics
Road density	m/ha	Cell level	Tree time points (~1890, 1960, 2002)	Total length per cell	Siegfriedatlas and Swiss national maps 1:100'000 (Swisstopo)
Livestock density	Grazing pressure units/ha	Municipal level	Approximately decennial	Area-weighted	Swiss federal statistics
Wood harvest volume	m^3/ha	Forest district level	Approximately annual	Cell center point	Forest service reports
Precipitation	mm	100 m × 100 m grid	Monthly	Area-weighted	Land use dynamics research unit (WSL)
Temperature	°C	100 m × 100 m grid	Monthly	Area-weighted	Land use dynamics research unit (WSL)

consider the impact of wild herbivores, such as red and roe deer, because their population was negligible compared with the stock of domestic animals grazing in forests (Breitenmoser 1998).

Wood harvest volume was used as an indicator of the intensity of coarse woody fuel removal. Most of the forests in the study region have been managed for a long time for producing timber and firewood and providing protection against natural hazards. This is likely to have influenced their susceptibility to fire, especially regarding ignition and spread conditions, by modifying stand structures and hence the arrangement and quantity of fuel (Anderson 1982; Tanskanen et al. 2005).

Next to anthropogenic proxies, we also considered climatic proxies given the importance of climate for fire occurrence (cf. Introduction section). As predictors, we used mean annual precipitation and mean annual temperature, which were available for the entire study period with a satisfying spatial resolution. Precipitation and temperature directly condition fuel moisture and thus the level of fuel flammability (Renkin and Despain 1992; Kunkel 2001). Besides this direct impact, temperature and precipitation may also have a lagged influence on fire occurrence by boosting or hindering fuel production (Swetnam and Betancourt 1998; Pausas 2004; Fry and Stephens 2006).

Data compilation

Data design

We compiled spatial data for the period 1904–2006 on fire events, road coverage, human population density, livestock density and wood harvest volume, as well as precipitation amount and average temperature (cf. Table 1; Fig. 2). The different datasets vary greatly in spatial resolution, which range from exact location to municipal (mean area = 17.6 km^2, SD = 15.8) or forest district levels (mean area = 335.4 km^2, SD = 87.7). We therefore divided the study area into 2 km × 2 km cells and attributed to each cell the values of the geographically corresponding variables. Only cells with forest cover were included in the analysis, resulting in a total number of 787 cells for the first half of the study period (1904–1955) and of 786 for the second half (1956–2006). A cell size of 4 km^2 was chosen for pragmatic reasons, because our historical fire data (see below) do not allow a very small cell size. Moreover, the chosen cell size is still small enough to capture the mountainous and heterogeneous nature of the landscape in the study region.

We compared two time periods (1904–1955 vs. 1956–2006). For this purpose, the values of the fire and environmental time lines were averaged for each period under consideration. While the averaging may imply a loss of power for the data available at higher time resolutions (e.g., annual or decennial), this represents a way of giving more power to our fire data. As the overall number of fires in Valais is relatively low compared with other regions, averaging the fire data provides a higher number of cells showing fire occurrence. If we instead had taken fire occurrence values for each year (or even decade) in each cell, this would have resulted in an inflated number of cells with no fire compared with the number of cells with fire occurrence.

The break point between the two periods was located in 1955 because the decade after World War II corresponds to a socioeconomic turning point in Valais. This turning point was evidenced by a recent study which demonstrated that 1955 was the final year of a changing period toward higher fire frequency in Valais (Pezzatti et al. 2011). The economy changed from being mainly agriculture based to more industry- and service based. This change led to the abandonment of many traditional forest practices and a strong decline in the number of people involved in the primary sector (Elsasser 1984; Kempf 1985; Gimmi and Bürgi 2007), which in turn is likely to have caused changes in fuel load and in how humans affect ignitions in the landscape and thus eventually fire occurrence (Pezzatti et al. 2011).

Fire occurrence

Fire data were taken from the forest fire inventory for Canton Valais (Zumbrunnen et al. 2009), which documents about 900 fires during the twentieth and early twenty-first centuries and provides information on ignition dates and locations. The accuracy of the information concerning the ignition points varies depending on the quality of the historical documents assessed. We distinguish between (1) exact coordinates; (2) approximate coordinates with an estimate of their accuracy (between 50 m and 1,000 m); (3) no indication of coordinates but of the municipality affected only. The procedure for assigning a fire occurrence value to each cell was as follows. First, fire occurrence at the municipal level was calculated for all fires with unknown ignition point coordinates ($n = 319$). For each municipality, the number of fires was summed and divided by the forest area. The results of this operation were then assigned to all the cells of the respective municipality. For each fire where the ignition point was known imprecisely ($n = 388$), we calculated the fire occurrence based on the summed forest area of the cells in which (given the uncertainty of the location) the fire could have started and assigned the average value to all of the possible cells. We summed the number of fires with exact ignition point coordinates ($n = 188$) for each cell and divided the total by the cell's forest area. Total fire occurrence for each cell was the sum of the three calculations.

Anthropogenic variables

The human population and livestock population data were extracted from official federal statistics (Departement des Innern 1908, 1918; Eidgenössisches Statistisches Amt 1934, 1945; BFS 1989, 1994, 2008). These data were collected at the municipal level. Human population data were collected each decade: livestock data were available on a more irregular basis. We then assigned the population density values (i.e., the average values of the different periods under consideration) to all the cells in the municipality. As the goal of including livestock in this study was to consider the potential impact of forest grazing on fire activity, we used an index of grazing pressure instead of raw livestock numbers. Gimmi et al. (2008) have defined an index of grazing pressure for Valais, based on the food requirements and the duration of the grazing season for goats and sheep, where a grazing pressure unit (GPU) is calculated as the number of goats plus 22 % of the number of sheep, divided by the grazed area, which in our case corresponded to the area of the municipality located below 2,300 m a.s.l. (corresponding roughly to upper tree line in Valais).

The annual reports of the Forest Service of Valais contain the wood harvesting data for almost every year between 1904 and 2003 at the forest district level. The overall wood harvest volume was divided by forest area for every district, and the resulting values (averages of the different periods) were assigned to all the cells of the respective districts.

Road density data were obtained by digitizing the road network for three time points: ~1890, 1960, and 2002 (Siegfriedatlas and Swiss national maps from Swisstopo; 1:100'000). The road density values were assigned to the grid cell by linearly interpolating between the three reconstructed values and taking the averages for the period under consideration.

Climate variables

Precipitation (sums) and temperature (means) data were obtained using climate fields (100 m × 100 m spatial and monthly temporal resolution) provided by the Research Unit Landscape Dynamics at WSL (Birmensdorf, Switzerland). These fields were calculated based on two datasets: (1) fine-scale maps created by interpolation of meteorological station data from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) and (2) coarse-scale climate maps provided by the Climatic Research Unit (CRU) at University of East Anglia (cf. Mitchell et al. 2004)

The fine-scale maps were created by interpolating daily MeteoSwiss meteorological station data in a 100 m × 100 m resolution, using the Daymet method (Thornton et al. 1997). As this fine-scale dataset was going back to 1930 only, it was combined with the coarser scale CRU dataset (monthly, 10-min resolution), which goes back to 1900, in order to dispose of temperature and precipitation data covering our entire study period.

From the daily Daymet maps, long-term monthly averages were aggregated for the baseline period of 1961–1990 to serve as the fine-scaled Daymet normal state. The same long-term monthly averages of the CRU maps were determined to serve as the coarse-scaled CRU normal state.

The CRU monthly dataset was then downscaled to the 100 m × 100 m resolution using the change factor method (Mitchell and Jones 2005). The CRU monthly values were calculated as anomalies to the normal state of the baseline period, and the resulting anomaly maps interpolated with inverse distance weighting and resampling. Finally, the downscaled anomalies were simply combined with the fine-scaled Daymet normal state to obtain fine-scale maps. Based on these climate maps, we determined the average annual sums of precipitation and mean temperature for the periods 1904–1955 and 1956–2006 for every 2 km × 2 km cell.

Data analysis

To stabilize the variance in the model, the response variable (i.e., forest fire occurrence) was square-root-transformed, and the population and livestock density data were log-transformed to reduce skewness.

A first exploratory analysis showed that fire occurrence was not linearly related to the environmental, suggesting the use of generalized additive models (GAM; Hastie and Tibshirani 1990), a widely applied technique in ecological modeling where there is a nonlinear relationship (e.g., Yee and Mitchell 1991; Guisan and Zimmermann 2000; Guisan et al. 2002). Spatial autocorrelation can be a problem when fitting spatially explicit data; we therefore used generalized additive mixed models (GAMM, Lin and Zhang 1999), which allow for the modeling of correlated data. To determine the appropriate spatial correlation structure for the model errors, we first fitted GAMs for each period (1904–1955 and 1956–2006) without considering any correlation structure. We then performed a Moran test on the residuals of the GAM fits and found that the errors showed spatial autocorrelation for the two models ($P < 0.01$ for both datasets). This was also confirmed by the semivariograms of the residuals (not shown), which indicated that a Gaussian correlation structure was suitable for the models. The optimal model for each period was selected by backward stepwise regression. The contribution of each variable to the final model was determined based on the P-values of the respective smooth terms; they correspond to the null hypothesis that each smooth term is zero and were calculated via a t-distribution with the degrees of freedom estimated from the residual degrees of freedom of the model fit.

To check for the possible nonparametric equivalent of collinearity between the smooth functions in each model, we evaluated the concurvity measures between the smooth terms. Concurvity in GAMs can cause problems of interpretation regarding the individual smooth curves and make estimates unstable due to the interactions between variables (Ramsay et al. 2003). Only significant predictor variables were retained in the final models ($P < 0.05$).

All statistical analyses were performed using R (version 2.12.1, R Development Core Team 2010). The GAMM were fitted using the *mgcv* package (R-package version 1.7–2; Wood 2000, 2004).

Results

During the period 1904–1955, the median fire occurrence with 0.003 fires/ha is significantly higher than during the period 1956–2006 with 0.0015 fires/ha (Fig. 3a; $P < 0.0001$, Wilcoxon rank sum test). Both proxy variables for ignition sources show higher median values during the second period (population: 0.48 inhabitant/ha; road: 7.3 m/ha; Fig. 3b) than during the first period (population: 0.38 inhabitant/ha; road: 2.4 m/ha; $P < 0.0001$). In contrast, median values of the proxy variables for fuel load are clearly higher during the first period (livestock: 0.14 GPU/ha; wood harvest volume: 1.3 m^3/ha) than during the second period (livestock: 0.07 GPU/ha; wood harvest volume: 1.0 m^3/ha; $P < 0.0001$). No significant difference in mean annual temperature is observed between the first (3.8 °C) and the second period (3.6 °C; $P > 0.05$), or in precipitation sums (112 vs. 115 mm/a; $P > 0.05$).

Fire occurrence for the period 1904–1955 is explained by population density and livestock density, wood harvest volume, and temperature ($P < 0.001$). Fire occurrence for the period 1956–2006 is explained by population density, livestock density, temperature ($P < 0.001$), road density ($P < 0.01$), and wood harvest volume ($P < 0.05$). The two models have similar explanatory power, with an adjusted R^2 of 0.33 for the period 1904–1955 and of 0.31 for the period 1956–2008.

According to the log-transformed P-values of the smooth terms, the variable contributing most to explaining the total variance of fire occurrence during the first period (1904–1955) was population density, followed by wood harvest volume (Fig. 4), whose contribution amounted to 63 % of that of population density. Temperature and livestock density had a smaller influence (32 and 28 % compared with population density). During the second period (1956–2006), temperature contributed most to explaining fire occurrence (Fig. 4), followed by population density, livestock density, road density, and wood harvest volume (77, 58, 46, and 34 % compared with temperature).

The concurvity measures showed that there were no interactions between predictor variables, except for temperature in the 1956–2006 model. This implies that the confidence intervals of the smooth term for temperature may be wider than those displayed in Fig. 5b.

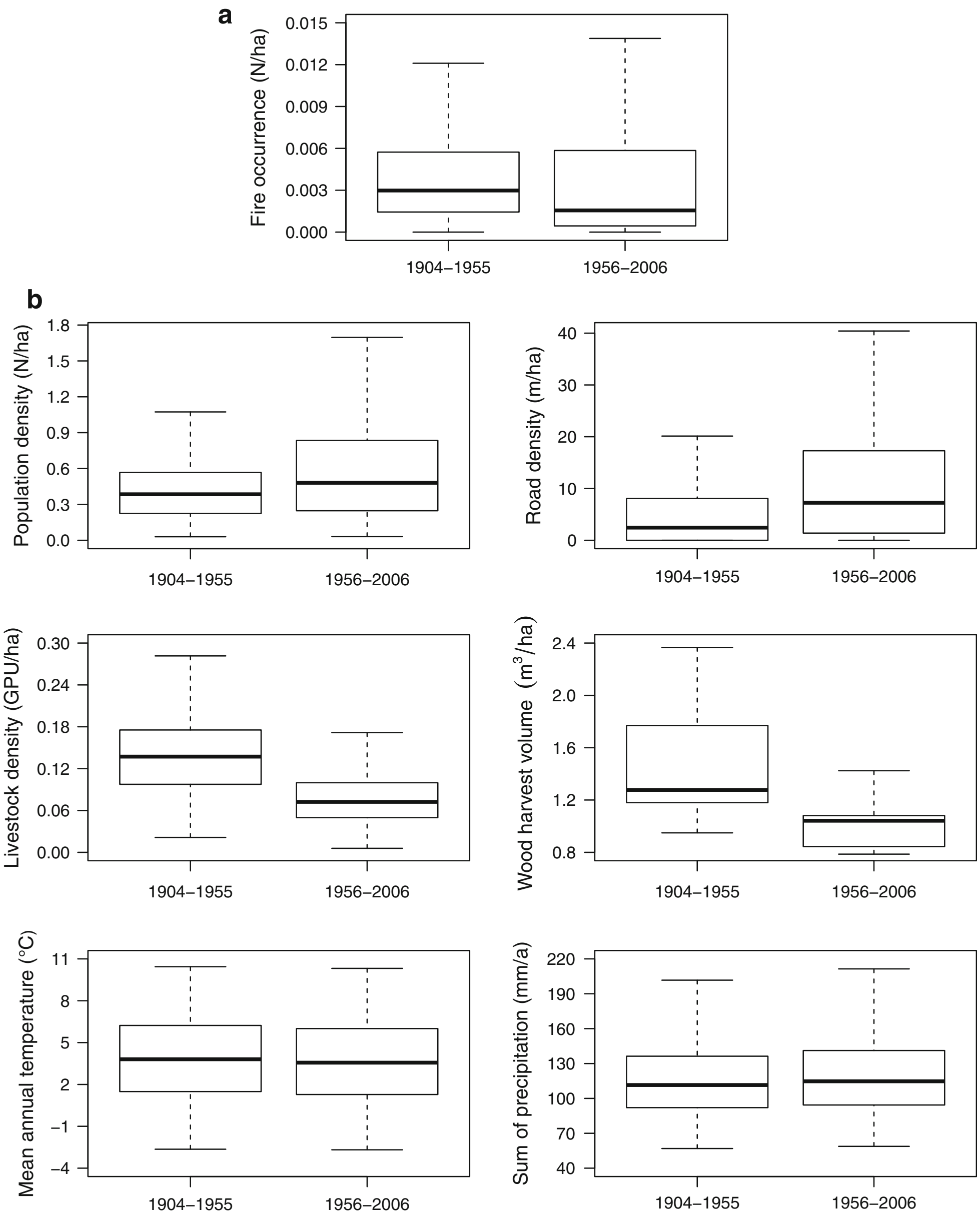


Fig. 3 **a** *Box plots* of fire occurrence data for the periods 1904–1955 and 1956–2006. **b** *Box plots* of predictor data for the periods 1904–1955 and 1956–2006

Fire occurrence increased with increasing population density during the two periods. The response curve of fire occurrence was relatively steady during the first period. During the second period, fire occurrence increased only slightly up to a population density of about 3 inhabitants/ha, and then much strongly as population density became higher (Fig. 5a, b).

During the first period, the effects of livestock density and wood harvest volume on fire occurrence were similar: fire occurrence decreased slightly up to 0.2 GPU/ha and a wood harvest volume of 2.1 m^3/ha and then more strongly at higher densities and volumes. In contrast, during the second period, the response curves of fire occurrence to livestock densities and wood harvest volume showed an inverse pattern: fire occurrence decreased when livestock density was very low (<0.05 GPU/ha) but increased when wood harvest volume was low (<1.2 m^3/ha). It then increased, first slightly and then strongly, when livestock density was moderate (>0.05 GPU/ha) to high (>0.2 GPU/ha) but decreased when wood harvest volume was moderate to high (>1.2 m^3/ha).

Road density significantly influenced fire occurrence during the second period only: fire occurrence slightly increased up to moderate road densities (<30 m/ha), but then dramatically dropped when road density was higher. Fire occurrence correlated positively and almost linearly with temperature during both periods.

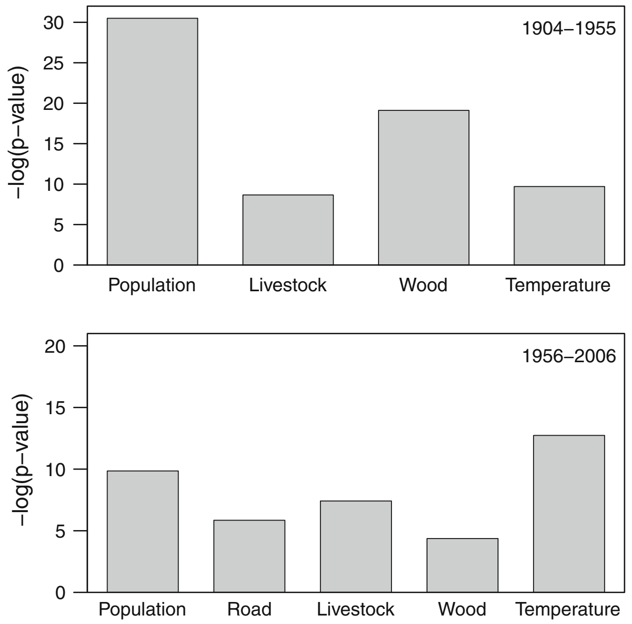


Fig. 4 Contributions of each predictor variable in the final models (1904–1955 and 1956–2006). The contribution of the variables was determined by negatively log-transforming the *P*-values of the respective smooth terms

Discussion

Relevance of the individual variables

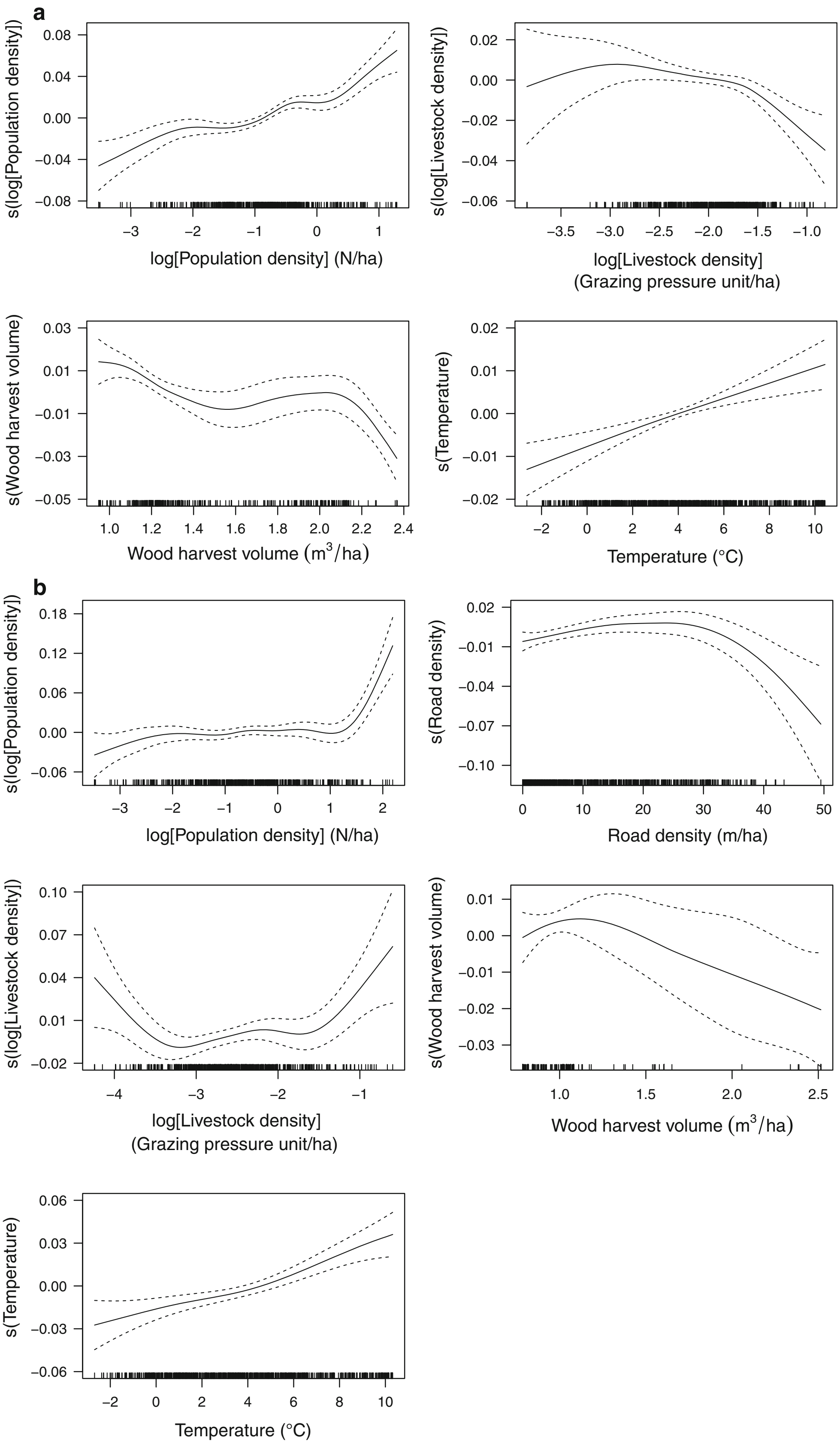
The significant positive correlation of fire occurrence with population density during both periods agrees with findings from numerous studies in regions where fires are mostly human induced (e.g., Cardille et al. 2001; Keeley and Fotheringham 2001; Syphard et al. 2008). While these studies employed linear methods to investigate fire occurrence, studies using nonlinear methods often showed that fire occurrence tended to decrease with higher population densities (e.g., Keeley 2005; Syphard et al. 2007, 2009). This pattern is not reflected by our results, probably because the generally sparse settlement distribution in Valais and the lack of densely populated urban areas still keep the relationship between population density and fire occurrence in the range of positive linear correlation. For instance, Syphard et al. (2009) demonstrated that the location of the inflection point differs according to the region considered and that in some cases fire occurrence peaked at about 300 inhabitants/km^2, a value corresponding to the upper limit of our dataset. Higher population densities are simply not found in Valais, although this may partly be an artifact due to the spatial resolution of the data: while the exact road length could be determined accurately for each grid cell, population density had to be determined based on data available at the coarser municipal level (cf. Sect. 2.3). Therefore, the same population density value was assigned to all the cells of a specific municipality. This has probably led to an underestimation of population density on those cells that actually feature the highest values (as well as an overestimation on cells with lower values), thus failing to capture the response of fire occurrence to very high population densities.

In contrast to population density, the response of road density to fire occurrence during the second period exhibits a pattern that is in line with the theory of high human presence constraining fires: fire occurrence slightly increases up to 30 m/ha and then decreases when road density is higher. This phenomenon may be due to the fact that areas with high road densities often correspond to highly urbanized areas or intensive farmland. These areas are little prone to fire, as infrastructure and high-intensity land use reduce fire ignition and spread by diminishing fuel load and continuity (e.g., Guyette and Dey 2000; Guyette et al. 2002). Moreover, the availability of suppression resources in such areas allows for a rapid extinction of fires at the initial stage. Therefore, it appears that road density in its upper range of values cannot be considered as a proxy for ignition sources but rather for other fire drivers, for example, fuel load or fire suppression.

We postulated that fire occurrence is controlled by fuel load in addition to the availability of ignition sources, using livestock density as a proxy for fine fuel removal and wood harvest as a proxy for coarse fuel removal. Livestock density is significantly negatively related to fire occurrence during the first period (1904–1955). This is consistent with the fact that wood pasturing was still widespread up to the late 1950s (cf. Sect. 2.2). Other empirical studies have shown grazing leads to a decline in ignitions or fire frequency due to a livestock-induced reduction in the herbaceous and/or shrubs layers (e.g., Madany and West 1983; Zimmerman and Neuenschwander 1984; Irwin et al. 1994; Romero-Calcerrada et al. 2008).

However, during the period 1956–2006, fire occurrence initially decreases within the range of low livestock densities but with higher livestock densities (>0.2 GPU/ha), more fires occur. Thus, this only partially agrees with our hypothesis that increasing livestock densities should be related to a decreasing fire occurrence. The relevance of wood pasturing has diminished strongly in the recent decades (cf. Sect. 2.2). A weakening of the negative relationship between fire and livestock may have been expected, but the augmentation of fire occurrence under high livestock density raises questions on the underlying mechanisms. As high livestock densities are associated with low population densities during the second period (<2 inhabitants/ha; result not shown), we cannot attribute this augmentation to a concomitant high level of potential anthropogenic ignition sources. In contrast, high livestock densities are clearly found in the very dry eastern part of

Fig. 5 **a** Response curves of fire occurrence to predictor variables for the period 1904–1955 with pointwise twice-standard-error curves (*dotted lines*). **b** Response curves of fire occurrence to predictor variables for the period 1956–2006 with pointwise twice-standard-error curves (*dotted lines*)



Valais (result not shown). This suggests that in these areas, higher fire occurrence is more likely to reflect dry conditions rather than fuel removal.

Wood harvest volume was negatively correlated with fire occurrence during the first period (1904–1955), and more weakly negatively correlated with fire occurrence during the second period (1956–2006). This agrees with our assumption that wood harvest is related to fire occurrence. It is also in line with the hypothesis that wood harvest volume may serve as a proxy for fuel load not only because of the likely effects of forest management on fire occurrence, but also because it is reasonable to assume that where a forest is harvested for timber and firewood, smaller woody fuels would be collected by the local population entitled to use the forest. The facts that the contribution of wood harvest volume to the final model (cf. Fig. 4) and the slope of the response curve (cf. Fig. 5a, b) are more marked during the first period support this assumption, as during this time traditional agriculture depending heavily on local resource extraction prevailed (Kempf and Scherrer 1982; Gimmi et al. 2008). These findings are consistent with the literature where fuel reduction measures, for example, prescribed burning or sylvicultural treatments, were found to mitigate fire potential (Martin et al. 1989; Rummer et al. 2003; Agee and Skinner 2005; Skog et al. 2006). In the first period, all cells where more than 2.2 m^3/ha are harvested, that is, where fire occurrence falls drastically, are actually situated in the westernmost part of Valais. This region exhibits the highest precipitation level due to the oceanic nature of its climate (result not shown). However, cells with less than 1.6 m^3/ha wood harvest volume, that is, where fire occurrence also declines, are located in the central part of Valais where a dry continental climate prevails. This suggests that besides the fuel load explanation, it is also possible that the decrease in fire occurrence where wood harvest increases may be due to less fire-conducive climatic conditions.

Temperature had a small explanatory power during the first period but accounted for a substantial part of the explained deviance during the 1956-2006 period. A potential explanation for this difference may be the shift of fire activity toward the lowlands over the twentieth century due to the abandonment of many agricultural and forestry activities at middle to high elevations (Zumbrunnen et al. 2010). In other words, fires during the first period were distributed rather uniformly over the study area, while they were concentrated at lower elevations during the second period. Our fire data show a smaller correlation with elevation during the first period than during the second (results not shown). Because temperature correlates strongly with altitude, this implies that the temperature signal may have been attenuated compared with the other variables during the first period because many fires occurred at higher elevations where the values of mean annual temperature are a priori less appropriate for fire occurrence than at lower elevations. Besides this explanation, we cannot rule out that the climate data had an impact on our results, as the data for the first decades were based on a coarser climatology due to the lack of many regional meteorological stations for this period (cf. Sect. 2.3); thus, it is possible that the different compilation methods influenced the quality of the temperature signal.

Methodological considerations

Our models explain roughly one-third of the total deviance. Several reasons may be responsible for this limited explanatory power. First, it would be illusive to pretend that such a multifaceted phenomenon as the occurrence of forest fires in a highly complex topography can be explained by only a few variables. Other land use, land cover, legal and socioeconomic variables would be needed to develop a more complete understanding of the determinants of forest fire occurrence under a historical perspective (cf. Pyne et al. 1996; Cardille et al. 2001; Chuvieco et al. 2008). However, it is difficult to collect reliable, temporally, and spatially explicit data on these factors over large study periods and regions. This limitation, which is inherent to historical-ecological investigations, applies in particular to land-cover data (e.g., forest composition, fuel availability, and soil types) and restricts the power of any statistical analysis.

Second, as a consequence of the lack of direct data, proxies had to be used as predictors. We hypothesized that these proxies had a given impact on fire drivers, which in turn impacted fire occurrence (cf. Fig. 2). From our analyses, we suggest that not all hypotheses regarding the proxies can be confirmed, for example, the impacts of livestock density (second period) and precipitation (both periods) on fire occurrence.

Third, the signal between the proxies and the fire drivers has likely been attenuated by the data processing (cf. Sect. 2.3). For instance, data with coarse time resolution required interpolation (e.g., road density), and data with coarse spatial resolution resulted in the attribution of identical values to neighboring cells (e.g., population and livestock densities). These constraints certainly caused a loss of signal for the predictor variables in time and/or space.

Conclusions

Although our modeling approach was based on proxy data and referred to a long period, it helped to increase our understanding of the factors driving fire occurrence in the Canton of Valais. In fact, our analyses of the two time periods suggest that land use, and thus the socioeconomic context, influences fire occurrence strongly and that changes in forest use are particularly important.

Specifically, our study shows that human factors were related to fire occurrence in Valais during the past 100 years, as people tend to be involved in starting fires. Also, our analysis demonstrates that land use practices contributing to removing biomass, such as livestock pasturing and wood harvest, were linked to fire occurrence. Forest management measures to reduce fuel loads, for example, may therefore have a mitigating impact on fire occurrence, which is becoming increasingly relevant in the study region and in the European Alps in general in the context of anthropogenic climate change and the prevention of natural hazards.

Temperature was found to be correlated positively with fire occurrence. The climate in regions such as Valais and the European Alps as a whole is likely to become warmer (Schär et al. 2004), and agricultural land is increasingly abandoned, particularly in remote, inaccessible areas (Gellrich et al. 2007). Therefore, fire occurrence is likely to increase there as well as in areas situated at the wildland-urban interface. However, anthropogenic ignitions may well drop where road density is high, thus counterbalancing the effects of fuel buildup and climate warming. Furthermore, the example of the neighboring Canton Ticino shows that coping with intensifying fire occurrence is possible. In spite of the increasing temperature there and the occurrence of drought episodes as well as considerable land abandonment, Ticino experienced a drastic decrease in fire frequency since 1990 after laws on fire prevention had entered into force (Rebetez 1999; Conedera et al. 2004; Reinhard et al. 2005; Baur 2006; Pezzatti et al. 2011). Therefore, enhancing legal measures could help to reduce fire occurrence in specific areas or during specific periods in our study region.

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