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Reconstructing and analyzing the fire history in a dry continental valley (Valais) of the Swiss Alps

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Summary

In many parts of the world, forest fires are of high ecological, social and economic importance. They represent an ecological disturbance factor in ecosystems and a significant natural hazard for human populations. Forest fire regimes are determined by many factors, particularly climatic, vegetation and anthropogenic factors, and are likely to experience considerable changes in the European Alps, in particular due to climatic changes. However, little is known about the recent regional fire history and the impact of its determinants on the fire regime during the 20th century.

In the present thesis, we therefore reconstructed the fire history in Canton Valais (Switzerland) during the 20th and early 21st century based on documentary evidence, and investigated the relationship between the reconstructed fire regime and its determining factors. We specifically wanted (1) to determine the spatiotemporal pattern of the fire regime in Valais, (2) to elucidate the relevance of potential driving factors of the fire regime, especially climate- and human-related factors, and (3) to identify possible differences between the fire regimes in Valais and the neighboring Canton Ticino.

In the first chapter, we compared the impact of temperature, precipitation, drought and dry foehn winds on the reconstructed 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. This chapter illustrates the occurrence of different fire regime patterns and their driving forces on small spatial scales. We also conclude that the strong rise in temperature over the past century has not profoundly changed the fire regime in Valais because 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.

In the second chapter, we investigated the impact of local human activities on fire occurrence in Valais during the period 1904–2006. We compared the impact of population and road density, biomass removal by livestock grazing and wood harvest, on fire occurrence during two subperiods (1904–1955 and 1956–2006) using generalized additive models. As fire occurrence is strongly related to climate, predictors reflecting climatic conditions, i.e. precipitation and temperature, were also considered to allow us to disentangle anthropogenic and climatic factors. This chapter provides evidence for the important role played by humans in shaping fire activity. It also illustrates consistently how fire activity has been influenced according to the land use and socioeconomic context of the time or the location under consideration. Changes in forest use/management within the study region seem to be particularly important. The existence of ignition sources appears to promote fire occurrence to a certain extent only, as high human presence tends to be related to fewer fires. Moreover, fuel removal through pasturing of livestock in the forest and wood harvesting appears to have significantly reduced fire occurrence during the first decades of the 20th century.

In the third chapter, we considered forest fires, land use and meteorological data over the period 1904–2008 in the neighboring mountain cantons of Valais and Ticino, which are characterized by distinct climatic regimes. We used generalized additive models to investigate the role of factors involved in fire occurrence. The presence/absence of fires was used as the response variable. We selected as predictors the Nesterov ignition index (as a proxy for fire weather), road density (for ignition sources), livestock density (for biomass removal), and change in forest area (for fire-prone abandoned agricultural areas). Fire weather played a key role in fire occurrence in both regions. Road and livestock densities had similar influences in the two cantons. However, while the increase in fire-prone areas was well correlated with fire occurrence in Ticino, no such correlation was evident in Valais, probably because land abandonment and forest cover change have been less extensive there. Moreover, our findings emphasize the nonlinear nature of the relationships between fire occurrence and anthropogenic drivers, as we found thresholds above which road density was no longer correlated with fire occurrence. This implies that the projected increase and spatial concentration of the human population may not result in a further increase in fire risk in intermediately to densely populated areas in both cantons.

In the fourth chapter, analyses were focused on temporal aspects of the fire regime in Valais. We determined, based on descriptive statistics, whether the fire regime had changed over the period 1904–2008, and, based on correlation analyses, what factors might have significantly influenced the fire regime. Our findings show that fire activity has moved towards the lowlands during the 20th century, likely because of increasing population density at low elevations. Fire seasonality has also changed. While most fires occurred during summer in the first half of the study period (1904–1955), the number of spring fires clearly increased during the second half (1956–2008). However, fire frequency and annual burnt area were not significantly different during the periods prior to and after 1955. The balance between the driving factors of fire frequency and burnt area has changed over the study period. While drought appears to have been crucial during the first decades of the 20th century, its relative importance seems to have diminished over time in favor of other factors, in particular fuel load.

In the fifth chapter, we used the change point approach to detect shifts in fire frequency and burnt area in the cantons of Ticino and Valais. We analyzed the detected changes in the fire regimes in the light of the implemented fire policy and the socio-economic evolution. In particular, we found that in the less fire-prone canton of Valais, major driving forces yielding shifts in fire regimes are of climatic and socio-economic origin, whereas in the fire-prone canton of Ticino fire policy measures also contributed to detectable changes. Legislative measures led to reduced fire frequencies, and improvements in fire-fighting resulted in a reduction of the burnt area.

The present thesis leads to the following conclusions. First, forest fires in Valais depend greatly on anthropogenic factors. Therefore, they cannot simply be considered as a natural disturbance, but they must be viewed as a human-induced factor that is strongly conditioned by the socio-cultural circumstances. Thus, there is much room for mitigating fire risk and specific properties of the fire regime, such as the area burnt.

Second, Valais can be subdivided into regions that are characterized by distinct fire regimes, which in turn are characterized by distinct driving factors. This calls for planning and implementing region-specific prevention and pre-suppression measures, rather than one unified strategy for the entire area.

Lastly, this study demonstrated that changes in the fire regime and in the relevance of its driving factors can occur within a few decades. Therefore, the validity and the pertinence over time of the measures undertaken for addressing forest fire issues should be assessed on a regular basis and adjustments may need to be undertaken, in particular in the new context of rapidly changing environmental conditions.

Résumé

Les incendies de forêt revêtent une importance écologique, sociale et économique particulière dans de nombreuses régions. Ils sont à la fois un facteur de perturbation écologique dans certains écosystèmes et un danger naturel majeur pour certaines populations. Les régimes des incendies de forêt sont influencés par divers facteurs climatiques, de végétation ou encore anthropiques, et vont probablement subir des changements importants dans les Alpes, notamment en raison du changement climatique. Toutefois, les connaissances concernant l'histoire récente des incendies de forêt dans cette région ainsi que l'impact des facteurs déterminants sur le régime des incendies au cours du siècle dernier sont encore limitées.

Dans le cadre du présent travail, nous avons tout d'abord reconstruit, au moyen d'archives documentaires, l'histoire des incendies de forêt des cent dernières années dans le canton du Valais (Suisse), puis étudié les relations entre le régime des incendies et ses facteurs déterminants. L'objectif de ce travail était (1) de déterminer le patron spatiotemporel du régime des incendies en Valais, (2) d'évaluer le rôle joué par les facteurs déterminants de ce régime et (3) d'identifier d'éventuelles différences entre le régime des incendies en Valais et celui du Tessin, un canton voisin.

Le premier chapitre propose une comparaison à plusieurs échelles spatiotemporelles de l'impact de la température, des précipitations, de la sécheresse et du foehn sur la fréquence et la saisonnalité des incendies ainsi que sur la surface brûlée. A l'étage subalpin, le régime des incendies semble avoir été principalement influencé par la température et les précipitations alors qu'à l'étage collinéen-montagnard, ces variables n'ont joué qu'un rôle secondaire. A cet étage, l'influence du foehn, et probablement d'autres facteurs non climatiques, a semble-t-il été plus importante. Durant la première moitié du XX^{e} siècle, la température et les précipitations ont joué un rôle primordial en ce qui concerne la fréquence des incendies et la surface brûlée. En revanche, durant la seconde moitié de ce siècle, ces deux variables ont perdu de leur prépondérance. Ce chapitre démontre donc l'existence de différents régimes des incendies à une échelle spatiale relativement restreinte. Il permet également de conclure que l'augmentation importante des températures au long du XX^{e} siècle en Valais n'a, pour l'instant, pas modifié de manière substantielle le régime des incendies, en particulier parce que, lors de la seconde moitié de ce siècle, la température n'a plus été un facteur déterminant majeur des incendies de forêt en comparaison des facteurs anthropiques et de la disponibilité en combustible.

Le deuxième chapitre traite de l'impact des facteurs anthropiques locaux sur l'occurrence des incendies de forêt en Valais au cours de la période 1904–2006. Nous avons comparé, au moyen de modèles additifs généralisés, l'impact de la densité de population et de routes ainsi que de la soustraction de biomasse en forêt due à la pâture du bétail et à l'exploitation de bois sur l'occurrence des incendies durant deux sous périodes (1904–1955 et 1956–2006). Etant donné que l'occurrence des incendies est fortement liée aux conditions climatiques, nous avons également inclus dans notre analyse la température et les précipitations comme variables explicatives. Ce second chapitre met en évidence le rôle important joué par l'être humain en matière d'activité des incendies de forêt. Il illustre également de façon cohérente comment l'activité des incendies a pu être influencée en fonction de l'utilisation du territoire et du contexte socioéconomique d'une période ou d'une zone données. Les changements intervenus dans l'utilisation et la gestion des forêts en Valais ont, selon toute vraisemblance, joué un rôle prépondérant. L'existence de sources d'ignition paraît favoriser l'occurrence des incendies jusqu'à un certain point seulement car le nombre d'incendies diminue dans les régions densément habitées. De plus, la soustraction de combustible en forêt due à la pâture du bétail et à l'exploitation de bois semble avoir réduit de manière significative l'occurrence des incendies durant les premières décennies du XX^e siècle.

Le troisième chapitre présente une comparaison de l'activité des incendies de forêt lors de la période 1904–2008 en Valais et dans le canton voisin du Tessin, deux régions présentant des régimes climatiques bien distincts. Nous avons utilisé des modèles additifs généralisés afin d'étudier le rôle de certains des facteurs déterminant l'occurrence des incendies. La présence/absence d'incendies a tenu lieu de variable dépendante. Nous avons choisi comme variables indépendantes l'indice de Nesterov (en tant que substitut des conditions météorologiques), la densité de routes (substitut des sources d'ignition), la densité de bétail (substitut de la soustraction de biomasse) et l'évolution de la surface forestière (substitut des surfaces agricoles abandonnées sensibles au feu). Il ressort de cette analyse que les conditions météorologiques ont joué un rôle crucial dans les deux cantons. La plupart des variables anthropiques semblent avoir eu des influences similaires également. Cependant, alors que l'augmentation des surfaces sensibles au feu est corrélée avec l'occurrence des incendies au Tessin, ce n'est pas le cas en Valais, probablement car la déprise agricole et l'augmentation de la surface forestière ont été moins marquées dans ce dernier canton. De plus, cette analyse a souligné le caractère non linéaire des relations entre l'occurrence des incendies et certains facteurs anthropiques.

Le quatrième chapitre aborde le régime des incendies en Valais sous une perspective temporelle. Nous avons déterminé au moyen de statistiques descriptives si le régime des incendies avait évolué au cours de la période 1904–2008 et, au moyen d'analyses de corrélation, quels facteurs avaient influencé de manière significative ledit régime. Nos résultats montrent que l'activité des incendies s'est déplacée vers la plaine au cours du XX^e siècle, probablement en raison de l'augmentation de la densité de population à basse altitude. La saisonnalité des incendies a également évolué. En effet, alors que la plupart des incendies ont eu lieu en été durant la première moitié de la période d'étude (1904–1955), le nombre d'incendies de printemps a nettement augmenté lors de la seconde moitié (1956–2008). La fréquence des incendies et la surface brûlée annuelle n'ont quant à elles pas été significativement différentes avant et après 1955. En revanche, la balance entre les différents facteurs influençant la fréquence des incendies et la surface brûlée annuelle s'est modifiée au cours de la période d'étude. Alors que la sécheresse semble avoir été prépondérante lors des premières décennies du XX^e siècle, son importance relative a selon toute vraisemblance diminué au profit d'autres facteurs, tels que la disponibilité en combustible.

Dans le cinquième chapitre, l'approche du "point de changement" a été utilisée afin de détecter les changements intervenus dans la fréquence des incendies et la surface brûlée dans les cantons du Tessin et du Valais. Les changements détectés ont été interprétés à la lumière des politiques de lutte contre les incendies ainsi que de l'évolution des cadres socioéconomiques prévalant dans ces cantons. Il ressort de cette analyse que, dans le canton du Valais, les principaux facteurs engendrant des modifications du régime des incendies de forêts sont de natures climatique et socioéconomique. Dans le canton du Tessin, les facteurs liés aux politiques de lutte contre le feu ont également provoqué des modifications notables. Alors que des mesures législatives ont contribué à réduire la fréquence des incendies, les améliorations en matière de lutte contre le feu ont conduit à une réduction de la surface brûlée.

Le présent travail permet de tirer les conclusions suivantes. Premièrement, il apparaît que les incendies de forêt en Valais dépendent fortement de facteurs anthropiques. De ce fait, les incendies ne peuvent être simplement perçus comme une perturbation naturelle, mais également comme un phénomène anthropique conditionné par son contexte socioculturel. Il existe donc des opportunités de réduction du risque d'incendie et de contrôle de certains aspects du régime des incendies, telle que la surface brûlée.

Deuxièmement, le Valais peut être subdivisé en différentes régions présentant des régimes des incendies bien distincts. Cela laisse supposer que les stratégies de planification et d'application des mesures de prévention et de présuppression nécessitent une approche locale plutôt qu'unifiée au niveau cantonal.

Enfin, la présente thèse a démontré que des changements au niveau du régime des incendies et de leurs facteurs déterminants peuvent intervenir dans un laps de temps de quelques décennies seulement. La validité et la pertinence des mesures prises en matière de gestion des incendies de forêt devraient donc être régulièrement réévaluées afin de pouvoir procéder à d'éventuels ajustements. Ce dernier point est particulièrement important dans le contexte actuel de changements rapides des conditions environnementales.

Introduction

1 Forest fires and their driving forces

In many parts of the world, forest fires are of high ecological, social and economic importance. They represent an ecological disturbance factor in ecosystems, such as in boreal and Mediterranean forests, by shaping the landscape, determining species composition and vegetation cover (Patterson and Backman 1988, Frelich 2002). Forest fires are also a tool for land management – *e.g.* slash-and-burn agriculture practiced in America by Native Americans and European settlers – by opening the forest cover and improving the short-term fertility of the soils (Pyne *et al.* 1996). At the same time, they represent a significant natural hazard, be it with natural or anthropogenic causes, for many human populations, *e.g.* in Mediterranean regions.

Forest fire regimes, defined as the spatial extent, intensity, and frequency of fires in a given area and over a given period (Johnson 1992), are determined by many factors. Climate is one of the major drivers of fire regimes. Climate causes water stress and dries out fuel (Renkin and Despain 1992, Kunkel 2001), ignites fires through lightning, and modulates fire behavior through wind (Cesti 1990, Pyne *et al.* 1996). The climate influences fire activity on a broad range of temporal and spatial scales. On the centennial and subcontinental scale, temporal climatic variability, such as temperature and precipitation variations, influences fire activity (*e.g.* Swetnam and Betancourt 1990, Swetnam 1993); on the short-term and local scale, wind influences the spatial pattern of fire activity (Agee 1993). Because of this close relationship between climate and fire activity, anthropogenic climate change may already have provoked changes in fire regimes (*cf.* IPCC 2007). For instance, increases in fire frequency or burnt area as well as an extension of the fire season have been observed during recent decades – or predicted for the future – in many regions, *e.g.* in Spain and in the western United States (Moreno *et al.* 1998, McKenzie *et al.* 2004, Westerling *et al.* 2006).

Anthropogenic factors are also decisive for fire regimes. Indeed, many studies have demonstrated the key impact of human demography and activities, such as land use and fire management, on fire activity at the global scale and over long periods (*cf.* Chuvieco *et al.* 2008, Marlon *et al.* 2008). Humans can influence fire regimes in various ways: they have an impact on biomass availability by removing potential fuels, *e.g.* through livestock grazing, thereby causing an extension of the fire rotation (Murray *et al.* 1998, Heyerdahl *et al.* 2001, Hessburg *et al.* 2005); they change vegetation composition, thus possibly removing or promoting fire tolerant tree species (Batek *et al.* 1999, Hessburg and Agee 2003); they start fires by arson or negligence (Keeley *et al.* 1999, Brosofske *et al.* 2007); and finally, they often fight fires, modifying fire rotations and intensities as well (Minnich 1983, Fulé *et al.* 1997, Cleland *et al.* 2004). Thus, if we want to be able to project future forest fire regimes, we need to understand the relative importance and relationships between these factors, in particular climatic and human factors.

2 Forest fires in Switzerland

Until recently, forest fires have not been considered as a key ecological phenomenon in Switzerland, neither as a disturbance factor nor as a natural hazard, with the exception of southern Switzerland (Bugmann 2005), and only a few studies are available on this subject (*e.g.* Delarze *et al.* 1992, Conedera *et al.* 1996, Tinner *et al.* 1999, Stähli *et al.* 2006), investigating in most cases the effects of fire on vegetation or very localized fire activity but not large-scale fire histories – defined as the chronological record of the occurrence of fire in an ecosystem (USDA Forest Service 2009) – for entire regions. To date, Conedera *et al.* (1996) have conducted the only large-scale, spatially explicit and temporally detailed reconstruction of fire regimes in Switzerland, describing and analyzing the fire regime on the southern side of the Swiss Alps since about 1900.

The lack of studies on forest fires in Switzerland should not be mistaken as an expression of missing relevance of forest fires in the past or in the future. Indeed, it appears that forest fires contributed significantly to shaping the vegetation in several parts of Switzerland. For example, forest associations seem to have regressed or disappeared on the northern as well as the southern side of the Alps due to the pressure of fire, while some tree species seem to have adapted to fire in continental regions where forest fires were quite frequent in the past (Tinner *et al.* 2005). Furthermore, the significance of forest fires in Switzerland is likely to increase in the future (Schumacher 2004). The study for Ticino mentioned above (Conedera *et al.* 1996) showed that fire frequency has started to increase since the mid-20th century. The main causes proposed for explaining this phenomenon are the increase in land abandonment as well as climatic changes. A prospective study by Schumacher (2004) predicted that forest fires would become a major disturbance factor in parts of the Swiss Alps where they were not important in the past, due to climatic warming and the concomitant increase of summer drought periods.

3 Methods for fire history reconstructions

Ecosystem dynamics and patterns can be investigated on very different temporal and spatial scales (Levin 1992). The understanding of some current ecological problems, such as climatic or landscape changes for instance, requires long-term perspectives, be it for the analysis of past conditions/processes or for predicting future changes. Ecological changes cannot always be captured within the time frame of typical experimental studies (Turner and Gardner 1991, Foster and Motzkin 1998), but ecological research questions requiring long temporal scale approaches can be addressed using historical-ecological methods. These methods derive from paleoecology and land-use history research techniques, and are particularly useful for reconstructing and investigating the history of natural or human-induced disturbances, such as forest fire, whose frequencies and extents can only be identified if chronologies of observation covering several decades or centuries are available (Foster *et al.* 1990, Swetnam *et al.* 1999).

Regarding fire history, most published studies are based on records of fire scars in tree rings (*e.g.* Larsen 1996, Buechling and Baker 2004, Hellberg *et al.* 2004) or the variation of charcoal abundance in sediments (*e.g.* Clark *et al.* 1989, Birks 1997, Bradshaw *et al.* 1997, Tinner *et al.* 2000) or soils (*e.g.* Berli *et al.* 1994, Motzkin *et al.* 1996). These approaches are particularly suitable for reconstructing fire histories over very long periods, *i.e.* over several centuries or millennia (*e.g.* Clark 1988, Tinner *et al.* 2005). However, they basically provide only binary data (presence/absence of fires), except in spatially explicit (and exceedingly labor-intensive) fire scar studies (*e.g.* Swetnam and Betancourt 1990). Also, the temporal resolution of sedimentary records is usually much less than one year, making high-resolution reconstructions exceedingly difficult. Furthermore, the implementation of such methods in regions where ecosystems have been greatly influenced by humans is problematic because of the destruction/modification of the archives through anthropogenic disturbances (*e.g.* lumbering, deforestation, etc.).

Although often overlooked, written documents can provide a wealth of valuable information regarding fire events, particularly if the underlying data were collected in a systematic manner, as *e.g.* in fire fighting reports or standardized reports from forestry officials (*cf.* Conedera et al. 1996, Motzkin et al. 1996, Pew and Larsen 2001, Mouillot et al. 2003). From historical records not only the occurrence of fires can be deduced, but often also their spatial extent, their severity, and their effects, which is a distinct difference to tree rings and sediments. Therefore, documentary evidence of fires could be quite useful for better understanding the causes and consequences of changes in the fire regime, in particular in Switzerland, where anthropogenic impacts on forests are high, and forestry activities and disturbances are comparatively well documented and archived (Gimmi 2006).

4 Selection of the study area and methodological approach

As mentioned in section 2, the southern side of the Alps – Ticino in particular – is the most fire-prone region in Switzerland, and fire regimes have already been much investigated there (*e.g.* Conedera *et al.* 1996, Weibel 2009). To a somewhat lower extent, the Central Alps, *i.e.* the cantons of Valais and Graubünden, are also affected by forest fires (Langhart 1999, Bochatay and Moulin 2000). While the fire regime over the past century in Graubünden has not been systematically explored yet, a preliminary study (Gimmi et al. 2004) revealed the existence of valuable archival sources concerning forest fires in Valais. Given the methodological advantages of archival sources (*cf.* section 3 above), we decided to reconstruct the fire regime in the canton of Valais (Switzerland) based on this source type.

5 Situation in the study area (Valais)

The climate in Valais can be characterised as continental, *i.e.* with low annual rainfall (*e.g.* 599 mm in Sion, 483 m a.s.l.) and high daily and annual temperature fluctuations (MeteoSwiss 2009). Climatic conditions have changed noticeably in this region over the past hundred years: while no change in the rainfall regime is obvious, temperature has clearly increased (Bader and Bantle 2004). Moreover, recent climatic projections suggest strong warming and increased summer drought for this area (Schär *et al.* 2004). It is likely that these past and expected future changes of the climate in Valais have induced – and will induce – changes in the fire regime.

The human impact on forests on the one hand and on the fire regime on the other hand has also changed in Valais over the past century. Indeed, the main economic activity in the study area has shifted during the second half of the 20th century from agriculture to an industry- and service-oriented economy today. As a consequence, many former forms of forest exploitation (*e.g.* forest pastures, collecting of litter and dead wood) have been abandoned (Kempf 1985, Kuonen 1993, Gimmi 2006). As a matter of fact, forests in Valais now have largely lost their role as a core resource for energy and fodder. This economical change has also included an abandonment of many unproductive or inaccessible agricultural lands, which in turn has generated an increase of the woodland and shrubland area (Kempf and Scherrer 1982, Walther and Julen 1986). In addition, the strict legal protection of the forested area and control against excessive lumbering should be mentioned as a cause of the increase of the forest area and the strong increase in standing volume observed over the past century (Kempf and Scherrer 1982, Walther and Julen 1986, Brändli and Cioldi 2009). Furthermore, current forest exploitation contributes to an increase of organic matter in forests by leaving logs in the stands to protect against natural hazards such as rockfall and snow avalanches, or by leaving unmarketable lumbering products in the stands because of economical rationalisation (Bugmann 2005). Thus, this development of forest and landscape management has strongly influenced forest dynamics and probably the fire regime in Valais by producing an obvious increase of potential fuel and – through the expansion of the forested area – promoting the connectivity between potentially flammable areas. Beside these changes in forest and landscape management, human impacts on the fire regime are also likely to have changed regarding fire suppression. Indeed, fire fighting in Valais has much improved over the study period, amongst others by the development of the road network and the introduction of helicopters (Gimmi et al. 2004). These changes in the socioeconomic, climatic, environmental and technical framework in Valais are most likely to have caused considerable changes in the fire regime, particularly regarding fire frequency, fire intensity and the size of the burnt areas.

6 Goals of the thesis and research questions

The significance of forest fires as a disturbance factor and natural hazard will likely increase in the canton of Valais (Schumacher 2004). However, our knowledge concerning the phenomenon in this region – particularly with regard to the characteristics of the fire regime – is limited. Bochatay and Moulin (2000) reconstructed the fire regime in Valais over the period 1973−2000, and Gimmi *et al.* (2004) discovered valuable documentary archives and made a first reconstruction of the fire regime for the period 1904−2004. However, long-term data and in-depth analyses of the controlling factors in Valais are still lacking.

As discussed above, weather, fuel build-up, forest and landscape management as well as fire management policies are considered in the literature as potential drivers of forest fires. The significance and the predominance of these various drivers depend strongly on the ecosystem under study. In addition, the relative importance of these driving variables is often unclear (Salvador *et al.* 2005). Moreover, it is not possible to extrapolate results from one area to another as every region is characterized by its specific fire-historical context (Lefort *et al.* 2003). Accordingly, it is impossible to base the understanding of forest fires in Valais on studies conducted in other perimeters, which is an additional motivation to conduct a comprehensive analysis on the development of fire regimes and its main driving forces specifically for Valais.

Therefore, the main goals of the present study are (1) to reconstruct the fire history of Valais over the 20th and early 21st century and to elucidate the spatiotemporal patterns of the fire regime in this region, (2) to identify and differentiate the driving variables of this fire regime, and (3) to compare these results with findings on the fire regime of a neighbouring region (the Ticino, Switzerland). In relation to these goals, the following research questions were formulated:

First, what was the nature of the fire regime in the study area (Valais) during the study period? In particular, is it possible to distinguish areas of different fire regime types, and has the fire regime changed over the study period?

Second, is it possible to elucidate the relevance of potential driving factors of the fire regime, especially climate- and human-related factors? Given that differences between sub-regions or changes in the fire regime over the study period can actually be observed, can we trace back these differences to the patterns of the previously identified driving factors, such as variability in climatic conditions and land use or land occupation?

Third, to what extent do the cantons of Valais and Ticino – two adjacent regions with very distinct climatic conditions – differ in their fire regimes? If differences between the two cantons are evident, are they only to be found in the respective, distinct climate/meteorological regimes, or do non-climatic factors also play a significant role?

7 Structure of the thesis

This thesis consists of three main and two auxiliary chapters. The first main chapter, entitled *Linking forest fire regimes and climate* − *a historical analysis in a dry inner Alpine valley*, aims to answer the first research question and a part of the second. This chapter depicts the fire regime of Valais during the 20th and early 21st century, and investigates the controlling role of climate on the fire regime for various time periods and regions within the study area. The fire data were gathered from archival sources and analyzed using descriptive statistics and correlation analyses.

The second chapter, entitled *Human impacts on fire occurrence – a case study on hundred years of forest fires in a dry inner Alpine valley in Switzerland*, aims to answer the non-climatic part of the second research question. It starts from hypotheses based on the unresolved points of chapter one. It addresses the controlling role of human factors, specifically ignition and biomass removal, on the fire regime using generalized additive models for two time periods (1904–1955 vs. 1956–2006). In contrast to the first chapter, where several components of the fire regime have been considered, only fire occurrence is investigated. The fire data are taken from the database built for chapter one.

The third chapter, entitled *Weather and human controls on forest fires: 100 years of fire history in two climatic regions of Switzerland*, contributes to answering the second research question as a whole, and the third question. This chapter compares the fire regimes of the 20th and early 21st century in Ticino and Valais. It investigates the combined role played by drought and human factors, such as ignition and biomass removal, for the fire regime using non-linear regression analyses. The fire data for Valais are taken from the database built for chapter one, and for Ticino from the Swiss Fire Database elaborated at the Federal Institute for Forest, Snow and Landscape Research (WSL 2008).

The fourth – auxiliary – chapter, entitled *The forest fire regime in Valais: one century under climatic and anthropogenic influences*, picks up elements already described in chapter one, but broadens the approach. It specifically addresses the fire regime with a focus on the temporal perspective, and investigates the controlling role of drought on the fire regime. Potential anthropogenic influences are discussed here as well. The fire data are taken from the database built for chapter one, and analyzed using descriptive statistics and correlation analyses.

The fifth – auxiliary – chapter, entitled *Fire regime shifts as a consequence of fire policy and socio-economic development: an analysis based on the change point approach*, addresses all three research questions. This chapter compares the fire regimes of the 20th and early 21st century and their driving factors in Ticino and Valais. This chapter focuses on quantifying fire regime shifts over time and elucidating the impacts of legislative aspects of fire management. The fire data for Valais are taken from the database built for chapter one, and for Ticino from the Swiss Fire Database (WSL 2008).

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Chapter 1

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 hundred years based on documentary evidence, and investigated the relationship between the reconstructed fire regime and 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 to 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.

1 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, *e.g.* in Mediterranean regions, regardless of whether they have natural or anthropogenic causes (Pyne *et al.* 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 *et al.* 1997, Clark *et al.* 2002). It can be a predisposing agent if it causes water stress and dries out fuel (Renkin and Despain 1992, Kunkel 2001), or act directly by igniting fires *e.g.* through lightning, or modulating fire behavior *e.g.* through wind (Cesti 1990, Pyne *et al.* 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 *et al.* 2005), in some subalpine coniferous stands (Nash and Johnson 1996, Conedera *et al.* 2006) and in Mediterranean forests in northern Baja California (Minnich *et al.* 1993). However, this type of ignition is less common in regions with a Mediterranean climate in Europe or Chile (Susmel 1973, Montenegro *et al.* 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 *et al.* 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 vs. 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, *e.g.* in the Swedish boreal forests (Niklasson and Granström 2000, Carcaillet *et al.* 2007) as well as on a global scale (Chuvieco *et al.* 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 *et al.* 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 of precipitation and/or relative humidity (Bergeron and Archambault 1993, Flannigan *et al.* 1998, Flannigan *et al.* 2001). Little is known, however, on possible recent changes in the fire regime in central Europe.

In this paper, 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 *et al.* 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 (*e.g.* Buresti and Sulli 1983, Stefani 1989, Cesti and Cerise 1992, Conedera *et al.* 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 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).

2 Material and methods

2.1 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 (Fig. 1.1). It covers an area of 5200 km^2, of which about half is 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), *i.e.* relatively low annual rainfall (*e.g.* 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 Fig. 1.1) is characterized by more oceanic climatic conditions with higher rainfall (*e.g.* 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 (*e.g.* Schär *et al.* 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 (Fig. 1.1). 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).

Today, forests in Valais cover an area of approximately 1100 km^2 (BFS 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 (Fig. 1.2). 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 *Q. robur* prevail, whereas in the continental region *Q. 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, while coniferous species dominate in the continental part (Werlen 1994).

Today, the population in Valais is of about 300,000 inhabitants. The number of inhabitants has more than doubled over the past hundred years (Fig. 1.2). 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 (BFS 2002, BFS 2005).

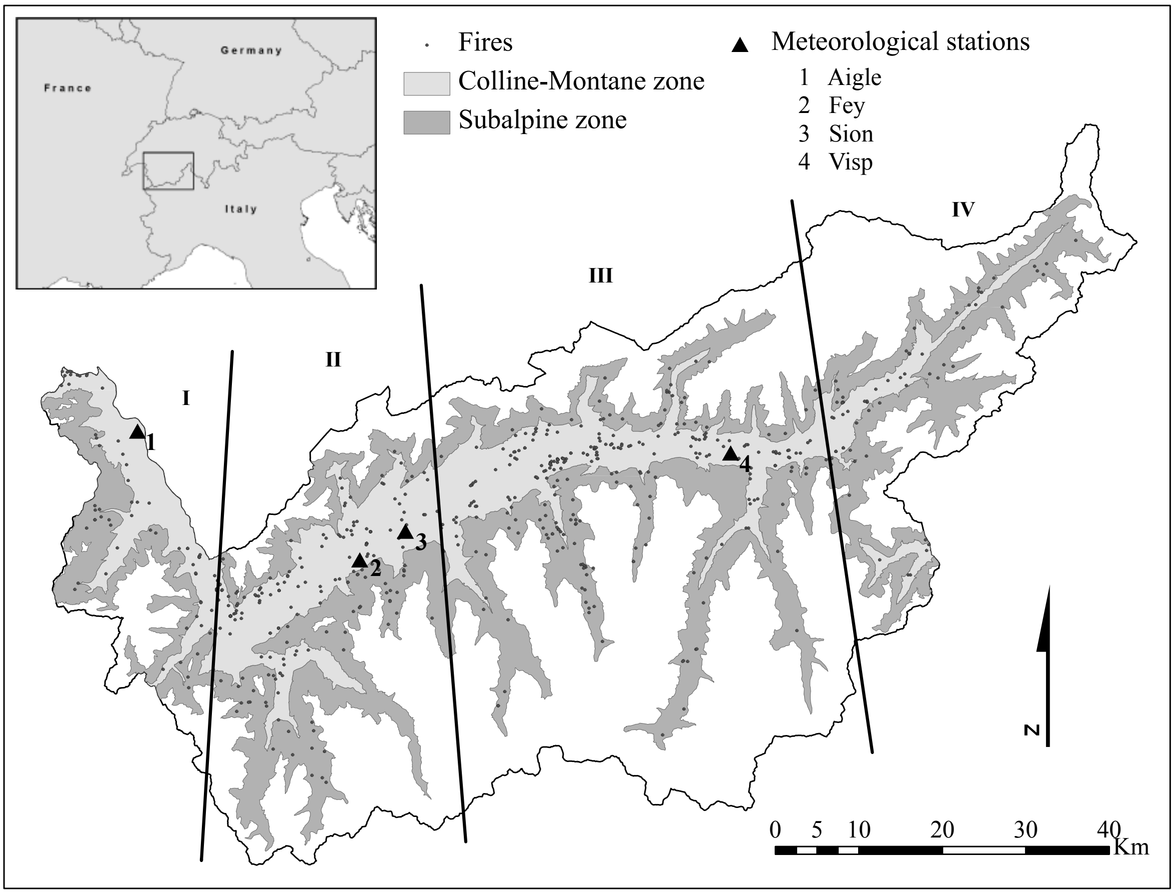

Figure 1.1. Study region (Valais) with the meteorological stations used in the study, altitudinal levels and ignition points of all documented fires with location information (1904–2006). The Roman numbers indicate the regions with foehn occurrence (I and III), and without foehn occurrence (II and IV) according to Bouët (1972). *Source of administrative boundaries*: Bundesamt für Landestopographie

2.2 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 *et al.* 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", *i.e.* those with an area <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.

In order 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.

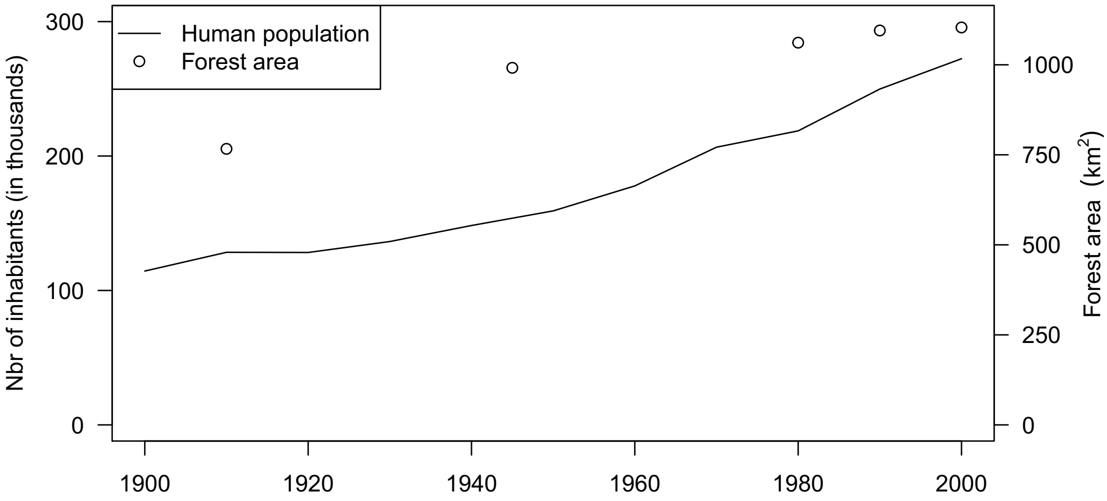

Figure 1.2. Changes in human population (BFS 2008) and in forest area (Ritzmann-Blickenstorfer 1996, BFS 2000) during the 20th century in the study region.

2.3 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 de-trending the series using kernel smoothing. We then calculated the cross-correlations (Pearson coefficient) between fire frequency and the 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), *e.g.* in Fry and Stephens (2006) and Heyerdahl *et al.* (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 *et al.* 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 temperature data by taking into account day length and the sun angle. (*cf.* 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; *cf.* Fig. 1.1) 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 *et al.* (1977). We also compared fire seasonality with the corresponding mean monthly wind speed and mean monthly water deficit (*cf.* 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 *et al.* (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 (*cf.* Fig. 1.1).

3 Results

3.1 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 (Fig. 1.1). 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 9 fires per year (SD = 8). Two periods of change are conspicuous: a slight increase during the 1940s-1950s and a stronger peak during the 1990s (Fig. 1.3a). Fire frequency evolved differently in the two elevation zones, *i.e.* the colline-montane vs. the subalpine zone (Fig. 1.3a). 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 towards the end of the 20th century at the subalpine level.

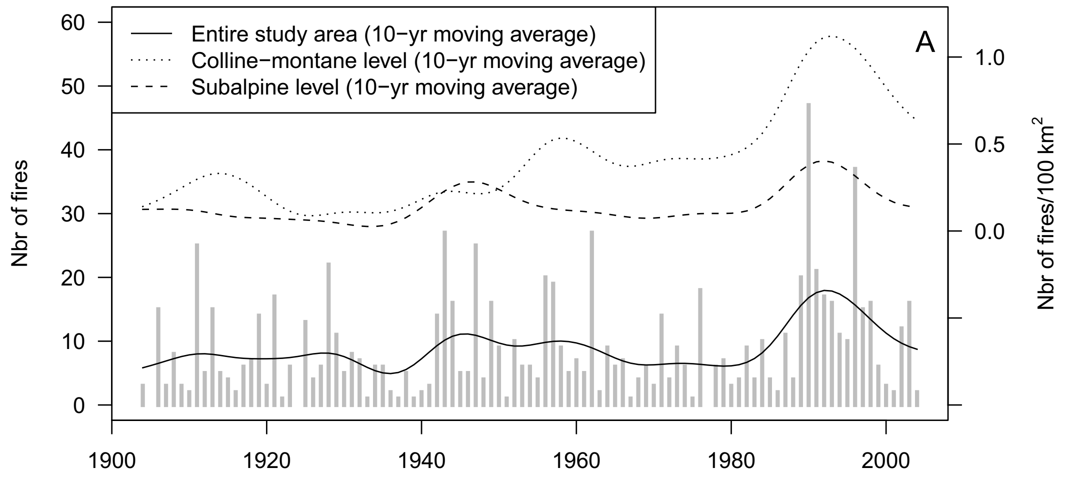

Figure 1.3a. Fire frequency for the entire study region (left axis), and fire frequency according to altitudinal levels (right axis; number of fires per 100 km^2 of forest).

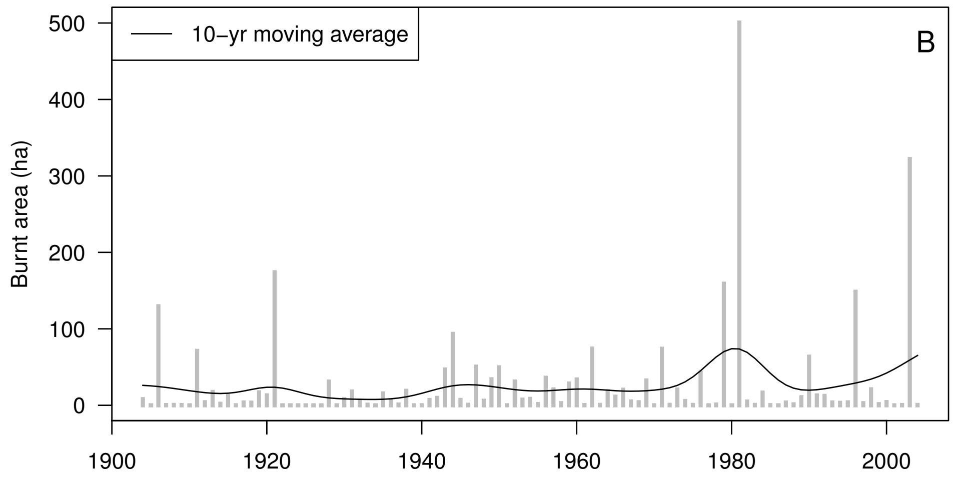

Figure 1.3b. Annual burnt area for the entire study region.

During the study period, forest fires burned about 2,700 ha in Valais, corresponding to an annual mean value of 26 ha, with a high interannual variability (SD = 65; *cf.* Fig. 1.3b). For instance, more than half of the total area burned in only six years (1906, 1921, 1979, 1981, 1996 and 2003), and this was mainly due to very few large events. These six 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.

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 (Fig. 1.4a). 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 (Fig. 1.4b). If we exclude the fires of unknown size (Fig. 1.4b, 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 class <0.1 ha (Fig. 1.4b, light grey), the test provides strong evidence for the alternative hypothesis, *i.e.* 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, *i.e.* 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 decreased during the second period, and then increased again during the last period.

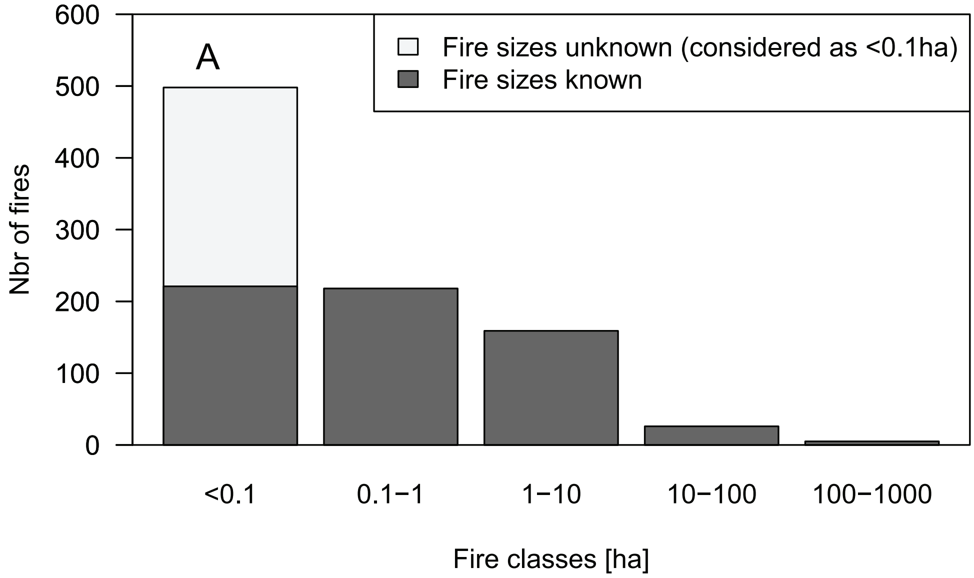

Figure 1.4a. Fire size distribution (*n* = 906). The *light-grey coloration* indicates the fires whose size is unknown (considered as <0.1 ha).

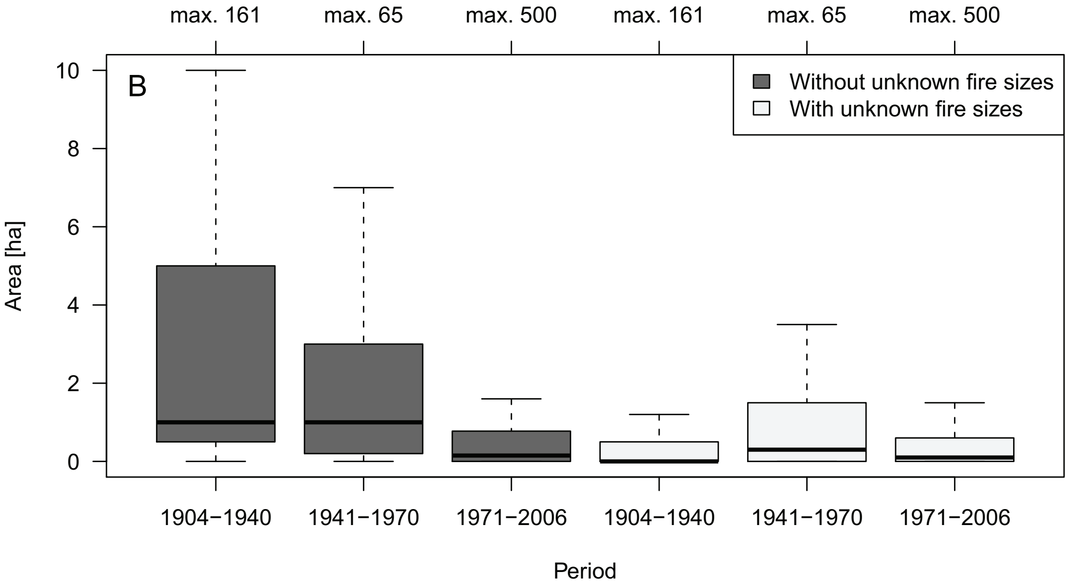

Figure 1.4b. Temporal changes in fire size distribution for all the fires documented (1904-2006). The *light-grey coloration* indicates the distribution when taking into account the unknown fire sizes.

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 (Fig. 1.5). Fires in winter are very rare. This "double-peak" pattern results from the combination of the seasonal fire distribution in the colline-montane vs. the subalpine level, *i.e.* a high fire activity in March-April at low elevations and in August at higher elevations (Fig. 1.5).

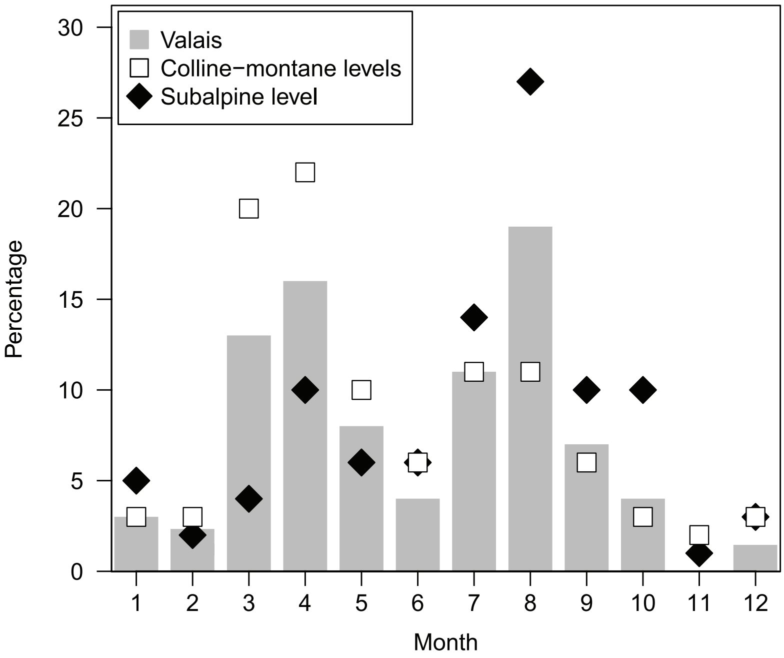

Figure 1.5. Fire seasonality for the entire study region and according to altitudinal level (1904–2006).

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.

3.2 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 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 1.1). 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 zone. In addition, a positive correlation between fire frequency and precipitation was evident with a negative time lag of three years for almost all regions and periods considered.

Table 1.1. Cross-correlation between fire frequency (1904–2006) and temperature (T) / precipitation (P) during the fire season (*i.e.* 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, *i.e.* March-October (Fig. 1.6a). The 1940s and 1950s were the driest decades, while the driest single years occurred during the first part of the 20th century (1906, 1911, 1921 and 1943). In spite of 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. While 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 (Fig. 1.6a).

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 (Fig. 1.6b). 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 (Fig. 1.6a, b).

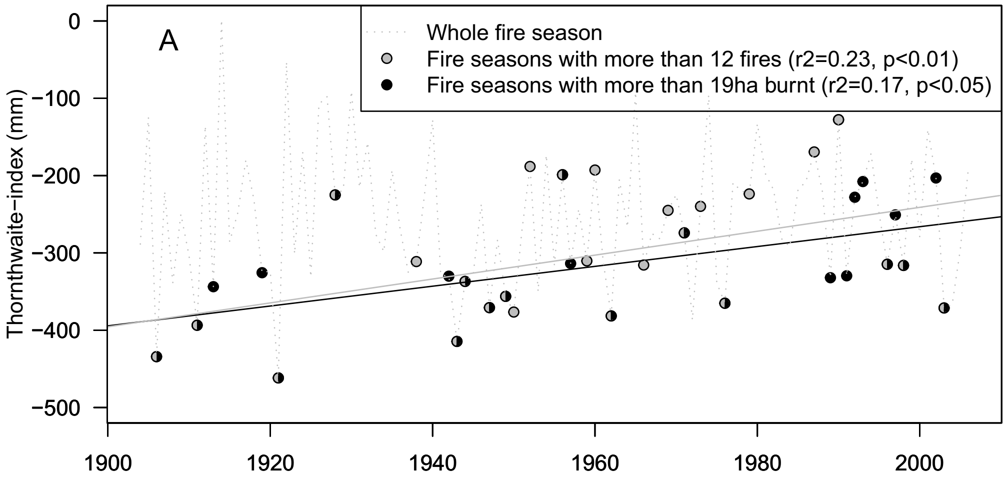

Figure 1.6a. Thornthwaite drought index (sum March-October) for all fire seasons (1904–2006) and fire seasons with a number of fires larger than 12 and a burnt area larger than 19 ha.

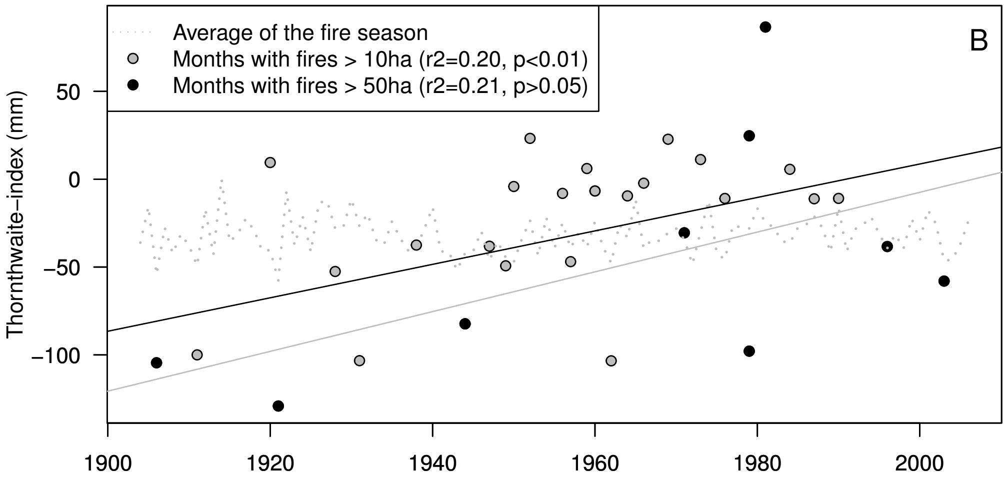

Figure 1.6b. Thorthwaite drought index for all fire seasons (1904–2006; average March-October) and for months with occurrence of fires larger than 10 ha and larger than 50 ha.

Fire size classes and foehn occurrence

The geographical distribution of the fire events according to size class was found to follow a distinct pattern (Fig. 1.7): fire events resulting in larger burnt areas tended to occur more often in approximately the centre 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, *i.e.* 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.

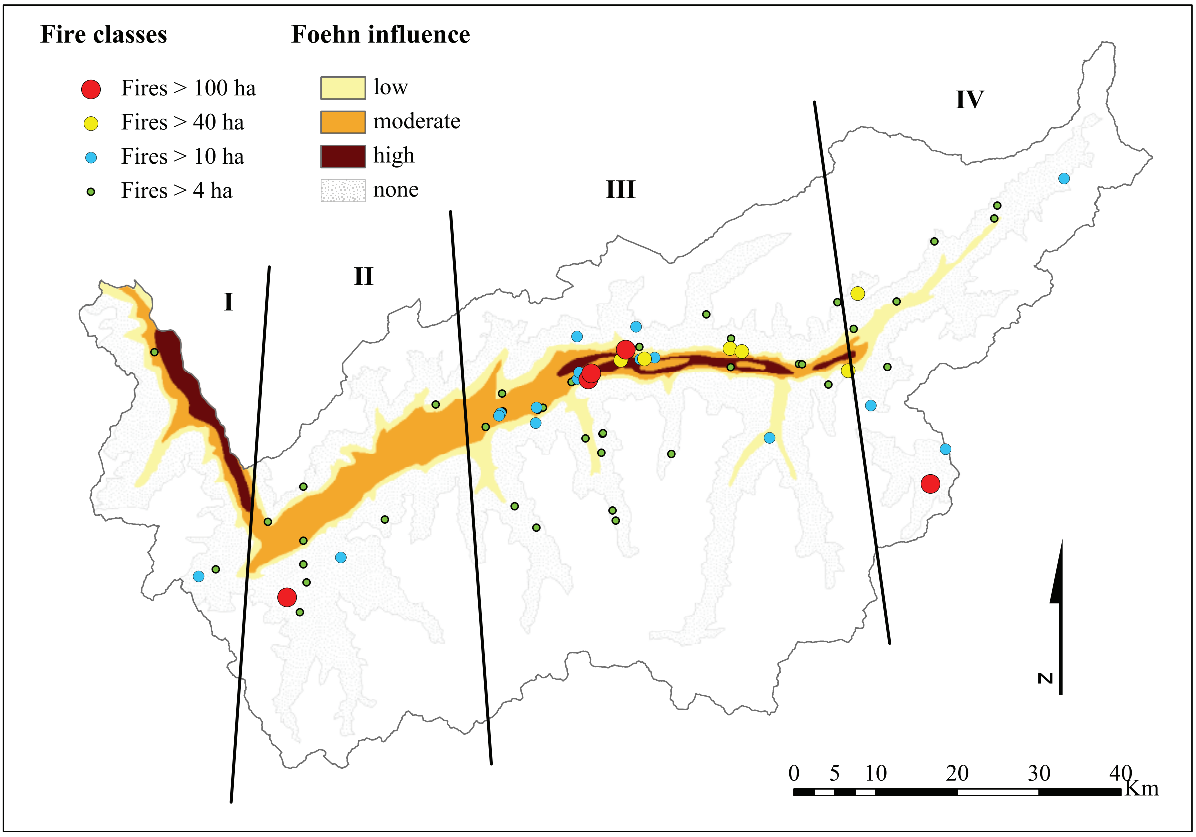

Figure 1.7. Geographical distribution of fire size classes; regions with foehn occurrence (I and III), and no foehn occurrence (II and IV) according to Bouët (1972); areas characterized by an increase in the temperature level due to foehn effects (Schreiber *et al.* 1977, modified). The region IV was excluded from the analysis, as very few fires are located within foehn boundaries. *Source of administrative boundaries:* Bundesamt für Landestopographie.

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 (Fig. 1.8). Fire seasonality in region I matched well with wind speed seasonality, *i.e.* 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 in spite of the rather moist conditions and the absence of foehn.

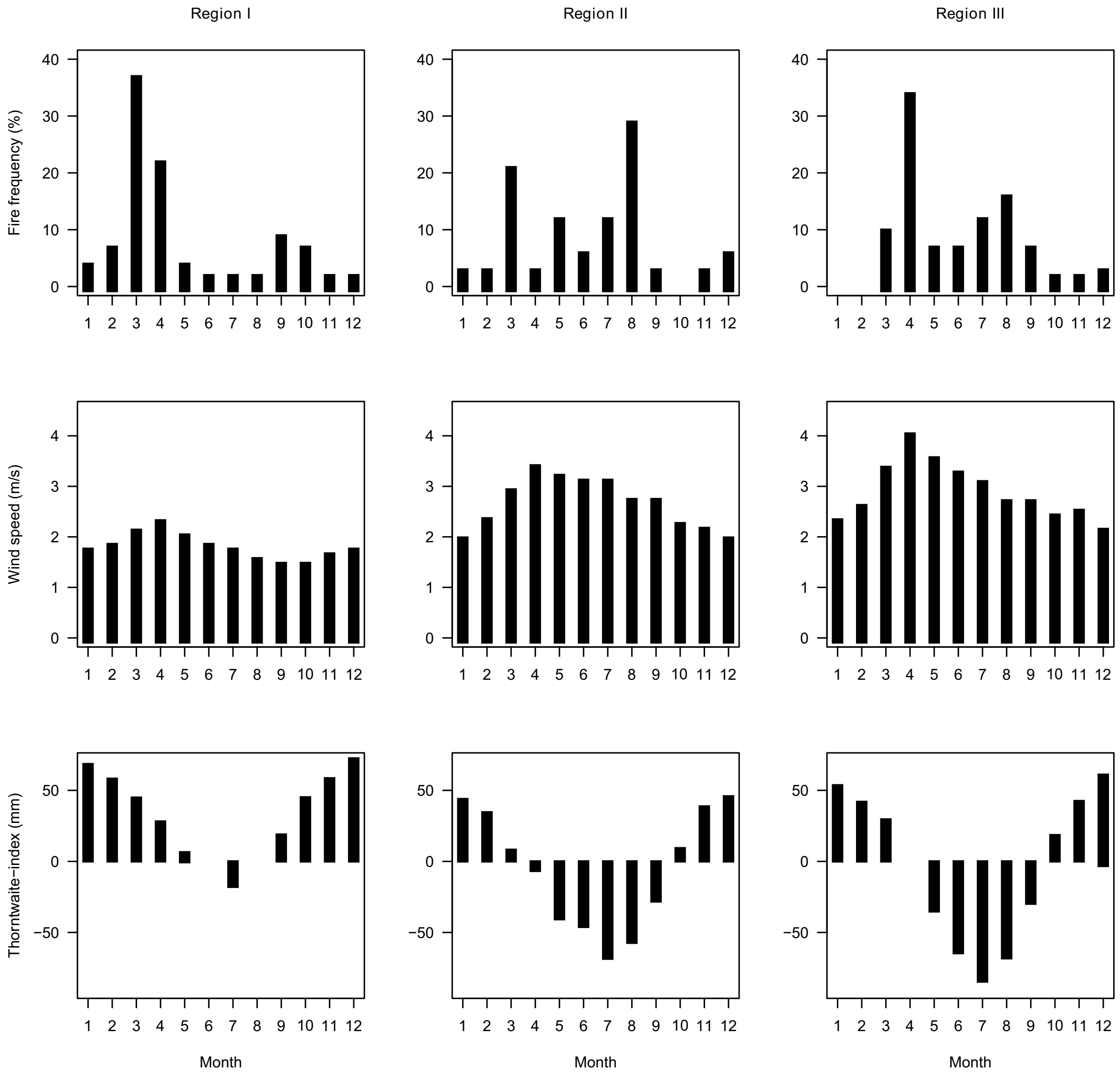

Figure 1.8. Seasonality of fire occurrence, mean wind speed, and mean monthly Thornthwaite drought index for the period 1981–2006 (*source of meteorological data*: MeteoSwiss) and foehn regions. Data exclude events outside foehn areas (*cf.* Fig. 1.7).

4 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 1.1). 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 (*e.g.* 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 *et al.* 2008), which may have influenced fire frequency and fire intensity, causing a relative decline in the 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 (Fig. 1.6a). Moreover, fuel load clearly also plays an important role in the fire regime since fire frequency was found to be significantly and positively correlated with precipitation with a time lag of three years (*cf.* Table 1.1). 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 *e.g.* 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 (BFS 2005). While 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 (Fig. 1.3a).

These dichotomous trends are probably caused by human populations shifting towards the lowlands (abandonment of high-elevation agricultural land, urbanization at low elevations) and by a concomitant relative decrease in ignition sources at higher altitudes (*e.g.* 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 *et al.* 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, while 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 *et al.* (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 (*cf.* Fig. 1.4b, 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 larger than 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 >19 ha and monthly conditions for fires >10 and >50 ha were wetter during the second part of the study period (Fig. 1.6a, 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 (Fig. 1.7). 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 (Fig. 1.5). 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, *e.g.* in the Aoste Valley (Cesti and Cerise 1992) and Ticino (Conedera *et al.* 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 *Quercus 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 the area covered by coniferous species (Werlen 1994). Moreover, the temperature and 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 while drought is the decisive factor in areas without foehn. In areas where both phenomena are relevant, such as in region III (*cf.* Fig. 1.7), spring foehn seems to play a much more important role than summer drought.

5 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 *e.g.* 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, since 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.

Acknowledgments

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Chapter 2

Human impacts on fire occurrence – a case study of hundred years of forest fires in a dry inner Alpine valley in Switzerland

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Abstract

Forest fire regimes are not only sensitive to climate, but also to direct and indirect anthropogenic influences, e.g. if humans alter ignition and fuel load conditions. However, little is known in the European Alps about the connection between regional fire regimes and anthropogenic factors. We investigated the impact of local human activities and climate on fire occurrence in a dry continental valley of the Swiss Alps (Valais) over the past 100 years. We compared the impact of population and road density, biomass removal by livestock grazing and wood harvest, as well of temperature and precipitation on fire occurrence during two subperiods (1904–1955 and 1956–2006) using generalized additive models. Our case study provides evidence for the important role played by humans in shaping fire activity. It also illustrates consistently how fire activity has been influenced according to the land use and socioeconomic context of the time or the location under consideration. Changes in forest use/management within the study region seem to be particularly important. The existence of ignition sources appears to promote fire occurrence to a certain extent only, as high human presence tends to be related to fewer fires. Moreover, fuel removal through pasturing of livestock in the forest and wood harvesting appears to have significantly reduced fire occurrence during the first decades of the 20th century. Thus these factors should be monitored carefully in the future, as they offer great opportunities for the mitigation of forest fire risk in the study region, a peripheral area that is, as many other regions in the European Alps, affected by climate warming and land abandonment.

1 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 (Patterson and Backman 1988, Pyne *et al.* 1996, Frelich 2002, Bowman *et al.* 2009). Changes in the forest fire regime, such as increases in fire frequency or burnt area, have been observed in many regions during recent decades, *e.g.* in Spain and in the western United States (Moreno *et al.* 1998, Westerling *et al.* 2006). These changes have triggered interest in identifying and disentangling the factors driving fire regimes.

Fire regimes are controlled by very a wide array of factors (Krebs *et al.* 2010). Climate and weather are crucial drivers of fire activity, if not the most important, in particular through high temperatures, low precipitation and/or wind occurrence (Agee 1993, Pyne *et al.* 1996). Moreover, temporal climate variability has been found to bring about long-term changes in fire activity (*e.g.* Swetnam and Betancourt 1990, Swetnam 1993). Non-climatic drivers, however, also need to be considered for a better understanding of fire regimes. Topography may greatly influence fire spread, fuel loads determine fire intensity, and human population density affects ignition rates, *e.g.* through arson or negligence (Susmel 1973, Pyne *et al.* 1996, Omi 2005).

Anthropogenic influences rank prominently among the non-climatic determinants of fire regimes. Recent studies have pointed out the decisive impact of human demography and activities, such as land use and fire management, on fire activity on a global scale and over long periods (*cf.* Chuvieco *et al.* 2008, Marlon *et al.* 2008). Marked changes in fire regime patterns have occurred in northern America during the past 100-200 years, partly induced by the settlement of Europeans (*cf.* Hessburg and Agee 2003). Although the impact of fire suppression 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 US 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).

In Europe, most ecosystems have been under strong anthropogenic pressure for many centuries if not millennia, and thus have not recently experienced such abrupt changes as those in North America. Nevertheless, signs of anthropogenic influences on fire regimes have been detected in Europe, including indications of human control of fire frequency through agricultural activities during some periods of the Holocene *e.g.* in the French and Swiss Alps (Tinner *et al.* 1999, Carcaillet *et al.* 2001, 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 16th and the 20th centuries to the expansion of human settlements and increasing population densities.

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). 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, a dry continental valley in the Swiss Alps, 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 20th 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 build-up and high population densities overlapped or blurred the signal of climate on fire frequency during the second part of the 20th 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, Gellrich 2006, Schumacher and Bugmann 2006).

The goal of the present study is to identify the impact of humans on fire occurrence, i.e. 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. 2.1 and section 2.1), 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, i.e. precipitation and temperature, were considered to allow us to disentangle anthropogenic and climatic factors.

2 Material and methods

2.1 Conceptual framework

Our analysis was based on a conceptual framework for the impact of potential drivers on fire occurrence (Fig. 2.1). We postulated that the most important anthropogenic drivers shaping fire occurrence are ignition potential and fuel load. Forests in Valais have been under strong anthropogenic pressure for many centuries (Kuonen 1993, Gimmi 2006), which makes it likely that humans have had a strong impact on the regional fire regime (Zumbrunnen *et al.* 2009). In this study, we used anthropogenic proxies to assess the influence of these factors on fire occurrence in Valais.

In order to assess the ignition potential in forests, we chose the density of roads and human population as proxies (Fig. 2.1). Road density was chosen to reflect forest accessibility. Roads have been found to increase the frequency of fire ignited by humans (*e.g.* Franklin and Forman 1987), and forest accessibility in Valais very much depends on roads because the terrain is mountainous and rough. Population density was chosen to quantify potential ignition sources because most fires with known causes in the study region originated from human activities (about 85%, Zumbrunnen *et al.* 2009).

In order to assess fuel load in forests, we considered proxies reflecting biomass removal associated with human activities (Fig. 2.1). First, livestock density was treated as an indicator of grazing pressure in forests. Livestock, mainly goats and sheep, had been grazing in the forests for centuries, and wood pasture contributed to the reduction of the herb layer and the understory, and hence to the removal of considerable amounts of fine fuel (Gimmi and Bürgi 2007, Gimmi *et al.* 2008). Second, we selected wood harvest volume 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, and they are thinned and used to produce timber and firewood, or to provide 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). We also assumed that wood harvest volume is a proxy of the intensity of the removal of other non-timber products and dead wood such as firewood, for which no direct data are available.

To include the major potential influences on fire, we also decided to consider predictors reflecting climatic conditions, namely precipitation and temperature, which directly condition fuel moisture (Renkin and Despain 1992, Kunkel 2001).

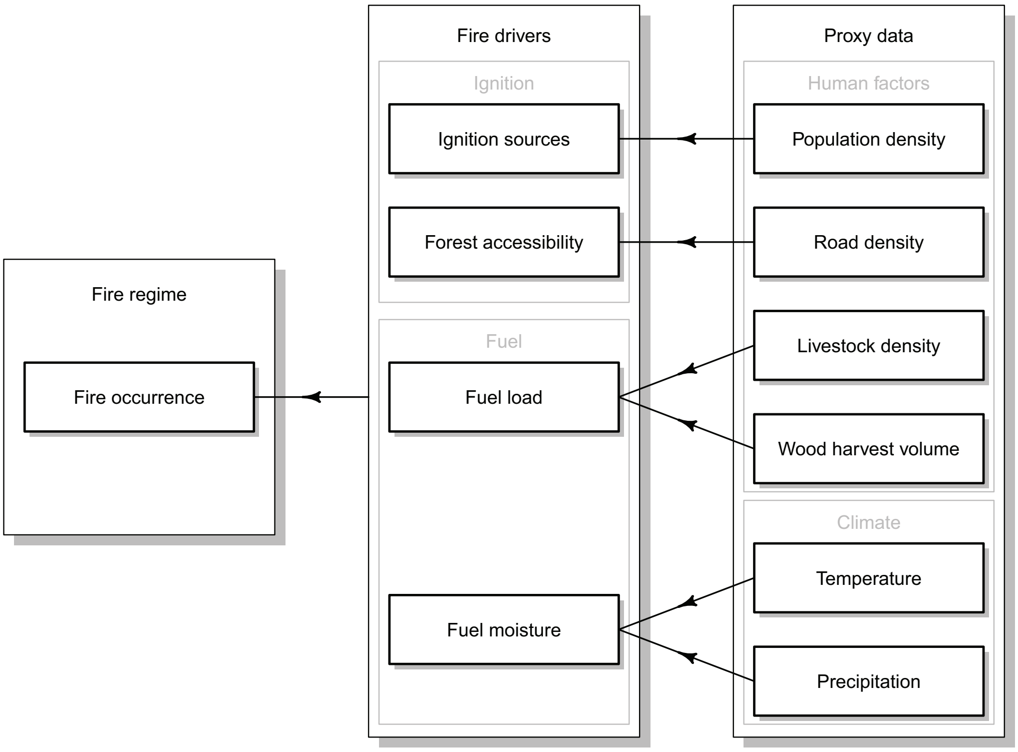

Figure 2.1. Conceptual model of the potential impact of human and climatic factors on fire occurrence through ignition and fuel conditions.

2.2 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. 2.2). 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, i.e. 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 well as by the occurrence of the foehn, a dry katabatic wind with strong gusts (Ficker and De Rudder 1943, Bouët 1972, Kuhn 1989).

The forest area in Valais has increased over the past century due to strict conservation measures and a decline in agricultural activity in less productive and/or more remote areas (Walther and Julen 1986, Kuonen 1993). While the forest area in Valais amounted to about 75,000 hectares at the beginning of the 20th century, forests today cover approximately 95,000 hectares (own data based on the Siegfriedatlas and Swiss national maps from Swisstopo). Their composition reflects the altitudinal gradient: forests at low elevations (400-800 m a.s.l.) are dominated by broadleaved species (mainly *Quercus pubescens*), at medium elevations (800-1400 m a.s.l.) by *Pinus sylvestris*, and at higher elevations (1400-2300 m a.s.l.) by other coniferous species, mostly *Picea abies* and *Larix decidua,* and *Pinus cembra* in the uppermost parts (Hainard 1969, Werlen 1994, Werner 1994).

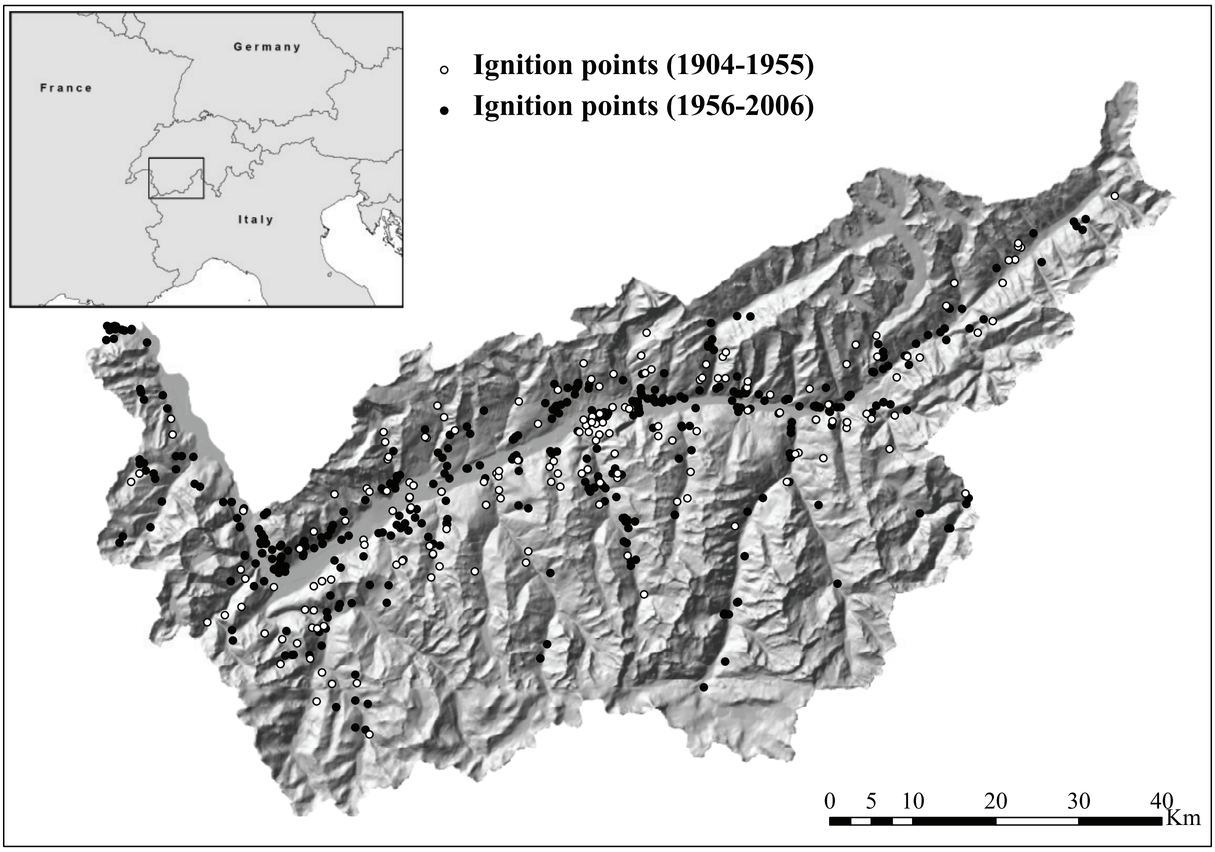

Figure 2.2. Study region (Valais) with the ignition points for the periods 1904–1955 and 1956–2006 (Source of administrative boundaries: Swisstopo; source of fire data: Zumbrunnen *et al.* 2009).

2.3 Data compilation

In order to evaluate the human and climatic impacts on fire occurrence according to the conceptual framework (*cf.* Fig. 2.1 and section 2.1), 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 2.1 and Fig. 2.1). We faced the problem that the different data sets vary greatly in spatial resolution. To achieve a homogeneous resolution, we divided the study area into 2 km x 2 km cells and attributed to each cell the values of the geographically corresponding variables. This is similar to the procedure applied by Bürgi and Turner (2002) to investigate the influence of soil properties and socio-economic factors on land cover changes in Wisconsin. 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.

Fire data were taken from an existing forest fire inventory for Canton Valais (Zumbrunnen *et al.* 2009). It refers to about 900 fires during the 20th and early 21st centuries, including information on, *e.g.*, ignition dates and locations. As with many historical data, our fire data have various levels of accuracy: (1) exact coordinates of the ignition point; (2) imprecise ignition point coordinates with an estimation of their accuracy (between 50 m and 1000 m); and (3) no exact ignition point indicated, but the municipality affected is known. According to the three levels of geographical accuracy, we split into three steps the procedure for assigning a fire density value to each cell. First, the fire density at the municipal level was calculated for all fires with unknown ignition point coordinates but with information about the municipality where the ignition took place. For each municipality, the number of such 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. Second, for every fire with imprecise ignition point coordinates, we calculated the density based on the summed forest area of the cells where the fire had potentially started. This density value was then assigned to all these cells. Third, we summed the number of fires with exact ignition point coordinates for each cell and divided the total by the cell's forest area. Finally, to obtain a fire density map, we summed up the three levels of fire densities for every cell.

The human population and livestock data were extracted from official federal statistics (Departement des Innern 1908, 1918, Eidgenössisches Statistisches Amt 1934, 1945, BFS 1989, 1994, 2008). These data had been collected at the municipal level. While human population data were collected each decade, data on livestock were available on a somewhat 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 of the respective municipalities. We applied the same procedure to obtain livestock density values. 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. This index, which Gimmi *et al.* (2008) had defined for Valais, is based on the food requirements and the duration of the grazing season for each type of livestock, as the two main species that were used for forest grazing, goat and sheep, have very different behaviors. The index is calculated as the number of goats plus 22% of the number of sheep (referred to as "grazing units" below), divided by the grazed area.

Wood harvest data were compiled from the annual reports of the Forest Service of Valais 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.

Table 2.1. Variables used in the models

Variable	Unit	Original spatial resolution	Original temporal resolution	Cell value	Source
Fire occurrence	Fires/$\text{ha}_{\text{forest}}$	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 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	100m x 100m grid	Monthly	Area-weighted	Land Use Dynamics research unit (WSL)
Temperature	°C	100m x 100m grid	Monthly	Area-weighted	Land Use Dynamics research unit (WSL)

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 cell of our grid by interpolating linearly between the three reconstructed values and taking the averages for the period under consideration.

Precipitation and temperature data were obtained using climate fields (100 m x 100 m spatial and monthly temporal resolution) provided by the Research Unit Land Use Dynamics research WSL (Birmensdorf, Switzerland). These fields were calculated based on datasets from the Climatic Research Unit at University of East Anglia (*cf.* Mitchell *et al.* 2004) and the Swiss Federal Office of Meteorology and Climatology. Based on these climate fields, we determined the average annual sums of precipitation and mean temperature for the periods 1904–1955 and 1956–2006 for every 2 km x 2 km cell.

2.4 Data analysis

In order 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 revealed that the main relationship between the response variable (forest fire occurrence) and the environmental variables showed serious discrepancies with the hypothesis of a linear model. Therefore, we decided to employ generalized additive models (GAM; Hastie and Tibshirani 1990) since their flexibility could take into account the nonlinear behavior of fire occurrence and the environmental variables introduced above. GAMs offer a larger flexibility than traditional generalized linear models, and have been found to be particularly useful in the field of ecological modeling (*e.g.* Yee and Mitchell 1991, Guisan and Zimmermann 2000, Guisan *et al.* 2002).

In many situations, spatial correlation might be a problem when fitting spatially explicit data, leading for example to falsely significant test statistics or biased parameter estimates. To address this issue, we decided to use generalized additive mixed models (GAMM, Lin and Zhang 1999), which allow for the modeling of correlated data, instead of traditional GAMs.

We tested whether spatial correlation needed be taken into account in our models, indicating that the optimal models should do so. In order to determine the appropriate spatial correlation structure for the errors in the models, we first fitted GAMs for our two sub-periods (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 correlation 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 final models were then 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.

In order to check for the possible nonparametric equivalent of collinearity between the smooth functions in the two models, we evaluated the concurvity measures between these smooth terms. Similar to multicollinearity in linear models, concurvity is an important aspect in GAMs, since it 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.

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

3 Results

The final model for the period 1904–1955 consisted of fire occurrence being explained by population and livestock density, wood harvest volume and temperature (for all variables, $P < 0.001$). The final model for the period 1956–2006 consisted of fire occurrence being explained by population density, livestock density, temperature (for these variables, $P < 0.001$), road density ($P < 0.01$) and wood harvest volume ($P < 0.05$). The two final models were very similar regarding their ability to explain forest fire occurrence, with an adjusted R-squared of 0.33 for the period 1904–1955 and of 0.31 for the period 1956–2008.

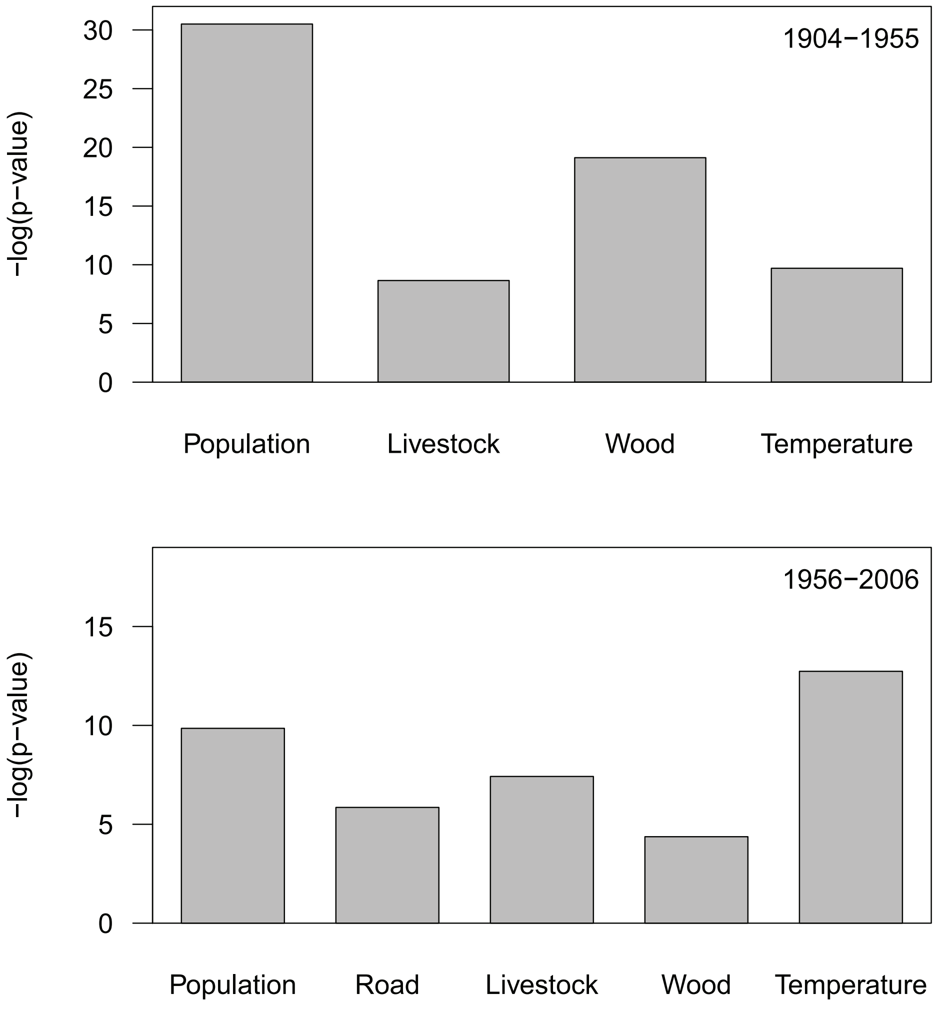

Figure 2.3. Contribution of each predictor variable in the final models (1904–1955 and 1956–2006). The contribution of the variables was determined by negatively log-transforming the p-values of the respective smooth terms.

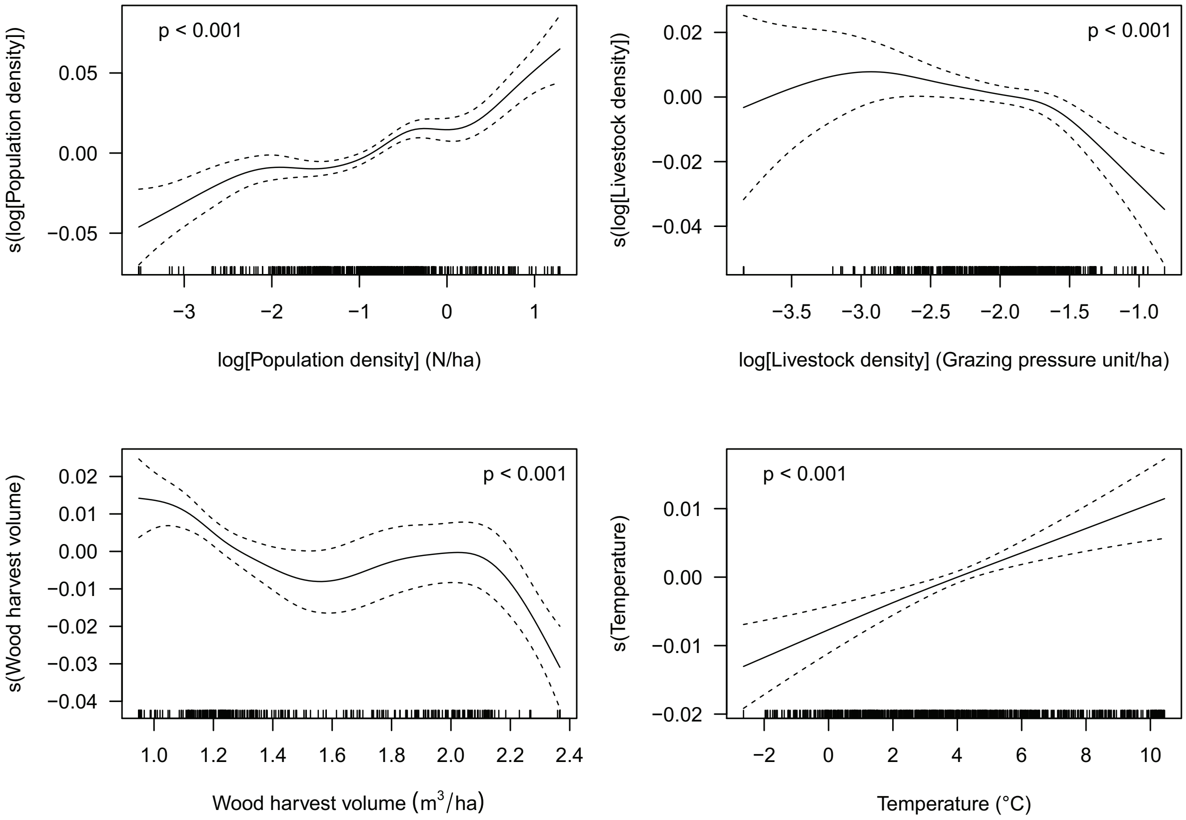

Figure 2.4a. Response curves of fire occurrence to predictor variables for the period 1904–1955 with point-wise twice-standard-error curves (dotted lines).

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 sub-period (1904–1955) was population density, followed by wood harvest volume (Fig. 2.3). Livestock density and temperature had a smaller influence. During the second sub-period (1956–2006), temperature and population density most contributed to explaining fire occurrence (Fig. 2.3).

The calculation of the concurvity measures showed that there was no explicit issue due to predictor variable interactions for the two final models, 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 Figure 2.4.

The shape of the response of fire occurrence to population density was relatively similar for the two sub-periods, with a slight increase in fire occurrence from low to moderate population densities, and then a stronger increase when population density becomes higher (Fig. 2.4a and Fig. 2.4b).

During the first sub-period, the effects of livestock density and wood harvest volume on fire occurrence were rather similar, with fire occurrence decreasing slightly at lower to middle livestock densities and wood harvest volumes, and then more strongly at higher densities and volumes. In contrast, during the second sub-period, the response curves of fire occurrence to livestock densities and wood harvest volume showed a somewhat inverse pattern, with fire occurrence decreasing when livestock density was very low but increasing when wood harvest volume was very low, and then increasing when livestock density was moderate to high but decreasing when wood harvest volume was moderate to high.

Road density significantly influenced fire occurrence during the second sub-period only: fire occurrence slightly increased up to moderate road densities, but then dramatically dropped when road density was high. Fire occurrence correlated positively and almost linearly with temperature during the two sub-periods.

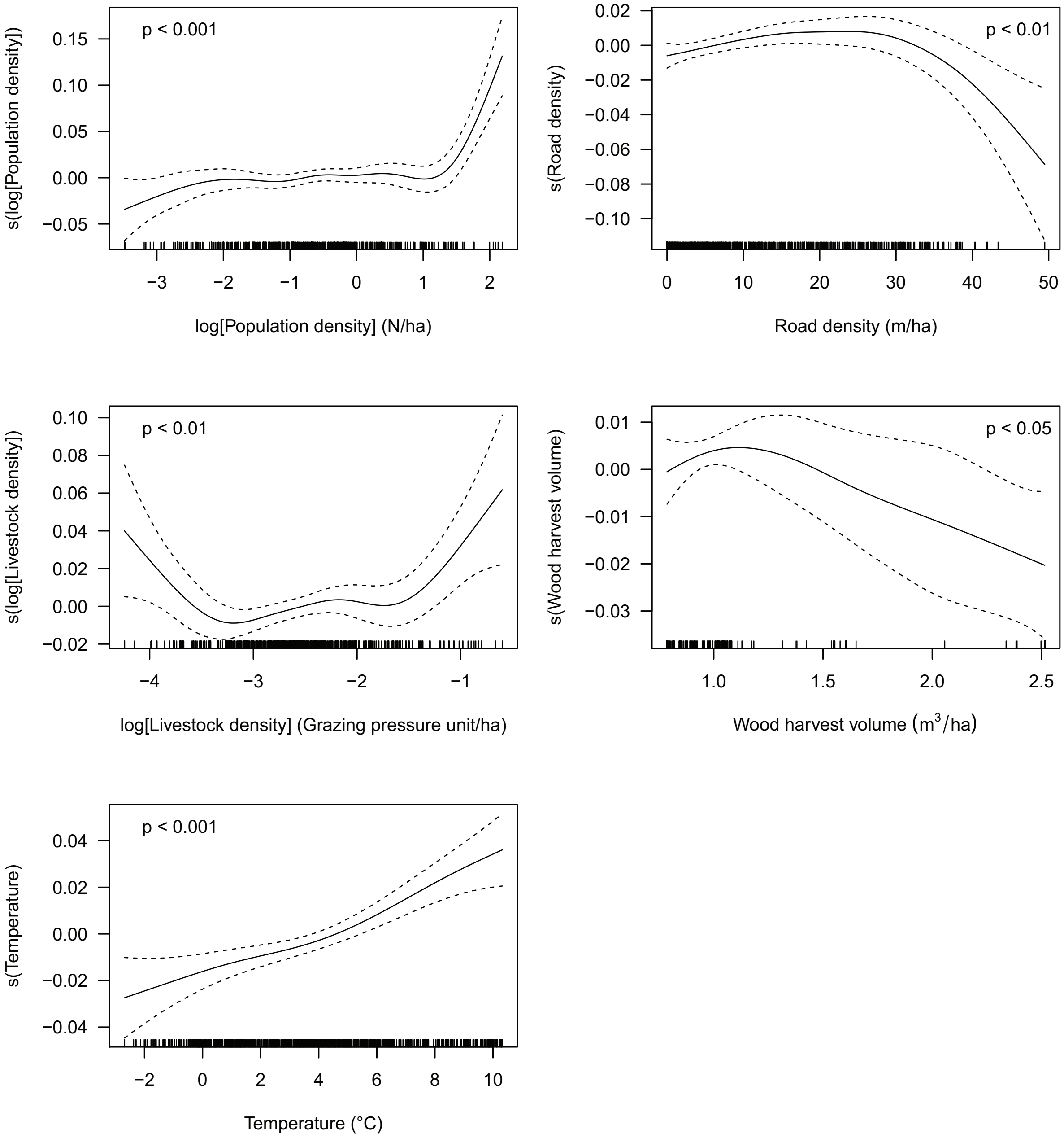

Figure 2.4b. Response curves of fire occurrence to predictor variables for the period 1956–2006 with point-wise twice-standard-error curves (dotted lines).

4 Discussion

4.1 Relevance of the individual variables

The significant positive correlation of fire occurrence with population density during both sub-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). However, the multivariate models often revealed contrasting patterns for the two sub-periods with regard to the responses of fire occurrence to anthropogenic and climatic variables, as discussed below.

During the second sub-period, fire occurrence slightly increased within the range of low to middle densities of population and roads. However, it strongly increased when population density was high but dramatically decreased when road density was high. This dichotomous pattern raises questions since high road densities are usually found where population density is high as well. The decline in fire occurrence where road density is high can be compared to the trends observed in other regions, *e.g.* in the Mediterranean, where fire occurrence decreases with higher human presence (Keeley 2005, Syphard *et al.* 2007, Syphard *et al.* 2009). 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 ignition and fire spread by diminishing fuel load and continuity (*cf.* Guyette and Dey 2000, Guyette *et al.* 2002).

As both road and population densities are hypothesized to reflect human ignition sources, a similar trend for the two variables was expected. A possible explanation for the divergent pattern may be due to the approach used for compiling the population and road data. While the exact road length was determined accurately for each grid cell, population density was determined based on data available at the municipal level only (*cf.* section 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.

We postulated that fire occurrence is controlled by fuel load in addition to the availability of ignition sources. Thus we selected two proxies, livestock grazing and wood harvest, for the assessment. Livestock density as a proxy for fine fuel removal had a significant negative influence on fire occurrence during the first period (1904–1955). This makes sense since wood pasturing was widely and intensively practiced during the first decades of the 20th century and essential for a large part of the population of Valais that depended on traditional agriculture (Loup 1965). It was still widespread up to the late 1950s (Kempf 1985, Kuonen 1993, Gimmi and Bürgi 2007), and has contributed to the elimination of large amounts of fuel. Livestock grazing is often mentioned as a potential reason for the alteration of fire frequency, the extent of burnt areas and fire intensity (Murray *et al.* 1998, Heyerdahl *et al.* 2001, Fry and Stephens 2006). Other studies have empirically linked grazing with a decline in ignitions or fire frequency due to a livestock-induced reduction of the herbaceous and/or shrubs layers (Madany and West 1983, Zimmerman and Neuenschwander 1984, Irwin *et al.* 1994). Our findings generally are in agreement with these studies.

The response curve of fire occurrence to livestock density during the period 1956–2006 is entirely different from that observed for the period 1904–1955. Fire occurrence initially decreased within the range of low livestock densities but with higher livestock densities, more fires occurred. Thus this only partially agrees with our hypothesis that increasing livestock densities should be related to a decreasing fire occurrence due to fuel load removal. During the period 1956–2006, higher densities probably did not lead to much biomass removal because a constant decline in the number of "grazing-units" started at the end of the 1930s (Gimmi *et al.* 2008), and laws and regulations prohibiting wood pasturing were introduced that resulted in livestock being largely excluded from forested areas (Stuber and Bürgi 2001).

Wood harvest volume was, similar to livestock density, negatively correlated with fire occurrence during the first period (1904–1955), and, to a lesser extent, during the second period (1956–2006). This confirms our assumption 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. Thus these findings are consistent with the literature where fuel reduction measures, *e.g.* prescribed burning or sylvicultural treatments, are said to mitigate fire potential (Martin *et al.* 1989, Rummer *et al.* 2003, Agee and Skinner 2005, Skog *et al.* 2006).

Temperature had a small explanatory power during the first sub-period compared to anthropogenic proxies. In contrast, this variable accounted for a substantial part of the explained variance in the 1956–2006 model. A potential explanation for this difference may be the shift of fire activity towards the lowlands over the 20th 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 sub-period were distributed rather uniformly over the study area, while they were concentrated at lower elevations during the second sub-period. Because temperature correlates strongly with altitude, this implies that the temperature signal may have been attenuated during the first sub-period because many fires occurred at elevations where mean annual temperature is *a priori* less appropriate for fire occurrence than at lower elevations. Although temperature was significantly associated with fire occurrence in both sub-periods, it becomes apparent that the relationship between climate and fire occurrence cannot be simply addressed without considering the human context.

4.2 Changes in the relative importance of drivers of fire occurrence (1904-1955 vs. 1956-2006)

Our findings suggest that (1) the relative importance of the variables influencing fire occurrence has changed over the past hundred years, and (2) different fire contexts may be distinguished. Substantial biomass removal occurred in forests during the first half of the study period because at that time the economy depended strongly on traditional agriculture. The local population used the forest for timber and other purposes such as forest grazing, litter raking, firewood collecting and timber extraction (Kempf and Scherrer 1982, Gimmi *et al.* 2008). Around the mid-20th century, 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 forest practices (Elsasser 1984, Kempf 1985, Gimmi and Bürgi 2007). Consequently, biomass removal diminished considerably after the 1950s, causing fuel build-up (*cf.* section 4.1).

Parallel to the fuel build-up, temperature increased (Bader and Bantle 2004). Zumbrunnen *et al.* (2009) suggested that during the first period (1904–1955), when fuels in forests were scarce, the factor that influenced the occurrence of fire most was climate: the years with most fires were the driest and warmer years. However, during the subsequent period (~1955–2006), the years with a high number of fires and/or large fires were noticeably less dry than during the first period, suggesting the emergence of a controlling factor other than climate, which could possibly be fuel load. Fuel removal by humans seems to have played a significant role in reducing fire occurrence during the first decades of the study period (1904–1955). It is not, however, possible to prove directly with our data that fuel load played a more decisive role than climate during the second half of the study period (1956–2006), since our data are proxies for fuel removal rather than for fuel presence. However, we suggest that if fuel removal causes fire occurrence to decrease, as our results indicate, then an increase in fuel load should make fire occurrence more likely. We can then conjecture that 1904–1955 was a period of fuel scarcity and moderate fire weather, where fire occurrence was most influenced by the occurrence of severe drought periods. During the second period (1956–2006), fuel was more abundant and appropriate fire weather more frequent. The critical conditions for fire occurrence during this period were the existence of an ignition source, as dry fuels were available relatively often.

5 Conclusions

This study shows that human factors have played a key role in shaping fire occurrence in Valais during the past 100 years, as people tend to be involved not only in starting fires but also in removing biomass via various land use practices. Our analyses of two different time periods suggest that land use, and thus the socioeconomic context, greatly influences fire occurrence. Changes in forest use and forest management within the study region seem to be particularly important.

Our findings suggest that fuel load is a relevant driver of the fire regime in Valais. 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 current context of anthropogenic climate change and the prevention of natural hazards.

The climate in regions such as Valais and the European Alps as a whole is likely to become warmer and drier (Schär *et al.* 2004), and agricultural land is increasingly abandoned, particularly in remote or inaccessible areas (Gellrich 2006). Fire risk is likely to increase in such areas, as well as in areas situated at the wildland-urban interface. However, anthropogenic ignitions may well drop where population and road densities are high, thus counterbalancing the effects of fuel build-up and climate warming. Furthermore, the example of the neighboring canton Ticino shows that coping with intensifying fire activity 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). 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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Chapter 3

Weather and human impacts on forest fires – 100 years of fire history in two climatic regions of Switzerland

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Abstract

Understanding the factors driving past fire regimes is crucial in the context of global change as a basis for predicting future changes. In this study, we aimed to identify the impact of climate and human activities on fire occurrence in the most fire-prone regions of Switzerland. We considered forest fires, land use and meteorological data over the period 1904-2008 in the neighboring mountain cantons (states) of Valais and Ticino, which are characterized by distinct climatic regimes. The presence/absence of fire ignitions was analyzed using the Nesterov ignition index (as a proxy for fire weather), road density (for ignition sources), livestock density (for biomass removal), and change in forest area (for fire-prone abandoned agricultural areas). We found that fire weather played a key role in fire occurrence in both regions. Road and livestock densities had similar influences in the two cantons. However, while the increase in forest area was well correlated with fire occurrence in Ticino, no such correlation was evident in Valais, probably because land abandonment and forest cover change have been less extensive there. Our findings emphasize the nonlinear nature of the relationships between fire occurrence and anthropogenic drivers, as we found thresholds above which road density was no longer correlated with fire occurrence. This implies that the projected future increase and spatial concentration of the human population may not result in a further increase in fire risk in intermediately to densely populated areas in both cantons. The driving factors behind fire activity differ slightly in the two cantons, in particular with increasing forest area enhancing fire occurrence in Ticino but not in Valais. These differences should be taken into account when assessing future fire risk, especially in Valais where the potential for an increase in the fire-prone area is still high. Fires are likely to become more frequent in a warmer climate, but future fire activity may develop differently in the two cantons. This should be taken into account when planning optimized fire prevention measures. This case study should help to better understand fire activity in highly populated regions where fire activity is still moderate but might markedly increase under a projected more fire-prone climate.

1 Introduction

Forest fires are a natural disturbance and a potentially major hazard in many regions of the world. They shape species composition and the spatial pattern of vegetation cover, as well as pose a threat to humans (Patterson and Backman 1988, Pyne *et al.* 1996, Frelich 2002, Bowman *et al.* 2009). In many regions, fire regimes, defined as the frequency, spatial extent, seasonality and intensity of fires in a given area, have undergone considerable changes during the past decades, in particular through increases in fire frequency and burnt area, and an extension of the fire season (Moreno *et al.* 1998, Westerling *et al.* 2006). As forest fires represent a risk for humans and have a strong impact on ecosystems, these changes call for scientists and managers to adapt their standards and strategies based on sound knowledge. Thus, it is essential to identify and disentangle the factors that influence fire regimes.

The factors influencing fire regimes range from biotic to abiotic, and affect small to large scales (Cardille *et al.* 2001, Moritz *et al.* 2005). Climate and weather are decisive drivers of fire activity, *e.g.* through high temperatures, low precipitation, wind occurrence and lightning (Agee 1993, Granström 1993, Pyne *et al.* 1996). They may also enhance biomass production and therefore increase the fuel load (Kitzberger *et al.* 1997, Clark *et al.* 2002). Temporal variations in climate have been found to affect fire activity in the long-term and on subcontinental scales (*e.g.* Swetnam and Betancourt 1990, Swetnam 1993), but the impact of particular climatic variables may differ greatly according to geographical region and ecosystem type. For example, in some boreal forests in eastern Canada, drought has been found to have a strong influence on fire frequency (Carcaillet *et al.* 2001), whereas there appears to be no correlation between drought intensity and fire frequency in some *Pinus ponderosa* forests in California (Fry and Stephens 2006).

Non-climatic factors may also play a considerable role in shaping fire regimes. For instance, fire spread may be influenced by topography, fire intensity by fuel load, and ignition rates by human population densities (Susmel 1973, Pyne *et al.* 1996, Omi 2005). Amongst the non-climatic factors, anthropogenic ones in particular affect fire activity. They include human demographic patterns and activities, especially land use and fire management (*cf.* Chuvieco *et al.* 2008, Marlon *et al.* 2008). Humans can directly ignite and suppress fires. They can also indirectly promote or restrain them, *e.g.* by modifying landscape patterns, forest composition or fuel amounts. For example, the settlement of Europeans in North America induced dramatic changes in local fire regimes (*cf.* Hessburg and Agee 2003). Likewise, some fire suppression measures are thought to have led to longer fire rotations and thus an increase in fuel loads, resulting in more intense fires (Minnich 1983, Fulé *et al.* 1997, Minnich 2001, Cleland *et al.* 2004). Forest pasturing, in contrast, tends to promote fire exclusion through fuel consumption and hence decreases in fire rotations and intensities (Murray *et al.* 1998, Heyerdahl *et al.* 2001, Hessburg *et al.* 2005). Lastly, substantial changes in fire frequency have been found to be linked with changes in human population densities in North America and Europe (Niklasson and Granström 2000, Keeley and Fotheringham 2001, Guyette *et al.* 2002, Wallenius *et al.* 2004).

It is quite likely that wildfires have contributed considerably to shaping the vegetation in some parts of Switzerland. For example, several forest associations or individual species such as mixed *Abies alba* forests, *Ulmus* spp. and *Tilia* spp. have regressed or disappeared in the Alps due to fire pressure, while some tree species adapted to fire in continental regions where wildfires were rather frequent in the past (Keller *et al.* 2002, Tinner *et al.* 2005). Furthermore, there is evidence of human control on fire frequency through agricultural activities during long periods of the Holocene in the Swiss Alps (Tinner *et al.* 1999, Gobet *et al.* 2003, Stähli *et al.* 2006).

The cantons (states) of Valais and Ticino, two neighboring mountain areas in southern Switzerland, are the regions that are currently most strongly affected by forest fires in Switzerland (Fig. 3.1). While Valais is characterized by a dry continental climate, warm and humid conditions prevail in Ticino. Both have fire regimes that are moderate compared with other areas in Europe or America. However, they are located on the edge of the Southern Alps and of the Mediterranean basin, which already today experience a substantial fire activity (Vélez 1997, Bovio 2000) that may well expand under a future warmer climate (IPCC 2007). Thus, an investigation of the fire regimes in Ticino and Valais should be particularly interesting given the changing climate and changes in land-use practices. As in many other parts of the European Alps, Valais and Ticino have both experienced noticeable increases in temperature and frequency of drought periods as well as major changes in the socio-economy and land cover/use, which are likely to become more pronounced in the future (Rebetez 1999, Mather and Fairbairn 2000, Zierl 2003, Bader and Bantle 2004, Johann 2004, Rebetez and Dobbertin 2004, Reinhard *et al.* 2005, Gellrich 2006). Moreover, it has been forecast that there will be substantial changes in the fire regime in the European Alps with the projected future climate (Schumacher and Bugmann 2006).

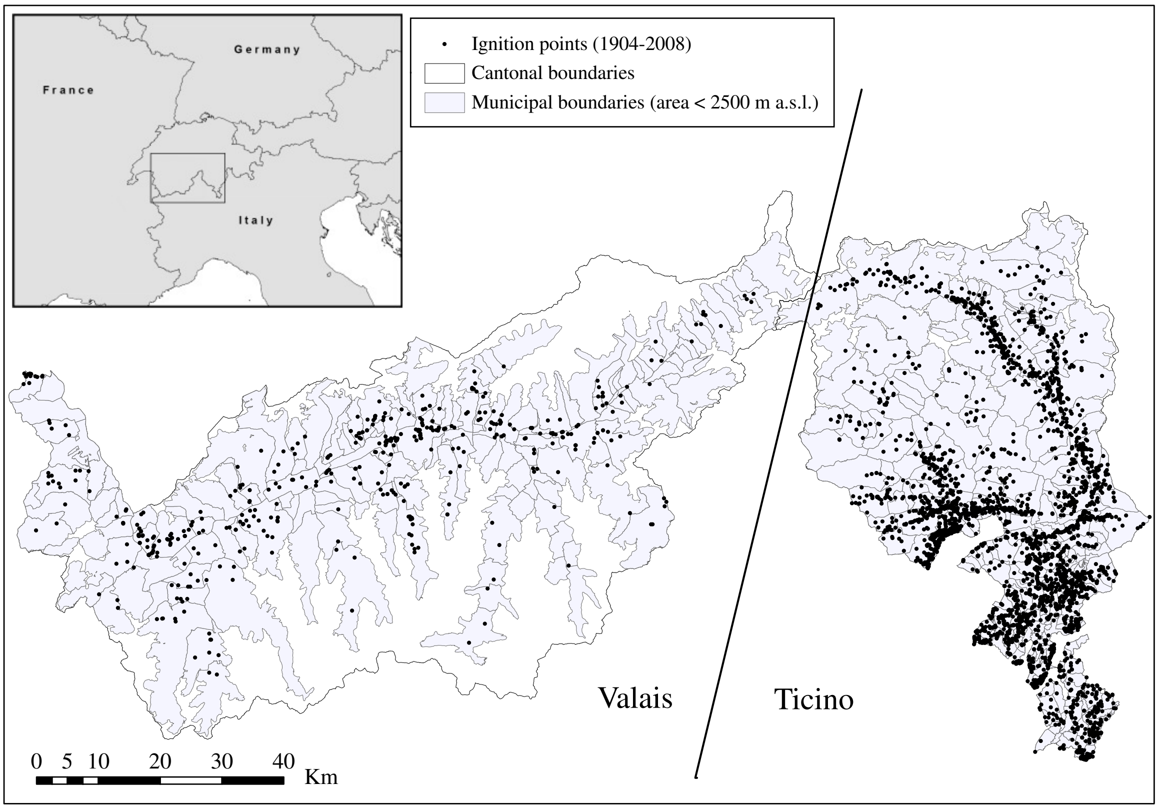

Figure 3.1. Study region (Valais and Ticino) with cantonal and municipal (< 2500 m a.s.l.) boundaries, as well as ignition points of all documented fires with information on the starting date with at least daily accuracy in Valais (n=533) and in Ticino (n=5640) for the period 1904-2008. *Source of administrative boundaries:* Swisstopo.

Few studies have analyzed fire regimes in the European Alps on a regional scale, and these have only covered periods of two or three decades (*e.g.* Buresti and Sulli 1983, Cesti and Cerise 1992). For Valais and Ticino, fire regimes have been documented for the entire 20th century (Conedera *et al.* 1996a, Pezzatti *et al.* 2005, Gimmi *et al.* 2004, Zumbrunnen *et al.* 2009), but the influence of meteorological and anthropogenic driving factors on fire occurrence, which we define as the ignition of fires, has been investigated for the recent decades only (*cf.* Weibel 2009). Investigating the relationships between fire occurrence and its driving factors over a larger period should allow us to better capture the variability of this system. Thus, this should help to provide a more complete picture of fire activity in our study regions, and to determine possible changes in the long-term.

Thus, the goal of the present study was to identify the impact of climate and humans on fire activity in Valais and Ticino during a period of more than a century, i.e. from 1904 to 2008. We focused our analyses on fire occurrence, i.e. one specific part of the fire regime. We investigated to what extent meteorological drought and human factors, such as ignition and biomass removal, influenced fire occurrence in these two regions. Moreover, how fire occurrence is controlled tends to differ in regions, since each region has its own fire history (Lefort *et al.* 2003). It has been found difficult to transpose fire models from Ticino to Valais and vice-versa, probably because their climate and patterns of land cover/use are very different (Weibel 2009). Therefore, we compared the driving factors underlying fire occurrence in the two cantons.

Our study region is located in a transition zone between regions characterized by a high fire activity and regions where forest fires are almost absent today. Thus the present study should be a contribution to a better understanding of – and dealing with – fire activity in regions where forest fires are little investigated because they are not currently considered as a key disturbance or hazard.

2 Material and methods

2.1 Study area

Canton Valais is a large inner-alpine valley in the western Swiss Alps borders of France (in the West, Italy (South), and the Cantons of Bern (North) and Ticino (East; Fig. 3.1). It consists of one main valley oriented along an east-west axis with many side valleys. About half its area of 5200 km^2 is covered by glaciers and rocks (BFS 2009). It has a continental climate, i.e. 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). Sometimes the south Foehn occurs, a dry katabatic wind with strong gusts coming down from the northern slopes of the crest of the Alps (Ficker and De Rudder 1943, Bouët 1972, Kuhn 1989).

In contrast to the inner-alpine Valais, Canton Ticino is a mountain region located on the southern side of the Alps, surrounded by Italy in the East, South and West (Fig. 3.1). It covers 2700 km^2, of which about 16 % are unproductive areas without vegetation (BFS 2009). Since it is South of the Alps, an insubrian climate prevails, characterized by high annual precipitation (*e.g.* 1668 mm in Locarno, 366 m a.s.l.), dry and mild winters, wet and warm summers, and a moderate temperature amplitude (Rebetez 1999, BFS 2009, MeteoSwiss 2009). It experiences the North Foehn, which has the same properties as the South Foehn in Valais, but it blows down from the southern slopes of the Alps (Ambrosetti *et al.* 2005).

Forest area has increased over the past century in both Valais and Ticino due to strong protection measures and the decline in agricultural activities in less productive and/or more remote areas (Walther and Julen 1986, Kuonen 1993, Bebi and Baur 2002). While forest area in Valais amounted to about 73,000 hectares (28 % of the total productive area) at the beginning of the 20th century, forests today cover approximately 110,000 hectares (42 %; Ritzmann-Blickenstorfer 1996, BFS 2000). In Ticino, forests covered about 73,000 hectares (27 % of the total productive area) at the beginning of the 20th century and about 142,000 hectares (52 %) at the beginning of the 21st century (Ritzmann-Blickenstorfer 1996, BFS 2002).

2.2 Fire regimes

Fire regimes are distinct in both cantons, with much more fire activity in Ticino than in Valais (Fig. 3.1). For the period 1904-2008, the median fire frequency in Ticino was about 1.6 fires per 100 km^2 (of the area located below 2500 m a.s.l., which corresponds to maximum treeline elevation) per year, whereas in Valais it was only 0.18. The median annual burnt area in Ticino was 12.7 ha per 100 km^2 per year, but in Valais only 0.18. Similarly in Ticino, the median fire size was 1 ha, but only 0.1 ha in Valais for the period 1904-2008 (Swiss Fire Database; WSL 2008). Fire frequency in Ticino greatly increased at the beginning of the 1960s and decreased at the beginning of the 1990s. In Valais, fire frequency has remained relatively constant with a strong peak during the 1990s. Burnt area slightly increased in Ticino from 1960 to the late 1970s. In Valais, from the late 1970s to the present there have been some years when fires resulted in extremely large burnt areas. Fire seasonality differs in the two regions. While most fires occur in Ticino between December and April with a peak in March-April, the fire season in Valais lasts from March to September, with peaks in March-April and July-August (Conedera *et al.* 1996a, Zumbrunnen *et al.* 2009, Pezzatti *et al.* subm.).

2.3 Conceptual framework

We based our analysis on an *a priori* conceptual framework for analyzing the potential impact of humans and weather on fire occurrence (Fig. 3.2). We assumed that the most important drivers shaping fire occurrence were ignition, fuel load and fire weather, as these have been generally described in the literature (*cf.* Countryman 1972, Agee 1993, Pyne *et al.* 1996, Moritz *et al.* 2005). Forests in many regions in Europe and America have been under strong anthropogenic pressure for centuries (Foster 1992, Bürgi *et al.* 2000, Hessburg and Agee 2003, Schelhaas *et al.* 2003), as have forests in Ticino and Valais (Kuonen 1993, Stuber and Bürgi 2001, Gimmi 2006). This implies that human activities are likely to affect the fire regime, which is why we used anthropogenic proxies to assess the influence of ignition sources and fuel load on fire occurrence (Fig. 3.2).

To assess changes in potential ignition sources, we chose as proxies the densities of roads and of the human population. Road density provides an indication of forest accessibility and has been found to be related to the frequency of anthropogenic fire ignitions (Franklin and Forman 1987). Forest accessibility in Ticino and Valais depends strongly on the road network due to the steepness and roughness of the terrain. Similarly, we chose population density to quantify ignition sources because most fires in the study regions with known causes were initiated by humans, i.e. about 93% in Ticino and 85% in Valais (Conedera *et al.* 2006, Zumbrunnen *et al.* 2009).

To assess fuel load, we selected proxies that provide indications of biomass removal due to human activities and the presence of easily flammable fuels. Livestock density is an indicator of overall forage and litter removal, since livestock, mainly cattle, goats and sheep, have been grazing in forests and their surroundings for centuries. They contributed to the reduction of the herb layer and the forest understory, and hence to the removal of considerable amounts of fuel during the 20th century. Moreover, providing forage and litter for all kinds of livestock meant removing sizeable quantities of biomass (Stuber and Bürgi 2001, Gimmi and Bürgi 2007, Gimmi *et al.* 2008). We also assumed that the early forest succession stages, i.e. when shrubs and coppices colonize open land, are particularly prone to ignition (Moreira *et al.* 2001, Mouillot *et al.* 2003). Thus, we selected the change in forest area as a proxy for the availability of easily flammable fuels.

Weather is also a key factor. Particularly drought intensity has been found to be related to fire occurrence (*e.g.* Clark 1988, 1989, Veblen *et al.* 1999), as it influences fuel moisture (Renkin and Despain 1992, Kunkel 2001). Weather conditions are especially important on short time scales, i.e. daily conditions (Bessie and Johnson 1995). We therefore decided to use a fire index with a daily resolution to capture the differences in fuel moisture on small temporal scales within the study area.

For methodological reasons, we chose not to consider some biophysical variables that are co-determining fire occurrence. For instance, vegetation composition was not included in the analysis simply because spatially explicit historical vegetation data were unavailable for the entire study period. Topographical characteristics such as slope and aspect were not included because a substantial part of the fire data were available on a municipal spatial resolution only, i.e. we know that a fire occurred in a certain municipality without having the precise geographical coordinates (*cf.* Fig. 3.1 and section 2.6). As many municipalities are relatively large polygons located in highly complex mountain terrain, it was not possible to assign reliable elevation or aspect values to the individual fires.

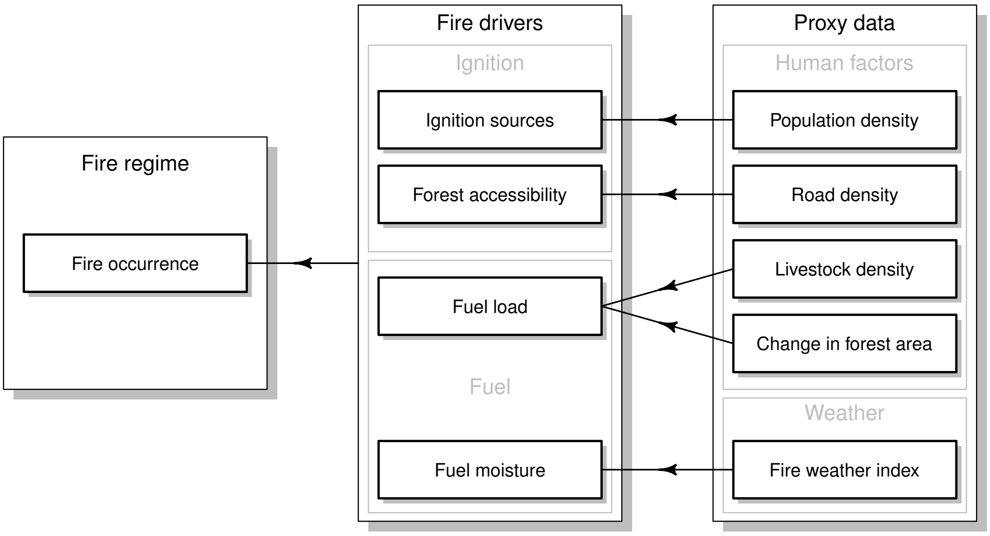

Figure 3.2. Conceptual model of the potential impact of human factors and weather on fire occurrence related to ignition and fuel conditions.

2.4 Selection of a fire index

Many fire weather indices have been developed to predict forest fires (*cf.* Haines *et al.* 1983, Viegas *et al.* 1999). To select an appropriate index to include in our analysis in addition to the non-climatic predictors (*cf.* section 2.3), we compared five daily indices: the Munger index (Munger 1916), the Nesterov ignition index (Nesterov 1949), the Keetch-Byram drought index (KBDI; Keetch and Byram 1968), the Angström index (*cf.* Chandler *et al.* 1983) and the Fuel moisture index (FMI; Sharples *et al.* 2009). These indices were chosen as they involve a simple calculation procedure and input data requirement, and have been used in earlier studies (*cf.* Reineking *et al.* 2010).

2.5 Data compilation

To evaluate the impact of humans and weather on fire occurrence according to the conceptual framework (*cf.* Fig. 3.2), we compiled the following data for the period 1904-2008 (Table 3.1): fire events, human population density, road coverage, change in forest area, livestock density, and meteorological data related to the fire weather indices.

The fire record data were taken from existing forest fire inventories and studies for the cantons of Ticino (Pezzatti *et al.* 2005) and Valais (Zumbrunnen *et al.* 2009) available on the Swiss Fire Data Base (*cf.* WSL 2008). It contains records of 5643 fires for the 20th and early 21st centuries in Ticino, and 914 fires in Valais. We only kept records of fire events where information about the geographical coordinates was available at least at the municipal level and about the starting date at least on a daily basis (*cf.* Fig 3.1; Ticino: n=5640, Valais: n=533).

The human population data were taken from the federal statistics (BFS 2008), and the road density data were obtained by digitizing the road network from national maps (Siegfriedkarte first edition, and Swiss national maps 1:100,000; *cf.* Table 3.1). The forest area data were obtained using the same procedure as for road density, i.e. by digitizing the forest area given in national maps (Siegfriedkarte first edition, and Swiss national maps 1:50,000; *cf.* Table 3.1). As we focused on increases or decreases in forest area rather than the forest area itself, we calculated time series consisting of the relative change (%) in forest area during the ten years preceding the actual observation. Livestock data were determined from federal and cantonal statistics to take into account the potential impact of overall biomass removal (i.e. grazing, forage and litter) on fire activity. We determined, from the official statistics (livestock censuses), the numbers of each type of livestock, i.e. cattle, goats, sheep, horses, mules and pigs. We then converted these figures into Livestock Units (LU; Fig. 3.3) based on the conversion factors proposed by FAO (2003) to determine the total food demand by livestock in our study areas.

The meteorological data for calculating the fire indices were provided by the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss). Daily data from two meteorological stations, one in each canton under study, are available for the entire study period (temperature, precipitation and relative humidity): Sion (Valais, 46°13.1'N/7°19.8'E) and Lugano (Ticino, 46°0.3'N/8°57.6'E).

2.6 Data resolution

All the data were designed to be analyzed on a municipal spatial resolution (*cf.* Fig. 3.1), and most of them were available in this form, i.e. fire occurrence, human population density, road coverage, change in forest area, and livestock density (Table 3.1). Meteorological data were, however, only available at the cantonal level, and we therefore attributed the corresponding value for the canton to all municipalities in that canton. Since weather conditions are synoptic, assigning the same index values to the municipalities in the same canton should not be problematic. For spatially explicit data, such as road coverage and forest area, only the area below 2500 m a.s.l. was considered, as it corresponds roughly to maximum treeline elevation in Valais and Ticino. Above that altitude, the climate is cold-wet in both cantons, which means that forests and woody vegetation are hardly found, and fires are unlikely to occur. As municipalities differ in size, all data were standardized according to the area <2500 m a.s.l. in the respective municipality.

The data were analyzed using a daily resolution where possible, but only the meteorological data were all available at this resolution (Table 3.1). The other data were available on a decennial resolution (population and livestock density), or on coarser and irregular resolutions (road coverage and forest area). Therefore, we interpolated between the known values to obtain the missing daily values. We assumed that these differences in time resolution between the meteorological and non-meteorological data would not be problematic as changes in ignition sources and fuel conditions take place much more slowly than changes in fuel moisture.

Table 3.1. Characteristics of the variables used in the models.

Variable	Unit	Original spatial resolution	Original temporal resolution	Source
Fire occurrence	Absence/presence	Municipal level	Daily	Forest service reports
Population density	Inhabitants/ha	Municipal level	Decennial	Federal statistics
Road density	m/ha	Municipal level	Tree points in time (~1890, 1960, 2002)	Siegfriedatlas and Swiss national maps 1:100'000 (Swisstopo)
Forest area (change in forest area)	ha (percent)	Municipal level	Tree points in time (~1890, 1970, 2002)	Siegfriedatlas and Swiss national maps 1:50'000 (Swisstopo)
Livestock density	Livestock units/ha	Municipal level	Approximately decennial	Federal and cantonal statistics
Meteorological data	-	Cantonal level	Daily	MeteoSwiss

2.7 Data analysis

To fit two statistical models, one for each canton (Ticino and Valais), a presence-absence data set (forest fire occurrence) with a spatiotemporal resolution (day · municipality) representing the response variable was used. The complete data set consisted of 6,097,968 spatiotemporal units for Valais (159 municipalities · 38,352 days) and 9,549,648 for Ticino (249 municipalities · 38,352 days). As we only had 533 fire events for Valais and 5640 for Ticino, there were a large number of spatiotemporal units without fire events. It was not technically possible to consider all these units without fires in our models, and we therefore followed the procedure proposed by Brillinger *et al.* (2003) and we randomly selected a sample of spatiotemporal units corresponding to 0.025% of all possible values (i.e. 15,245 units for Valais and 23,874 for Ticino). The number of spatiotemporal units with fire events was then subtracted from both overall sample sizes. This resulted in a sample size of "absence" points equal to 14,712 for Valais and 18,234 for Ticino. Out of all ‘absence’ points a random day and a random municipality were selected. Each randomly sampled "absence" point thus represented about 414 spatiotemporal units without fire events in Valais and 523 in Ticino. The unequal sampling probabilities of fire and non-fire events were taken into account by including an offset of $\ln(P_1/P_2)$ in the models (see *e.g.* Brillinger *et al.* 2003; Keating and Cherry 2004; Albright *et al.* 2009), where $P_1 = 1$ and $P_0 = 1/414$ for Valais and $P_0 = 1/523$ for Ticino are the inclusion probabilities of fire and non-fire events, respectively.

In a preliminary step, the binary response variable (forest fire occurrence) was related to each fire weather index (univariate models) to identify the index with the best predictive power for our models (*cf.* section 2.4). In a second (main) step, the response variable was related to the continuous environmental variables outlined in sections 2.3 and 2.5, i.e. the fire index selected in the previous phase, road density, forest area change and livestock density. Population density was excluded as it correlated strongly with road density.

A first exploratory analysis revealed that, when considering a logit link function, the main relationships between the response and the predictor variables were unlikely to be linear (multivariate models). Therefore, we decided to use generalized additive models (GAM; Hastie and Tibshirani 1990) with a logit link transformation of the response variable and binomially distributed errors to assess the relationship between the covariates and fire occurrence. Generalized additive models offer a greater flexibility than traditional generalized linear models, and have been found to be particularly useful in the field of ecological modeling (*e.g.* Yee and Mitchell 1991, Guisan and Zimmermann 2000, Guisan *et al.* 2002).

To identify possible linear relationships linking fire occurrence and certain predictors, a stepwise regression based on the Akaike information criterion (AIC; Akaike 1974) was conducted. We evaluated all possible linear and nonlinear models (i.e. with and without smoothers) for all predictor variables. The best models according to the AIC statistic were those without any linear relationship. Consequently, all predictors were smoothed in the final analyses.

The contribution of each predictor to the full model was quantified with hierarchical partitioning, using deviance explained as the performance measure (Chevan and Sutherland 1991, Mac Nally 1996).

All statistical analyses were performed using R (R version 2.9.2, R Development Core Team 2008. The generalized additive models were fitted using the gam package (R-package version 1.01, Hastie 2009).

3 Results

3.1 Comparison of fire indices

The five fire indices differed in how well they could explain fire occurrence in Ticino and Valais (Table 3.2). In Ticino, the Nesterov index was clearly better than the others ($D^2 = 0.14$), followed by the Munger index. In Valais, the FMI Index was most appropriate ($D^2 = 0.11$), followed by the Angström ($D^2=0.10$) and the Nesterov index ($D^2=0.09$). Based on these results, we opted to use the Nesterov ignition index in both Ticino and Valais since a single index for the two cantons allows the models to be compared more easily. Although the Nesterov index did not perform best in Valais, it was nevertheless chosen because none of the other indices that performed well (Munger in Ticino or Angström and FMI in Valais) provided satisfactory results in the other canton.

Table 3.2. Fire index ranking according to AIC and explained deviance (D^2).

Index	Valais		Ticino	
	AIC	D^2	AIC	D^2
Angström	4185	0.096	24683	0.054
FMI	4123	0.110	25283	0.031
KBDI	4441	0.042	25159	0.036
Munger	4439	0.041	23461	0.101
Nesterov	4232	0.086	22363	0.143

3.2 Correlation between explanatory variables

To avoid including inter-correlated predictors in the regression analysis, Pearson correlation coefficients for all combinations of predictors were calculated. Population density and road density were strongly correlated in both Ticino and Valais (r = 0.76; Table 3.3). As they both were aimed to reflect potential ignition sources (*cf.* Fig. 3.2), we decided to remove population density from our models to avoid redundancy. Livestock density was markedly correlated with road density in Ticino and with changes in forest area in Valais (r = 0.41 in both cases). The correlations between the other predictors were small and therefore unproblematic ($r \leq 0.28$).

Table 3.3. Correlation coefficients between predictors. The values on the left correspond to Ticino, and on the right to Valais. All correlations are significant at the 0.05 level.

Variable	Nesterov index	Population density	Road density	Change in forest area	Livestock density
Nesterov index	-	-	-	-	-
Population density	0.08 / 0.02	-	-	-	-
Road density	0.11 / 0.02	0.76 / 0.76	-	-	-
Change in forest area	–0.01 / 0.02	–0.06 / 0.08	–0.02 / 0.28	-	-
Livestock density	0.06 / 0.00	0.24 / 0.13	0.41 / 0.13	–0.17 / 0.41	-

3.3 Temporal variation of the explanatory variables

The explanatory variables (annually compiled raw data) showed distinct patterns over time when evaluated for the entire study area (Fig. 3.3). The timelines of the Nesterov ignition index were characterized by relatively similar patterns in Ticino and Valais. The values were generally higher in Valais than in Ticino, except for a period during the 1940s and early 1950s. Although both timelines are characterized by peaks in the 1920s, 1940s and 1990s, no noticeable increasing or decreasing tendency was found in the study period.

Road density, i.e. the proxy variable for potential ignition sources, has increased noticeably during the past 100 years in both Ticino and Valais, especially after the 1950s. It was roughly the same in both cantons at the beginning of the study period, i.e. 360 m/km^2 in Valais and 420 m/km^2 in Ticino. Road density doubled in Ticino during the study period, reaching about 780 m/km^2 at the beginning of the 21st century, and it almost quadrupled in Valais, rising to 1400 m/km^2.

The proxy variables for fuel show distinct tendencies, with livestock densities decreasing considerably in both cantons, from around 18 to 5 LU/km^2 in Ticino, and from 25 to 11 LU/km^2 in Valais. In contrast, forest area has increased greatly, especially in Ticino. Both regions experienced the greatest period of change during the 1970s and 1980s, with the forest area expanding in Valais by nearly five percent. During the same period in Ticino, however, it was even above 20 percent.

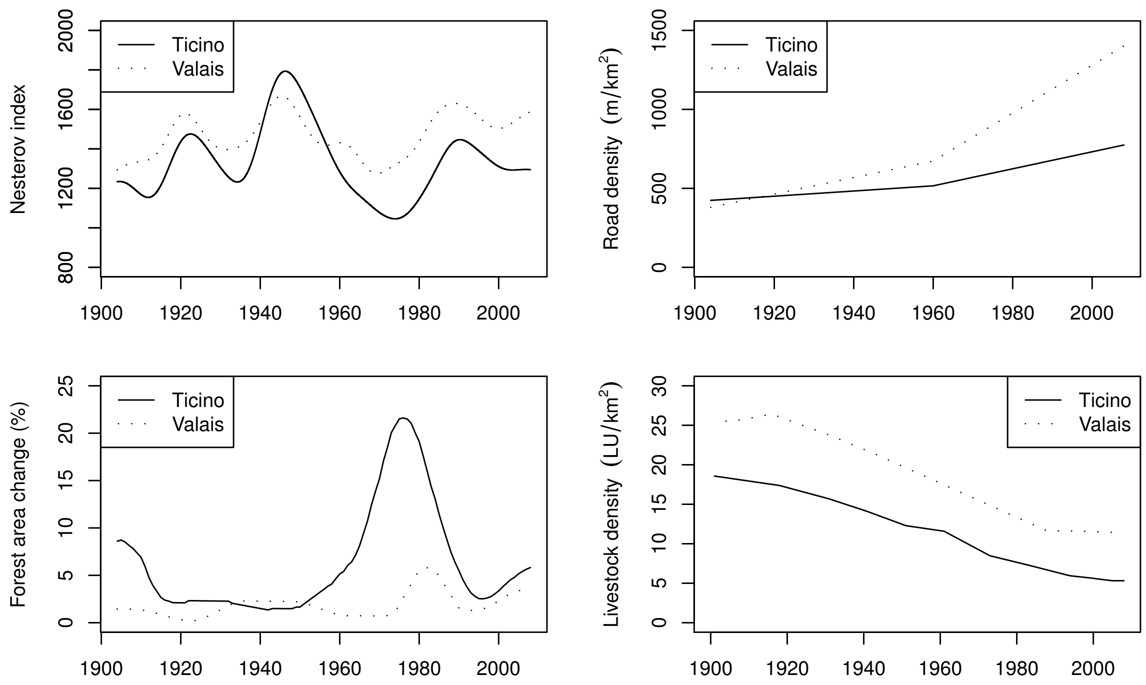

Figure 3.3. Changes in the predictors for the entire study area (Valais and Ticino) from 1904 to 2008: Nesterov ignition index (10-year moving average), road density, change in forest area (during the preceding decade), and livestock density. The reference surface for calculating the road and livestock densities corresponds to the area in the canton under 2500 m a.s.l.

3.4 Weather and human impacts on fire occurrence

The models differed in how well they could explain fire occurrence. The model for Ticino explained 31% of the total deviance, while for Valais this amounted to only 16%. When the FMI index was used instead of the Nesterov index in Valais (*cf.* section 3.1), the explained deviance increased to 18%.

All predictor variables were highly significant in both cantons ($P < 0.01$). In Ticino and Valais, the predictors contributing the most to explaining the total deviance were the Nesterov index ($D^2 = 0.14$ for Ticino and 0.08 for Valais) and road density ($D^2 = 0.13$ for Ticino and 0.06 for Valais), as illustrated by the results from hierarchical partitioning (Fig. 3.4). The overall contributions of changes in forest area and livestock density were small in Valais. A marked difference in the contribution of road density was conspicuous for Ticino when tested both alone ($D^2 = 0.16$) and in the full model ($D^2 = 0.13$).

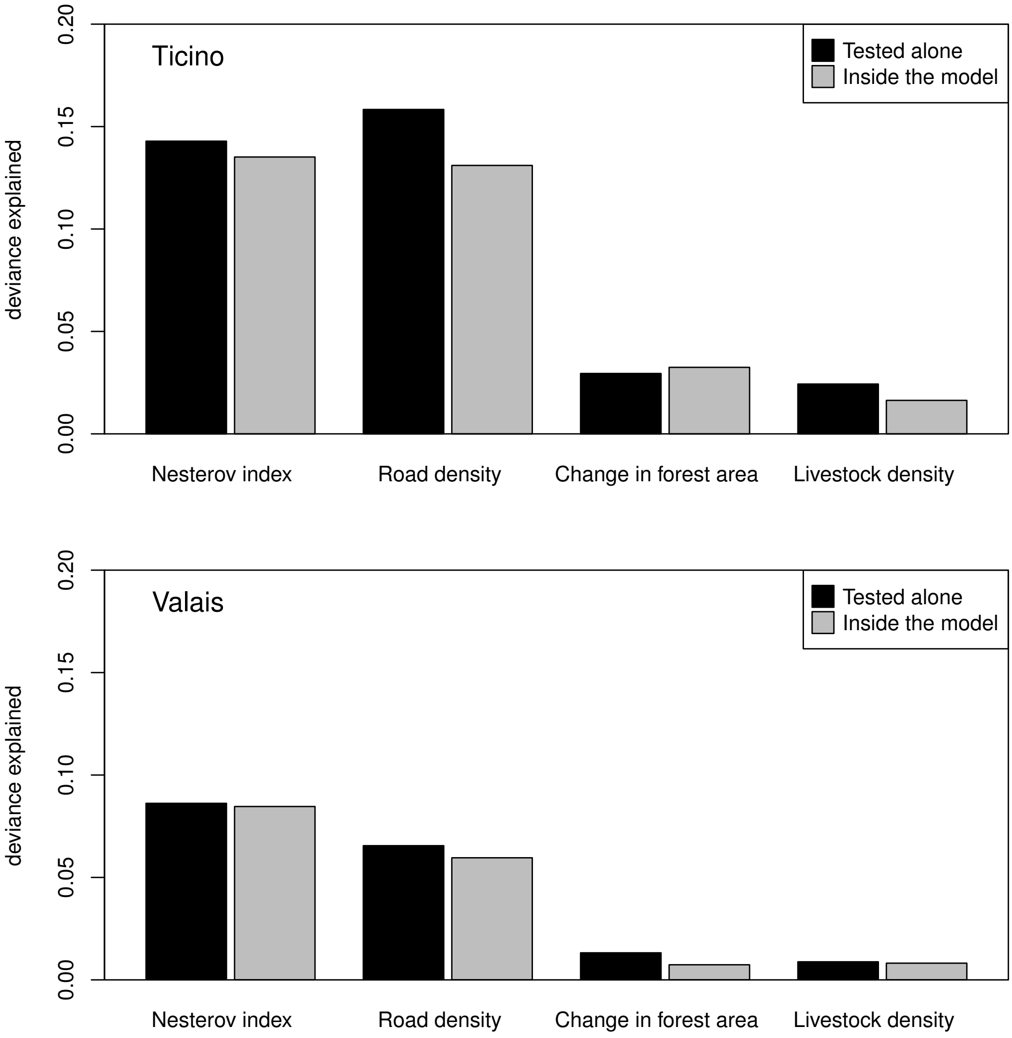

Figure 3.4. Deviance explained by each predictor when tested alone (in black) and in the full model (in gray). The relative contribution of each predictor in the full model (independent effect) was determined based on hierarchical partitioning.

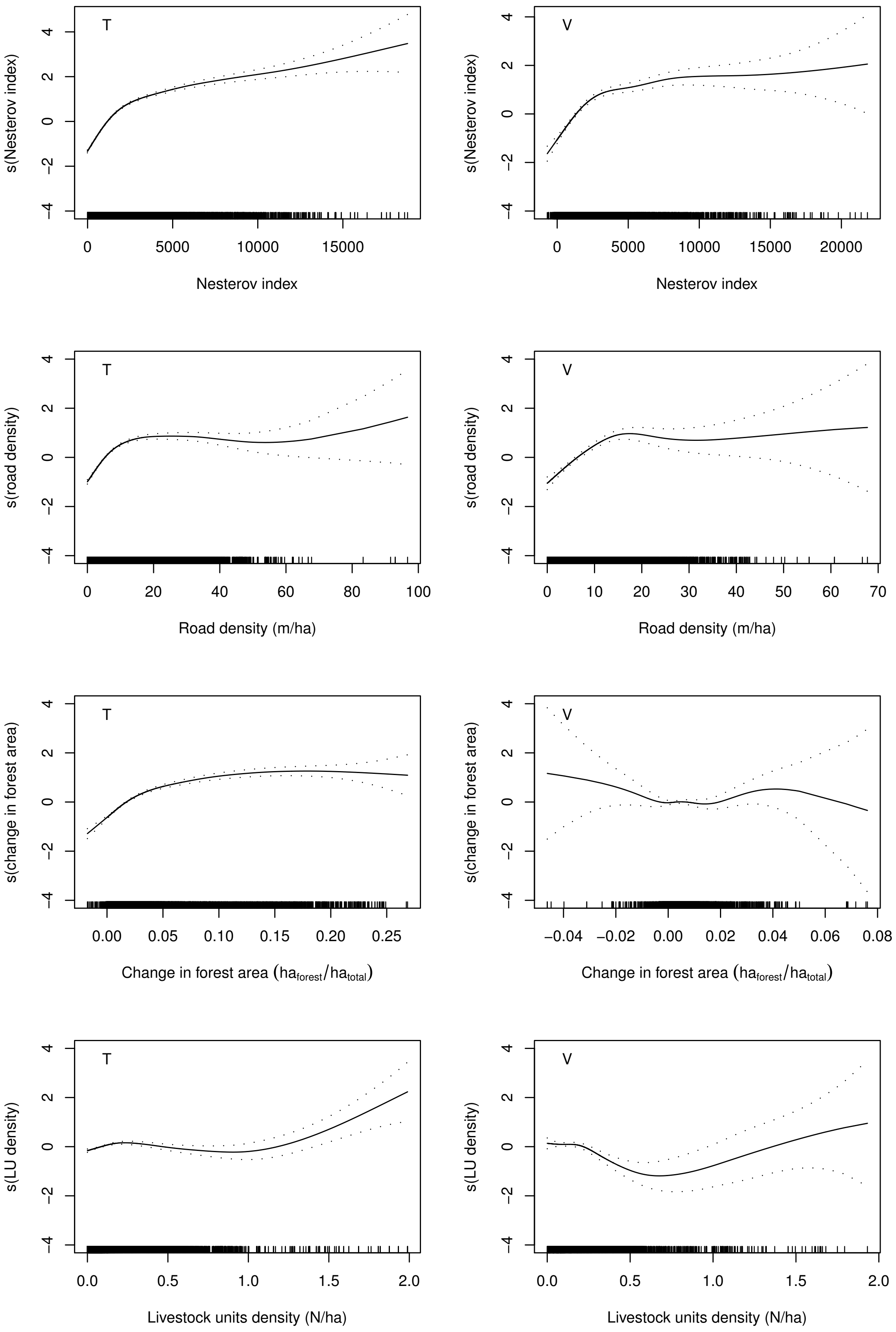

Figure 3.5. Response curves of fire occurrence to predictor variables for Ticino (T) and Valais (V) with point-wise twice-standard-error curves (dotted lines).

The shapes of the response curves of the predictors to fire occurrence showed many similarities in the two cantons (Fig. 3.5). Fire occurrence was positively correlated with the Nesterov ignition index, first increasing sharply up to an index value of 2500 and then continuing to increase but with a smaller slope. The response of fire occurrence to road density was very similar in both Ticino and Valais, correlating strongly up to about 15 m'/ha and leveling off at higher densities. We found no clear signal that could indicate that an increase in forest area in Valais affected fire occurrence, whereas in Ticino fires occurred more frequently with up to a 10 % expansion in forest area and then leveled off. The effects of livestock on fire occurrence were rather similar in both cantons, with fire occurring slightly less frequently at lower livestock densities, and increasing at higher densities.

4 Discussion

4.1 Evaluation of fire indices

Ticino and Valais are characterized by different climatic regimes, and this difference was clearly reflected by the fire index comparison, as the ranking of the fire indices according to their ability to predict fire occurrence revealed rather different results for Ticino and Valais. Overall, the index with the best predictive power was the Nesterov index, which was appropriate in Ticino and performed relatively well in Valais, too. The difference in the ranking of the fire indices for Ticino and Valais corresponds to the findings of Weibel (2009), who evaluated different fire indices in the same cantons for the period 1974-2005, and concluded that transferring fire weather models from one region to another was problematic, mainly because each canton features distinct weather conditions and forest composition (*cf.* section 2.1). The best indices identified in our study differ from Weibel's (2009), possibly because we used a longer period (1904-2008), during which weather conditions have changed. For example, temperatures have increased significantly in both Valais and Ticino. In Ticino, the increase has been primarily in winter, i.e. the fire season in this canton (Bader and Bantle 2004). Higher temperatures may have caused a shift in the relative contribution of the individual meteorological variables to the different indices, which has possibly affected their predictive power.

Forest conditions have also evolved tremendously, with much more biomass in forests since the abandonment of traditional agriculture and changes in forest management (Kempf 1985, Stuber and Bürgi 2001, Conedera *et al.* 2004, Bugmann 2005, Gimmi *et al.* 2008). The composition of the forests in Valais has changed as well, with larger areas covered by oaks and a decrease in the area covered by pines (Kienast *et al.* 2004). In Ticino, pure chestnut stands have developed towards mixed broadleaved forests (Conedera *et al.* 2001). Both phenomena are largely due to the abandonment of traditional land use practices. Thus it makes sense for indices to perform differently under different environmental conditions, which is why it cannot be assumed that indices will be easily transferable in space. Weibel (2009) concluded that a transfer of indices in time was feasible, so long as the study period was not too long. Our findings corroborate this hypothesis, suggesting that it is difficult to draw conclusions about the effects of weather on fire occurrence at the centennial time scale, particularly in regions such as Ticino and Valais where changes in socio-economic and environmental conditions have been so marked during the past century.

The nature of the most suitable fire indices identified here indicates some of the potential differences regarding fire weather in the two cantons. While the most suitable indices in Ticino (Nesterov and Munger) depend very much on a "rainfall" component in the form of the number of days since the last rainfall, this is not the case for the best indices in Valais (FMI and Angström), which only require relative humidity and temperature as input variables. In Ticino, where rainfall is very abundant and temperatures high compared to Valais (*cf.* section

2.1), this difference may emphasize the relevance for fuel moisture, and subsequently fire occurrence, of temporal rainfall distribution, especially the duration of periods with very little or no precipitation, which is decisive, as the Nesterov and Munger indices reset to zero as soon as there is non-zero precipitation (Munger 1916, Nesterov 1949). In Valais, in contrast, rainfall is scarce throughout the year, and fire occurrence probably depends less on the occurrence of marked periods without rainfall than on periods with low relative humidity and high temperature, which enhance evapotranspiration and the drying out of fuels. This difference between the cantons indicates that rainfall is a limiting factor for fire occurrence in warm-humid regions like Ticino, whereas in dry continental regions like Valais temperature is more relevant.

The Nesterov index is based on relative humidity, temperature and the number of days since the last rainfall. These three variables seem to relate to fire occurrence in both regions, which is why the Nesterov index is likely to be better at capturing the diverse affects of weather on fire occurrence in different regions than other more simple indices. The Nesterov index yielded good results in both Valais and Ticino, which are climatically fairly different regions. Other studies have also successfully implemented it in regions with very diverse climatic and vegetation conditions, such as those prevailing in Mediterranean or boreal zones (*e.g.* Stocks *et al.* 1996, Viegas *et al.* 1999, Venevsky *et al.* 2002, Groisman *et al.* 2007).

4.2 Response of fire occurrence to environmental predictors

Ticino and Valais share many similarities regarding the responses of fire occurrence to environmental factors, with all explanatory variables, except for change in forest area, showing roughly the same patterns (Fig. 3.5). The response of fire occurrence to the Nesterov index was similar in both cantons. The stabilization of the response curve around a Nesterov index value of 3000 is consistent given that values over 4000 are usually thought to indicate a high fire risk (*e.g.*, Stocks *et al.* 1996). Above this threshold, weather conditions are so favorable for fire that increasing Nesterov values are probably no longer decisive for explaining fire occurrence.

In both cantons, fire occurrence increased with increasing road density (up to approx. 15 m'/ha), but then tended to level off. Such a pattern is comparable to the one found in other regions, in particular in Mediterranean regions, where fire frequency levels off, or even decreases, with more human presence (*e.g.* Keeley 2005, Syphard *et al.* 2007, Syphard *et al.* 2009). This suggests that already with a moderate road density, the perimeter under consideration is fully accessible and thus saturated with potential ignition sources. On the other hand, this pattern may also be due to the fact that areas with high road densities often correspond to highly urbanized areas and/or land not covered by forests but rather by farmland or settlements, i.e. surfaces much less prone to fire than sparsely inhabited perimeters. These findings are thus in agreement with the theory suggesting that, in human-dominated landscapes, fire frequency is initially related to anthropogenic ignitions when landscape occupation by humans is low, but in subsequent stages when the population increases, ignitions reach saturation point. Then, more infrastructure and high-intensity land use reduce ignition and fire spread as they diminish fuel load and continuity (*cf.* Guyette and Dey 2000, Guyette *et al.* 2002).

The influence of the proxy variables for biomass was less striking than those for ignition. Livestock density had similar effects on fire occurrence in Valais and Ticino. Fire occurrence decreased with initially increasing but still low livestock densities in Valais, and remained the same in Ticino. With higher livestock densities, however, more fires occurred in both cantons. This result is only partly in agreement with our hypothesis that increasing livestock densities should be associated with a decreasing fire occurrence due to fuel load removal (*cf.* section 2.3), and goes against findings from many studies in North America and Europe (Savage and

Swetnam 1990, Irwin *et al.* 1994, Heyerdahl *et al.* 2001, Fry and Stephens 2006, Kalabokidis *et al.* 2007). This hypothesis holds for low to moderate livestock densities only, i.e. <1 LU/ha. Higher densities probably do not lead to any biomass removal, but rather indicate an increase in potential ignition sources due to more intense human activities, since high livestock densities are usually associated with industrial livestock husbandry in easily accessible areas. This interpretation is supported in Ticino, where the highest livestock densities have occurred mostly in the second half of the study period, when livestock was largely excluded from forests (Stuber and Bürgi 2001).

Although the change in forest area was significant in the models for both cantons, this variable had an increasing effect on fire occurrence only in Ticino. Thus our assumption that early forest succession stages are particularly prone to ignition was not confirmed for Valais (*cf.* section 2.3). Ticino has, however, experienced much more extensive land abandonment than Valais (Bätzing 2002, Baur 2006), and thus a much greater forest expansion (*cf.* Fig. 3.5). Moreover, the warm-humid climate of most parts of Ticino probably allows forests to expand faster than in Valais (Gellrich and Zimmermann 2007). In Valais, the increase in forest area has taken place primarily on remote and less productive former agricultural areas at high altitudes (Kempf 1985, Julen 1988, Gimmi *et al.* 2008). At those altitudes, wet and cold conditions render vegetation much less prone to fire than at lower altitudes, and ignition sources are less abundant. This may explain why the response pattern of forest area change to fire occurrence is much less clear in Valais. In Ticino, in contrast, forests have expanded most at low altitudes, in particular on steep slopes covered by hardwood stands, mainly chestnuts, which are characteristic of much of the landscape. There, climatic and fuel conditions are particularly conducive to fire (Delarze *et al.* 1992, Conedera *et al.* 1996b, Tinner *et al.* 1999). These conditions are likely to be more similar to those prevailing in Southern Europe, where a considerable correlation between fire occurrence and land abandonment/forest expansion has been observed (*cf.* Moreira *et al.* 2001, Vázquez and Moreno 2001, Mouillot *et al.* 2003), than to those prevailing in the mountain forests of Valais. We may thus interpret these different responses of fire occurrence to forest area change in the two cantons as a consequence of the distinct locations where forest expansion has mainly occurred, and thus to the distinct pyrologic environments.

4.3 Methodological considerations

The Nesterov index and road density, as well as the proxies for fuel moisture and ignition sources, were the predictors that contributed most to model performance in both cantons (Fig. 3.4). The contributions of forest area change and livestock density, i.e. the proxies for fuel load, were much smaller. It seems that fuel load per se may not be of major relevance in large areas of Ticino and Valais, especially in the coniferous forests at the subalpine level (*cf.* section 2.1). These forests share many similarities with the closed-canopy subalpine and boreal coniferous forests of North America (Ellenberg 1996, Bugmann 2001), where it has been suggested that the fire regime is mainly climate-driven, and that fuel availability basically had no limiting influence (Agee 1993, Johnson *et al.* 2001, Baker 2003, Sibold *et al.* 2006). However, the main reason for the differences in contributions of the predictor relates probably more to the level of "directness" in the relationship between the selected proxies and the fire drivers they stand for. Indeed, the Nesterov index reflects the direct influence of weather on fuel moisture, and road density reflects the number of anthropogenic ignition sources in a certain area. The impact of forest area change and livestock density on fuel load, however, is less straightforward, as expanding forests probably do not always consist of fire-prone vegetation, and livestock density does not systematically correspond to fuel removal in forests (*cf.* section 4.2). Therefore, the proxies for ignition sources and fuel moisture used here are probably more suitable for explaining fire occurrence than those used to characterize fuel load (*cf.* Fig. 3.4).

The overall explanatory power of our models is limited for several reasons. First, only four predictors were used here. 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, coarse variables. Many other meteorological, land-use, land-cover, legal and socio-economic variables would be necessary to develop a more complete understanding of the determinants of forest fires (*cf.* Chandler *et al.* 1983, Pyne *et al.* 1996, Cardille *et al.* 2001, Chuvieco *et al.* 2008). It is probably impossible to obtain reliable, temporally and spatially explicit data for a study period of more than hundred years and for a study region larger than 8,000 km^2. This constraint applies especially to weather and land-cover data (*e.g.* forest composition, fuel availability and soil types). Moreover, the natural and socio-economic environment of forest fires has changed continually over the study period (*cf.* section 4.1). Some factors are quite difficult to quantify and incorporate in a model, *e.g.* legal amendments and their impact, the environmental awareness of the local population and land-use methods. These have all evolved considerably over the past century (Stuber and Bürgi 2001, 2002, Gimmi and Bürgi 2007, Pezzatti *et al.* subm.), and most likely also affected the relationships between fire occurrence and the proxies we selected as predictors. Finally, although this is probably not the main reason for explaining the small explained deviances of our two models, using coarse, temporally interpolated (land-use) or spatially uniform (weather) data might have contributed to weakening the signal between the predictors and fire occurrence, and, as a possible consequence, slightly diminish the predictive power of the models.

The explanatory power of the models for Ticino and Valais differ greatly, with the explained deviance for Valais only half of that for Ticino. This disparity is possibly due to the poorer quality of the fire dataset in Valais. While in Ticino the entire fire dataset was available, only about 500 fires from a total of more than 900 fires could be used in Valais. The remaining fires had to be excluded from the analysis due to lack of information about ignition coordinates and time. This implies that more than 400 spatiotemporal units were defined as absence points in the model although they were in fact presence points, which probably affected the quality of the model for Valais.

5 Conclusion

In this study, we found that the response curves of fire occurrence to most predictors are similar in the two study regions, implying that the mechanisms of the controlling factors for wildfires do not differ between Valais and Ticino, despite some *a priori* contextual differences, in particular highly different climatic conditions. The only substantial divergence was found in the expansion of fire-prone areas over time: fire occurrence was positively correlated with forest area change in Ticino, but no such pattern was apparent in Valais.

The Nesterov index performed relatively well in both cantons, suggesting a similar influence of fire weather on fire occurrence. However, the suitability of this index for both cantons is an exception, as most of the fire weather indices we evaluated appeared to be rather canton-specific, probably reflecting the fact that the main meteorological factor that influences fire occurrence in Ticino, a warm-humid region, is rainfall, whereas in Valais, a dry-continental region, temperature is more important.

The present study has demonstrated the non-linear character of the relationship between fire occurrence and the selected predictors, in particular the leveling off of fire occurrence when potential anthropogenic ignition sources increase. Therefore, the projected increases in the number of inhabitants in Ticino and Valais (BFS 2007) and the associated expansion of urbanized areas and road coverage may well *not* result in more fires, except if this increase in population occurs in less-inhabited areas. The expansion of human settlements is most likely to follow the trend of the past century and take place at low elevations in the main valleys of the Alps, which are well developed and industrialized already (Bätzing 2002). In contrast, the future warming and the concomitant occurrence of drought periods in the Alps (Schär *et al.* 2004) are likely to generate more fire-prone vegetation and could thus result in more fires, especially in Valais, at middle to high elevations where there is still a considerable amount of residual marginal land on which forest expansion is possible (Gellrich 2006, Gellrich *et al.* 2007).

In both Valais and Ticino, forest fire activity represents a threat for humans and infrastructure. This threat is likely to become greater if climate changes as predicted, and this must be taken into account in future land management in these regions. In particular, the potential differences in the development of fire activity, be it between the two cantons (due to climate/forest conditions) or within each of them (in less vs. highly populated areas) needs to be considered when planning optimized and geographically specific fire prevention measures.

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Chapter 4

The forest fire regime in Valais – one century under climatic and anthropogenic influences

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Abstract

Forest fire regimes are particularly sensitive to climatic variability and anthropogenic influences. In the European Alps, fire regimes are likely to undergo considerable change due to climatic and land-use changes. The history and determinants of forest fires during the 20th century in Valais have, however, received little attention. In this study, we used descriptive statistics to assess whether the fire regime had changed over the period 1904–2008, and correlation analyses to analyze what factors might have significantly influenced the fire regime. Our findings show that fires have become more frequent in the lowlands during the 20th century, probably because population densities at low elevations have increased. Fire seasonality has also changed. While most fires occurred during summer in the first half of the study period (1904–1955), the number of spring fires clearly increased during the second half (1956–2008). However, fire frequency and annual burnt area were not significantly different during the periods prior to and after 1955. The balance between factors affecting fire frequency and burnt area has changed over the past 100 years. While drought appears to have been crucial during the first decades of the 20th century, its relative importance seems to have later diminished in favor of other factors, in particular fuel load. Where other factors besides climate influence the current fire regime, then concrete steps can be taken to diminish the risk of fire.

1 Introduction

Forest fires are a major natural disturbance and hazard in many regions of the world. They shape local species composition as well as the spatial pattern of vegetation cover, and may have considerable impact on human societies (Patterson and Backman 1988, Pyne *et al.* 1996, Frelich 2002, Bowman *et al.* 2009). In many of these regions, the fire regimes have undergone considerable change during recent decades, in particular through increases in fire frequency, burnt area and the extension of the fire season (Moreno *et al.* 1998, Westerling *et al.* 2006). This has triggered great interest in identifying and disentangling the factors driving fire regimes.

Very different biotic and abiotic factors can influence fire regimes, and may act on small, but also very large scales (Cardille *et al.* 2001, Moritz *et al.* 2005). Climate and weather are decisive drivers of fire activity, *e.g.* through high temperature, low precipitation, wind occurrence, or lightning (Agee 1993, Granström 1993, Pyne *et al.* 1996). Non-climatic drivers also play an important role in shaping fire regimes. For instance, topography may influence fire spread patterns, fuel load fire intensity, and human population densities local ignition rates (Susmel 1973, Pyne *et al.* 1996, Omi 2005). Recent studies show that, among the non-climatic factors, anthropogenic impacts on fire activity are especially important. These include human demography and activities, as well as land use and fire management (*cf.* Chuvieco *et al.* 2008, Marlon *et al.* 2008).

The fire regime in Canton Valais is rather marginal compared with other areas in Europe or America. It is located on the fringe of the Southern Alps and of the Mediterranean basin where fire activity is substantial (Conedera *et al.* 1996, Vélez 1997, Bovio 2000). Thus an investigation of the fire regime in Valais could be particularly interesting in the context of changing environmental conditions, such as global warming and land abandonment in peripheral areas, which is expected to create more fire-prone conditions. As in many other areas in the European Alps, canton Valais has experienced noticeable increases in temperatures and in the frequency of drought periods as well as major socioeconomic and land cover/use changes that are likely to continue in the future (Rebetez 1999, Mather and Fairbairn 2000, Zierl 2003, Bader and Bantle 2004, Johann 2004, Rebetez and Dobbertin 2004, Reinhard *et al.* 2005, Gellrich 2006). Moreover, substantial changes in the fire regimes in the European Alps have been predicted in projected future climate scenarios (Schumacher and Bugmann 2006).

Reconstructing the fire regime in Valais requires data on historical fire events, which can be derived from various sources. Bochatay and Moulin (2000) produced an initial forest fire inventory covering the period 1973-2000. The article published a few years later by Gimmi *et al.* (2004) extended this period to 1904-2004, and Zumbrunnen *et al.* (2009) supplemented it by localizing the ignition points precisely and providing a detailed reconstruction and analysis of the fire regime for the 20th and early 21st centuries.

In the present study we first determine whether the fire regime, which refers to fire frequency, annual burnt area and fire seasonality, has changed over the period 1904-2008 in Valais. Second, we want to assess what role the different driving factors of the fire regime, in particular climate, might have played in the regime changes found.

2 Material and methods

2.1 Temporal structure of the study

The forest fire data used in the present study were taken from the inventory of Zumbrunnen *et al.* (2009). This data collection is based on documentary evidence, mainly forest service reports, but it also includes data from previous forest fire inventories in Valais (Bochatay & Moulin 2000, Gimmi *et al.* 2004).

In order to detect changes in the fire regime during the 20th century, the first (1904–1955) and second (1956–2008) halves of the study period were compared. The rationale for this is that around the middle of the century major changes took place in socioeconomics and land use in Valais (Kempf 1985, Stuber and Bürgi 2001, Gimmi 2006). Thus we expected these two periods to be characterized by distinct pyrologic conditions. Splitting the study period allows a comparison of two periods that a priori seem relatively homogenous with respect to anthropogenic influences on the fire regime. Wilcoxon rank sum tests were then performed in order to verify whether the altitudinal distribution of fires, fire frequency and annual burnt area during the periods prior to and after 1955 were significantly different.

2.2 Determining climatic influences on the fire regime

Having identified the fire regime for the two sub-periods, we tried to determine the influence of climate on fire frequency and annual burnt area. We calculated a drought index according to Thornthwaite's (1948). The Thornthwaite index is particularly convenient because it is based just on monthly precipitation and temperature data. Moreover, it has been successfully applied in other studies of drought and forest dynamics in Valais (*e.g.* Bigler *et al.* 2006). The Thornthwaite index (DRI) is calculated by subtracting the estimated potential evapotranspiration (PET) from the annual sum of precipitation (P; $DRI = P - PET$). The calculation of potential evapotranspiration is based on temperature and takes into account day length and the angle of sun (*cf.* Thornthwaite and Mather 1957). The meteorological data to calculate this index were recorded at the meteorological station in Sion and provided by the Swiss Federal Office for Meteorology.

The relationship between fire frequency and annual burnt area, on the one hand, and the annual Thornthwaite index, on the other, was analyzed by cross-correlating (Pearson coefficient) both the annual number of fires and the burnt area, with the annual Thornthwaite index at various time lags. This correlation analysis was conducted for the entire study period, as well as for the two sub-periods, 1904–1955 and 1956–2008.

3 Results

3.1 Forest fire regime

The location of the forest fires recorded in Valais are shown for the two periods in Fig. 4.1. While most fires during the second sub-period (1956–2008) occurred at low elevations, i.e. mostly in the Rhone Valley, the fires that took place during the first sub-period (1904–1955) seem to have been distributed more uniformly over the canton, including at higher elevations. This is illustrated by the box-plots showing the altitudinal distribution of ignition points according to sub-period: the median elevation of ignition points was 1300 m a.s.l. for the period 1904–1955, and only 1000 m a.s.l. for the period 1956-2008 (Fig. 4.2). A Wilcoxon test confirms that the median elevation of ignition points was higher during the first sub-period than during the second sub-period ($p < 0.0001$).

During the whole period 1904-2008, about 2720 hectares of forest were burnt by 914 fires. During the first sub-period, the median fire frequency was six fires per year, and the median annual burnt area was 6.4 hectares. During the second sub-period, the median fire frequency was seven fires per year, and the median annual burnt area was 5.9 hectares (Fig. 4.3). Although the most extreme fire years occurred during the second sub-period, the median fire frequency and the annual burnt area were not significantly different during the two sub-periods, as confirmed by the Wilcoxon test (fire frequency: $p = 0.226$; annual burnt area: $p = 0.319$).

In Valais, the main fire season lasts from March until October, when approximately 90 % of all fires occur. It is characterized by a peak in March-April and another peak in July-August (Fig. 4.4). Fire seasonality during the first sub-period was distinct from that during the second sub-period. Prior to 1955, most fires took place in August, while after 1955, a seasonal distribution characterized by two peaks appeared, with more fires occurring in spring.

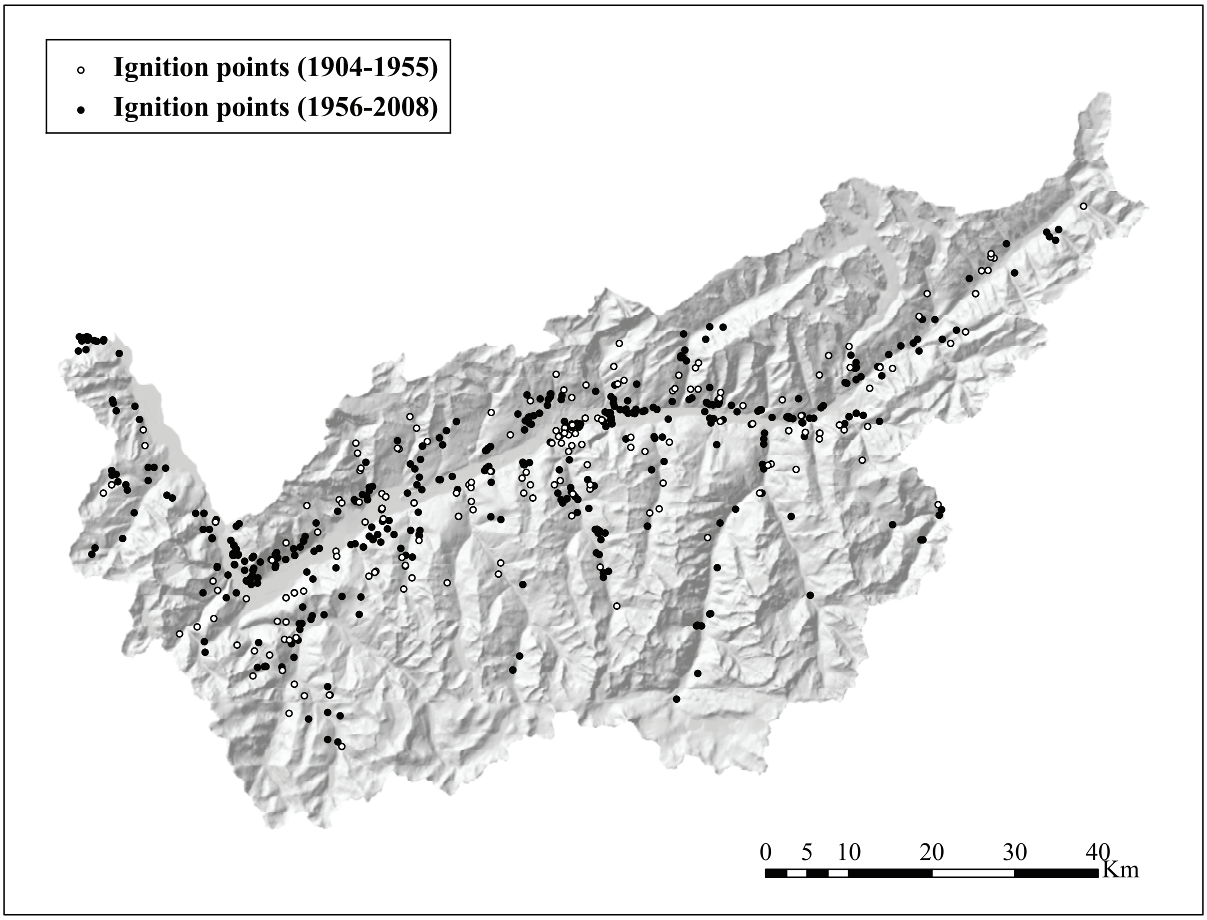

Figure 4.1. Study area (Canton Valais) and ignition points for the periods 1904–1955 (n = 186) and 1956–2008 (n = 422).

3.2 Climatic influences on the fire regime

The results of the cross-correlation analyses of the fire frequency and the annual burnt area with the Thornthwaite index revealed differences for the two sub-periods (Table 4.1). While fire frequency was significantly and negatively correlated with the Thornthwaite index of the same year during the period 1904–1955, it was not correlated anymore during the period 1956–2008. On the contrary, there was a significant and positive correlation with a time lag of three years between the fire frequency and the Thornthwaite index during the period 1956–2008. In other words, we find a significant increase in the number of fires three years after especially humid years. No such significant correlation was found for the period 1904–2005.

Table 4.1. Cross-correlations between the annual Thornthwaite index and the fire frequency / annual burnt area during different periods.

Period	Fire variable	Time lag (years prior to fire)				
		0	1	2	3	4
1904–2008	Frequency	-0.13	0.11	-0.09	**0.24***	-0.0
	Annual burnt area	-0.10	0.03	-0.07	0.02	0.07
1904–1955	Frequency	**-0.32***	0.18	-0.08	0.17	-0.11
	Annual burnt area	**-0.37***	0.22	-0.03	0.00	0.00
1956–2008	Frequency	0.01	0.00	-0.15	**0.34***	-0.05
	Annual burnt area	-0.03	-0.09	-0.06	0.04	0.01

The numbers in bold with asterisks indicate significant correlations (p<0.05)

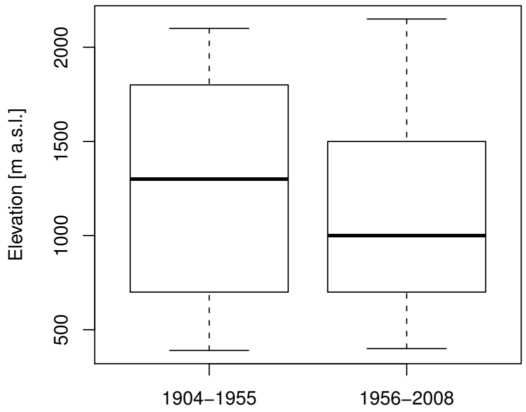

Figure 4.2. Altitudinal distribution of ignition points for the periods 1904–1955 (n = 145) and 1956–2008 (n = 382).

Figure 4.3. Fire frequency and annual burnt area distributions for the periods 1904–1955 and 1956–2008.

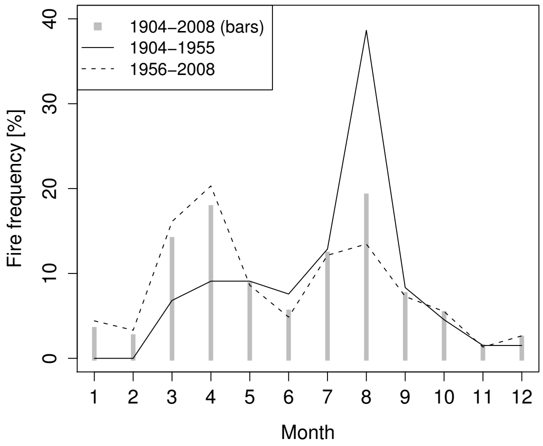

Figure 4.4. Fire seasonality for the periods 1904–2008 (*n* = 585), 1904–1955 (*n* = 132) and 1956–2008 (*n* = 453).

4 Discussion

Fire activity shifted to lower elevations between the first and the second sub-period. This change is likely due to more potential ignition sources being created at low elevations as the population and urbanized areas increased (Kempf 1985). Moreover, the number of ignition sources at higher elevations probably decreased as agriculture and forestry there declined. The gradual abandonment of the vertical seasonal migration from the lowlands to alpine pastures since the mid 20th-century has probably also played a role (Kempf 1985, Bunce *et al.* 2004, Gil Montero *et al.* in press).

The altitudinal shift of fire activity might explain the difference in fire seasonality found between the two sub-periods. The climatic regime at high elevations is prone to fires almost exclusively during summer months. Moreover, high elevation zones are usually inhabited only in summer. The increase in potential ignition sources at lower elevations has probably allowed the fire season to extend into the spring months. This hypothesis is corroborated by the fact that most spring fires where found to have started at low altitudes while most summer fires started at higher altitude (Zumbrunnen *et al.* 2009). The large number of spring fires in Valais is in line with observations made in neighboring regions, namely Ticino (Conedera *et al.* 1996) and the Val d'Aoste (Cesti and Cerise 1992). The peak in fire activity during March-April may be partly driven by the availability of more fuel at the end of winter, when large amounts of not yet decomposed litter provide an ideal fuel bed in deciduous stands that prevail at low elevations in Valais (Werlen 1994). Moreover, because of the absence of green leaves in the canopy, insolation of the forest floor is enhanced and the fuel subsequently dries out. Moreover, foehn winds tend to occur frequently at moderate to low elevations, mainly between March and May (Bouët 1972). It dries out fuels and helps to spread fires.

While fire seasonality changed over the study period in Valais, the fire frequency and the annual burnt area were similar during the first and second sub-periods despite extreme fire years (1981, 1990 and 2003, in particular). These findings are relatively unexpected given that the factors that are supposed to intensify fire activity, such as temperature, population, forest area and fuel load in forests, have markedly increased over the 20th century in the study area (Ritzmann-Blickenstorfer 1996, Bader and Bantle 2004, BFS 2008, Gimmi *et al.* 2008). Changes in these factors have caused noticeable changes in the fire regime in other regions, such as Ticino (Conedera *et al.* 1996) and the Iberian Peninsula (Moreira *et al.* 2001, Pausas 2004). In Valais, it is possible that the introduction of several regulations for fire prevention (Pezzatti *et al.* subm.), and improvements in fire-fighting material and methods (Gimmi *et al.* 2004) have counterbalanced the "aggravating" effects of these factors on the frequency of fires and the burnt area.

Although fire frequency and annual burnt area did not significantly differ during the first and second sub-periods, the direct relationship between these two variables and climate, which is reflected here by the Thornthwaite index, changed. During the first sub-period, the fire variables were both significantly and negatively correlated with the index for the same year, i.e. the drier the climatic conditions, the higher the number of fires and the burnt area. There was no such correlation during the second sub-period. This change might be attributed to "new" factors that interfere between the climatic signal and fire activity. One of these could be the result of socioeconomic changes since around the mid 20th century. These have led to the gradual abandonment of former traditional forest practices, such as forest pasturing or collecting litter and firewood. Consequently, motr living and dead biomass has become available in forests, while it was very scarce at the beginning of the century (Gimmi *et al.* 2008). This has probably led to a decline in the relative importance of climatic factors, such as drought (*cf.* Thornthwaite index), in comparison with non-climatic factors, in explaining fire frequency and annual burnt area.

The hypothesis that the fuel load played an increasingly important role in the course of the study period is corroborated by the cross-correlation analysis. There was a significant and positive correlation with a time lag of three years between fire frequency and the Thornthwaite index during the period 1956–2008, which was not the case during the period 1904–1955. This lagged correlation suggests that the build-up of fine fuel (*e.g.* grasses and shrubs) that occurs during humid years, i.e. when index values are high, causes in turn an increase in fire frequency a few years later. Comparable effects have been observed in other regions, such as the south-western United States (Swetnam and Betancourt 1998), California (Fry and Stephens 2006) or Spain (Pausas 2004).

The significant and negative correlation between the Thornthwaite index and the annual burnt area during the first sub-period, and the absence of such a correlation during the second sub-period, are probably to be attributed to improvements in fire prevention and fighting during the study period. At the beginning of the 20th century, there was not an extensive road network in Valais and thus access to forested areas was often difficult. Moreover, fire fighting equipment was poorly developed. Thus the probability that a fire would spread then depended greatly on the meteorological conditions prevailing at the time of ignition. Increases in road density, in particular in forests, and improvements in fire fighting, in particular with the use of helicopters (Gimmi *et al.* 2004), have meant that fires can mostly be prevented from spreading, even during extreme fire weather. Furthermore, the successive introduction of legal regulations prohibiting the burning of waste and biomass on specific days or during particular periods may have also helped to prevent ignitions during periods of higher fire danger, *e.g.* during strong droughts or windy periods. These various factors could help to explain the loss of correlation between burnt area and drought periods in the course of the 20th century.

5 Conclusions

The fire regime in Valais changed to some extent between 1904 and 2008. Although extreme fire years have occurred recently, *e.g.* 1990 when there were the highest number of fires during study period, and 2003 when an extensive area was burnt, the fire frequency and the annual burnt area did not change much during the 20th century. One important difference has been, however, the shift of fire activity toward the lowlands, probably due to population densities increasing at lower elevations. This shift has probably led to a change in fire seasonality, in particular through the occurrence of more spring fires.

Our findings suggest that, while the two main components of the fire regime, i.e. fire frequency and burnt area, did not change over the 20th century in Valais, the balance between the driving factors of fire activity did change. While drought was a crucial factor during the first decades of the 20th century, it seems to have lost its relevance later on compared to other factors, such as fuel load, which today plays a more important role.

If the build-up of fuel and increases in population density are more important influences on the current fire regime than climate, this could lead to ways of reducing fire risk. These factors should be thus considered carefully when developing fire prevention and management measures.

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Chapter 5

Fire regime shifts as a consequence of fire policy and socio-economic development: an analysis based on the change point approach

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Abstract

When fire events remain recurrent in a given area over a certain period of time they usually result in a specific fire regime. Where humans interact with the landscapes, changing their flammability and acting as fire initiators or suppressors, fire regimes may change. Developing an objective and quantitative method for detecting short term changes in fire regimes could be of paramount importance for addressing the effectiveness of fire management measures. We used the change point approach to detect shifts in fire frequency and extent in a 100-year fire dataset of two Swiss cantons (Ticino and Valais) differing in environmental, socio-economic and legal context. We then analyzed the detected changes in fire regimes in the light of the implemented fire policy and the socio economic evolution. Our results show the suitability of the approach for detecting change points. We found in particular that in the less fire-prone Canton of Valais, major driving forces that yield shifts in fire regimes are of climatic and socio-economic origin, whereas in the fire-prone Canton of Ticino fire policy measures also contributed to detectable changes. Fire legislative measures led to reduced fire frequencies, whereas improvements in fire-fighting resulted in a reduction of burnt area. Policy makers may learn from such analyses for planning future measures.

1 Introduction

Wildfires are uncommon and irregular events that display a complex spatio-temporal distribution (Sousa 1984). Their frequency, intensity and distribution are controlled and determined by the coinciding of basic conditions such as the presence of vegetative resources (fuel), fire-conducive environmental conditions (*e.g.* meteorology) and ignition energy (lightning or humans) (Krawchuk *et al.* 2009). When fire events remain recurrent and consistent in a given area over a certain period of time, they usually result in a specific fire regime (Krebs *et al.* 2010). Nevertheless, fire regime components display a great spatial and temporal variability (Morgan *et al.* 1994), making the fire regime definition very much a scale-dependent issue. This is particularly true in areas with strong anthropogenic pressure, where humans interact with the landscape, consequently changing its flammability, and act as fire initiators or suppressors. In such cases, human influence may cause sudden changes in fire frequency, intensity and extent. There is, however, very little research on how to clearly estimate the degree of variability and time span required to notice a change or a shift in a fire regime (Conedera *et al.* 2009, Whitlock *et al.* 2010). Developing an objective and quantitative method for detecting short-term changes in fire regimes could be of paramount importance for addressing the effectiveness and suitability of fire management measures, such as fire policy acts, firefighting organization and sylvicultural measures aimed at preventing wildfires and mitigating post-fire effects.

In the present study, we propose using the change point approach to detect shifts in fire frequency and area burnt. For this purpose we used two 100-year fire data series from the Swiss cantons of Ticino and Valais, analyzing and interpreting the detected changes in fire regimes (if any) in the light of existing fire policy measures, climatic changes, and socio-economic developments. We aim to answer following questions in particular:

- Are there any suitable mathematical approaches that would enable the detection of short term shifts in fire regimes in the study areas?
- It is possible to link such shifts to fire policy measures, climatic conditions or land-use changes in the corresponding study area?
- What can we learn from this study for future fire management applications?

2 Study areas

We selected two areas representing the two most fire-prone cantons of Switzerland, i.e. the neighboring mountainous cantons of Ticino and Valais (Fig. 5.1). The Canton of Ticino has a population of 320,000 and a total area of 2,812 km², of which about 16 % are unproductive areas without vegetation (http://www.bfs.admin.ch). It is located on the southern slope of the Alps and is characterized by a marked altitudinal gradient (from 200 to 3400 m a.s.l.) and a rather heterogeneous geology, dominated by siliceous rocks originating in connection with the tectonics of the Alps. Depending on the elevation and the geographical location, the mean annual precipitation ranges from 1,600 to 2,600 mm, and the mean annual temperature from 3 to 12 °C. Considerable summer rain (800 to 1,200 mm in the period June-September) is characteristic for the whole area, including the lowlands around the lakes Verbano and Ceresio where the Insubric climate is dominant (Fig. 5.2). The Insubric climate is also characterized by dry and mild winters that generally include several days (40 days a year on average) with strong gusts of a katabatic (descending) dry wind from the north (foehn), which causes drops in the relative humidity to values as low as 20 %. In summer, long periods without rain or even of drought may alternate with thunderstorms, and short and heavy spells of precipitation (Spinedi and Isotta 2004, MeteoSwiss 2009).

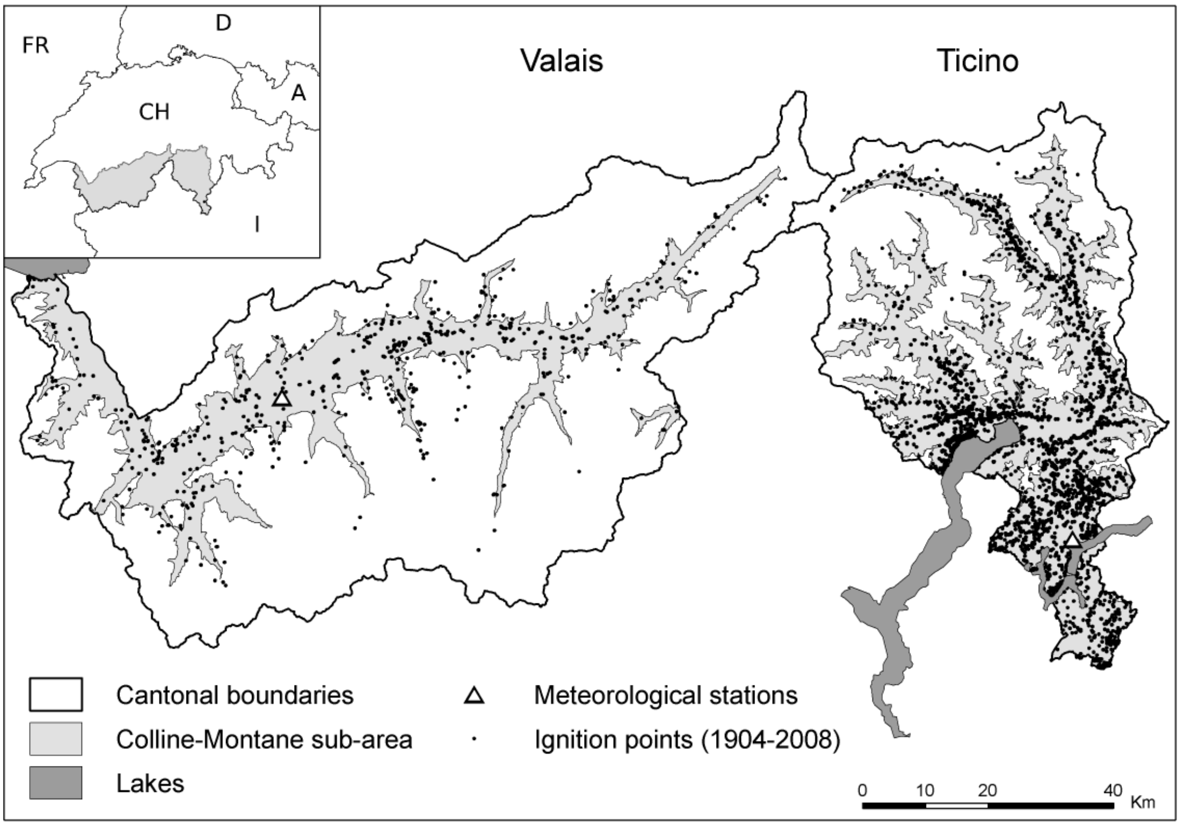

Figure 5.1. Study area (Canton Ticino and Canton Valais).

At the beginning of the last century, Ticino was mainly a rural canton. This situation changed dramatically in the last post-war period, when the Canton of Ticino experienced a socio-economic shift towards a more service-oriented economy. This dramatic change, while ensuring prosperity and a strong increase in population, also caused the almost total abandonment of traditional agricultural, livestock breeding and land management activities. According to the different data sources (Brändli 2000), the forest area more than doubled, passing from ca. 62,900 ha in 1900 to around 129,000 ha (Tab. 1). Nowadays, forest vegetation is dominated at low elevations (up to 900-1100 m a.s.l.) by chestnut trees (*Castanea sativa*). Chestnut forests are anthropogenic monocultures occasionally interrupted by the presence of other broadleaved species, such as *Tilia cordata*, *Quercus petraea*, *Q. pubescens*, *Alnus glutinosa*, *Prunus avium*, *Acer* spp., or *Fraxinus* spp. At medium elevations (900-1400 m a.s.l.), the forests mostly consist of pure stands of *Fagus sylvatica*, followed by coniferous forests (*Picea abies* and, at higher elevations, *Larix decidua*). On south-facing slopes, the beech belt is sometimes missing completely. The presence of *Abies alba* has been reduced to small patches on north-facing slopes in the central part of the area, and pine forests are confined to very particular sites: *Pinus sylvestris* on dry south-facing slopes, and *P. cembra* on the most continental areas of the upper regions (Ceschi 2006).

The canton of Valais has 300,000 inhabitants and covers an area of 5,200 km^2, of which about half is covered by glaciers and rocks (http://www.bfs.admin.ch). It consists of a main large inner-alpine valley oriented along an east-west axis with several side valleys. The area is characterized by a continental climate (Fig. 5.2), i.e. relatively low annual precipitation, cold winters, high irradiation, and high daily and annual temperature fluctuations (Braun-Blanquet 1961), as well as by the occurrence of south foehn sliding down from the slopes of the Alps (Ficker and De Rudder 1943, Bouët 1972, Kuhn 1989).

Due to the decline in agricultural activities in less productive and/or more remote areas, in the Valais the forest area also increased over the past 100 years by approximately 24%, going from about 81,100 ha at the beginning of the 20th century to approximately 100,500 ha today (Walther and Julen 1986, Kuonen 1993, Brändli 2000, Tab. 1). Forest species distribution reflects the altitudinal gradient: forests at low elevations (400-800 m a.s.l.) are dominated by broadleaved species and in some spots by *P. sylvestris* which in turn dominates at medium elevations (800-1400 m a.s.l.). At higher elevations (1400-2300 m a.s.l.), other coniferous species are predominant, specifically *Picea abies*, *Larix decidua*, and *Pinus cembra* in the uppermost areas (Hainard 1969, Werlen 1994, Werner 1994).

In order to take into account the clear elevation gradient existing in both study areas and the related heterogeneity in terms of pyrological conditions (Conedera and Pezzatti 2005, Zumbrunnen *et al.* 2009), we took two different altitudinal levels into consideration, corresponding to the colline-montane zone (areas up to 1500 m a.s.l.) and the subalpine zone (areas above 1500 m a.s.l.; Fig. 5.1).

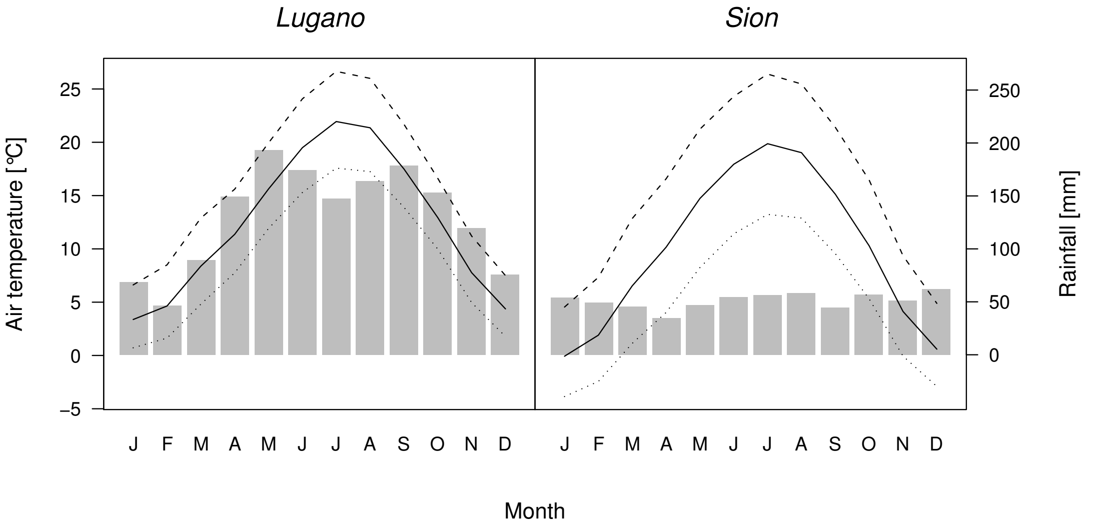

Figure 5.2. Monthly mean values of air temperature and rainfall for the meteorological stations of Lugano (Ticino) and Sion (Valais) during the period from 1979 to 2008. Bars represent rainfall; dotted, plain and dashed lines show respectively average values of minimum, mean and maximum air temperature.

3 Materials and methods

3.1 Forest fire data

In Switzerland, forest fires are usually documented by the local forest service. In the canton of Ticino, where forest fires are very frequent, the information has been systematically collected and centralized using a standardized protocol since the beginning of the 20th century. In the canton of Valais, the registering of forest fires has not been a standardized task for a long time, and the information remained dispersed until recent archiving work (Bochatay and Moulin 2000, Gimmi *et al.* 2004, Zumbrunnen *et al.* 2009). Fortunately, some basic information such as date, time, cause of ignition, fire duration, burnt area, or fire type, exists for most forest fires. This allowed us to organize the fire data in a relational database (Pezzatti *et al.* 2005), and to select all the fires of anthropogenic origin to be considered in this paper.

In the period 1904–2008, we obtained data for 5,171 georeferenced fire events of anthropogenic origin for Ticino and 625 for Valais. Table 5.1 summarizes the main characteristics (total and forested area, number of forest fires and burnt area) of each sub-region considered.

Table 5.1. Total area, forest area, number of fires and total burnt area in the period 1904–2008 for the four sub-areas considered.

Canton	Sub-area	Abbr.	Total area (ha)	Estimated forest area 1900 (ha)	Estimated forest area 2000 (ha)	Number of forest fires	Burnt area (ha)
Ticino	colline-montane	TI-col	151,259	47,382	94,615	4,961	53,112
	subalpine	TI-sub	117,087	15,557	34,506	210	2,622
	total	*TI*	*268,346*	*62,939*	*129,121*	*5,171*	*55,734*
Valais	colline-montane	VS-col	117,440	37,175	47,588	434	2,020
	subalpine	VS-sub	216,967	43,941	52,879	191	498
	total	*VS*	*334,407*	*81,116*	*100,468*	*625*	*2,518*

3.2 Change point approach

According to Chen and Gupta (2000), from a statistical point of view, a change point is a place or a point in time where observations follow one distribution up to that point and follow another distribution after that point. Many change point estimation methodologies have been developed (Chen and Gupta 2000), involving different approaches (*e.g.* likelihood ratio, Bayesian, non parametric). In the present study we used two approaches, the cumulative sum of deviations (CUMSUM) and the nonparametric Pettitt-test (Pettitt 1979), most commonly used in meteorological and hydrological investigations (Sneyers 1992, Fealy and Sweeney 2005, Dou *et al.* 2009, Zhang *et al.* 2009), but also in other contexts such as finance (Oh and Han 2000, Oh *et al.* 2005), genetics (Avery and Henderson 1999), and phenology (Rutishauser *et al.* 2009).

The CUMSUM consists of the cumulative sum of the deviations from the mean over the period of interest (Sneyers 1992) and is defined as follows:

$$S_t = \sum_{i=1}^{t} (X_i - k)$$

where k is the average of the time series.

The CUMSUM approach is simple but has a major weakness in its sensitivity to outliers. The Pettitt method is more robust and is calculated as follows:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} \operatorname{sgn}(X_i - X_j)$$

where sgn(x)=1 for x>0, 0 for x=0 and -1 for x<0, and T is the length of the time series.

For continuous data, an approximate significance probability can be calculated from:

$$p(t) = 1 - \exp\left(\frac{-6 \cdot U_{t,T}^2}{T^3 + T^2}\right)$$

This methodology allows for the identification of the highest probable change point in the investigated period. To identify multiple change points, we applied the Pettitt index using two different options. We first used a hierarchical stepwise approach, consisting of identifying a main change point and then considering the two resulting sub-periods for detecting secondary change points. A second option consisted of calculating the Pettitt index value for the central point of a moving time window (running Pettitt index). For this second approach, we tested three different sub-options with time windows of 11, 21 and 41 years, respectively.

The change points or intervals were finally obtained when most of the applied methods gave a consistent indication of an existing abrupt (point) or smooth (interval) change in the Pettitt-index, indicated by a corresponding high p-value (p >0.8). In Figures 5.3 and 5.4, examples are given for the forest frequency and burnt area change points respectively in the colline-mountain level of Canton Ticino (TI-col).

The effectiveness of the selected change points and intervals was then statistically verified by testing the existing differences in fire frequency or burnt area for the periods preceding and following the detected change points using a Wilcoxon rank sum test (Mann-Whitney test).

3.3 Socio-economic development

We selected different descriptors for depicting the socio-economic evolution of the two study areas. In particular, we used the number of livestock units (LU) as a proxy for the positive (i.e. mitigating fire activity) removal of fuel biomass, and the increase in forest area as a proxy for negative (i.e. promoting fire activity) evolution of the land use. We also used the resident population and the proportion of livestock owners as an indicator of the potential number of ignition sources (Superweb statistical database, http://www.bfs.admin.ch).

As it was impossible to split municipal data according to the altitudinal levels, data on socio-economic development are presented for cantons as a whole. Data on forest area development were obtained by interpolating existing data from various statistical sources and forest inventories such as the Swiss National Forest Inventory, federal statistics on land use, forest statistics, yearly cantonal reports, and the first Swiss topographic map dating back to the beginning of the 20th century (Siegfriedkarte)(see also Brändli 2000). Similarly, the data on livestock units were obtained from federal and cantonal agricultural statistics. We calculated the overall proportion of biomass consumed by livestock by converting the number of each type of animal into Livestock Units (LU) according to food requirement conversion factors (cow 0.9, horse 0.8, mule 0.4, goat 0.1, sheep 0.1, and pig 0.25) proposed by the Swiss federal Ordinance on agricultural terminology (SR 910.91).

3.4 Meteorological data

The effect of climate on fire regimes can be assessed by using fire weather danger indices, most of which are just based on climate and weather variables (*e.g.* Munger 1916, Nesterov 1949, Baumgartner *et al.* 1967, Keetch and Byram 1968, van Wagner 1987, Kunkel 2001, Goodrick 2002, Badeck *et al.* 2003, Larjavaara *et al.* 2004). A limiting factor for using such fire weather danger indices in the present study is represented by the long time span taken into consideration here (100 years) and the associated difficulty in identifying meteorological stations with corresponding long data series for the broad number of meteorological variables needed. We therefore decided to refer to a single meteorological station per canton (Fig. 5.1) that had a long series of meteorological data and provided the meteorological variables needed for some indices that proved to be suitable for the study areas. According to Reineking *et al.* (2010), the Nesterov (1949) and the KBDI (Keetch and Byram 1968) indices appear to be among the most suitable for the summer period in the area considered, while the Angstroem-Index (Chandler *et al.* 1983) is appropriate to reconstruct the winter fire weather conditions. The meteorological data for calculating the fire indices were provided by the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss).

3.5 Fire policy data

Information on fire prevention and firefighting organization was obtained by surveying documentary records from different archives and written sources such as local literature, archives of the Forest Services, official acts of cantonal administrations and of cantonal parliaments, official cantonal and federal legislation, or fire brigade archives (see also in Conedera *et al.* 2004 and Zumbrunnnen *et al.* 2009).

4 Results

4.1 Change points in fire regimes

Figures 5.3 and 5.4 show two representative examples of the results obtained by the different change point approaches implemented for fire frequency and burnt area in the colline-montane level of Ticino (TI-col). Whereas the stepwise approach returns precise and mathematically calculated values of the presumed change points, the moving window graphs require further interpretation. In particular, different change points may be highlighted according to the size of the moving window being considered. The development of the cumulative sum coincides with the Pettitt approach in case of smooth trends without abrupt changes or outliers (as it is the case for the fire frequency in Fig. 5.3) whereas it strongly deviates from the Pettitt curves in case of extreme events as is typically the case for the yearly burnt area (Fig. 5.4). The change points and change intervals we determined for fire frequency and burnt area are reported in Table 5.2 and Figure 5.5, according to canton and altitudinal level. The detailed plots of the colline level of Ticino are reported in Figure 5.3 (fire frequency) and Figure 5.4 (burnt area), while the plots of the other cases are included in the electronic supplementary material. Identified changes (points or intervals) are significant throughout (Table 5.2) but may differ in time and in some cases may also exhibit opposite trends (increase vs. decrease), not only between the two main study areas, but also between the altitudinal levels within a canton.

4.2 Land use indicators

Figure 5.5 illustrates the general trends of land-use indicators and fire weather indices for the whole cantons of Ticino and Valais in relation to the evolution of the fire frequency, burnt area, and the identified change points in the analyzed sub-areas.

The forest area increase reaches its highest absolute values in Ticino (around 2000 ha·yr^{-1}) when compared to Valais (peak of 500 ha·yr^{-1}). In Valais, however, there is a significant increase already between the 1930s and the 1960s, followed in the period 1975-85 by a shorter and initially delayed main peak with respect to Ticino (1965-85). At the end of the last century, a second main wave of increase in forest area seems to take place in both cantons.

Livestock units have decreased monotonically in Ticino in the course of the entire study period, with a slight acceleration between 1960 and 1970, whereas in Valais there is a steady drop between 1920 and 1990. As a result, in both cantons the percentage of livestock breeders among the population dropped dramatically during the period, with an acceleration of the process between 1940 and 1970 in Ticino and between 1945 and 1985 in Valais.

Population regularly increased during the whole study period in Valais, whereas Ticino experienced an acceleration in population increase between 1960 and 1970.

Table 5.2. Results of the change point analysis.

Canton	Area	Parameter	Change point	P-value	Shift
TI	col	fire frequency	1955-61	< 0.001	upwards
			1990	< 0.001	downwards
		burnt area	1929-36	< 0.05	upwards
			1955-61	< 0.01	upwards
			1980-90	< 0.001	downwards
	sub	fire frequency	1964	< 0.01	upwards
			1989	< 0.05	upwards
		burnt area	1964-68	< 0.001	upwards
VS	col	fire frequency	1920	< 0.01	downwards
			1940-54	< 0.001	upwards
			1989	< 0.05	upwards
		burnt area	1942-46	< 0.001	upwards
	sub	fire frequency	1942	< 0.01	upwards
			1963	< 0.05	downwards
			1985-87	< 0.01	upwards
		burnt area	1943	< 0.001	upwards
			1985-87	< 0.05	upwards
			1943	< 0.01	upwards
			1985-87	< 0.001	downwards
			1987	< 0.001	upwards

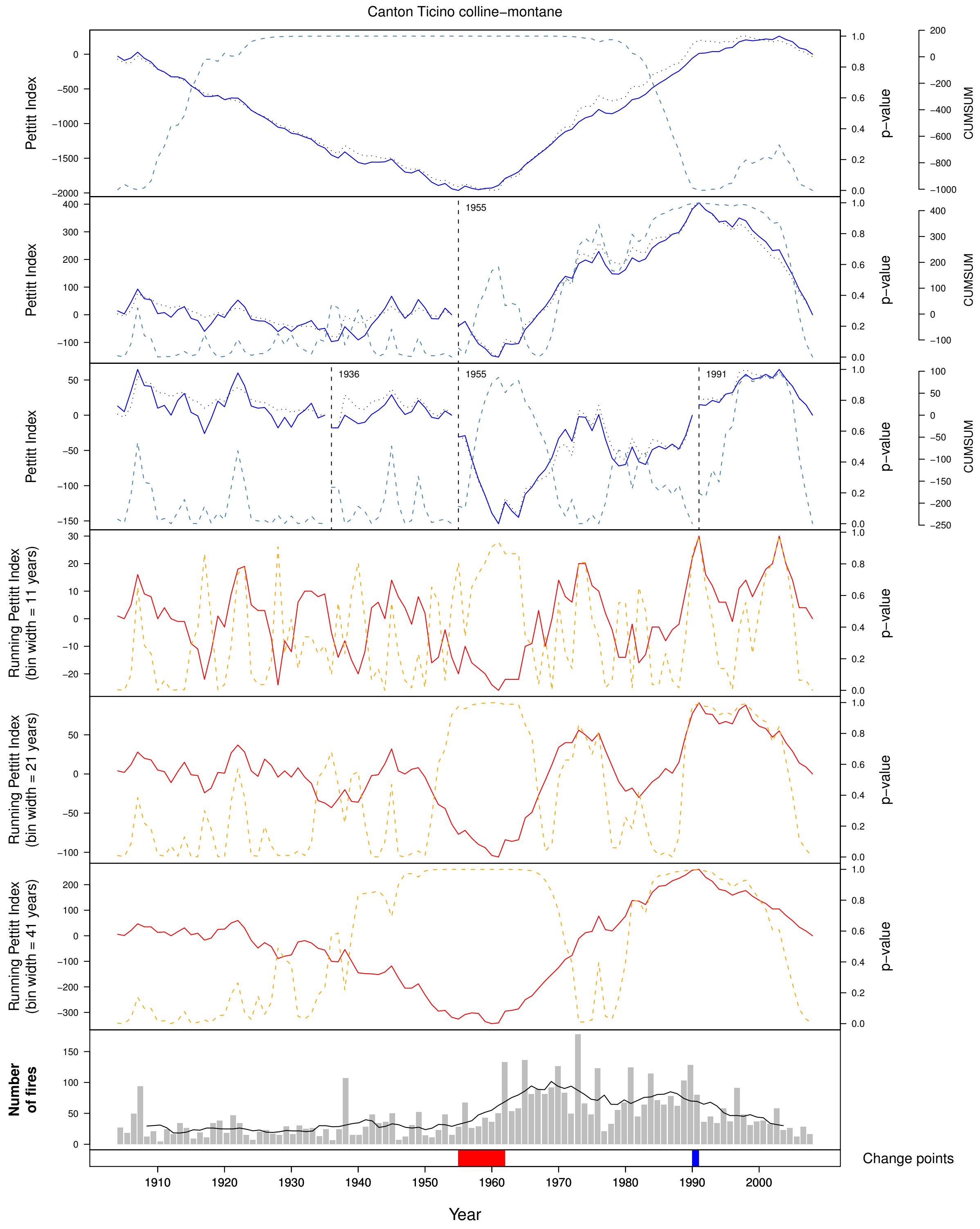

Figure 5.3. Change point analysis for the frequency of forest fires in canton Ticino since 1904. The first three plots show a Pettitt stepwise approach, while the fourth to sixth plots show a running Pettitt index according to different reference periods (respectively 11, 21 and 41 years). Plain lines represent the Pettitt index in all but the last plot, where the line shows a running mean on 9 years; the dotted lines represent the cumulative sums of deviations (CUMSUM) and the dashed lines the p-values indicating the approximate probability of a change point.

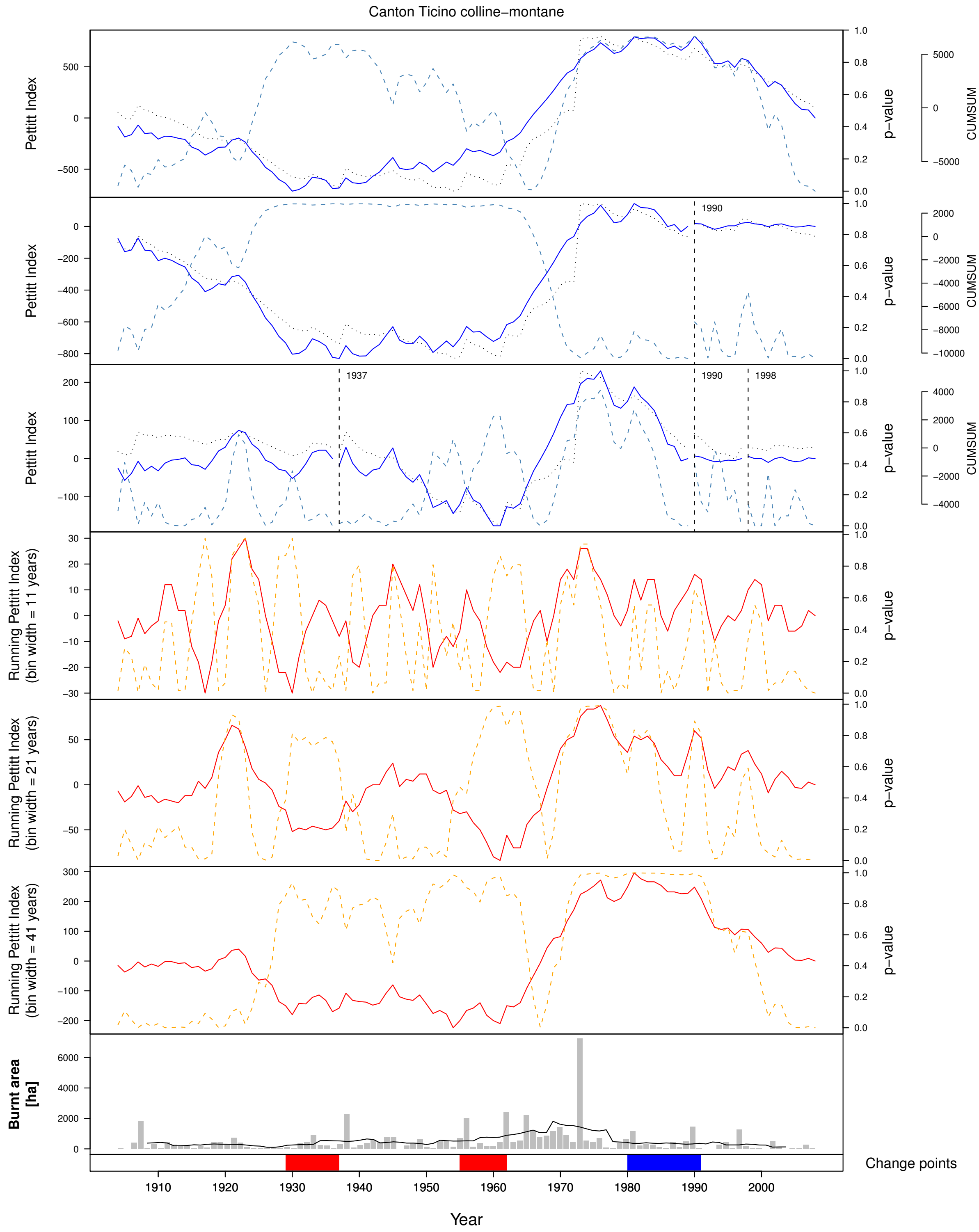

Figure 5.4. Change point analysis for the burnt area in canton Ticino since 1904. The first three plots show a Pettitt stepwise approach, while the fourth to sixth plots show a running Pettitt index according to different reference periods (respectively 11, 21 and 41 years). Plain lines represent the Pettitt index in all but the last plot, where the line shows a running mean on 9 years; the dotted lines represent the cumulative sums of deviations (CUMSUM) and the dashed lines the p-values indicating the approximate probability of a change point.

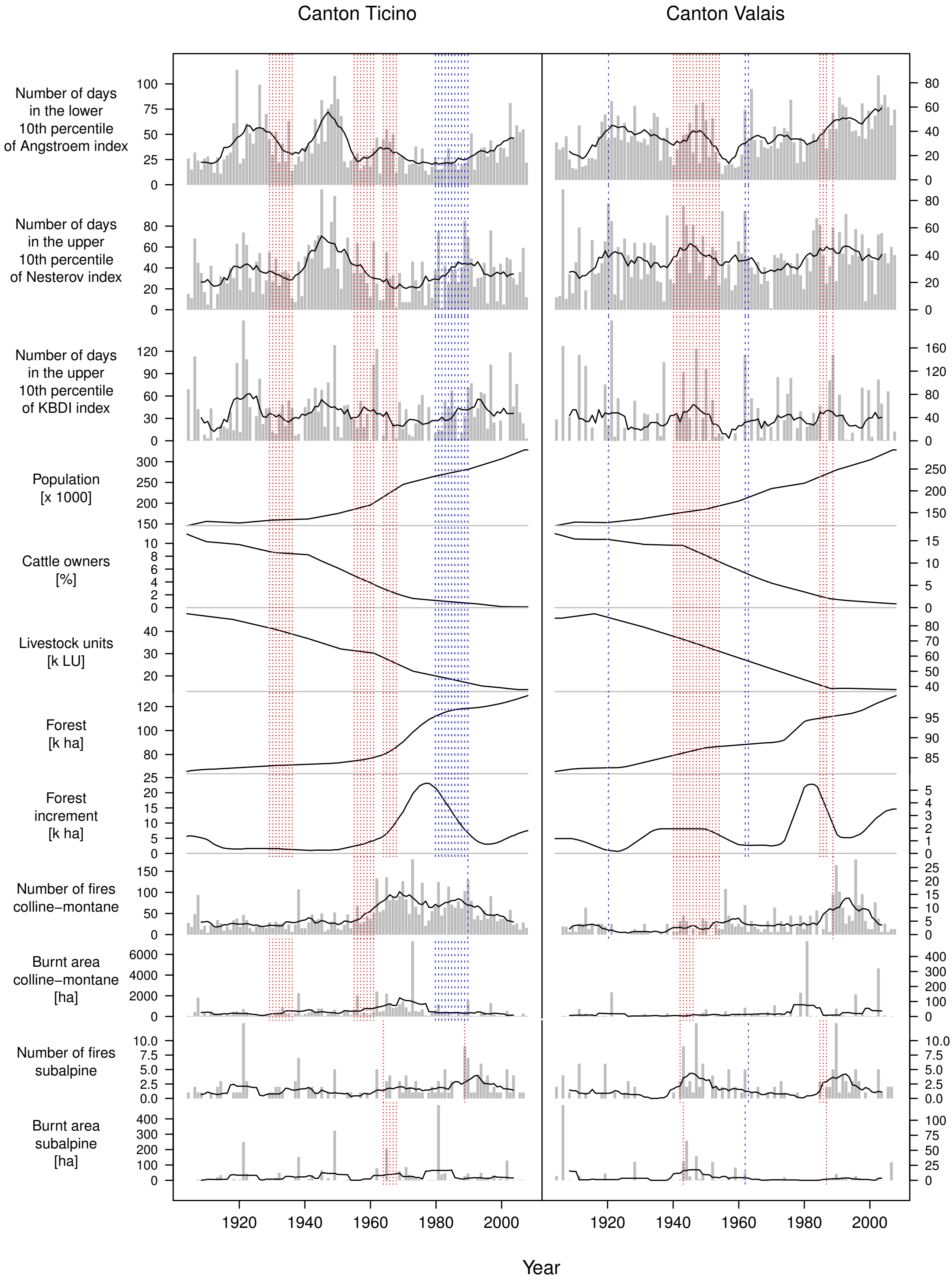

Figure 5.5. Meteorological and socioeconomic factors possibly related to the fire regimes of canton Ticino and canton Valais, from 1904 to 2008. The vertical lines represent the change points summarized in Table 5.2, highlighting the increasing (dotted lines) and decreasing (dashed lines) fire regime aspects (fire frequency and burnt area in each sub-region).

4.3 Climatic indicators

The fire weather indicators reported in Figure 5.5 are expressed as the yearly number of days with values exceeding the 90th percentile of the corresponding danger scale. For Ticino, an initial period of high meteorological fire danger is reported for 1920 to 1930 (1935) and a second one from 1945 to 1955. The Nesterov and KBDI indices additionally suggest meteorological conditions that enhanced fire danger over the 1990s, while the Angstroem index indicates a prolonged phase of fire enhancing meteorology starting in those years. In Valais the situation seems generally more balanced, apart from the Angstroem index which shows an increase in the number of fire weather days since the 1980s.

4.4 Fire policy

In the fire-prone canton of Ticino, there is a greater number of policy acts, and particularly a larger body of local literature that deals with the problem (see Conedera 2009 for a review). As reported in Tables 5.3 and 5.4, besides the cantonal forest and fire policy laws, there are manifold specific decrees and organizational acts that have been enacted through the years. This is less the case in the canton of Valais, where very few fire-specific legal acts exist, even if forest fire policy is systematically addressed in forest legislation (Table 5.5).

5 Discussion

The change point analysis of time series with outliers (like burnt areas) and/or low numbers is much more difficult with respect to regular time series. This is particularly true when using the CUMSUM approach. Concerning the two different Pettitt approaches presented, the main difference between the two options consists in the fact that in the stepwise approach, the index values depend strongly on the size of the periods given by the previous steps, whereas the running Pettitt index highlights equivalent change points, since they all refer to the same length of investigation period. In the running Pettitt approach, however, the choice of the bin width is very important and should mirror the scale of the process being investigated. In our case, the best results are obtained using the 41 years bin width. In addition, the running Pettitt is less effective in the marginal regions of the reference period (at a distance of half of the bin width from the boundaries).

Nevertheless, as already suggested by other authors dealing with hydrological or ecological topics (*e.g.* Dou *et al.* 2009, Eslami-Andragoli *et al.* 2009, Rutishauser *et al.* 2009), by integrating the results of the changing point analysis with other response or explanatory variables it was possible to effectively verify the existing temporal coincidence between the suggested shifts in the fire regime (change points or change intervals) and a potentially related change in the climatic or anthropogenic frame conditions, including fire policy and fire management measures.

In TI-col, the burnt area experienced an increase starting in the period 1929–1936 without any corresponding changes in land use or meteorological indicators. Conedera *et al.* (2004, 2007) suggest a link to the former habit of pasture fires being used by the local population in a highly deregulated and illegal way until the 1940s. The specific legislation acts aimed at improving firefighting organization, have been modified in Ticino since 1933, very likely in the attempt to better control the burnt area which has been increasing in the colline region since 1929. For this period, the results show no similar patterns for Valais.

The two cantons' fire regimes were also observed to exhibit different reaction patterns in the 1940s, where a change point was detected only for Valais, although both cantons started to experience a change in the socio-economic system as reflected by a decrease in the percentage of stockbreeders in the population. Concerning the canton of Valais, livestock grazing took place in forests in many areas until the 1950s (De Kalbermatten 1966, Peter 1966, Gimmi and Bürgi 2007). Around the mid-century, Valais turned to a more industry- and service-oriented economy. Consequently, the former non-timber forest uses (i.e. wood pasture and litter collecting) were progressively abandoned (Kempf 1985, Kuonen 1993), thereby probably causing fuel build-up and a rapid increment of the forest area, which may have resulted in an increased fire risk. Moreover, in the 1940s and in the beginning of the 1950s, the climate in Valais was characterized by the repeated occurrence of dry years with a very high frequency of days with elevated temperatures (Bader and Bantle 2004, Bigler *et al.* 2006). This is also confirmed by the relatively high number of days above the 90th percentile of the KBDI index in Figure 5.5. As a consequence, the fire regime in both the VS-col and VS-sub regions experienced a change towards an increase in fire frequency and burnt area. Although the climatic conditions in canton Ticino feature a similar (or even stronger) peak in fire weather days (see Angstroem and Nesterov indices in Fig. 5.5) in the 1940s and at the beginning of the 1950s, the area did not experience any corresponding shift in fire regime.

The major shifts in fire regime experienced in the canton Ticino between 1955 (at the start of the change interval in the colline region) and 1968 (the end of the regime shift concerning the burnt area in the subalpine region), only partially coincided with a period of fire prone weather (Angstroem index and partially KBDI in Fig. 5.5). These shifts are much more related to the dramatic change in land use experienced in Ticino starting in the mid-1950s (Conedera *et al.* 1996). Due to the different vegetation dynamics related to the altitudinal gradient, we assume that such a change took place first in the colline level and with only a few decades of delay in the subalpine area (Brändli 2010). Correspondent changes in land-use indicators, although with a slight delay, consist of an increase of the rate of spread of the forest area and a definitive drop in livestock units. Such a time-lag may be due to the retrospective character of the land-use data, which are collected only periodically (*e.g.* every decade) and usually refers to the period preceding the surveying date. In addition, before abandoned agricultural land grows into forest, there is a quite long-lasting fallow land phase with very flammable vegetation that may be overlooked in such indicators. The legislative acts and the organizational measures taken by the authorities during this period were merely attempts to curtail the negative consequences in terms of the number of fires and burnt area and did not result in an effective mitigation of the fire regime.

The canton of Valais experienced a last positive change point towards an increase in fire frequency between 1985 (subalpine area) and 1989 (colline level). This may be due to an increase in fire weather days (Angstroem index) and possibly to a new acceleration in the forest area increment.

Concerning negative change points, a first drop in fire frequency took place in the VS-col in 1920. This may be related to the new cantonal forest law of 1910 and the slight reduction in forest area growth. A further likely explanation may be the intensification of the use of local natural resources, such as firewood, litter and pastures, because of World War I. This intensification probably contributed to a reduction in fuel load in forests and in the surrounding fire-prone areas, which in turn resulted in a decrease in fire frequency.

The drop in fire frequency and burnt area for the subalpine area in Valais at the beginning of the 1960s is probably due to a general decrease in both the forest area growth rate and a period with less suitable fire weather conditions. This is particularly the case with regards to summer temperatures which dropped off after the mid-1950s and remained relatively low until the beginning of the 1980s (Bader and Bantle 2004). This is also indicated by the Nesterov-index and – to a less extent – by the KDBI-index (Fig. 5.5).

Table 5.3. Legislative acts related to fire prevention in Canton Ticino since 1904. *Grey background:* legislative acts still in force.

Date	Legislative act	Preventive measures
26.06.1912	Cantonal forest law	Prohibition of making fire in forests, in the forest neighborhood and in pastures without taking the necessary precautions. Limekilns and charcoal places forests are prohibited without the permission of the Forest authorities and must be thoroughly monitored. Pasturing is prohibited in freshly burnt areas. Forest service may order the forestation of burnt areas.
08.11.1933	Modification of the Cantonal forest law	The cantonal authorities may constrain the community in fire-prone areas to organize a fire-alert service.
14.04.1936	Executive cantonal decree	The fire-alert service is extended to the whole Canton.
13.10.1949	Cantonal fire policy law	Prohibition of setting fires in urban areas, in open areas, and in forests during drought or high wind periods.
21.12.1956	Federal decree	Costs for technical prevention measures may be financed by the Swiss Confederation up to 70% of the total costs.
16.05.1958	Executive cantonal decree	The cantonal authorities may also financially support fire prevention measures such as fire-guards, alarm-service, training of fire brigades and information boards on fire danger.
21.07.1958	Executive cantonal decree	Costs for technical preventive measures in the context of forest projects may be financed up to 50% of the total costs.
30.04.1975	Modification of the executive cantonal decree of 16.5.1958	Prohibition to set fires in the open during drought periods or windy days; periods of prohibition are to be decided by the Swiss Meteorological Service in Locarno-Monti and broadcasted by the mass-media.
13.12.1976	Cantonal fire policy law	Any activity related to fire danger is prohibited, in particular setting fires in the open during drought or windy periods.
04.07.1978	Application rules of the cantonal fire policy law	The rules prohibiting fires in the open are confirmed by the Swiss Meteorological Service in Locarno-Monti.
21.10.1987	Executive cantonal decree	Prohibition of burning garden debris in the open.
11.07.1990	Executive cantonal decree	The absolute prohibition of starting fires in the open in case of fire danger is extended to fireworks and ceremony fires.

Date	Legislative act	Preventive measures
12.02.1992	Partial revision of the cantonal executive decree 21.10.1987	Exceptions to the prohibition of burning garden debris in the open is allowed for phytosanitary reasons.
28.03.1995	Partial revision of the cantonal executive decree 21.10.1987	The application of the decree concerning the prohibition of burning garden debris in the open should be executed by the municipal authority.
05.02.1996	Cantonal fire policy law	Any activity related to fire danger is prohibited, in particular starting fires in the open during drought or windy periods.
04.03.1998	Partial revision of the cantonal executive decree 21.10.1987	Authorization of burning dry garden debris in the open in the regions above 600 m a.s.l.
07.04.1998	Application rules of the cantonal fire policy law	Prohibition to make fires in the open during drought periods or windy days; periods of prohibition are decided by the Swiss Meteorological Service in Locarno-Monti and broadcasted by the mass-media.
21.04.1998	Cantonal forest law	Wildfires are for the first time included in the list of natural hazards to be prevented in order to preserve the territory.
		Promotion of general preventive measures against natural hazards.
		Financial support for fire prevention.
22.10.2002	Application rules of the cantonal forest law	The Forest Service is in charge of fire prevention.
		The Forest Service collaborates with MeteoSwiss in deciding the periods of absolute prohibition of making fires in the open and organizes a stand-by service.

Table 5.4. Technical and organizational measures related to fire prevention and fire fighting in Canton Ticino since 1904.

Date	Technical or sylvicultural measure	Remarks
1912	Municipalities are obliged to organize wildfire fighting and extinction. Forest Service should prosecute the responsible parties.	Cantonal Forest Law (26.6.1912)
? – 1913	Electrification of the Gotthard railway.	
1929	Political Municipalities are asked to organize standing firefighting teams and to collaborate with neighbouring communities for fighting border-crossing fires.	CRCS 1929; Pometta (1929)
1933-40	Political Municipalities are asked to organize standing firefighting teams and firefighting tools (blades, palms, rakes) and to collaborate with neighbouring communities for fighting border-crossing fires. For the first time, firefighting brigades reap the benefit of causality insurance.	Cantonal decrees (8.11.1933; 14.4.1936) adding art. 48bis to the Cantonal Forest law; Official Bulletin (8.3.1940)
1940	The two existing fire brigade associations are merged into the new Cantonal Federation of Fire Brigades that represents all fire brigade units in the Canton.	Corti (1990)
1945	A forest fire commission was created with the aim of involving existing civil fire brigades in forest firefighting.	Corti (1990)
1958	Fire-guard and fire alarm service, fighting costs and purchase of firefighting tools will be financed by the cantonal authority. Civil fire brigades and their facilities (*e.g.* water tank vehicles, mobile water reservoirs, etc.) may also be used for controlling forest fires.	Cantonal decrees (16.5.1958)
1958 -	A hydrant-net is to be normally combined with the construction of a new forest road. Civil fire brigade facilities (*e.g.* water tank vehicles, mobile water reservoirs, etc.) may also be used for controlling forest fires.	Decree 16.5.1958
(1961) – 1967 -	Progressive introduction of radio equipment for internal communication during firefighting.	CRCS 1961, 1968, 1969, 1972
1962 -	Progressive introduction of aerial craft for transport of fire brigades and direct firefighting.	Pohl (1965; 1967); Meyer (1967); CRCS 1968
1967 -	Hydrant-nets and water reservoirs are possible also for new plantations.	Pohl (1967)
1968	Organization of three fire watching points.	CRCS 1968
1974 -	Swiss army helicopters may be used for firefighting.	CRCS 1974

Date	Technical or sylvicultural measure	Remarks
1974	The army introduces several fire prevention rules concerning the use of war munitions during exercises.	CRCS 1974
1974 - 1990 (?)	Construction of spark-barriers along the Gotthard railway.	CRCS 1974
1975	Preparation of a firefighting field book for the heads of the fire brigades and of a map with flying obstacles for helicopters.	CRCS 1976
1975 -	Introduction of automatic refillable water tanks for helicopters.	CRCS 1975, Corti (1990)
1978	Creation of official mountain forest fire brigades in addition to urban fire brigades.	Fire law (13.12.1976) and executive regulation (4.7.1978); Corti (1996)
1982	Organisation of a helicopter stand-by service in case of fire danger during the week-ends.	Corti (1990)
1987 -	Introduction of new and lighter firefighting tools (tubes, mobile water reservoir, etc).	Corti (1990)
1987 -	High capacity helicopters (Superpuma with 3,000-3,500 litres of water capacity) are introduced in firefighting.	Corti (1990)
1998	Mountain forest fire brigades are better integrated into the fire brigade organization. Collaboration rules with the army and the civil service in case of firefighting are defined.	Fire law (5.2.1996) and executive regulation (7.4.1998)
2001 -	A convention with private and army helicopters is concluded for a permanent stand-by service in case of fire danger (last update: 26.10.2004).	Corti (2001); Zamboni (2001)
2002 -	Permanent stand-by service of Foresters in case of fire danger.	Cantonal Forest Law (21.4.1998) and executive regulation (22.10.2002)

Table 5.5. Legislative acts, technical and organizational measures related to fire prevention and firefighting in Canton Valais since 1904.

Date	Legislative act	Preventive measures
11.05.1910	Cantonal forest law	Observed fires must be announced immediately to officials and people in the surroundings must assist in suppressing the fire. Prohibition of making fire in forests, in the forest neighborhood and in pastures without taking the necessary precautions. Limekilns and charcoal places in the forest are prohibited without the permission of the forest authorities and must be thoroughly checked. The non-observation of these articles is sanctioned by a fine.
11.05.1910	Application rules of the cantonal forest law	Forest officials are responsible for prescribing prevention measures against fires. In case of fire, they organize suppression in collaboration with municipal authorities.
19.05.1911	Cantonal fire policy law	The cantonal government prescribes security measures against fire if they have not already been prescribed or undertaken by municipal authorities. Production and transport of explosive and flammable substance are regulated
19.07.1928	Cantonal executive decree	Smoking and starting a fire is forbidden in all forests.
25.07.1929	Cantonal executive decree	Smoking and starting fires is forbidden in all forests during summer months (from June until September).
12.04.1933	Cantonal executive decree	Burning of grass and shrubs is prohibited.
10.05.1938	Application rules of the cantonal fire policy law	Burning of grass and shrublands in open land is prohibited; starting fires in forest is prohibited, except for forest officials in certain areas. Bonfires are prohibited, except if the police have explicitly authorized them, and only at high altitude.
21.07.1976	Cantonal executive decree	Prohibition of setting fires in open land, forests and alps (with some exceptions); prohibition of selling and using pyrotechnic articles and material (with some exceptions).
18.11.1977	Cantonal law concerning the protection against fire and natural hazards	Individual responsibility for setting fires in open land; municipalities define the conditions for burning grasslands.
01.02.1985	Cantonal forest law	Every action that can cause fire damage in forests is prohibited. Fires in forest are only allowed in specific places. All fires must be extinguished before leaving the area. The forest service can forbid fires in forests. The cantonal government can prescribe prevention measures if necessary.

Date	Legislative act	Preventive measures
21.06.1990	Application rules of the cantonal forest law	Prohibition of burning waste material in open land, apart from natural waste material in remote regions.
12.12.2001	Cantonal executive decree	Prohibition of grass and shrubland burning.
12.12.2001	Application rules of the cantonal law concerning the protection against fire and natural hazards	Delimitation by municipalities of perimeters where grass and shrublands cleaning by pasturing or cutting is mandatory.
20.06.2007	Cantonal executive decree	Prohibition of burning any kind of waste material in open land.

The first organizational measures that proved to anticipate or at least coincide with a change point in the fire regime are related to the decrease in the burnt area in the colline region of canton Ticino starting in the 1980s (Fig. 5.5). We assume that the main driving forces behind this change period were the reorganization of fire brigades with the law of 1976, and the related executive regulation of 1978 that called for the creation of specific forest fire brigades, as well as the transfer of the responsibility for the civil fire brigades from the municipal to the cantonal level (Table 5.4). Thanks to this new hierarchical organization, the benefits of the concomitant improvement in aerial fighting facilities and techniques were maximized (Conedera *et al.* 2004). This in turn soon resulted in a reduction in the mean fire size of single events and in the total amount of burnt area as opposed to the total number of fires (Conedera and Pezzatti 2005).

Concerning fire prevention (that is reduction of fire frequency), the most efficient legal acts resulting in a reduction in the number of fire ignitions are most likely those regarding the interdiction in canton Ticino of burning garden debris in the open (Cantonal decree approved on October 21, 1987, but operational with the corresponding penalties since January 1, 1989) and the prohibition of fireworks and celebration fires during the Swiss National Day of August 1st when a fire danger alarm is effect (Cantonal decrees of July 11, 1990). This has led to a drop in fire frequency in the colline region despite no significant changes in fire weather and a slight increase in the growth-rate of the forest area (Fig. 5.5). At higher elevations (TI-sub), no such effect has been detected. This is probably due to the relatively fire-prone summer weather in the last decade (see KBDI-index in Fig. 5.5) and the still significant increment in forest area (Brändli 2010). Last but not least, the consistent amount of lightning fires at higher elevation (Conedera *et al.* 2006) and the partial revision of the decree prohibiting the burning of garden debris in the open (abrogated in 1998 at elevations above 600 m a.s.l. for practical reasons - Table 5.3), probably not only inhibited a similar evolution but caused instead a positive change in fire frequency (Fig. 5.5).

6 Conclusions

The change point approach tested in this paper proved to be a suitable tool for detecting shifts in fire regimes, which could partially solve the problem raised by Krebs *et al.* (2010) of discriminating between the normal variability within a fire regime and a significant shift in a fire regime.

As expected, the simple CUMSUM index was sensitive to outliers and thus less suitable than the Pettitt indices. In particular, the running Pettitt option seems to be an useful alternative since it can condensate, in one single plot, the most relevant information when an appropriate bin width is chosen.

Concerning the study areas, it was possible to demonstrate how changes in fire regimed did not occur simultaneously in Ticino and Valais, and that the mechanisms behind fire frequency and burnt area likely differ in these two cantons. This confirms that every region – even neighboring ones – has its own specific fire-historical context, and thus emphasizes the need for local fire history studies in order to better understand fire regimes. For the less fire-prone canton of Valais major driving forces that yield positive shifts (increasing fire frequency or burnt area) in fire regimes are of climatic and socio-economic origin, whereas legislative acts never had a direct impact on fire regimes. On the other hand, in the fire-prone Canton of Ticino, besides climatic and socio-economic triggers, fire policy measures also contributed to detectable changes in the fire regime. In particular, fire legislative measures led to reduced fire frequency, whereas improvements in firefighting organization and strategies resulted in a reduction of burnt area. Paradoxically, the most efficient measure in terms of fire prevention is represented by a decree prohibiting the burning of garden debris in the open which was originally aimed at preserving air quality. Fire events are a relatively rare and inconstant phenomenon. Consequently, the needed political support for specific fire legislation can only be achieved during catastrophic years. This was the case only once in the Canton of Ticino after the catastrophic fire year of 1973 that stimulated a successful reorganization of the fire brigades. One major lesson that can be taken from the study case of Canton Ticino is that only though absolute fire bans it is possible to detect a significant reduction in fire ignition frequency. Temporary or not absolutely mandatory fire policy measures related to the interpretation of short term fire weather situations often fail because of the inadvertence of the people.

The present study also highlights the importance and the suitability of long term statistical fire data that would allow retrospective analyses on the effectiveness of past legislative and organized fire controlling efforts.

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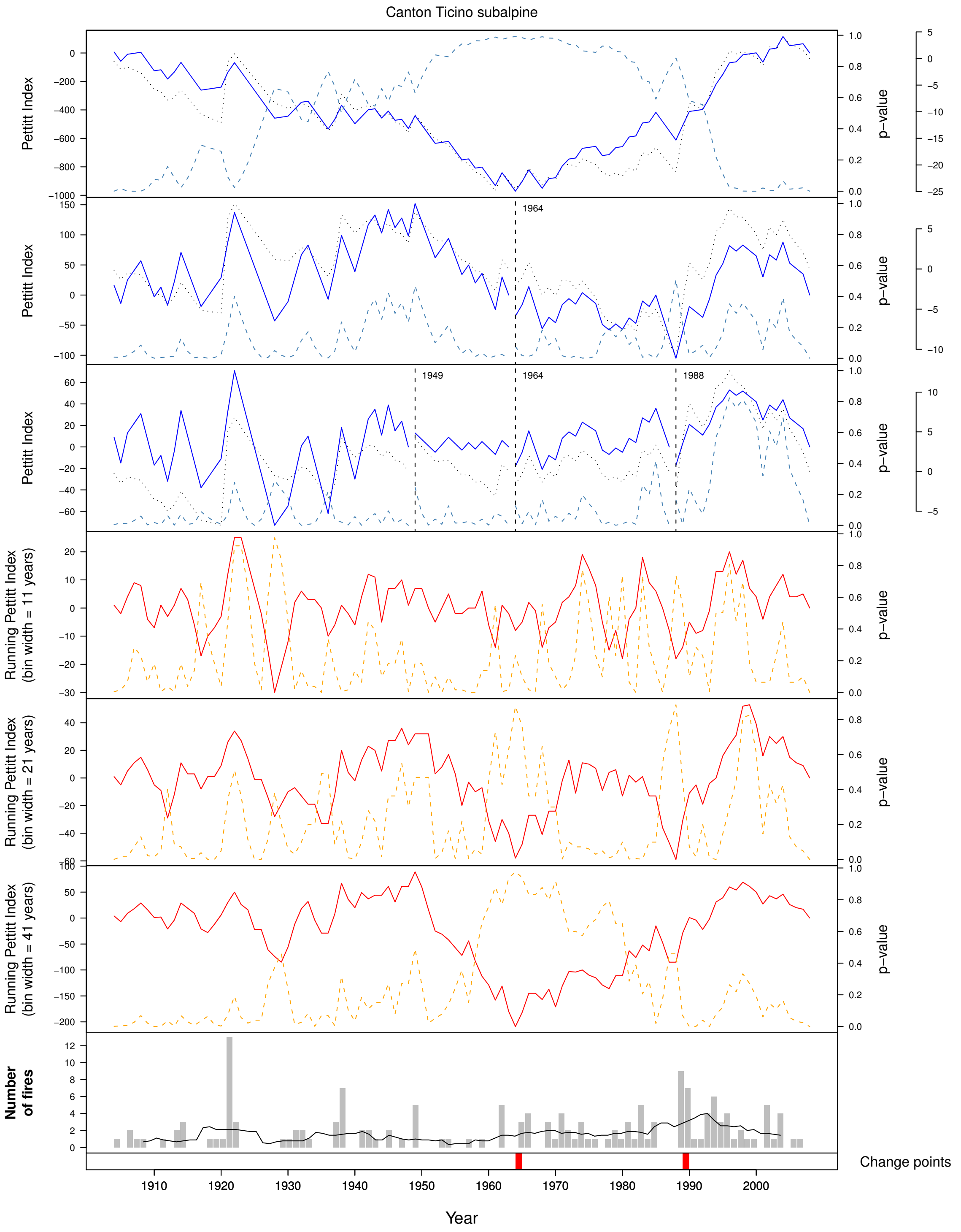
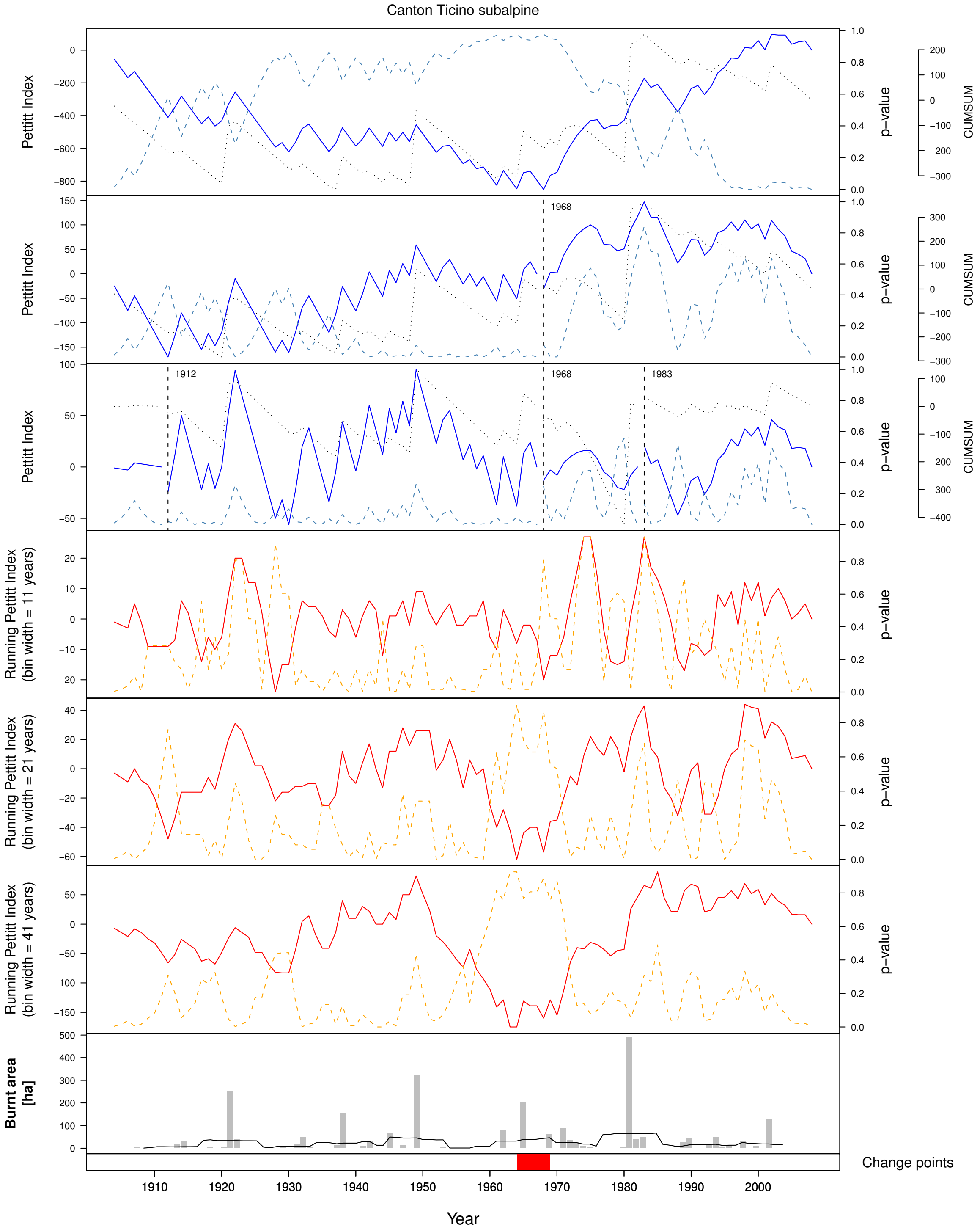
Supplementary material

Appendix 1. Change point analysis for the frequency of forest fires in Canton Ticino at the supalpine level since 1904.



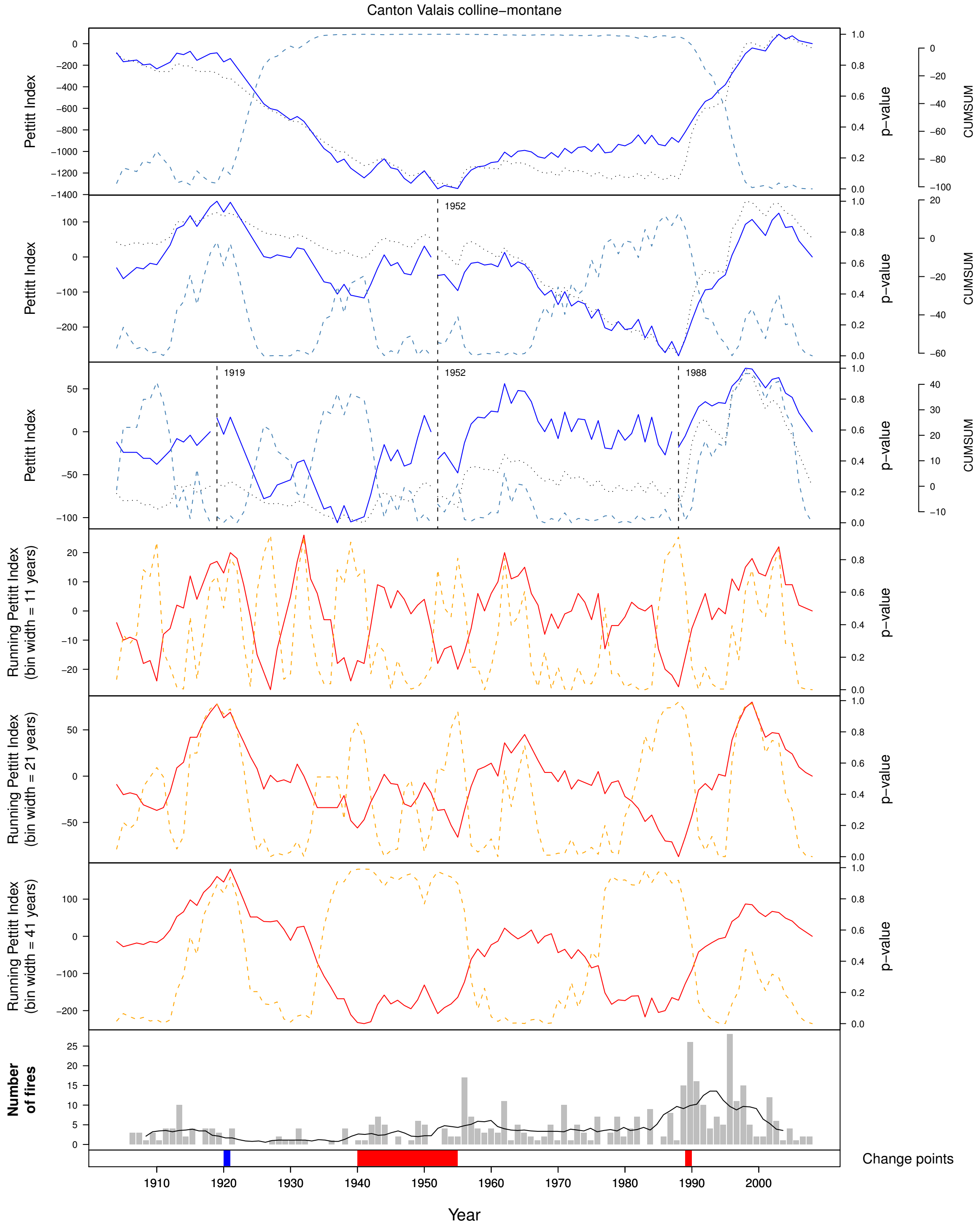
The first three plots show a Pettitt stepwise approach, while the fourth to sixth plots show a running Pettitt index according to different reference periods (respectively 11, 21 and 41 years). Plain lines represent the Pettitt index in all but the last plot, where the line shows a running mean on 9 years; the dotted lines represent the cumulative sums of deviations (CUMSUM) and the dashed lines the p-values indicating the approximate probability of a change point.

Appendix 2. Change point analysis for the burnt area in Canton Ticino at the subalpine level since 1904.



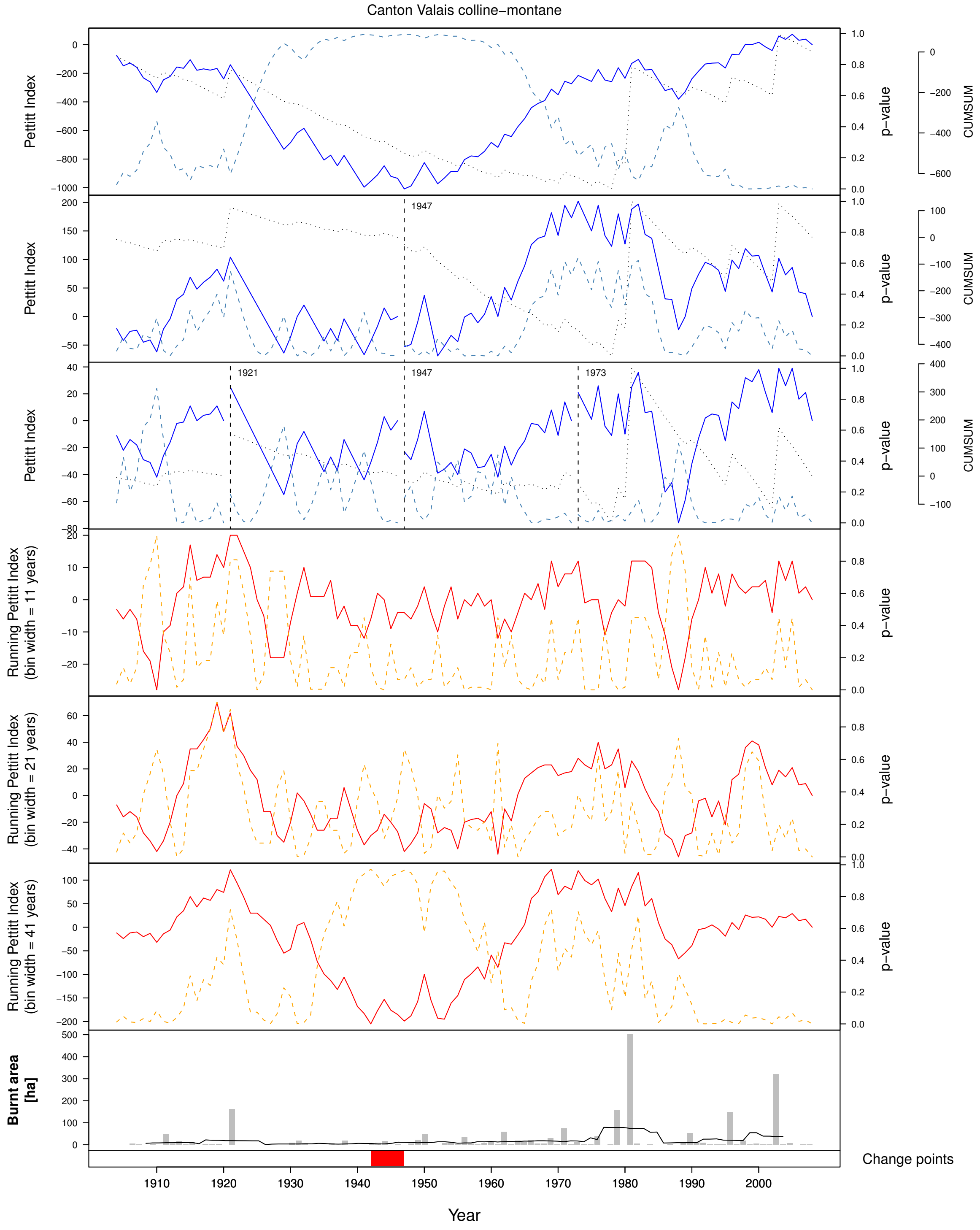
The first three plots show a Pettitt stepwise approach, while the fourth to sixth plots show a running Pettitt index according to different reference periods (respectively 11, 21 and 41 years). Plain lines represent the Pettitt index in all but the last plot, where the line shows a running mean on 9 years; the dotted lines represent the cumulative sums of deviations (CUMSUM) and the dashed lines the p-values indicating the approximate probability of a change point.

Appendix 3. Change point analysis for the frequency of forest fires in Canton Valais at the colline-montane level since 1904.



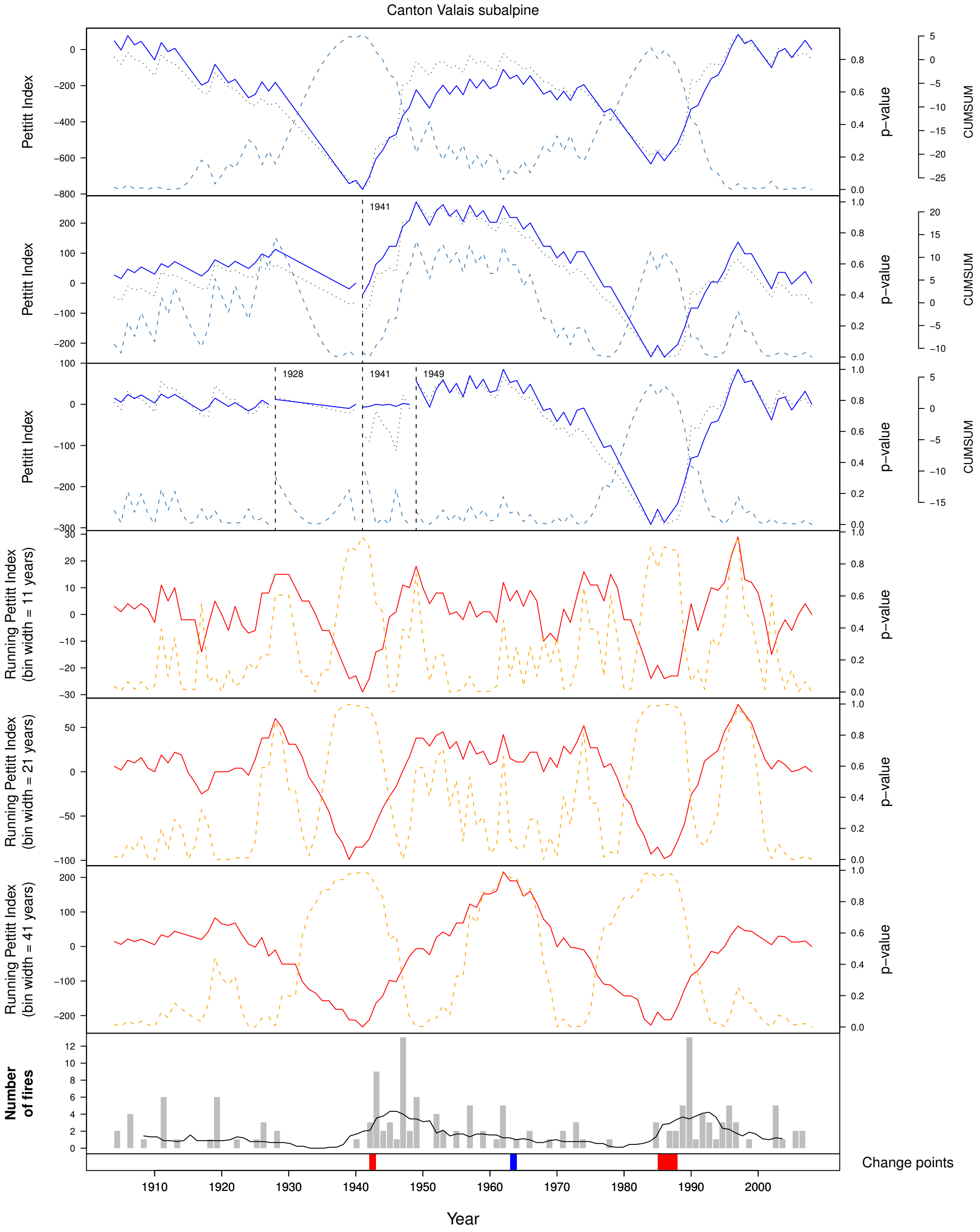
The first three plots show a Pettitt stepwise approach, while the fourth to sixth plots show a running Pettitt index according to different reference periods (respectively 11, 21 and 41 years). Plain lines represent the Pettitt index in all but the last plot, where the line shows a running mean on 9 years; the dotted lines represent the cumulative sums of deviations (CUMSUM) and the dashed lines the p-values indicating the approximate probability of a change point.

Appendix 4. Change point analysis for the burnt area in Canton Valais at the colline-montane level since 1904.



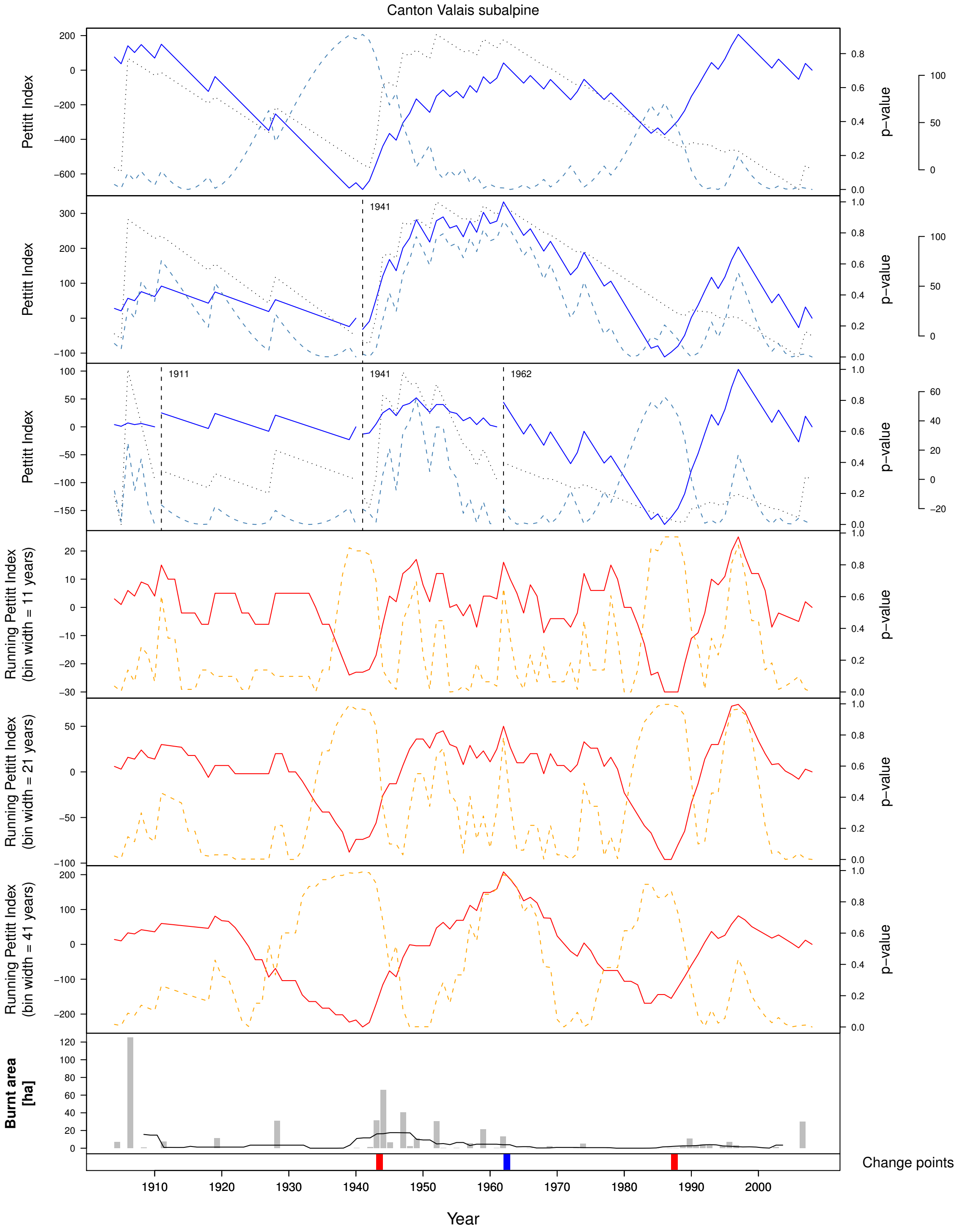
The first three plots show a Pettitt stepwise approach, while the fourth to sixth plots show a running Pettitt index according to different reference periods (respectively 11, 21 and 41 years). Plain lines represent the Pettitt index in all but the last plot, where the line shows a running mean on 9 years; the dotted lines represent the cumulative sums of deviations (CUMSUM) and the dashed lines the p-values indicating the approximate probability of a change point.

Appendix 5. Change point analysis for the frequency of forest fires in Canton Valais at the subalpine level since 1904.



The first three plots show a Pettitt stepwise approach, while the fourth to sixth plots show a running Pettitt index according to different reference periods (respectively 11, 21 and 41 years). Plain lines represent the Pettitt index in all but the last plot, where the line shows a running mean on 9 years; the dotted lines represent the cumulative sums of deviations (CUMSUM) and the dashed lines the p-values indicating the approximate probability of a change point.

Appendix 6. Change point analysis for the burnt area in Canton Valais at the subalpine level since 1904.



The first three plots show a Pettitt stepwise approach, while the fourth to sixth plots show a running Pettitt index according to different reference periods (respectively 11, 21 and 41 years). Plain lines represent the Pettitt index in all but the last plot, where the line shows a running mean on 9 years; the dotted lines represent the cumulative sums of deviations (CUMSUM) and the dashed lines the p-values indicating the approximate probability of a change point.

Synthesis and conclusions

1 The fire regime and its driving factors in Valais

A consistent reconstruction of the fire regime over the study period (~1904-2008) based on archival sources was achieved in the framework of the present study. Compared to the previous forest fire inventory (*cf.* Gimmi *et al.* 2004), we were able to slightly increase the number of fires registered in the study area, and we refined the information about already registered fires. A major improvement was in particular to localize numerous fire events, which was a *sine qua non* condition for identifying spatial patterns of the fire regime in Valais, and thus performing area-specific analyses.

This study demonstrated the occurrence of different fire regime patterns and driving forces within a comparatively small area. We found distinct differences in the fire regime along an altitudinal gradient. Specifically, fire seasonality was characterized by a peak in August at high elevations, while most fires at lower elevations occur in March-April. At high elevations, the fire regime – particularly fire frequency and seasonality – appears to have been driven mainly by temperature and precipitation, while these two variables played only a secondary role at low elevations, where the influence of foehn winds and other non-climatic factors such as fuel load and human ignitions were probably more important. We also found a west-east gradient in the fire regime. The occurrence of large fires was concentrated in a perimeter located approximately between Sierre and Brig, *i.e.* the driest area of Valais, and seems to have been favored by the low amount of precipitation due to continentality in combination with foehn winds, which are regionally constrained. In other parts of the Rhone valley, large fires were rare.

Potential changes in the fire regime were also investigated under a temporal perspective. No significant changes in median fire frequency and annually burnt area were conspicuous between the first and the second half of the study period, although fluctuations were recorded, in particular due to increases in the number of fires in the 1940s and 1990s and the occurrence of "very large" fire events since the end of the 1970s. As fire frequency and burnt area are two essential components of the fire regime, it would be inappropriate to assert that the fire regime has fundamentally changed over the study period in Valais. However, changes in fire seasonality are visible, as fires tended to take place in summer during the first decades of the study period, whereas the fire season extended to spring during the later 20th century, likely due to the shift of human activities, and thus fire activity, to lower elevations.

We found that temperature, precipitation and drought severity 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 climate warming, clearly evident from the meteorological records in Valais, has not caused an increase in fire frequency and burnt area so far, in contrast to what might have been expected given the results of studies conducted in other regions (*cf.* Moreno *et al.* 1998, Pausas 2004, Westerling *et al.* 2006).

Besides climate/weather, anthropogenic factors also have played a key role in shaping fire occurrence in Valais during the past hundred years, as people tend to be involved not only in starting fires but also in removing fuel. While the provision of ignition sources by humans was of relevance throughout the study period, fuel removal by pasturing of livestock in the forests seems to have reduced fire occurrence during the first decades of the 20th century. Moreover, wood harvesting also had a negative impact on fire occurrence when the use of wood as domestic energy source was widespread. These results suggest that fuel load is an important driver of the fire regime in Valais, and that the removal of biomass by human-related activities has an impact on the fire regime, as it was also observed elsewhere in Europe and North America (Savage and Swetnam 1990, Irwin *et al.* 1994, Heyerdahl *et al.* 2001, Fry and Stephens 2006, Kalabokidis *et al.* 2007) .

Based on these findings, *i.e.* regarding the effects on fire activity of climate and humans, two distinct pyrological contexts can hence be defined. We postulate that the first half of the study period was a period of fuel scarcity and moderate fire weather, where the fire regime was mostly influenced by the occurrence of severe drought periods. This is somewhat similar to what can be found in many subalpine and boreal forests where the fire regime is mainly climate-driven (Agee 1993, Carcaillet *et al.* 2001, Johnson *et al.* 2001, Baker 2003, Sibold *et al.* 2006). By contrast, during the second period fuel was more abundant and appropriate fire weather more frequent. Fire occurrence during this period was limited by ignition sources, as dry fuels were often available in abundance. This pattern is comparable to that found in many Mediterranean ecosystems where dry biomass and human ignitions are the major drivers of fire regimes (Keeley *et al.* 1999, Keeley and Fotheringham 2001, Montenegro *et al.* 2004, Romero-Calcerrada *et al.* 2008). Changes in fire regimes or in the determining factors due to changing socioeconomic contexts, land abandonment and increasing fuel load/flammability have also been found in other regions in Europe, above all in the Mediterranean basin (Moreira et al. 2001, Mouillot et al. 2003, Romero-Calcerrada and Perry 2004).

2 Differences in the fire regime between the cantons of Valais and Ticino

Our reconstruction of fire history in the Valais shows that the number of fires and the burnt area were, and still are, much smaller in comparison with other areas, for instance neighboring regions like the Val d'Aoste (Italy; Bovio 2000) or the canton of Ticino (Switzerland; WSL 2008). In Ticino, during the period 1904–2008, the forest fire density was 4 fires/km^2 of forest area, but only 0.85 in Valais. During the same period in Ticino, 43 ha/km^2 of forest area have burnt, but only 2.5 in Valais.

Regarding the existence of differences in the driving factors in these two cantons, the present study was not entirely conclusive. Some similarities were found, for instance regarding the response patterns of fire occurrence against selected driving factors. In particular, the responses to the densities of livestock and roads were comparable in both cantons. However, important dissimilarities were conspicuous as well. For instance, the evaluation of various daily fire weather indices showed that most of them were unable to predict properly fire occurrence in both Valais *and* Ticino, thus implying that the mechanisms of short-term weather control on fire differ in the two cantons. This corresponds to the earlier findings of other studies, in particular Weibel (2009) for Switzerland and Viegas *et al.* (2009) for different countries in Europe, concluding that transferring fire weather models from one region to another was problematic, mainly because each had distinct weather conditions and forest composition.

Moreover, determining the change points in the time lines of fire frequency and annually burnt area during the study period reveals some differences. The changes in fire frequency and burnt area did not occur simultaneously in Valais and Ticino. As most anthropogenic and/or climatic factors follow roughly the same temporal patterns in Ticino and Valais, these differences imply that the incidence of the determining factors over time on both fire frequency and burnt area must have been different. This finding is in line with other studies comparing contiguous regions in North America where land use/human activities have been found to result in different fire regimes over time, *e.g.* Minnich (2001) in California and Lefort *et al.* (2003) in eastern Canada.

3 Methodological considerations

As the present study is based on documentary evidence, the sources and data used have to be viewed with caution. Particular attention should be paid to the comprehensiveness of the data and their quality, as some variations in the fire regime, and consequently the nature of the relationships between fire and driving factors, may possibly have been established erroneously due to a biased dataset.

Concerning the comprehensiveness of the data, it seems unlikely for several reasons that a substantial amount of fires is lacking in the dataset used here. Indeed, it has been stipulated in the forest laws of Valais since the end of the 19th century that forest service officials must report every observed forest fire[1]. As Valais is densely settled and areas without a minimal human presence are very rare below upper treeline, it is highly improbable that many fires have gone unnoticed and were not reported. This view is supported by the fact that fire frequency has remained constant over the period studied, although one might have expected that, because of an improving reporting and archiving of fire events over time, fire frequency might have been artificially smaller at the beginning of the study period than at its end.

However, effects of an improvement of data quality over time are clearly visible in the dataset. Most fires that took place during the last decades of the study period are relatively well described regarding the time and place of ignition, whereas the corresponding information regarding the fires of the first half of the 20th century is often imprecise or even lacking entirely. For instance, numerous fires during that period lack a precise ignition date or exact geographical coordinates. While it was possible in this study to reconstruct many coordinates based on place names that were mentioned in the records, it was unfortunately impossible to refine those start dates that were given at a monthly or annual level only.

The lower data quality at the beginning of the study period together with the limited overall number of fires (~900) in the study region limited the choice of potential analyses. For example, dividing the dataset for comparative analyses into short time periods or small perimeters was strongly restricted by the small number of fires. Likewise, we were not able to perform analyses requiring fires with day-precise information for the first half of the study period although they could be very useful for investigating fire-weather relationships (Bessie and Johnson 1995).

The acquisition of data about the driving factors of fire activity was also particularly challenging, even though such a task is of course inherent to all historical-ecological investigations. Very few data were covering the entire study period and region, restricting thereby the amount of variables that could be selected. Moreover, the variables fulfilling this condition did not always have appropriate spatial and temporal resolution. Some variables with a high spatial resolution (*e.g.* reconstructed forest area and road coverage) had a very low temporal resolution, and time series for these variables had to be built by inter- and extrapolating between a few known values. On the other hand, other variables with a higher temporal resolution had a much lower spatial resolution, *e.g.* on the municipal level (human population and livestock densities).

The coarse resolution of the fire data was thus a major limitation of the present study, as it was not possible to perform highly detailed analyses and comparisons on small spatial and temporal scales. However, we were able to reconstruct and analyze the fire regime in Valais over a time period long enough to capture features that are likely representative of the fire regime in Valais. A study considering shorter time windows, *e.g.* a few decades as done in many fire studies, would have been less suitable for catching the variability of the fire regime. In conclusion, in the case of Valais, the loss of fire data precision due to the long study period

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[1] Règlement forestier d'application de la loi forestière cantonale (May 27, 1873; art. 9 and 19) and subsequent cantonal forest laws (1910 and 1985).

is counterbalanced by the gain of a much more complete picture of the fire regime, which is essential for better understanding its determinants.

Besides the temporal aspect of the fire regime, spatial considerations are of high relevance as well. Although the definition of a fire regime is spatially scale-free, as it merely consists of the typology of fire activity in a certain area or ecosystem, fire regimes are usually described and investigated for large reference perimeters, typically several hundreds to thousands of square kilometers, *i.e.* areas much larger than our study perimeter. However, the present study highlighted important variations in the fire regime on small spatial scales, and thus demonstrated the presence of sub-regimes within Valais. This leads us to conclude that there is no simple, uniform fire regime in Valais, and that the variations in fire activity in space and (to a certain extent) in time are probably as high as the variations in the driving factors. This conclusion, associated with the differences regarding fire activity and fire drivers found between Ticino and Valais, has two important implications. First, it confirms the local specificity of fire histories and the lack of transferability of findings from one area to another, including neighboring areas, as every region is characterized by its specific fire-historical context. This underlines the need for local fire studies in order to achieve a better understanding of forest fires. Second, it suggests that particular attention should be paid to choosing a reference area when assessing fire danger and/or potential fire prevention/fighting measures, as assessments based on too large spatial windows may be misleading due to the heterogeneity in the fire regime.

4 Practical implications and outlook

Although Valais is characterized by a modest fire activity compared to other regions globally, and forest fires have not been considered as a major issue for landscape management in the past, they represent a threat for humans and infrastructures that has to be addressed. Over the last years, forest fires in Valais have become a major concern for the authorities and the forest service, as demonstrated by the recent development of a cantonal strategy for preventing and fighting forest fires (Canton du Valais 2009).

In this context, the development of appropriate fire management strategies requires a detailed and in-depth knowledge of fire history, as well as of past and current relationships between forest fires and their driving factors. Acquiring the necessary knowledge can only be achieved if detailed data are available. However, although forest fires have always been recorded in Valais, a detailed, rigorous and systematic reporting methodology has been lacking until recently. The development of the Swiss Fire Data Base (WSL 2008) and the recent involvement of Canton Valais in this project a few years ago may contribute to resolving this drawback. A considerable improvement regarding fire management in Valais would thus be to better report fires by precisely determining fire characteristics, such as fire type, extent, intensity, but also environmental conditions such as fuel and/or soil properties, in order to be better able to investigate, analyze and predict forest fire occurrence and behavior.

It was not the primary objective of the present work to provide practical recommendations for fire management purposes. Also, the analyses performed here were based on a coarse spatial and temporal resolution, thus rendering practical recommendations difficult. Nevertheless, it is possible to outline general practical implications from the results of the present thesis, as detailed below.

First, we were able to confirm that forest fires in Valais depend greatly on anthropogenic factors. Therefore, they cannot be simply considered as a natural disturbance, but they must be viewed as a human-induced factor that is strongly conditioned by the socio-cultural circumstances. Thus, there is much room for mitigating fire risk and specific properties of the fire regime, such as the area burnt.

Second, Valais can be subdivided into regions that are characterized by distinct fire regimes, which in turn are characterized by distinct driving factors. This calls for planning and implementing region-specific prevention and pre-suppression measures, rather than one unified strategy for the entire area. For instance, optimizing legal amendments, fire surveillance and availability/preparedness of fire fighting resources may be achieved better by taking into account the nature of fires, *e.g.* spring wind-driven or summer drought-driven fires, or fire regime characteristics such as fire density and fire size distribution in specific regions or seasons.

Third, the present study suggests that fuel load plays an important role for fire occurrence. Since there is still a large potential for forest expansion on former agricultural areas, fuel reduction measures may be envisaged in specific, particularly fire-prone parts of Valais. Similarly to the prescribed burning undertaken in other fire-prone regions in order to restrain fire intensity and extent (Haines *et al.* 2001), reintroducing or mimicking wood pasturing in order to maintain low fire frequency and burnt area may be an option. Biomass increase in forests and forest expansion in Valais due to the abandonment of agricultural activities and traditional forest uses is not only an issue for forest fire prevention, but also for other ecological issues such as shifts in tree species composition and losses in habitat and species richness (*cf.* Gimmi 2006, Gellrich *et al.* 2007). Thus, considerable opportunities for exploiting synergies exist.

Lastly, the present study demonstrated that changes in the fire regime and in the relevance of its driving factors can occur within a few decades. Therefore, the validity and the pertinence over time of the measures undertaken for addressing forest fire issues should be assessed on a regular basis and adjustments may need to be undertaken, in particular in the new context of rapidly changing environmental conditions (*e.g.* Schumacher and Bugmann 2006). The predicted increase in temperature and in the frequency of drought periods and the resulting changes in vegetation composition and biomass production have the potential to result in strong changes in the complex interactions between fire activity and its driving factors, and thus in changes in the spatiotemporal pattern of the fire regime in Valais.

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