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Modelling and assessing fire regimes in mountain forests of Switzerland

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Summary

Forests provide important goods and services to humans, but these ecosystems will undergo strong changes regarding their importance and thus need to be studied with respect to ecosystem processes and the interactions between their biotic and abiotic components. Forest fires are an important disturbance agent in many forested landscapes today, and anthropogenic climate change is likely to increase their importance because of warmer conditions and shifts in precipitation patterns. Forest fires are characterised by three main processes: frequency of fire ignitions, rate of fire spread and thus fire size, and fire effects depending on severity. Many factors affect these processes, such as weather and climate, vegetation, land use, topography, and human activities. Thus it is not surprising that the relationships between climatic changes, forest dynamics, and forest fire regimes are not fully understood.

Thus, the overall aim of this thesis is to better understand the fire regimes of the past decades in two regions of the southern Swiss Alps by modelling and assessing the relevant processes, factors, and relationships.

The first part of this thesis considers lightning- and human-induced forest fires separately and aims to evaluate the relative importance of weather conditions, forest composition and human activities for the occurrence of forest fire ignitions in the most fire-prone region of Switzerland, the Ticino. The independent variables include 14 drought and fire weather indices representing weather conditions, forest composition as a measure of fuel characteristics and distance to infrastructure as a proxy for the intensity of human influences. These independent variables are related to daily records of forest fires over a 37-year study period (1969-2005) using logistic regression models. The results show large differences in the importance of environmental and human controls on forest fire ignitions between lightning- and human-induced events: lightning-induced forest fires occur in a small range of weather conditions and without an appreciable influence of human activities, whereas human-induced fires occur in a broader range of weather conditions, where the proportion of deciduous forest stands is high, and they strongly correlate with distance to human infrastructure. Thus, the suitability of drought and fire weather indices varies dramatically with ignition source, which is an important factor in addition to known environmental and human controls of forest fire occurrence.

As fire models are often developed to be used outside the specific area or climatic conditions for which they have been calibrated, e.g. under scenarios of future climate, their general validity is investigated in the second part. The focus is on logistic forest fire ignition models for Ticino and Valais, two regions in southern Switzerland that feature distinct climatic conditions. Using high-resolution data, two subsequent 16-year periods from 1974-2005 are evaluated. Models containing the Angstroem Index for human-induced forest fires and the Keetch and Byram Drought Index or the LandClim Drought Index for lightning-induced forest fires are reasonably transferable in time within a given study region. In contrast, transfer in space between study regions is not possible. Thus, the transferability of forest fire ignition models is strongly limited and should be evaluated before using such models in research and in practice to assess e.g. the impacts of global change on forests and forest fires.

In the third part, the landscape model LandClim is further developed by incorporating the results from the first two parts of this thesis in its fire module. The improvements include several modifications and extensions: calculation of daily drought index values; incorporation of the Angstroem index; modification of the exponential function that converts drought index values into fire probabilities to a sigmoidal translation function; and the introduction of minimum and maximum fire probabilities. With these improvements, the LandClim model is tested and evaluated in two sub-regions, the Leventina in Ticino and the south central Valais, for the period 1970 to 2000, showing a good match between observed and simulated numbers of forest fires and fire size distributions. The model improvements result in appreciably better model performance. Thus, the landscape model LandClim is a good candidate for further model tests (e.g. in other biogeographical regions) and, eventually, for studying the implications of climate change on forest fire occurrence in mountain forests.

Zusammenfassung

Wälder erbringen für die Menschen wichtige Leistungen, doch diese Ökosysteme sind starken Veränderungen hinsichtlich ihrer Bedeutung unterworfen. Deshalb ist es wichtig, Wälder im Bezug auf Ökosystemprozesse und auf Wechselwirkungen zwischen der belebten und der unbelebten Natur zu untersuchen. Bereits heute sind Waldbrände in vielen bewaldeten Gebieten ein wichtiger Störfaktor, und es kann erwartet werden, dass ihre Bedeutung durch die vom Menschen verursachte Klimaveränderung noch ansteigen wird. Dies kann mit erhöhten Temperaturen und Verschiebungen in den Niederschlagsmustern erklärt werden. Wäldbrände werden im Allgemeinen durch drei Prozesse beschrieben: die Häufigkeit der Feuerauslösung, die Feuerausbreitung – also die Grössen der Brände – und die Feuerauswirkung, die von der Intensität abhängig sind. Eine ganze Reihe von Faktoren, wie Wetter und Klima, Vegetation, Landnutzung, Topographie sowie die vielfältigen Aktivitäten von Menschen, beeinflusst diese Prozesse. Daher erstaunt es nicht, dass das Wissen über die Zusammenhänge zwischen Klimaveränderung, Waldentwicklung und Waldbränden unvollständig ist.

Das Hauptziel dieser Doktorarbeit besteht darin, Waldbrände in zwei Regionen der Schweizer Südalpen – in den Kantonen Wallis und Tessin – besser zu verstehen, indem die relevanten Prozesse, Einflussfaktoren und Zusammenhänge während den letzten Jahrzehnten untersucht und modelliert werden.

Im ersten Teil der Arbeit werden Blitzschlagbrände und von Menschen ausgelöste Waldbrände getrennt betrachtet. Dabei werden im Kanton Tessin – in der am meisten von Waldbränden betroffenen Region der Schweiz – Faktoren untersucht, die für das Auftreten von Waldbränden verantwortlich sind: das Wetter, die Waldzusammensetzung und die menschlichen Aktivitäten. Als erklärende Grössen werden 14 Trockenheits- und Feuer-Wetter-Indizes verwendet, welche die Witterungsbedingungen repräsentieren. Dazu kommen die Waldzusammensetzung als Mass für das Brandgut, sowie die Distanz zu menschlicher Infrastruktur als Mass für die Intensität des menschlichen Einflusses. Um die Einflüsse dieser Faktoren auf das Auftreten von Waldbränden zu untersuchen, werden für die 37 Jahre umfassende Untersuchungsperiode (1969-2005) tägliche Waldbranddaten sowie logistische Regressionsmodelle verwendet. Die Ergebnisse dieser Untersuchungen zeigen für die beiden Brandursachen grosse Unterschiede in der Bedeutung der verschiedenen Umweltfaktoren und der menschlichen Faktoren: Blitzschlagbrände treten unter sehr spezifischen Wetterbedingungen auf und sind nicht von menschlichen Aktivitäten abhängig; von Menschen ausgelöste Waldbrände hingegen sind nicht von bestimmten Wetterlagen abhängig, treten häufiger in Laubwäldern auf und sind stark korreliert mit menschlichen Aktivitäten. Der erste Teil dieser Arbeit zeigt, dass neben bekannten Umweltbedingungen, wie Klima, Wetter und Brandgut, auch die Brandursache mitentscheidend dafür ist, welche Trockenheits- und Feuer-Wetter-Indizes besonders gut geeignet sind, um das Auftreten von Waldbränden zu beschreiben.

Die allgemeine Gültigkeit von Waldbrandmodellen wird im zweiten Teil der Arbeit untersucht. Dies ist wichtig, weil Modelle oftmals für eng begrenzte Bedingungen entwickelt werden, dann aber ausserhalb dieses Geltungsbereichs oder unter anderen klimatischen Bedingungen (z. B. für zukünftige Klimaszenarien) angewendet werden. Die allgemeine Anwendbarkeit von logistischen Regressionsmodellen für Waldbrandauslösung wird hier in den zwei klimatisch verschiedenen Kantonen Wallis und Tessin sowie in zwei aufeinander folgenden 16-Jahre-Perioden von 1974-2005 geprüft. Die verwendeten Daten sind räumlich und zeitlich hochauflösend. Für Waldbrände, die von Menschen ausgelöst wurden, sind Modelle mit dem Angstroem-Index zwischen den Perioden übertragbar. Modelle für Blitzschlagfeuer mit dem Keetch und Byram Trockenheitsindex oder dem LandClim Trockenheitsindex sind zwischen den Perioden ebenfalls übertragbar. Für beide Brandursachen ist die Übertragbarkeit der Modelle zwischen den Regionen hingegen nicht möglich. Daraus lässt sich schliessen, dass die Gültigkeit von Modellen zur Waldbrandauslösung stark eingeschränkt ist und im Einzelfall untersucht werden muss, bevor solche Modelle in der Forschung oder in der Praxis angewendet werden. Dies gilt insbesondere auch, wenn der Einfluss von Klimaveränderungen untersucht werden soll.

Im dritten Teil der Arbeit fliessen die Erkenntnisse aus den beiden vorhergehenden Teilen in die Weiterentwicklung des Waldbrandmoduls im Landschaftsmodell LandClim ein. Diese Weiterentwicklung umfasst verschiedene Anpassungen und Erweiterungen: die Werte der Trockenheitsindizes werden täglich berechnet; der Angstroem-Index wird integriert; die exponentielle Funktion, welche die Werte der Trockenheitsindizes in Feuerwahrscheinlichkeiten umrechnet, wird in eine sigmoide Funktion umgewandelt; schliesslich wird die Feuerwahrscheinlichkeit im unteren und oberen Bereich begrenzt. Das weiterentwickelte LandClim wird im südlichen Zentralwallis und in der Leventina (Tessin) getestet. Für den Zeitraum 1970-2000 zeigen die Simulationen eine gute Übereinstimmung mit der beobachteten Anzahl von Waldbränden und der beobachteten Feuergrössenverteilung. Dank der Weiterentwicklungen erzielt LandClim dabei merkliche Verbesserungen der Modellgüte. Somit ist das Landschaftsmodell LandClim ein geeigneter Kandidat für weitere Tests (z. B. in anderen biogeographischen Regionen) und allenfalls

auch um die Auswirkungen von Klimaveränderungen auf Waldbrände in Gebirgswäldern zu untersuchen.

General introduction

Background

Forests cover almost one-third of the earth's continental surface (FAO 2006) and are of particular significance for humans, from global to local scales, by providing a wide range of goods and services (de Groot *et al.* 2002; Huber *et al.* 2005). For example, in the global cycle of matter, forests are an eminent agent as storage for carbon and water; at the local and regional scales, their functions include production of wood, protection against natural hazards, opportunities for recreation and touristic relevance, and many others.

The properties of forest landscapes, which are pivotal to the provision of many ecosystem goods and services, result from the intricate and interrelated effects of small-scale successional processes, the physical environment (e.g. soils, topography, climate), and large-scale disturbance events (Wohlgemuth et al. 2002). Among the various natural disturbances, forest fires are one of the key drivers of vegetation development in many regions of the world (Thonicke et al. 2001), as they strongly shape landscape structures, such as the proportion of stands in each stage or stand age, and they determine species composition (Patterson and Backman 1988; Frelich 2002). For example, from 1950 to 2000 an annual average of 35 million m^3 of wood was damaged in European forests by disturbances, and fires were responsible for 16% of this total damage (Schelhaas et al. 2003); thus, fires are among the prominent disturbance agents in terrestrial ecosystems also in Europe, and certainly worldwide (Bond and van Wilgen 1996).

Fire regimes

Forest fire regimes comprise the patterns of fire frequency (i.e. occurrence as defined by the number of ignitions), fire sizes (which crucially depend on landscape patterns, topography, and rates of spread), and fire effects (Johnson 1992) for a given area and over a defined period of time. They can be visualized in a conceptual framework (Figure 1) indicating the main processes and relations. Weather and climate play an important role for the control of fire ignitions and fire spread (Johnson 1992). Temperature and precipitation are directly linked to fuel moisture (Littell et al. 2009), and wind is a direct driver of the rate of fire spread (Viegas 1998; Keeley and Fotheringham 2001). All these weather-related factors act on short time scales, i.e. from minutes to days. Fuel properties such as fuel moisture (Viegas et al. 1992), fuel load, and diameter distribution (Hall and Burke 2006) influence fire ignition and rate of spread and depend on forest type, which can be used as a proxy for fuel flammability (Cumming 2001). The relative importance of weather vs. fuel conditions for shaping the fire regime is still debated. Several studies have suggested that climate is the key factor determining forest fires especially on time scales of days (e.g. Carcaillet *et al.* 2001; Whitlock *et al.* 2003). Bessie and Johnson (1995) argued that the relative importance depends on the variability of weather and fuel. In their study area, weather conditions were much more variable over time than fuels were among stands. Thus, with the high variation in weather conditions, this factor determined fire occurrence dominantly, i.e. under extreme drought conditions fires ignited independently of stand type, whereas under wet conditions no fires ignited in any stand type. If weather conditions were not extreme, the only important influence of fuel was the variation in fuel loads among stands of differing forest type (Bessie and Johnson 1995). On time scales of years, however, the influence of vegetation type became more crucial. For example, the fraction of coniferous- and deciduous-dominated stands in a mixed-wood boreal forest was more important for the occurrence of forest fires than weather characteristics (Krawchuk et al. 2006). Thus, the relative importance of weather and forest composition depends on the spatial and temporal scale considered, and it may differ between regions with different patterns of variation of weather and forest types.

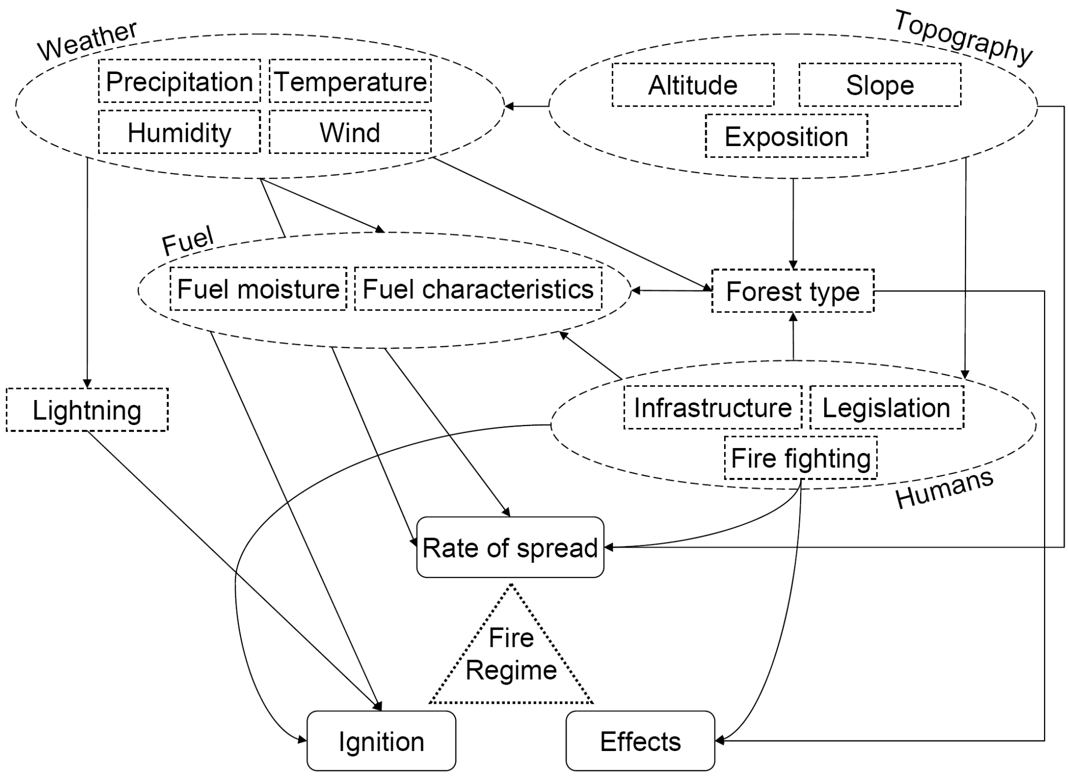

Figure 1. Conceptual framework of factors influencing the fire regime.

Topography influences weather conditions (e.g. Sevruk and Mieglitz 2002), forest composition (e.g. Muster et al. 2007), and fire spread (e.g. Rothermel 1972; Johnson 1992), and it strongly determines many processes affecting the forest fire regime. The influences of humans are diverse and range from direct impacts such as unintentional (negligence) and intentional (arson) ignitions and fire fighting, thus reducing or stopping fire spread, to indirect influences via the management of forest composition and fuel load (e.g. Johnson *et al.* 1990; Conedera and Tinner 2000; Cardille *et al.* 2001; Sturtevant *et al.* 2004).

The processes and factors affecting all these aspects of fire regimes have been investigated intensively in many studies and regions worldwide. Comprehensive studies in the Pacific Northwest (Agee 1993) and the North American boreal forest (Johnson 1992; Johnson and Miyanashi 2001) highlighted different aspects of Figure 1, such as the role of vegetation for fuel characteristics, the importance of weather for fuel moisture, the need of ignition sources, e.g. lightning in natural systems, or the driving role of wind for the rate of fire spread. More specific studies found regional differences in the importance of weather and fuel conditions, e.g. for ignition patterns and seasonality in Finland (Larjavaara et al. 2004) or regarding the interactions among forest composition, forest structure, fuel loading and fire (Drobyshev *et al.* 2008). The latter authors identified the variability of stand composition, structure and diversity to be related to fuel characteristics and thus to fire history. In a recent study of factors controlling the fire sizes in all of Africa south of the Equator (on a 100 km x 100 km grid), Archibald et al. (2009) found tree cover and precipitation to mainly influence the number of fire ignitions and fire sizes. Parisien and Moritz (2009) investigated the environmental controls on the spatial distribution of fires at multiple spatial scales from ecoregions to continents using habitat distribution models. They found that their models and the related concepts are useful for characterizing environmental controls on forest fires, but they also concluded that more work is needed to refine the understanding of the causal factors controlling wildfire at different spatial scales.

Due to anthropogenic changes of the climate in the 21st century, it is quite likely that forest structure and dynamics will be affected by direct impacts on the growth and population dynamics of individual species (e.g. Bugmann 1997), but also indirectly through changes in the disturbance regimes (e.g. Overpeck *et al.* 1990; Schumacher and Bugmann 2006). The current state of knowledge on climate change and its impacts on terrestrial ecosystems (IPCC 2007) suggests that fire frequency is likely to increase, especially in regions with dry and hot summer conditions. Local decreases in precipitation, spatial shifts in precipitation patterns and/or increases in summer temperature could lead to increased fire occurrence in many regions worldwide (IPCC 2001; IPCC 2007).

Thus, it would be of utmost importance to be able to assess future forest fire regimes. Before the investigation of future forest fire regimes under potential future climate is possible, however, a thorough understanding of the current and past relations between the fire regime and the various controlling factors is needed.

Therefore, the relative importance of the different environmental and human factors of forest fire regimes and their optimal representation via quantitative variables will be the focus of this thesis. The fire regimes will be investigated at the landscape scale and on temporal scales of days and years.

Forest fire research and choice of methods

Forest fire regimes can be studied using a broad range of research methods including paleo-ecological and historical approaches as well as experiments and modelling. Below, I present an overview of these methods using selected examples of case studies that were conducted in the recent past and I evaluate them regarding the use for investigating the relative importance of different environmental and human factors of forest fires in this thesis.

Among many other authors, Tinner et al. (1999) investigated long-term forest fire dynamics and disturbance ecology using paleo-ecological pollen and charcoal analysis from lake sediments. They found a reduction of fire-sensitive plants after increases of fire frequencies in the past 7 000 years and suggested that in the absence of forest fires, some tree species (fir and various deciduous broadleaved tree taxa) would be much more abundant in Swiss forests today at the expense of spruce, Scots pine and beech (Ellenberg and Klötzli 1972; Brändli 1996). In a study in the French Alps, comparable shifts in vegetation composition depending on the occurrence of forest fires were found (Genries et al. 2009). Such paleo-ecological approaches allow for the investigation of long-term natural forest fire disturbance regimes. However, it is quite difficult to derive information on forest fire regimes and the underlying mechanisms on short time scales of years or even days and under specific topographic conditions.

Using historical data, various factors depicted in the conceptual model (Figure 1) have been studied. For example, Zumbrunnen et al. (2009) analysed historical data of fire regimes and local climatic conditions in the Valais in Switzerland across the 20th century. They found areas where the fire regime was driven mainly by temperature, whereas in adjacent areas wind and non-climatic factors were more important. Hence, the role of the different driving forces of forest fire regimes may differ strongly within rather small regions. This indicates that investigating fire regimes at the landscape scale is important. Lafon and Grissino-Mayer (2007) investigated the spatial variation in the occurrence of natural and anthropogenic fires in Virginia since 1970. They found a distinct topographic pattern as the ignition probability declined with increasing elevation. The use of historical fire data in combination with data on environmental conditions allows for studying the roles of different driving factors of forest fires for clearly defined temporal and spatial extents.

Considerably rarer are fire experiments that aim to measure all aspects of interest under controlled conditions before, during, and after an experimental fire. One example is the crown fire modelling experiment that focused on the physical fire behavior and the effects of fires (Stocks et al. 2004). Another field experiment aimed to understand the atmospheric feedback of wildland grass fires (Clements *et al.* 2007). In southern Switzerland, a small-scale fire experiment (0.25 ha) was conducted in 1998 in a chestnut forest (Marxer and Conedera 1999; Marxer and Conedera 2000). In this experiment soil properties and runoff after fire were investigated rather than the mechanisms of fire spread. The results from such experiments can help for modelling cause-effects relationships of fire regimes, but they are quite expensive to conduct and dangerous because of the problem of fire escape. Although a deeper insight in fire mechanisms is possible, experiments hardly allow for analyzing fire regimes over years and on landscape scale.

All these approaches allow for extending the knowledge of historic fire regimes. In fact, most of these methods are largely descriptive. With the aim not only to study past fire regimes but also to be able to predict fire regimes under future climate, more quantitative approaches are needed. Modelling can provide the opportunity to do so, and therefore I will concentrate on modelling approaches in the following.

A key starting point of fire modelling was the work by Rothermel (1972), who developed a mathematical model for fire propagation. It was designed for predicting the rate of fire spread and fire intensity as a function of detailed information on fuel loading, fuel depth, fuel surface-area-to-volume ratio, fuel particle moisture, and mineral content. Van Wagner (1977) adopted some parts of these fire spread algorithms and introduced a crown fire model, where crown fuel is represented as a layer of uniform bulk density. The broad range of statistical approaches that are available comprises, among others, the work by Mandallaz and Ye (1997), who used statistical Poisson models for the prediction of forest fires in several Mediterranean countries and in Switzerland. They incorporated a fire danger index combined with other important explanatory variables. Another statistical approach was used by Brillinger et al. (2006), who developed stochastic generalized mixed models including fixed and random effects. They assessed the probability of fire occurrence using the location (coordinates) and the day of the year as explanatory variables. Over the last decade, many authors used other statistical approaches, among them Podur et al. (2002) with statistical quality-control methods to detect changes in the annual fire occurrence and area burned in Canada. They used the first half of their record as a baseline to test for significant changes in the second half of the record. In the 1980s, van Wagner (1987) developed the Canadian Forest Fire Weather Index System (CFFWIS), which meanwhile is being applied in many regions worldwide. It allows to evaluate forest fire danger from weather data, but many other drought and fire weather indices had been developed already much earlier (Munger 1916; Nesterov 1949; Keetch and Byram 1968) and during the last decades (Fosberg 1978; Bugmann and Cramer 1998; Goodrick 2002; Skvarenina *et al.* 2003). All these indices allow for condensing different aspects of weather information into single index values.

From the modelling approaches presented in the previous section, several methodological aspects seem to be interesting starting points for this thesis. The use of fire weather indices allows for including weather information in a simple way, and they can be combined with other explanatory variables in statistical models (Mandallaz and Ye 1997). The representation of environmental factors influencing fire regimes has not always to be at a high level of detail, as van Wagner (1977) demonstrated with a uniform layer of fuel. When investigating the relative importance of environmental and human determinants on forest fires at the landscape scale, the required datasets are very large and a sub-dataset sampling may be necessary (e.g. Brillinger et al. 2006). For comparing fire regimes in different periods, Podur et al. (2002) split their dataset what can be an approach in this thesis as well.

Besides statistical modelling that employed a wide range of drought and fire danger indices, a large variety of dynamic fire models have been developed worldwide, typically as a part of forest succession models. Keane et al. (2004) classified 44 fire succession models based on factors such as the temporal (day, week, month, year, decade) and spatial scale (regional, i.e. thousands of km^2; landscape, i.e. tens of km^2; forest stand, i.e. <1 ha), the spatial resolution (fine, <50m pixel; mid, <500m pixel; coarse, >500m pixel), the ecosystems (boreal, conifer, broadleaf, eucalypts), the application (management, development, research), and the representation of forest succession, fire ignition, fire spread and fire effects. A few particularly prominent examples are LANDIS (Mladenoff *et* *al.* 1996; He and Mladenoff 1999; Mladenoff 2004; Yang *et al.* 2004), a model including forest succession processes and disturbance regimes in combination with vegetation dynamics, EMBYR (Hargrove et al. 2000), a broad-scale probabilistic model of forest fires that has been developed to simulate the effects of large fires burning through heterogeneous landscapes and to derive appropriate management schemes, SEM-LAND (Li 2000) that allows for the simulation of the effects of forest fires, or the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ) with the integrated fire model Glob-FIRM (Thonicke *et al.* 2005) for the analysis of long-term changes in the interactions between forest fires, vegetation and the atmosphere. LandClim (Schumacher *et al.* 2004; Schumacher *et al.* 2006) is an offspring of LANDIS (He and Mladenoff 1999), with a more detailed representation of forest succession as well as some seminal changes to the modelling of fire spread. The purpose of LandClim is to simulate vegetation patterns in disturbed landscapes under climate change, different disturbance regimes (fire, windthrow) and forest management. This model has been developed for mountain forests, and it was tested in the Swiss Alps (Schumacher and Bugmann 2006) and the Rocky Mountains (Schumacher et al. 2006). The forest fire sub-model incorporates the interactions of forest fires, landscape structures, and weather conditions over long periods in a spatially explicit manner.

All these dynamic models provide the opportunity to study fire regimes in interaction with forest succession. Therefore, they are highly suitable to investigate the relative importance of environmental and human determinants of forest fire regimes at the landscape scale.

From the methodological considerations of forest fire research, I derive that modelling approaches – statistical as well as dynamic – allow for the investigation of forest fire regimes with respect to the different driving forces. They are flexible and can be adapted to different regions. The combination of a modelling approach with historical records of forest fire data, data on weather conditions and land use provides an excellent starting point for improving our understanding of forest fire regimes.

In this thesis, I therefore investigate forest fire regimes using logistic regression models (Menard 1995) and the dynamic landscape model LandClim (Schumacher 2004). I thus combine statistical and dynamic modelling, using fire weather indices for the representation of weather conditions. The use of logistic regression models allows for investigating the ignition of fire regimes (presence vs. absence) with a high spatial and temporal resolution, whereas the landscape model LandClim allows for the inclusion of results from the statistical modelling investigations by improving different elements of the model. With this approach, this thesis combines different methodologies leading to a deepened insight into the forest fire regimes of the study regions.

Study regions

In Europe outside the Mediterranean area, disturbance regimes and especially fires have not been the focus of much research, in contrast to the situation e.g. in the western United States or in Australia. Yet, it is likely that climate change will have strong effects on the disturbance regimes in many European forests. With a focus on mountain forests of the Swiss Alps, this thesis addresses the determinants of the forest fire regimes in the Valais and the Ticino (Figure 2).

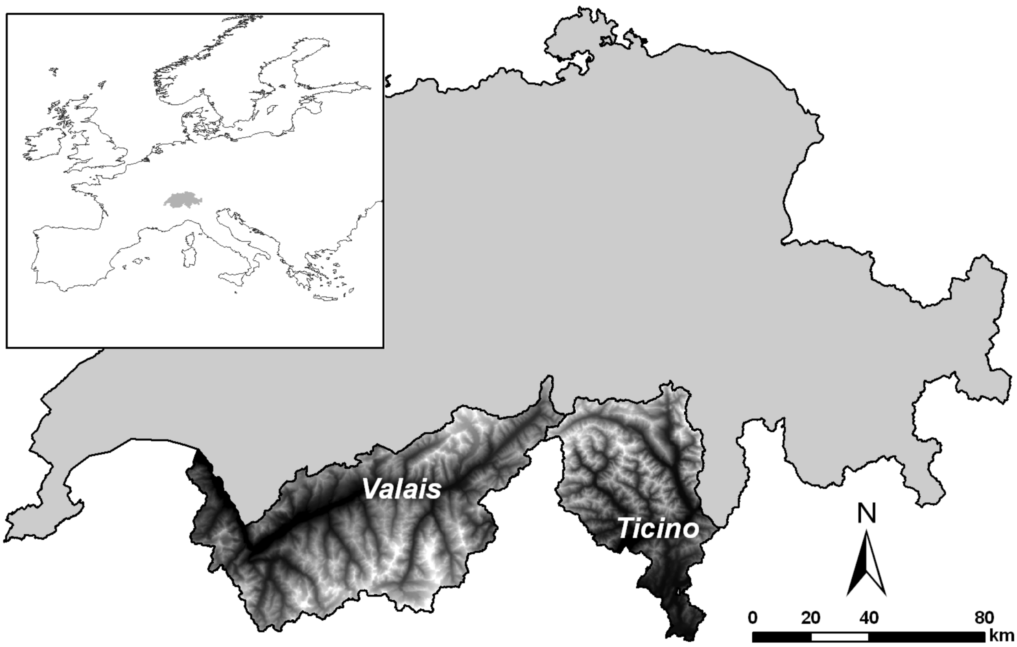

Figure 2. Map of Switzerland with the two study regions Valais and Ticino. The inset shows the position of Switzerland in Europe.

The consideration of the two regions Valais and Ticino allows me to assess and compare two areas that are characterized by strongly different climates and different dominant tree species. Recent studies in the cantons Ticino (Conedera *et al.* 1996a; Conedera *et al.* 2006) and Valais (Gimmi *et al.* 2004; Zumbrunnen *et al.* 2009) found that fire frequency has increased over the 20th century in both regions, caused by changes in forest use and increased drought. For the Ticino, the most fire-prone region in Switzerland, plenty of knowledge about forest fires exists. Conedera et al. (1996a; 1996b) investigated the influences of weather conditions, humans (i.e. leisure activities, agriculture), legislation, and the increase in stock of wood due to reduction in the exploitation of timber on fire frequency. They also analysed human- and lightning-induced forest fire ignitions, and the spatial extent and distribution of forest fires. Nowhere else in Switzerland do forest fires occur more frequently, but normally little damage occurs because the fires remain small as a consequence of rigorous fire fighting (Bugmann 2005). The largest forest fire in the last years was the 2003 forest fire in Leuk, located in the second strongly fire-prone region of Switzerland – the Valais – with a burned area of about 300 ha (Gimmi *et al.* 2004; Moser *et al.* 2006). The fire regime in the canton Valais with respect to historical changes in climatic and non-climatic factors such as human activities and biomass availability was studied by Zumbrunnen et al. (2009). However, the relationships between changes in climate, forest dynamics, and fire regimes in the southern Swiss Alps are still not fully understood. From all these efforts, an extensive forest fire data base developed by the Swiss Federal Institute of Forest, Snow, and Landscape Research WSL is available for these two cantons (Pezzatti et al. 2005). This data base allows for applying logistic regression models and LandClim for additional analyses of the fire regimes.

Although several aspects of forest fire regimes in the Ticino and the Valais have been investigated in previous research, the interactions between weather conditions, fuel characteristics, human activities, and the fire regime as visualized in Figure 1 have never been studied. In this thesis, I focus on the influences of environmental and human determinants on two aspects of fire regimes: fire ignition and rate of fire spread.

Research aims

This thesis aims at filling an important gap in scientific understanding regarding the relationships between climatic changes, human activities, vegetation properties, and two aspects of forest fire regimes, i.e. fire ignition and rate of fire spread. The environmental determinants of forest fires are investigated by comparing natural and human-induced forest fires with the following specific research aims:

- Investigating whether the importance of weather conditions, forest composition, and human activities on forest fire ignition varies with ignition source.
- Testing the general validity of statistical forest fire ignition models by transferring these models both in time, i.e. between two consecutive periods, and in space, i.e. between the two regions Ticino and Valais.
- Evaluating the ability of the dynamic landscape model LandClim to simulate forest fire regimes, i.e. fire ignition by comparing observed and simulated numbers of

forest fires and fire spread by comparing observed and simulated fire size distributions, and to improve the forest fire module if needed.

- Deriving practical recommendations from the findings of the previous aims because settlements and other human infrastructure in the Alpine area are generally more prone to natural hazards than those in the lowlands.

Based on economical as well as ecological considerations, protective forests are a main measure to assure a permanent settlement particularly in the dry inner alpine valleys. Therefore, information about historical and potential future changes in forest fire regimes is of high relevance especially for those regions.

Structure of the thesis

Environmental determinants of lightning- vs. human-induced forest fire ignitions differ in a temperate mountain region of Switzerland

In this first part, the relationships between the probabilities of forest fire ignitions and three key factors affecting forest fire occurrence are analysed. A better understanding of the environmental and human determinants of forest fire ignitions is crucial for sustainable landscape management. Therefore, the relative importance of weather conditions, forest composition, and human activities on the occurrence of forest fire ignitions in the most fire-prone region of Switzerland, the Ticino, is evaluated. The focus is on distinguishing the major ignition sources, lightning vs. human activities.

For the evaluation of the influences of the environmental and human controls on lightning- and human-induced forest fire ignitions, logistic regression models are used. Weather conditions are represented by 14 drought and fire weather indices, forest composition and human influences are derived from the land use statistics of Switzerland. Data are used from the 37-year period 1969-2005.

The results of this part are a representation of an individual region – the Ticino – with insubrian climate and forests that are dominated by deciduous tree species. A broader view on the validity of the regression results is not possible, but would be crucial to assess their validity under different climatic conditions.

On the generality of forest fire ignition models – a case study from two Swiss mountain regions

Based on the previous part, the methodology developed for the Ticino is extended to the second most fire-prone region of Switzerland, the Valais. With an emphasis on testing the validity of logistic forest fire regression models, the models are not only fitted separately in two geographic regions with distinct climatic and forest composition conditions, but also for two subsequent periods. Thus, the transferability of the models in time and space is investigated.

The information on transferability is important as in recent years models have increasingly been applied to study fire regimes beyond the spatial and temporal scope for which they were developed, e.g. under scenarios of future climate. To obtain reliable results, however, it is crucial that a model is transferable to such new conditions.

This part allows me to determine the most suitable representation of weather conditions by testing different drought and fire weather indices under various conditions and to better understand the mechanisms of fire regimes. This information is useful for implementing these findings in dynamic forest landscape models that include forest fire disturbances.

Calibrating and testing a dynamic forest fire model in complex topography

The purpose of the third part is to improve the forest fire module of the forest landscape model LandClim by including the findings of the previous parts. This improved model is evaluated by comparing simulated and observed forest fire regimes, i.e. the numbers of forest fires and the fire size distributions, which is an important step to improve model reliability. Nonetheless, only few rigorous tests of dynamic forest landscape models exist, mostly for North America. For the European Alps, such an approach is novel. LandClim is used in two study regions, the Leventina in Ticino and the south central Valais.

LandClim is a tool that allows for the investigation of forest succession and the influence of forest fires at the landscape scale. In contrast to other dynamic fire models, the fire return interval and the fire sizes are emerging properties of LandClim.

The evaluation of LandClim indicates that this model is a good candidate for further tests, e.g. under other climatic conditions, in other forest ecosystems, or for other topographies and probably also for the simulation of forest fire regimes under future climatic conditions in mountain forests.

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Chapter 1

Environmental determinants of lightning- vs. human-induced forest fire ignitions differ in a temperate mountain region of Switzerland

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Abstract

Understanding the environmental and human determinants of forest fire ignitions is crucial for landscape management. In this study we consider lightning- and human-induced fires separately and evaluate the relative importance of weather, forest composition and human activities for the occurrence of forest fire ignitions in the most fire-prone region of Switzerland, the Canton Ticino. Independent variables included 14 drought/fire weather indices, forest composition and human influences. Logistic regression models were used to relate these independent variables to records of forest fires over a 37-yr period (1969-2005). We found large differences in the importance of environmental and human controls on forest fire ignitions between lightning- and human-induced events: lightning-induced fires occurred in a small range of weather conditions well captured by the Duff Moisture Code from the Canadian Forest Fire Weather Index System and the LandClim Drought Index, and with negligible influence of distance to human infrastructure, whereas human-induced fires occurred in a wider range of weather conditions well captured by the Angstroem and the Fosberg Fire Weather Index, mainly in deciduous forests, and strongly depending on proximity to human infrastructure. We conclude that the suitability of fire indices can vary dramatically between ignition sources, suggesting that some of these indices are useful within certain regions and fire types only. The ignition source is an important factor that needs to be taken into account by fire managers and when developing models of forest fire occurrence.

Introduction

Forest fires are important drivers of vegetation dynamics in many regions of the world (Thonicke *et al.* 2001; Bond *et al.* 2005). Fires shape landscape patterns, influence species composition (Patterson and Backman 1988; Frelich 2002) and affect a multitude of ecosystem services, e.g. protection against debris flows, landslides, and avalanches (Cannon 2001; Conedera *et al.* 2003). During the last decades, the frequency and severity of forest fires have been increasing in many regions, and anthropogenic climatic change is expected to exacerbate this trend at least in some areas (Schumacher and Bugmann 2006; Westerling *et al.* 2006). For effective landscape and fire management, it is essential to understand the environmental and human determinants of forest fires. Considerable recent effort has focused on quantifying the importance of different factors, combinations of factors, and interactions between them for determining the number of forest fire ignitions and the area burned, such as climate and weather, human activities, vegetation, fuel characteristics, topography and landscape patterns (e.g. Johnson 1992; Agee 1993; Cardille *et al.* 2001; Hely *et al.* 2001; Johnson and Miyanashi 2001; Larjavaara *et al.* 2004; Vigilante *et al.* 2004; Conedera *et al.* 2006; DeWilde and Chapin 2006; Hall and Burke 2006; Maingi and Henry 2007; Yang *et al.* 2007; Zumbrunnen *et al.* 2009).

A considerable emphasis in previous research has been on describing fire weather conditions, and integrating different meteorological variables into fire indices. These efforts resulted in a wide array of fire danger rating systems and indices that can be used to assess forest fire hazard (e.g. Nesterov 1949; Haines *et al.* 1983; Viegas *et al.* 1999; Skvarenina *et al.* 2003; Dolling *et al.* 2005). Some of these systems include relationships between moisture, fuel properties, weather conditions and fire activity, such as the Canadian Forest Fire Weather Index System (CFFWIS; van Wagner 1987). Viegas *et al.* (1999) compared methods for evaluating fire danger and concluded that the predictive value of individual indices varied greatly depending on the environmental conditions under which they were applied. They evaluated five fire danger methods that had been developed in four countries either for summer or winter fires and applied them in six different regions of France, Italy, and Portugal. They found that the predictive quality (number of fire days, number of fires, area burned) of the fire danger methods was different for summer and winter fires and also depended on the region for which the methods were applied.

Few studies have been conducted to elucidate the importance of the ignition source (lightning- vs. human-induced) and its interaction with fire weather conditions (Mandallaz and Ye 1997; Venevsky *et al.* 2002; Conedera *et al.* 2006; DeWilde and Chapin 2006). Also, the relative importance of factors such as weather, forest composition and human influence on forest fire behavior is still debated (e.g. Cumming 2001a). The prevailing paradigm suggests that climate and weather are the most important factors determining forest fire ignition (e.g. Carcaillet *et al.* 2001; Ryan 2002; Whitlock *et al.* 2003). Weather conditions are especially important on short time scales, i.e. daily conditions (Bessie and Johnson 1995). In some ecosystems, however, heterogeneity in forest composition and thus different fuel conditions explain more variation in annual forest fire initiation than short term weather conditions (Krawchuk *et al.* 2006). However, extreme climate and weather conditions can override the influence of fuels and stand structure on fire behaviour (Schoennagel *et al.* 2004), such that all stands in a region exceed the threshold required for crown fire development (Bessie and Johnson 1995). In addition, humans strongly influence the spatial and temporal patterns of fire ignition through forest management and their individual behaviour (Sturtevant *et al.* 2004; DeWilde and Chapin 2006; Dickson *et al.* 2006; Quintanilha and Ho 2006). The anthropogenic component of forest fire ignitions is likely to be especially relevant in highly developed regions such as central and southern (Mediterranean) Europe, where most of the wildland fires are human-induced (Botelho *et al.* 1998; Diaz-Delgado *et al.* 2004). As a consequence, human activities associated with fire ignition are also controlled by legislation (e.g. Vigilante *et al.* 2004; Conedera and Pezzatti 2005).

The various factors affecting forest fire ignition can be summarized in a conceptual framework (Figure 1). Forest fire ignition is directly influenced by fuel moisture and characteristics (Johnson 1992) and depends on specific ignition sources from lightning and humans, either accidentally or intended (arson). Generally, the conditions under which a forest fire ignites differ between lightning- and human-induced fires. Lightning-induced forest fires depend on lightning strikes that reach the surface and on the moisture content of the organic layer of the forest floor (Wotton *et al.* 2003; Conedera *et al.* 2006; Pezzatti *et al.* in press). An ignition can smoulder until the fuels are dry enough to ignite a real surface fire (Wotton *et al.* 2003). By contrast, the ignition of a human-induced forest fire mostly depends on the moisture conditions of the fine fuels when a fire brand reaches the fuel bed. Wotton *et al.* (2003) define fine fuel as cured needles and twigs and other small diameter woody or grassy materials lying on the forest floor. These fine fuels are also very important for the propagation of forest fires. The properties of fuel depend on forest type, weather conditions, and human actions (land use, forest management) as indicated in Figure 1 (Bessie and Johnson 1995; Schoennagel *et al.* 2004). Ultimately, the topographic characteristics of a region co-determine weather conditions (e.g. for precipitation, Sevruk and Mieglitz 2002), forest composition, and also the patterns of settlements, transportation routes, and other human activities.

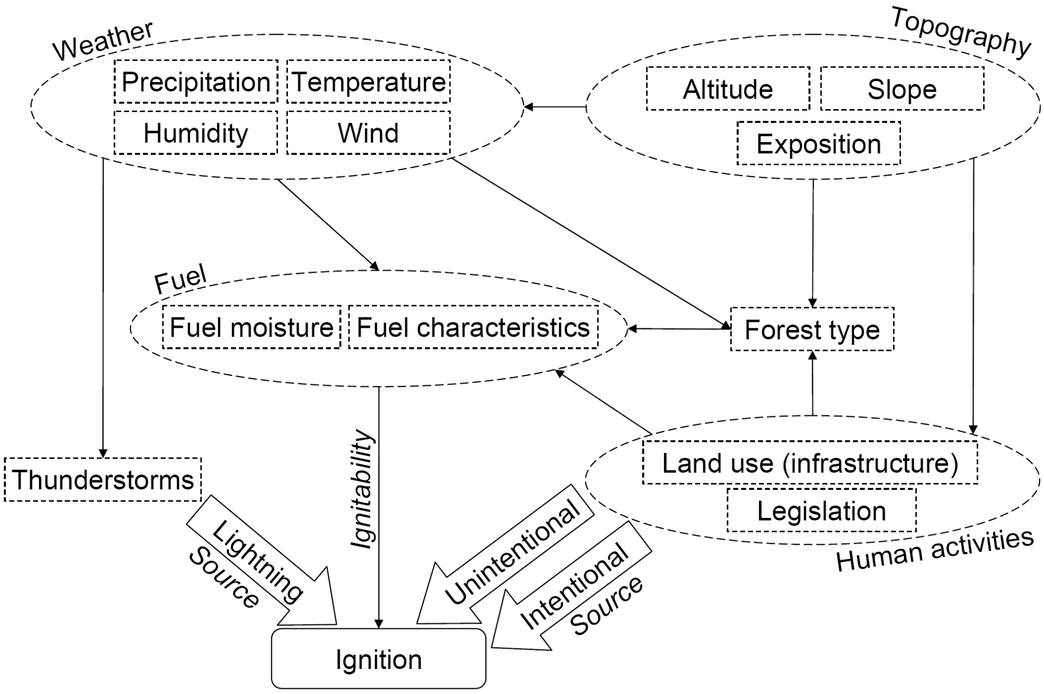

Figure 1. Conceptual framework of factors influencing forest fire ignition.

The overall goal of this paper is to quantify key links in the conceptual model: We analyse the relationship between the probability of forest fire ignitions and weather conditions, forest composition, and human influences. We focus on the number of forest fire ignitions because fire ignitions are the initial point of a fire regime. Thus we distinguish the major ignition sources, lightning vs. human activities, when investigating whether the importance and optimum representation of three key factors affecting forest fire occurrence varies with ignition source: (a) weather, represented by different drought and fire weather indices, (b) intensity of human activities, represented by distance to human installations, and (c) fuel type, represented by forest composition.

We hypothesize (1) that weather conditions for lightning-induced fires differ from those of human-induced fires because of the specific constellation required for the occurrence of lightning. Due to the specific weather conditions, lightning-induced fires are expected to be better predictable than human-induced fires. Furthermore, we expect that weather conditions are more important for lightning- than for human-induced fires; (2) that human activities only account for human-induced fires and that the distance to infrastructure has an influence on these fire ignitions; and (3) that changes in legislation affected the frequency of human-induced fires only.

Material and methods

Study region

As a case study region, we use the Canton Ticino, the most fire-prone region in Switzerland (Conedera *et al.* 1996). In this mountain region, both lightning- and human-induced forest fires are frequent (in a sub-continental context) and well documented (Conedera and Pezzatti 2005; Pezzatti *et al.* 2005). The region features a pronounced altitudinal gradient in forest composition and a clear geographical pattern of human activities, which makes it particularly suitable as a study system for our purposes.

The Canton Ticino (Figure 2) covers an area of approximately 2 800 km². Elevation ranges from 190 m a.s.l. at Lake Maggiore to current upper treeline between 1 800 and 2 000 m a.s.l. (Ott *et al.* 1997). The 'insubrian' climate of Ticino is characterized by mild winters and warm summers with a mean January temperature of 3.4 °C and a mean July temperature of 21.5 °C at Locarno-Monti (Appendix 1) during the period 1901-2001. Mean annual precipitation is 1 844 mm (at Locarno-Monti, period 1969-2005). In contrast to Mediterranean climates, in Ticino most precipitation falls during summer, when prolonged periods without rain (or even of drought) alternate with short spells of heavy precipitation. Strong gusts of a katabatic, dry foehn wind from the north, which causes decreases in the relative air humidity down to values of 20%, occur occasionally in the main valleys of the study area (Spinedi and Isotta 2004).

Forests cover about 50% of the study area. Typical forests at low elevation (up to 900 to 1 100 m a.s.l.) are dominated by sweet chestnut (*Castanea sativa*), a tree species that was first cultivated and probably introduced in the Ticino area by the ancient Romans (Conedera *et al.* 2004). Chestnut forests are anthropogenic monocultures with occasional presence of other broadleaved species such as small-leaved lime (*Tilia cordata*), sessile oak (*Quercus petraea*), pubescent oak (*Quercus pubescens*), black alder (*Alnus glutinosa*), wild cherry (*Prunus avium*), maple (*Acer* spp.) and ash (*Fraxinus* spp.). At medium elevations (900 to 1 400 m a.s.l.), forests consist mostly of pure stands of European beech (*Fagus sylvatica*), followed by coniferous forests dominated by Norway spruce (*Picea abies*) at higher elevations (Ellenberg and Klötzli 1972). European silver fir (*Abies alba*), pine species (*Pinus* spp.) and European larch (*Larix decidua*) complete the set of coniferous tree species, but they typically do not dominate larger stands.

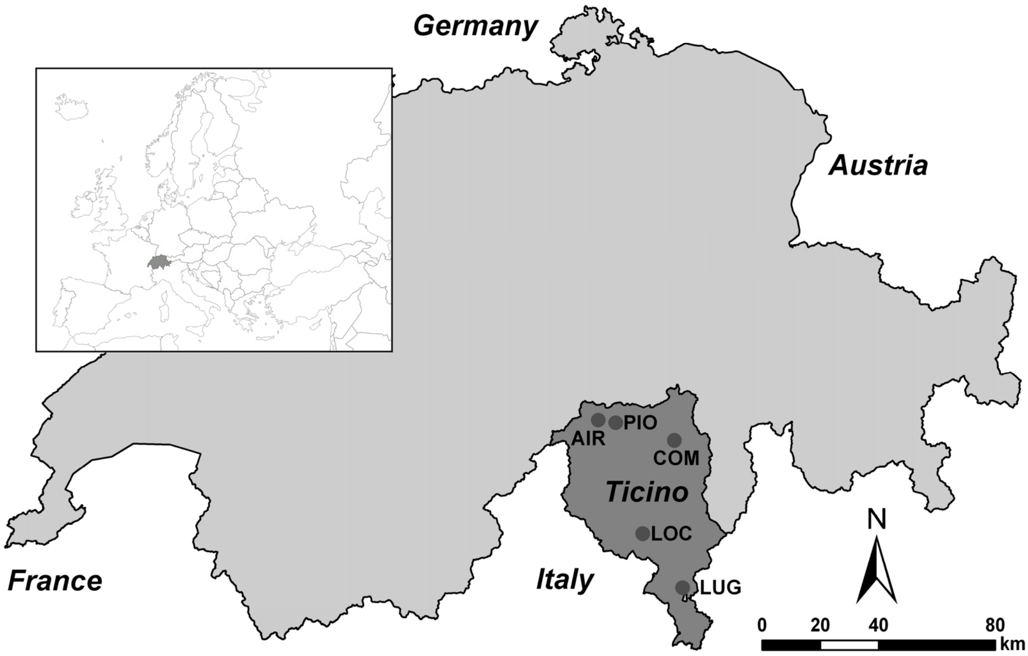

Figure 2. Map of the study region Ticino in southern Switzerland with position in Europe (inset map) and the neighbouring countries Italy, France, Germany, and Austria. The main weather station is located at Locarno (LOC), 366 m a.s.l. As additional weather stations (see also Appendix 1), Airolo (AIR), Piotta (PIO), Comprovasco (COM), and Lugano (LUG) were used to calculate the lapse rates (Appendix 2).

Forest fire data

A forest fire database for the Canton Ticino was developed by WSL (the Swiss Federal Institute for Forest, Snow and Landscape Research), containing more than 5 900 fire events in forests and grasslands from AD 1880 to present. Since 1969, the data have been collected systematically according to an extended standard protocol. We restricted our analysis to the period from 1969 to 2005 because of variation in data quality. In this 37-year period, 2 157 forest fires were recorded, with an average of 58 fires per year, and for all of them the geographical coordinates of the ignition point are known. Additional variables in the database are the date and time of the start and end of the fires, topographic parameters, area burned, the type of fire, damage, forest type, the main tree species of the burnt forest, and the cause of ignition (Pezzatti *et al.* 2005). Most of these forest fires were of anthropogenic origin (93.3%; Figure 3a) and occurred during wintertime (December to April, 70%). Human-induced forest fires had diverse ignition sources and resulted from negligence, arson, forestry, agricultural and military activities, and sparks from railways. The distribution within the different human causes was 54.4% unintended ignitions, 15.1% arson, and 30.6% of unknown cause. Lightning, the only natural forest fire ignition source, accounted for the remaining 6.7% (Figure 3b) of forest fires. Owing to an efficient organization of the fire brigades and sophisticated fire fighting

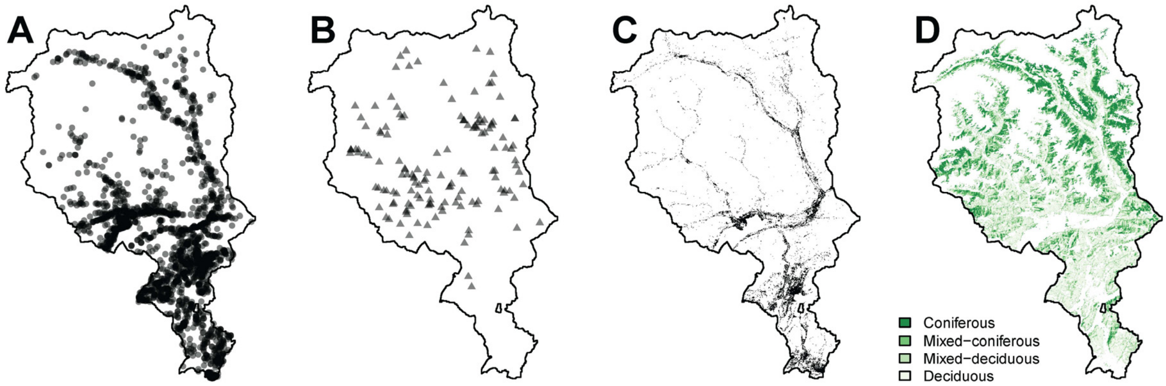

Figure 3. Maps of the Canton Ticino with the spatial location and distribution of (A) human-induced forest fires between 1969 and 2005, (B) lightning-induced forest fires during the same period, (C) location of human infrastructure (settlements, industry, leisure time, and traffic), and (D) non-forested and forested areas with 4 categories of forest composition.

techniques that include aerial fire fighting, almost 60% of the forest fires were smaller than or equal to 1 ha, and almost 90% were smaller than 10 ha. The average forest fire size was 10 ha, and the largest fire affected an area of 1 600 ha (Pezzatti *et al.* 2005). The relatively low number of forest fires and the size distribution with a high proportion of small fires represent a clear difference to other fire-prone regions such as Mediterranean ecosystems in Europe (Viegas *et al.* 1999) or the North American Mediterranean region, e.g. California (Zedler 1995; Keeley and Fotheringham 2001; Syphard *et al.* 2007). Nonetheless, this pattern is typical for most regions located on the southern slope of the Alpine Arc, from the Ligurian Inland to the Friuli-Venezia Giulia (Stefaní 1989; Cesti and Cerise 1992; Bovio 1996) and also for boreal forests (Stocks *et al.* 2002). Similar values of fire size and numbers of forest fires can be found in other human-dominated landscapes (Viegas *et al.* 1999; Venevsky *et al.* 2002).

Fire weather indices

The probability of forest fire ignition can be assessed by various fire danger indices that depend on climate and weather variables (e.g. Munger 1916; Nesterov 1949; Keetch and Byram 1968; van Wagner 1987; Gerstengarbe and Werner 1999; Kunkel 2001; Goodrick 2002; Badeck *et al.* 2003; Skvarenina *et al.* 2003; Larjavaara *et al.* 2004; Peng *et al.* 2005). We evaluated 14 drought and forest fire weather indices, seven of which had been developed in the context of the Canadian Forest Fire Weather Index System CFFWIS (Table 1). We selected these candidate indices based on their level of complexity, calculation concept, input variable requirements, and use in earlier studies. Additionally, a clear documentation and description of the calculation procedure was a prerequisite for their implementation and use in our study.

We used weather data from the Locarno-Monti weather station, which is operated by the Swiss Meteorological Agency. Four values were required for the calculation of most fire indices considered here (cf. Table 1): daily precipitation sum (mm), daily maximum and mean temperature (°C), daily mean relative air humidity (%), and daily maximum wind speed (m/s). Additionally, when required daily potential evapotranspiration was calculated according to Thornthwaite and Mather (1957). To take into account the variation of temperature, precipitation, and relative air humidity with elevation, these variables were adjusted by monthly elevational lapse rates (Appendix 2), which were calculated using five weather stations at different elevations in Ticino (Figure 2; Appendix 1). Depending on the month and the elevation of each space-time unit of our data set, the elevation-adjusted values for temperature, precipitation, and relative air humidity were calculated by linear regressions. This simple approach was substantiated by Schüepp *et al.* (1978) who showed for the Ticino that the change of precipitation and temperature with elevation is almost linear. This correlation was confirmed by Sevruk and Mieglitz (2002) for precipitation. Values for wind speed were not adjusted because no clear relationship between wind speed and elevation was evident from the data.

Anthropogenic component

We evaluated human impacts on forest fire occurrence based on an analysis of the land use statistic of Switzerland dating from 1992 to 1997, which provides information on 74 land use categories for 1 ha grid cells (Hotz *et al.* 2005). We pooled 37 of these 74 land use categories (Figure 3c) in 4 sectors related to human activities: 8 categories of settlements, 11 categories of industry, 8 categories of leisure time, and 10 categories of traffic (Appendix 3). For the analysis, the intensity of human activities on each forested cell was represented by the distance to the nearest cell with human infrastructure for these 4 sectors and for the combination of all sectors representing total human activities (cf. Table 2). We acknowledge that the land use statistic refers to a different period (1992-1997) than the forest fire database (1969-2005). An earlier land use statistic (1979-1985) is available, but we abandoned the idea of using this data source because the classification categories had changed between the two inventories. Hence, the representation of possible spatial changes of human influence over time cannot be taken into account in our study due to data limitations.

Table 1. Overview of the 14 evaluated drought and fire indices.

Overview of the 14 drought and fire weather indices used in this study, with formula (where sufficiently compact), required input variables, and reference for further information.

Name and Reference	Formula	Input variables	
Munger (Munger 1916)	$munger = \frac{1}{2} \bullet w^2$	w	number of days since last daily rainfall >0.05”
Nesterov (Nesterov 1949)	$nesterov = \sum_{i=1}^{w} (T_i - TD_i) \bullet T_i$	T TD w	temperature [°C] dew point temperature [°C] number of days since last daily rainfall >3mm
KBDI (Keetch and Byram Drought Index) (Keetch and Byram 1968)	$KBDI = Q + \frac{(800 - Q) \bullet (0.968 \bullet e^{0.0486 \bullet T} - 8.30) \bullet \Delta t}{1 + 10.88 \bullet e^{-0.0441 \bullet PA}} \bullet 10^{-3}$	Q T Δt PA	previous day’s KBDI temperature[degree Kelvin] time increment (1 day) mean annual rainfall [inch]
FFWI (Fosberg Fire Weather Index) (Fosberg 1978)	$FFWI = \frac{\eta \bullet \sqrt{1 + U^2}}{0.3002}$	η U	function of temperature [°F] and relative air humidity [%] wind velocity [mph]
mFFWI (modified FFWI) (Goodrick 2002)	$mFFWI = (0.000002 \bullet KBDI^2 + 0.72) \bullet FFWI$	see FFWI and KBDI	
Angstroem (Skvarenina *et al.* 2003)	$angstroem = \left(\frac{RH}{20}\right) + \left(\frac{27 - T}{10}\right)$	RH T	relative air humidity [%] temperature [°C]

Name and Reference	Formula	Input variables
LCDI (LandClim Drought Index) (Bugmann and Cramer 1998)	(see reference)	temperature [°C], potential evapotranspiration, precipitation [mm]
FFMC (Fine Fuel Moisture Code), ISI (Initial Spread Index), FWI (Fire Weather Index), DSR (Daily Severity Rating) (van Wagner 1987)	(see reference)	precipitation [mm], relative air humidity [%], wind velocity [m/s], temperature [°C]
DMC (Duff Moisture Code), BUI (Buildup Index) (van Wagner 1987)	(see reference)	precipitation [mm], relative air humidity [%], temperature [°C]
DC (Drought Code; van Wagner 1987)	(see reference)	precipitation [mm], temperature [°C]

Table 2. Independent variables

Overview of the independent variables: drought and fire indices (index), distance to infrastructure, legal amendment (period), and forest composition. These variables were used in the logistic regression models. For forest composition and human activities the definitions are based on the land use statistics of Switzerland, 1992 to 1997 (BFS 2001). For each variable the minimum and maximum value in the data set is indicated as well.

Name	**Description**		**Minimum**	**Maximum**
Index	One of the 14 drought and fire indices (Table 1)	MUNGER	0	23 328
		KBDI	-4.91	747.42
		NESTEROV	-3 971.71	112 927.08
		FFWI	0.13	28.35
		ANGSTROEM	0.43	8.56
		MFFWI	0.09	33.52
		FFMC	0	93.81
		DMC	0	361.52
		DC	0	1 023.62
		ISI	0	12.86
		BUI	0	372.05
		FWI	0	39.50
		DSR	0	18.22
		LCDI	0	1
Distance to infrastructure	Distance in meters to human activities in space: total pooled land use categories and for the following sectors settlements, work, leisure time, and traffic (for more Details see Appendix A)	Total	0	4 244
		Settlements	0	5 660
		Work	0	8 301
		Leisure time	0	12 850
		Traffic	0	5 826

Name	Description	Minimum	Maximum
Period	Human activity in time: before and after the coming into effect of the amendments of law	Categorical	Categorical
Forest composition	Forest composition		
Coniferous	>90% coniferous trees	Categorical	Categorical
Mixed-coniferous	50-90% coniferous trees	Categorical	Categorical
Mixed-deciduous	50-90% deciduous trees	Categorical	Categorical
Deciduous	>90% deciduous trees	Categorical	Categorical

Notes: factor coding for period (before amendment period 1969-1990 = 1, after amendment period 1991-2005 = 2).

Legal amendment

A cantonal decree that banned the burning of organic garden debris outdoors provided an opportunity to study temporal changes of human influence on forest fire initiation. This legal amendment, published on 21st October 1987, has been in force since 1989. A second decree concerning the possibility to prohibit fireworks during the Swiss National Holiday (1st August) was implemented in 1990. We therefore considered 1990 as the beginning of the post-amendment period (Conedera *et al.* 2004), and tested for differences in the probability of forest fire ignitions prior to and after the introduction of the amendment.

Forest composition

Forest composition data were taken from the land use statistics of Switzerland, which was derived from Landsat TM scenes (BFS 2001). The raster map with 1 ha grid cells contained non-forested area, unclassified cells, and four categories of forest composition as follows: coniferous forest (>90% coniferous tree species), mixed-coniferous forest (50-90% coniferous tree species), mixed-deciduous forest (50-90% deciduous tree species), deciduous forest (>90% deciduous tree species), and non-classified forest. Unclassified cells resulted from the constraints in the classification of Landsat imagery, including topographical shading and cloud cover. The total forested area covered 1 307 km^2 (46%) of the land area of Ticino. Non-forested and unclassified areas were not considered further in our study. Within the forested areas, the percentages of the different forest types were as follows: 18.5% coniferous, 21% mixed-coniferous, 26.5% mixed-deciduous, and 34% deciduous (Figure 3d).

Modelling approach

For our analysis, we used daily records of forest fires and weather variables, and spatial data on forest composition and human activities. All spatial variables were measured on or interpolated to a 100 m x 100 m (1 ha) sampling grid. Using a presence-absence data set with space-time units with and without forest fires, logistic regression models were fitted and interpreted regarding the different influences of weather, forest composition, and human activities on forest fire ignition. We developed separate models for lightning- and human-induced forest fires. The final data consisted of a binary response variable (forest fire ignition) and a set of continuous and categorical environmental explanatory variables, including fire weather indices, forest composition, and distance to human infrastructure.

Logistic regression (e.g. Menard 1995; Hosmer and Lemeshow 2000) has proven to be a highly suitable approach for statistical modelling of such presence-absence data sets. While a range of alternative approaches have been developed for modelling occurrence data (for a recent overview see Elith *et al.* 2006), logistic regression features an attractive balance of predictive performance and ease of interpretation.

As we were interested in comparing alternative predictors, e.g. fire weather indices or distance to human infrastructure, rather than identifying the overall best model structure, we used the same model structure throughout. We used the following elements as explanatory variables: one of the drought and fire weather indices, one of the measures of distance to human infrastructure, forest composition, and the legal amendment. Only one of the drought and weather indices was used in each model because we were interested in the suitability of different approaches to use weather information for the calculation of forest fire danger rather than in possible interactions between these intercorrelated indices. We included a non-linear relationship between distance to human infrastructure and the logit of forest fire probability by using restricted cubic spline (RCS) functions (Hastie and Tibshirani 1990) with three knots since we wanted to account for potential unimodal effects. Models with RCS functions are composed of piecewise third-order polynomials within intervals determined by knots. The connections between the polynomials are forced to be smooth, and the composite function is constrained to be linear in the tails (Stone and Koo 1985; Harrell 2001). We performed the analysis in two steps: First, we investigated whether different categories of human-induced forest fires respond differently to the explanatory variables. To this end, we split the human-induced fires into three groups: arson, unintended ignitions, and unknown human ignition sources. For each of these three groups, we ran models with one of the 14 drought and fire weather indices (or none), one of the 5 distances to human infrastructure (i.e. settlements, traffic, industry, leisure, or the combination of these), forest composition, and the legal amendment, resulting in 3 x 15 x 5 = 225 models. Secondly, we investigated the relative performance of different drought and fire weather indices between lightning- and human-induced fires. Here, we used only the pooled human-induced fires, and did not differentiate further between different types of human-induced fires. We also focused on only one of the distances to human infrastructure, namely the distance to pooled, total human infrastructure, since it best captured the distance to human infrastructure in the first step. We ran models for each of the two causes (human and lightning), with one of the 14 drought and fire weather indices (or none), distance to pooled, total human infrastructure, forest composition, and the legal amendment, resulting in 2 x 15 = 30 models.

We quantified the relative importance of the four groups of explanatory variables with hierarchical partitioning, using log likelihood as the performance measure (Mac Nally 2000).

We employed two measures of model performance. First, model discrimination performance, i.e. the ability of models to distinguish space-time units with from those without fires was measured with the area under the curve for the receiver-operator characteristic (AUC). The AUC can be interpreted as the probability that a randomly drawn space-time unit with a fire event has a higher predicted probability of fire ignition than a randomly drawn space-time unit without fire. Second, overall model predictive performance was measured with log-likelihood.

Cross-validation

We performed 16-fold cross-validation to improve the reliability of model performance estimates over naive estimates on the training data set. Because of spatial and temporal autocorrelation in the data (see below), we used a spatially and temporally stratified sampling to make the validation samples as spatio-temporally distinct as possible and thereby aiming at a conservative estimate of model performance. The training data were first split in half at the west-east coordinates, each half then at the north-south coordinates, and each of these four spatial blocks was twice halved along the time variable, yielding $2^4 = 16$ equally-sized partial data sets. Each of these 16 parts was in turn excluded from the training data, the model was refitted on the 15 other parts, and the prediction on the left-out part stored. The cross-validated performance estimate was calculated using the original observations of fire presence and absence and the combined predictions from the 16 left-out parts.

Collinearity between explanatory variables

To avoid including inter-correlated explanatory variables in the regression analysis, we calculated pairwise Pearson correlation coefficients for all combinations of drought and forest fire weather indices, distance to human infrastructure, and forest composition. All these correlations were unproblematic for both the lightning- and the human-induced fire data set, with a maximum absolute r-value of 0.26 (results not shown).

Large sample size

With the daily and 1 ha resolution of our study, the full spatio-temporal data set consists of approximately 1.77 billion space-time units (13 513 days $\cdot$ 130 678 ha). Because of the large number of forested space-time units without forest fire events, it was not technically feasible to include all data of fire absence in the model calculations. Instead, a random sample of 20 000 fire-free space-time units was selected ('absence' events). The sampling procedure was first to collect a random date and then a random cell out of all 'absence' points. The selection of the combination of date and cell was without replacement, following the protocol adopted by Brillinger *et al.* (2003). The logistic regression analyses included all 145 lightning-induced or 2 012 human-induced forest fire events for analysis. Thus we had approximately 90% 'absence' points (no fires) and 10% 'presence' points (fires) in the data sets for the statistical analyses. Each randomly sampled 'absence' event thus represented 88 292 space-time units without forest fire ignition. We accounted for this unequal sampling probabilities of fire and non-fire events by adjusting the intercept of the regression models (Keating and Cherry 2004; Albright *et al.* 2009): $beta_{0\_adj} = beta_0 - \ln(P1/P0)$, where $beta_{0\_adj}$ is the adjusted intercept, and $P1 = 1$ and $P0 = 1/88\,292$ are the inclusion probabilities of fire and non-fire events, respectively.

Spatio-temporal autocorrelation

Autocorrelation of the residuals is a typical problem of models for spatially and temporally explicit data; specifically, it can lead to erroneously significant test statistics or biased parameter estimates. A recent review compared a range of methods for dealing with spatial autocorrelation in large data sets (Dormann *et al.* 2007). To assess the extent of residual spatial autocorrelation in our models, we tested each year of the selected presence-absence data set separately using Moran's I, for each of the 15 models with human-induced fires. In addition, we calculated the distance over which spatial dependence was detectable using spline correlograms.

To assess the extent of residual temporal correlation, we first created 16 equally-sized groups by recursively splitting the data spatially four times along the west-east- and north-south-axis. For each of these 16 groups, we calculated the autocorrelation function and assessed the lag number of residuals over which autocorrelation was significant.

We found significant spatial autocorrelation in 23 out of 37 years. Spatial correlation distances, estimated with spline correlograms, were in 90% of cases less than 7 100 m, maximum observed values were up to 19 400 m. In 9 out of 16 spatial units, significant temporal autocorrelation decayed within about 80 observations; in four cases they extended up to more than 160 observations, corresponding to temporal autocorrelation of slightly more than four years.

Bootstrap

While a range of approaches exist for dealing with spatial autocorrelation (Dormann *et al.* 2007), the range of available methods dealing with spatio-temporal autocorrelation is limited. We were unable to run generalized linear mixed models with spatio-temporal error structure on the large data set due to limits of available computer memory, and the models did not converge on subsets of the data.

Since tests of significant differences between alternative predictor variables like the Vuong test or commonly applied methods of model selection based on AIC are sensitive to autocorrelation, we employed a non-parametric, block bootstrap in an attempt to reliably establish differences in the suitability of different predictor variables within and between the two ignition causes.

In the block bootstrap, blocks of spatially and temporally contiguous data are resampled rather than individual observations, in order to represent the spatio-temporal dependence structure of the original data. We recursively split the data 4 times spatially and then 3 times temporally, leading to 2^4 x 2^3 = 128 blocks. The midpoints of these blocks were at least 7 700 m apart in space, and each block contained 173 or 174 observations, corresponding to the dimensions of the spatial and temporal autocorrelations observed in the residuals of models on the original data set. A bootstrap sample was formed from these blocks by sampling 128 blocks with replacement. From each block in the bootstrap sample, we used all fire events, and 16 non-fire events were drawn without replacement. Within each bootstrap sample, model performance was calculated based on the 16-fold cross-validation procedure described above. We used 199 bootstrap replicates.

Software

All analyses were performed using R, a language and environment for statistical computing (R version 2.10.0; R Development Core Team 2009). Logistic regression models were fitted with the *glm* function, and restricted cubic splines (RCS) were calculated using the *Design* package (R-package version 2.3-0; Harrell 2009); hierarchical partitioning was performed using the *hier.part* package (R-package version 1.0-3; Walsh and Mac Nally 2008); Moran's I was calculated using the *spdep* package (R-package version 0.4-50; Bivand 2009); spline correlograms were calculated using the *ncf* package (R-package version 1.1-3; Bjornstad 2009); bean plots were created using the *beanplot* package (Kampstra 2008).

Results

Comparison of different human causes

For all three groups of human ignition sources – arson, unintended, and unknown causes of human ignitions – the best fire weather indices were Angstroem and FFWI, and we restrict our analyses of different human cause to these (cf. Figure 4). When using the FFWI, fires caused by arson could be predicted substantially better than fires caused by the two other sources. Independent of the weather index, three of the distance measures – distance to total infrastructure, settlements, and traffic – produced substantially better models than those based on distance to leisure or industry. No interactions in model performance of human ignition source and distance to types of infrastructure were evident.

Comparison of lightning- vs. human-induced fires

The range of the AUC values of the models differed for lightning- and human-induced forest fires. All top ranked models performed well regarding AUC: Models for lightning-induced fires showed AUC values ranging from 0.89 to 0.88 (Figure 5, Table 3), whereas for human-induced fires AUC values varied between 0.87 and 0.86 (Figure 5, Table 4).

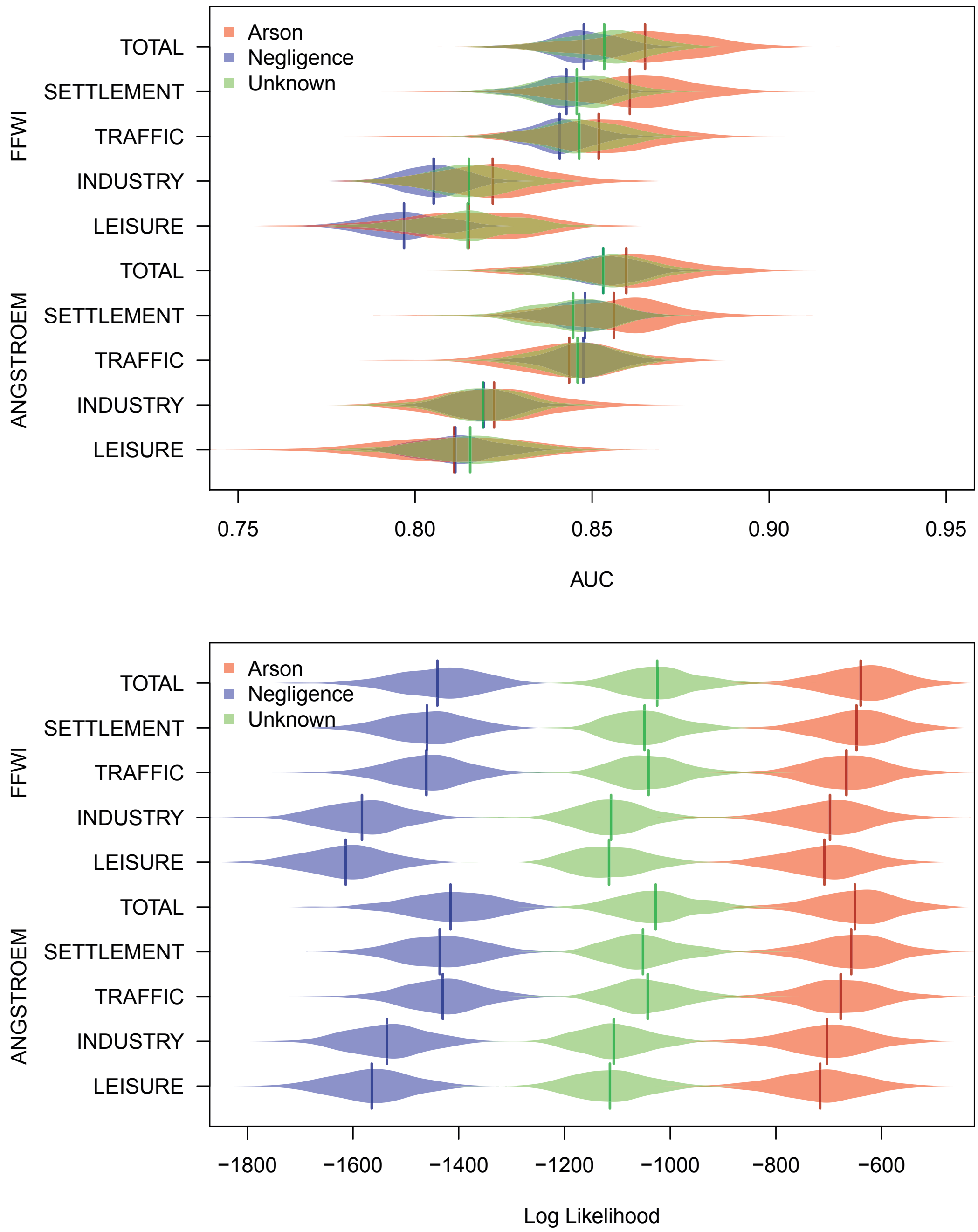

Figure 4. Effects of distance to different types of infrastructure on model performance for three groups of human ignition sources. Model performance was measured as cross-validated AUC values (upper figure) and log likelihood (lower figure), for 199 bootstrap replicates. The "violins" represent the density, i.e. frequency distribution of AUC values. The bold lines indicate the mean value of the bootstrap replicates. Note that sample sizes differ across the three groups of human ignition sources, and that therefore the log likelihood values are not directly comparable.

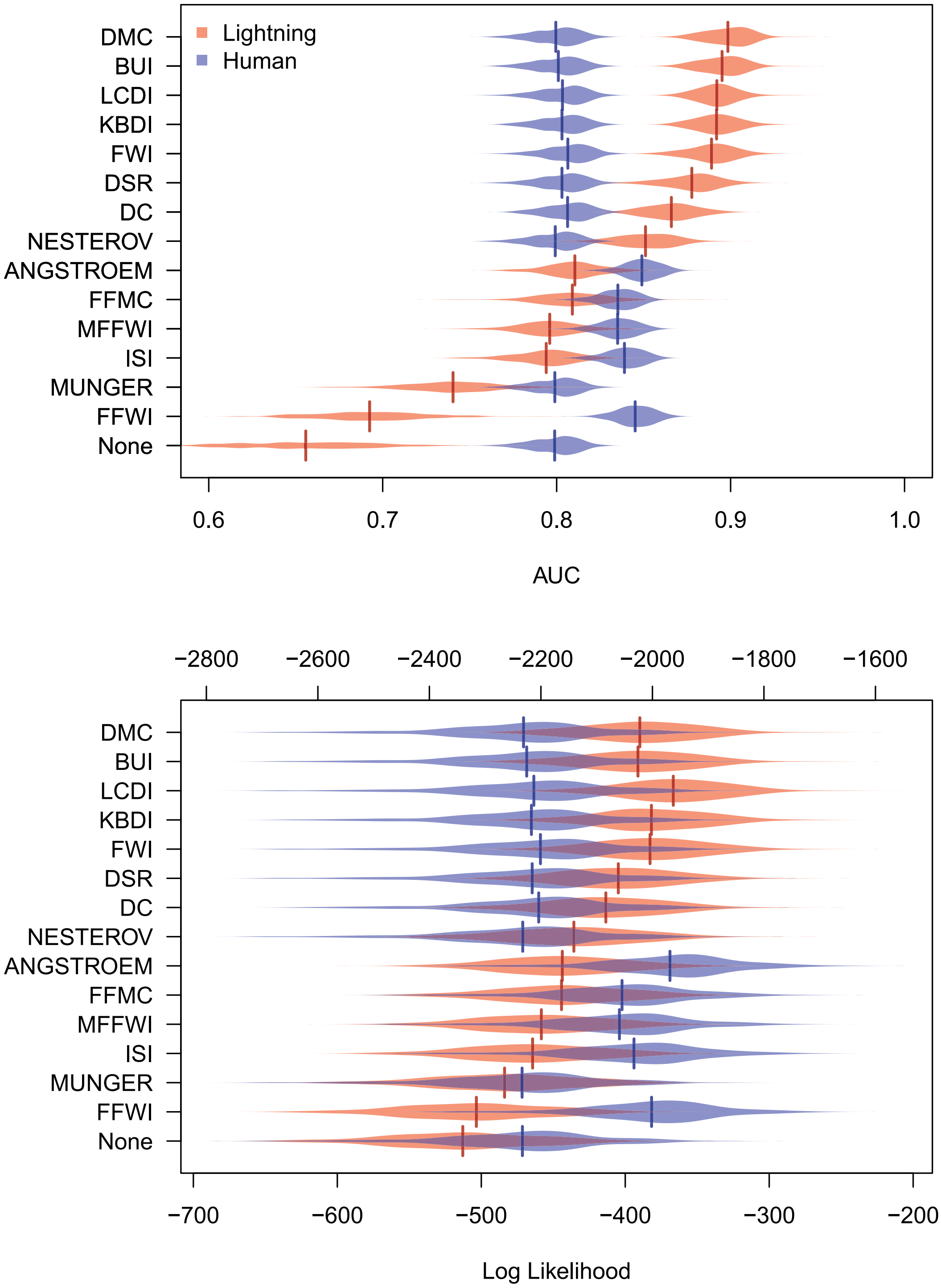

Figure 5. Model performance measured as cross-validated AUC values (upper figure) and log likelihood (lower figure), from 199 bootstrap replicates. The "violins" represent the density, i.e. frequency distribution of values. The bold lines indicate the mean value of the bootstrap replicates. The fire weather indices are ordered by their mean bootstrapped AUC value for the lightning-induced fires. Note that sample sizes differ across lightning- and human-induced fires, and that therefore the log likelihood values are not directly comparable. The log likelihood scale for human-induced fires is shown on the top, the one for lightning-induced fires on the bottom of the figure.

Table 3. Logistic regression results for lightning-induced forest fire ignitions

Parameters and performance measures of logistic regression models (full data set, with 20 000 non-fire events) for lightning-induced forest fire ignition probabilities of space-time units for the top five drought and fire weather indices (daily probability on a 100 m x 100 m grid). The apostrophe with distance to infrastructure' indicates the quadratic term in the logistic regression model (non-linear influence of this variable). The values of the forest composition classes are given in reference to coniferous forests. Models are presented in descending order of the mean cross-validated AUC values on the bootstrap samples. **Bold values** indicate parameters with p-values <0.001 (not corrected for autocorrelation). Values in brackets for AUC.cv.boot and LogLik.cv.boot represent 95% confidence intervals, calculated from the quantiles of the bootstrap sample.

Index	AIC	AUC.cv	LogLik.cv	AUC.cv.boot	LogLik.cv.boot	(Intercept)	Index	Distance to infrastructure	Distance to infrastructure'	Period	Forest deciduous	Forest mixed-deciduous	Forest mixed-coniferous
DMC	1422	0.886	-721	0.898 (0.874/0.917)	-390 (-468/-324)	**-18.2**	**$1.61 \bullet 10^{-2}$**	$4.95 \bullet 10^{-4}$	$-1.25 \bullet 10^{-3}$	**0.93**	-0.066	0.005	0.091
BUI	1425	0.883	-722	0.895 (0.872/0.914)	-391 (-469/-326)	**-18.3**	**$1.42 \bullet 10^{-2}$**	$5.22 \bullet 10^{-4}$	$-1.27 \bullet 10^{-3}$	**0.88**	-0.088	-0.018	0.088
LCDI	1362	0.883	-693	0.892 (0.871/0.912)	-367 (-439/-306)	**-77.1**	**$6.15 \bullet 10^{+1}$**	$6.26 \bullet 10^{-4}$	$-1.36 \bullet 10^{-3}$	**0.94**	-0.166	-0.075	0.080
KBDI	1393	0.882	-705	0.892 (0.87/0.914)	-382 (-458/-319)	**-18.7**	**$6.12 \bullet 10^{-3}$**	$7.25 \bullet 10^{-4}$	$-1.35 \bullet 10^{-3}$	**0.74**	-0.260	-0.155	0.073
FWI	1398	0.879	-707	0.889 (0.861/0.911)	-383 (-455/-315)	**-18.9**	**$1.63 \bullet 10^{-1}$**	$8.54 \bullet 10^{-4}$	$-1.50 \bullet 10^{-3}$	**0.91**	-0.351	-0.226	0.112

Table 4. Logistic regression results for human-induces forest fire ignitions

Parameters and performance measures of logistic regression models (full data set, with 20 000 non-fire events) for human-induced forest fire ignition probabilities of space-time units for the top five drought and fire weather indices (daily probability on a 100 m x 100 m grid). The apostrophe with distance to infrastructure' indicates the quadratic term in the logistic regression model (non-linear influence of this variable). The values of the forest composition classes are given in reference to coniferous forests. Models are presented in descending order of the mean cross-validated AUC values on the bootstrap samples. **Bold values** indicate parameters with p-values <0.001 (not corrected for autocorrelation). Values in brackets for AUC.cv.boot and LogLik.cv.boot represent 95% confidence intervals, calculated from the quantiles of the bootstrap sample.

Index	AIC	AUC.cv	LogLik.cv	AUC.cv.boot	LogLik.cv.boot	(Intercept)	Index	Distance to infrastructure	Distance to infrastructure'	Period	Forest deciduous	Forest mixed-deciduous	Forest mixed-coniferous
ANGSTR.	9705	0.867	-4867	0.849 (0.828/0.866)	-1969 (-2248/-1754)	**-10.1**	**-0.683**	**$-5.07 \bullet 10^{-3}$**	**$6.25 \bullet 10^{-3}$**	**-0.44**	**1.41**	**1.30**	**0.96**
FFWI	9731	0.865	-4870	0.845 (0.825/0.864)	-2002 (-2284/-1780)	**-14.3**	**0.200**	**$-5.34 \bullet 10^{-3}$**	**$6.45 \bullet 10^{-3}$**	-0.17	**1.59**	**1.47**	**1.08**
ISI	9783	0.859	-4901	0.839 (0.816/0.857)	-2033 (-2334/-1800)	**-13.9**	**0.343**	**$-5.33 \bullet 10^{-3}$**	**$6.50 \bullet 10^{-3}$**	**-0.36**	**1.57**	**1.45**	**1.07**
MFFWI	10002	0.856	-5009	0.835 (0.814/0.854)	-2059 (-2348/-1835)	**-14.0**	**0.204**	**$-5.45 \bullet 10^{-3}$**	**$6.57 \bullet 10^{-3}$**	**-0.27**	**1.60**	**1.48**	**1.09**
FFMC	10015	0.855	-5022	0.835 (0.812/0.854)	-2055 (-2344/-1819)	**-15.6**	**0.035**	**$-5.38 \bullet 10^{-3}$**	**$6.53 \bullet 10^{-3}$**	**-0.32**	**1.59**	**1.46**	**1.06**

Relative importance of weather, human infrastructure, period, and forest composition

The relative importance of weather conditions, distance to human infrastructure, and forest composition differed strongly between lightning- and human-induced forest fires, as illustrated by the results from hierarchical partitioning (Figure 6).

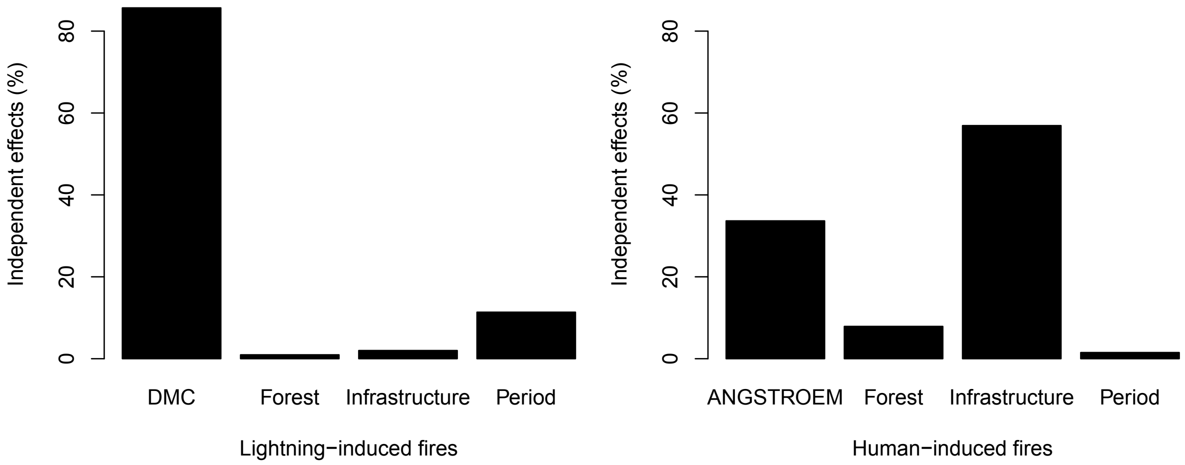

Figure 6. Independent effects of the four groups of explanatory variables, based on hierarchical partitioning of the "full" data set (i.e. 20 000 absence points), with log likelihood as the performance measure. For each fire type, the best fire weather index was chosen (highest AUC).

To simplify the presentation, we focus on the result of hierarchical partitioning for the models with highest discriminative performance for both lightning- and human-induced fires. For lightning-induced fires, weather was the single dominant variable, with independent effects amounting to 86%. Period was the next important variable, with a contribution of 11%. Forest composition and distance to infrastructure had negligible effects, with less than 3% independent contribution in total. For human-induced fires, in contrast, both distance to infrastructure as well as weather contributed substantially to model performance (independent effects amounting to 57% and 34%, respectively). Forest composition contributed 8% and legal amendment less than 2%.

Relative performance of different fire weather indices

For both lightning- and human-induced forest fires there were strong differences in the performance of the various models, as indicated by the large AUC and log-likelihood differences (Figure 5 and Tables 3 and 4). While the rankings of fire indices were not identical across all measures of model performance, some robust pattern emerged.

For lightning-induced fires, the DMC was always top-ranked with respect to AUC, followed by BUI and LCDI, whereas LCDI showed the best performance as measured by the log-likelihood. Both DMC and BUI are indices from the CFFWIS. On the subsequent ranks, the other indices from the CFFWIS came up with two exceptions: FFMC was on position 10 and ISI on position 12. Finally, KBDI was on ranks 2 to 4, depending on the statistical measure employed for the ranking. It is also notable that the model without a fire weather index was always on the last rank.

The pattern for human-induced fires showed an almost inverse pattern. Here, the Angstroem index was typically top-ranked, followed by FFWI. Among the indices from the CFFWIS, ISI was best on rank 3. Again, the model without a fire weather index was for all measures among the last ranks.

Differences in the rankings of the models between "lightning-caused" and "human-caused" fires disappeared when we randomly shuffled the assignments of fires to lightning- or human-induced causes, although the cross-validated AUC values of the "lightning-caused" fires were consistently larger, which is due to effects of sample size (results not shown).

Effects of distance to human infrastructure, legal amendment, and forest composition

Distance to human infrastructure did not significantly influence the probability of lightning-induced forest fire ignition. In contrast to our expectations, the legal amendment was related to the probability of lightning-induced forest fires, as they were more frequent in the period after 1990. This increase of lightning-induced fires coincided with a simultaneous decrease in precipitation and increase in temperature, but needs to be interpreted with care (Figure 7). Not surprisingly, human influence in space (distance to infrastructure) and time (change in legislation) played a more important role for human-induced forest fires (Table 4), supporting our hypothesis. The legal amendment resulted in a reduction of human-induced forest fire ignitions.

Lightning-induced fires tended to be more likely in coniferous and mixed-coniferous forests (Conedera *et al.* 2006; Pezzatti *et al.* in press), and human-induced forest fires were preferentially located in deciduous-dominated forests. Out of all human-induced forest fires, 85% ignited in deciduous-dominated forest stands (i.e. at lower elevations) that only account for 60.5% of total forested area. In addition, the results of the logistic regression support this interpretation as the parameter estimates of all other forest types are positive with regard to coniferous forests ($p < 0.001$; Table 4).

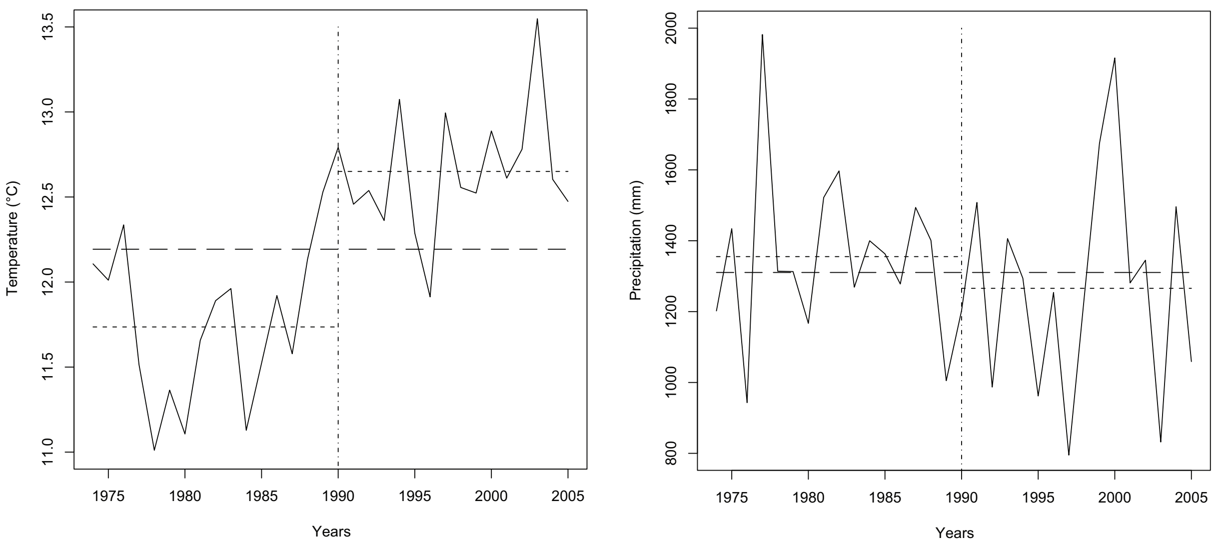

Figure 7. Changes in mean annual temperature (left) and annual precipitation sum (right) during the study period (1974-2005). The long term mean values are indicated by long dashed horizontal lines as well as the mean values before and after 1990 (dashed horizontal lines). Mean annual temperature increased considerably during the study period, whereas annual precipitation sum decreased moderately.

Discussion

The influence of weather conditions on forest fire ignition probability, as described by fire weather indices, greatly depends on ignition source. For lightning-induced forest fires, the duff moisture code (DMC) from the CFFWIS (van Wagner 1987) and the LandClim Drought Index (LCDI) are highly suitable, but they perform relatively poorly for explaining human-induced forest fires. Conversely, the most relevant indices for human-induced forest fires are the Angstroem and the Fosberg Fire Weather Index (FFWI), but they are not appropriate for lightning-induced forest fire prediction in the Ticino. The reason for this difference lies mainly in the different conditions under which lightning- and human-induced forest fires ignite, as formulated in our first hypothesis.

In fact, according to our results lightning-induced forest fires occur only under highly specific weather conditions. During dry periods, lightning strikes that reach and ignite dry fine fuel without any subsequent significant amount of precipitation are required. This meteorological phenomenon occurs during dry, hot periods with convection and thunderstorm build-up, and these are best represented by the DMC and LCDI among the indices that we examined. The DMC represents the moisture of the duff layer an can be interpreted as a proxy of soil moisture deficit, which is also represented by the LCDI. Besides the weather indices, the period is the only statistically significant variable in the models of lightning-induced fires. We assume that this surprising result is not linked to the legislation amendment, but probably due to the coincidence that after 1990 the study region experienced an unprecedented number of drought periods and warm summers (Figure 7; Conedera *et al.* 2006). Although not significant, the tendency of coniferous forest to be more affected by lightning-induced fires matches with previous results of other studies: Pezzatti *et al.* (in press) found lightning-induced fires in the Ticino between 1982 and 2005 to ignite significantly more often in spruce stands, and other authors found that deciduous forests have a lower probability of lightning-induced forest fires in other regions (Cumming 2001b; Krawchuk *et al.* 2006). In summary, our study supports the view that climate and weather are the most important factors determining forest fire ignition in the case of lightning-induced fires, as phrased in our first hypothesis (e.g. Bessie and Johnson 1995; Ryan 2002).

In contrast, human-induced forest fires were found to ignite under a wide range of weather conditions, due to the fact that human activities depend only weakly on weather conditions and may provide enough initial energy for igniting a fire even when fuel moisture level is not extremely low. The Angstroem index and the FFWI turned out to be the most relevant indices for human-induced forest fires. These are not a simple measure of drought – as it is the case for the indices best characterizing lightning-induced forest fires – but they represent more general weather conditions. Both include information on temperature and relative air humidity, and FFWI in addition uses wind speed. The Angstroem index is a linear function of relative air humidity and temperature and can be interpreted as a proxy of fuel moisture (Skvarenina *et al.* 2003). Higher values indicate higher moisture and lower temperatures, and thus a lower risk of fire ignition. The FFWI is basically a non-linear filter of meteorological information on temperature, relative humidity, and wind speed (Goodrick 2002). The need of wind speed data makes it particularly difficult to calculate this index at high temporal or spatial resolution, which may partially limit its applicability in other regions. Nevertheless, the performance of FFWI is good even with the wind data used in our study, which are not of excellent quality.

The Nesterov Ignition Index is widely used in forest fire research (e.g. Viegas *et al.* 1999; Venevsky *et al.* 2002), but it did not perform well in our study region. This is probably because the simple relationship between air temperature, dew point temperature, and days since the last rainfall does not represent environmental variability well enough in the topographically multifaceted Ticino. Overall, there are considerable differences in the suitability of these indices across different climatic conditions such as the Mediterranean part of Europe (Viegas *et al.* 1999), the North American Mediterranean region (Haines *et al.* 1983), and the Ticino with its 'insubrian' climate. This suggests that the various fire indices sometimes do not sufficiently capture the role of climatic conditions and that their applicability may vary strongly from region to region and with the quality of the available data.

The drought and fire weather indices used here were calculated based on data from one meteorological station, but precipitation, temperature, and relative air humidity data were adjusted for elevation using lapse rates (cf. Haines *et al.* 1983; Viegas *et al.* 1999). Thus, small-scale spatial variations in weather conditions may not be represented accurately. It is noteworthy that the Ticino features a distinct variation in topography, and thus spatial variations in climatic conditions may have led to some noise in our results. Therefore, it would be worth while to derive and use weather data sets that are spatially explicit for Ticino, e.g. from large-scale gridded climate fields.

In our study area, coniferous forests have a lower probability of featuring human-induced forest fires than deciduous forests. In the Ticino, conifers are predominantly located at higher elevations where human activity is rare, whereas valleys are more accessible and typically dominated by deciduous tree species (Conedera *et al.* 2006). In addition, snow cover is common in high-elevation conifer forests during the main fire season of human-induced forest fires (i.e. in the dry winter months).

In the Ticino, a wide range of human influences strongly affect the spatial and temporal distribution of human-induced forest fire ignitions, as expressed in our second hypothesis. With increasing distance from human infrastructure, the probability of a forest fire ignition is initially decreasing, but at larger distances the probability is increasing again. A possible explanation is that anthropogenic activities related to forest fires, such as agriculture, forestry, tourism and arson, mainly occur adjacent to human infrastructure with a well-developed urban-forest interface.

A limitation in our analysis of spatial human influence on fire activity lies in the fact that human activities were captured by a single land use classification period dating from 1992 to 1997, which was applied to the entire period from 1969 to 2005. We therefore were unable to consider spatial variations of human activity over time, with the exception of the legal amendment in the late 1980s. Further research could focus on developing a timeline of land-use change and identifying specific human activities that could be expected to be related directly to human-induced forest fires, but this would be a demanding exercise that would have been beyond the scope of our study. It is not clear to us whether the return on investment of such an effort would be justified, taking into account that the rate of land-use changes over the last 35 years has not been dramatic in this part of the world, even though forest area has increased considerably (LFI/WSL 2007). Overall, we expect the effect of legal amendments to be stronger than the changes in land use at decadal time scales.

The legal amendment shows a clear effect on the probability of human-induced forest fire ignitions, with a reduction after 1990, as expected in our third hypothesis. When considering the meteorological anomalies since the 1990s, such as the decrease in annual mean precipitation and the increase in annual mean temperature over the study period (Figure 7), we surmise that the actual effect of the legal amendment on human-induced forest fires has been larger, as the observed climatic change may have offset some of its effect. We conclude that humans can mitigate the effect of climate change on forest fire ignitions by appropriate measures and behaviour, at least to a certain degree.

Our study clearly shows that no single factor can be invoked to predict forest fire ignition, but a wide range of environmental and human determinants as well as the ignition source play a role (Cardille *et al.* 2001; Vigilante *et al.* 2004; Falk *et al.* 2007; Yang *et al.* 2007). Weather conditions, forest composition, and human influence show different relative strengths in the models for lightning- vs. human-induced forest fire ignitions. In particular, weather conditions represent the main factor influencing lightning-induced fires as expected in our first hypothesis and shown in other studies (e.g. Bessie and Johnson 1995; Ryan 2002); distance to infrastructure (hypothesis two) and weather conditions are the main drivers for human-induced fires. The differences between lightning- and human-induced forest fires regarding the importance of all investigated factors are considerable and lead us to conclude that the ignition source is a crucial piece of information for understanding forest fire ignition.

Summary and Conclusions

Our study shows that no single factor is able to account for forest fire danger, and the predictive power of each single determinant strongly depends on the ignition source (natural vs. anthropogenic). In a management context, we conclude that systems for forest fire prediction are likely to profit from a differentiation between ignition sources. The differences in fire weather conditions that best discriminate lightning- and human-induced forest fire ignition patterns should be taken into account, e.g. for planning the disposition of fire fighters. Our analyses suggest that the use of multiple fire weather indices is likely to improve forecasting in a study area, even if this is not a usual practice in operational fire management systems to date. Results from our study may also allow for the derivation of fire probability maps of particularly high fire danger (based on human activities in space and forest composition). This is relevant e.g. for spatial planning with regard to the accessibility of fire-prone forest areas, possibly necessitating the construction of additional access roads or water reservoirs for fire fighting purposes.

In a research context, it would be interesting to investigate the effects of separately modeled lightning- and human-induced forest fires in landscape succession models on the large-scale properties of the simulated forests. As the environmental characteristics and the disturbance regimes of lightning- and human-induced fires differ, it can be expected that there are also differences regarding their influence on successional processes (e.g. Schumacher and Bugmann 2006). Thus, the knowledge gained in the present project allows for a more realistic modelling of forest succession with respect to disturbance regimes from forest fires.

If a differentiation of ignition sources in a research project is not possible and one index has to be chosen, the Angstroem index would be more relevant than DMC, LCDI or FFWI in the Ticino region for the following reasons. First, the Angstroem index is appropriate especially for human-induced forest fire ignitions; in a region with more than 90% human-induced forest fires the focus should be on the majority of fire ignitions. Second, the calculation of the Angstroem index is rather simple because only information on temperature and relative air humidity is required. If high-resolution data on wind speed are available, the FFWI may also be appropriate for forest fire ignition modelling.

Overall, the differentiation of forest fire ignition sources is a promising field of research in regions with more than one ignition source because all investigated independent variables showed different importance and different influences on forest fire ignition. To enhance forest fire prediction systems, the models developed in our study should be evaluated in other regions; there is the potential that they could be generalized to other fire-prone ecosystems such as savannahs and Mediterranean scrublands.

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Supplementary material

Appendix 1. Weather stations

Names, coordinates (Reference System "CH1903", SWISSGRID coordinates Easting/Northing) and elevation of the weather stations (Figure 2) that were used for the calculation of lapse rates (Appendix 2).

Name	Coordinates	Elevation
Airolo	688 910 / 153 400	1 139 m a.s.l.
Piotta	694 930 / 152 500	1 007 m a.s.l.
Comprovasco	714 990 / 146 440	575 m a.s.l.
Locarno-Monti	704 160 / 114 350	366 m a.s.l.
Lugano	717 880 / 095 870	273 m a.s.l.

Appendix 2. Lapse rates

Monthly lapse rates used for the calculation of elevation-dependent daily values of precipitation, maximum and mean air temperature, and air humidity. The values are calculated for changes in mm, °C, and % per 100 meter of elevation difference. Underlying data derived from 5 weather stations (cf. Figure 2 & Appendix 1).

Month	Precipitation (mm / 100 m)	Maximal air temperature (°C / 100 m)	Mean air temperature (°C / 100 m)	Air humidity (% / 100 m)
January	1.22	-0.626	-0.643	0.231
February	2.37	-0.634	-0.678	0.333
March	-1.04	-0.677	-0.700	0.128
April	-1.60	-0.704	-0.723	-0.035
May	-3.41	-0.591	-0.658	-0.377
June	-4.29	-0.559	-0.675	-0.403
July	-3.06	-0.590	-0.700	-0.118
August	-5.93	-0.603	-0.701	0.031
September	-2.90	-0.586	-0.675	-0.109
October	3.24	-0.540	-0.654	-0.197
November	2.40	-0.688	-0.695	0.125
December	1.84	-0.637	-0.651	0.305

Appendix 3. Definition of land use categories for distance to infrastructure

Overview on the original categories of the land use statistics of Switzerland used for the definition of distance to infrastructure. Four sections of activities are differentiated: settlements, work, leisure time, and traffic. The overall distance to infrastructure combines all four sections. The numbers in the column 'Original land use categories' correspond to Hotz et al. (2005).

Land use type	Original land use categories	Description
Settlements	25	Single-family and duplex buildings
	26	Row and terrace buildings
	27	Appartment buildings
	29	Non-specified buildings
	45	Surrounding of single-family and duplex buildings
	46	Surrounding of row and terrace buildings
	47	Surrounding of appartment buildings
	49	Surrounding of non-specified buildings
Industry	21	Industrial buildings
	24	Buildings on special settlement areas
	28	Agricultural buildings
	41	Surrounding of industrial areas
	48	Surrounding of agricultural buildings
	61	Other public utility use and waste disposal systems
	62	Energy supply installations
	63	Sewage installations
	64	Dumpsides
	65	Mining areas
	66	Construction sites
Leisure time	20	Ruins
	23	Buildings in recreation areas and public parks
	51	Sports facilities
	52	Garden plots
	53	Camping, Caravan
	54	Golf courses
	56	Churchyarda
	59	Public parks

Land use type	Original land use categories	Description
Traffic	31	Highways
	32	Accompanying highway green
	33	Roads, streets
	34	Parking areas
	35	Railway stations
	36	Railway lines
	37	Airports
	38	Airfields, accompanying airport green
	67	Accompanying railway green
	68	Accompanying road green

Chapter 2

On the generality of forest fire ignition models – a case study from two Swiss mountain regions

Patrick Weibel, Björn Reineking & Harald Bugmann (in preparation).

Abstract

Models of forest fire regimes are typically calibrated for specific conditions, but one rationale for these models is the application beyond the spatial and temporal conditions for which they were developed, e.g. under future climate scenarios. We tested the transferability of logistic regression models (GLMs) of fire occurrence in two regions in Southern Switzerland that feature distinct climatic conditions and forest composition, in Ticino (TI) and Valais (VS). Weather variables were represented by 14 drought and forest fire danger indices. Using high-resolution data (1 day; 1 hectare), we evaluated model transferability temporally between two consecutive 16-year periods from 1974-2005, and spatially across the two regions.

For human-induced forest fires (> 90% of all fires), models based on the Angstroem index turned out to be most suitable. The conditions for lightning-induced forest fires were represented best by models based on the Keetch and Byram Drought Index or the LandClim Drought Index.

GLMs were reasonably transferable in time within a given study region (True Skill Statistic TSS > 0.4), but transfer in space between study regions was not possible (TSS < 0.4). This is likely to be due to the fact that weather conditions and forest composition are more different between regions than between periods in a region. The drought and fire weather indices are generally higher in VS than in TI, and forest composition is different with a domination of coniferous forests in VS and deciduous forests in TI.

The use of forest fire ignition models in research and practice has to take into account this limited transferability, e.g. when applying the models under future climate scenarios. We recommend to rigorously test models for their transferability and to evaluate uncertainties before applying them under new conditions.

Introduction

Forest ecosystems are affected by climate change both directly, e.g. via changing growth conditions, and indirectly, e.g. via changing disturbance regimes; therefore it is important to be able to project forest development under the influence of climate change and changing disturbance regimes such as forest fires. Over the past decades, the frequency and severity of forest fires have been increasing in some regions already (but see Flannigan et al. 1998), and anthropogenic climatic change is expected to exacerbate this trend (Gillett *et al.* 2004; Schumacher and Bugmann 2006; Westerling *et al.* 2006). There is no doubt that fire activity and climate are linked, but the exact nature of this relationship seems to depend on region-specific factors, making it difficult to derive general rules (Littell et al. 2009). Insights from modelling studies can help to better understand the determinants of forest fires, and to identify effective and efficient landscape and fire management schemes. To this end, modules of large-scale disturbances in models of forest dynamics have to be reliable, robust, and transferable in time and space.

Statistical and dynamic modelling approaches in forest fire research are used for various purposes: (1) to predict forest fire ignitions and patterns (e.g. Mandallaz and Ye 1997; Cardille *et al.* 2001; Nitschke and Innes 2008), (2) to predict forest fire propagation (e.g. Rothermel 1972; e.g. Finney 1998; Finney 2005), (3) to study forest succession processes including disturbance regimes in combination with vegetation dynamics (e.g. He and Mladenoff 1999; Mladenoff and He 1999), and (4) to develop appropriate management schemes (e.g. Hargrove *et al.* 2000; Klenner *et al.* 2000; Keane *et al.* 2002; Yang *et al.* 2004; Syphard *et al.* 2008). These modelling approaches are typically developed for specific regions with specific conditions, but often applied over a broader temporal and/or spatial extent. For example, based on knowledge about present and/or past conditions, vegetation models that include a fire module have often been used to predict future changes at the global scale under the assumption that current relationships will remain valid in the future (e.g. Dynamic Global Vegetation Models, Friedlingstein et al. 2006).

Before applying a model under novel conditions, its scope and transferability in time and space should be tested (Schröder and Richter 1999), which is a non-trivial problem and challenge. Whereas in species distribution modelling, tests of transferability are firmly established (e.g. Bonn and Schröder 2001; Randin *et al.* 2006; McAlpine *et al.* 2008; Vernier *et al.* 2008; e.g. Barbosa *et al.* 2009), there are still only a few examples in the field of forest fire research: Parisien and Moritz (2009) calibrated regression fire models on three different spatial scales and transferred the models between different areas. Transfers were successful especially when a model derived for a larger spatial extent was applied to a sub-area. With respect to time, Girardin and Mudelsee (2008) used a historical relationship between drought indices and fire occurrence calibrated in one period and a reconstruction of drought for a longer period in the past to estimate past and future wildfire activity. They concluded that the choice of the reference period is a sensitive parameter to the rejection or not of the null hypothesis of "no significant change in wildfire activity". In the case of forest fire danger systems, there is considerable experience regarding the applicability of e.g. the Canadian Forest Fire Weather Index System (CFFWIS; Canadian Forestry Service 1970; CFFWIS; van Wagner 1987; de Groot *et al.* 2003; Wotton *et al.* 2005) and the Nesterov ignition index (Nesterov 1949), both of which are used in many regions of the world (e.g. Viegas *et al.* 1999; e.g. Skvarenina *et al.* 2003; Weibel *et al.* subm.). Viegas *et al.* (1999) compared methods for evaluating fire danger and concluded that the predictive value of individual indices varied greatly depending on the environmental conditions under which they were applied. They evaluated five fire danger methods that had been developed in four countries either for summer or winter fires and applied them in six different regions in France, Italy, and Portugal. They found that the predictive quality (number of fire days, number of fires, area burned) of the fire danger methods was different for summer and winter fires and also depended on the region for which the methods were applied. However, the use of a particular index in various parts of the world does not imply that statistical models predicting the probability of forest fires from the index value are structurally robust when extrapolated across space or time. Thus, knowledge on the transferability of such forest fire models in space and time is still quite limited.

In this study, we examine the transferability of logistic forest fire regression models in space and time, i.e. between two neighbouring regions in the Swiss Alps that feature strongly different climatic conditions (insubrian climate in Ticino vs. continental climate in Valais) and between two consecutive 16-year periods (1974-1989 vs. 1990-2005). Our models comprise information on weather data, forest composition, and human activities, and they differentiate between lightning- and human-induced fires.

The specific objectives of our study are (1) to calibrate statistical forest fire ignition models for the two neighboring regions Ticino and Valais in Southern Switzerland, with an emphasis on identifying those models containing the most suitable drought and fire danger indices, and (2) to test the transferability of these models in both space and time, i.e. between the two regions and between two consecutive periods.

Material and methods

Study regions

The two study regions Ticino (TI) and Valais (VS) cover parts of the Southern and South-Western Alps in Switzerland with an elevation gradient of forested areas from 190 to 2 400 m a.s.l. (Figure 1; Appendix 1 A & B). A comparison of the environmental determinants and the number of forest fires in TI and VS is given in Table 1, Figures 2 & 3, and Appendix 1.

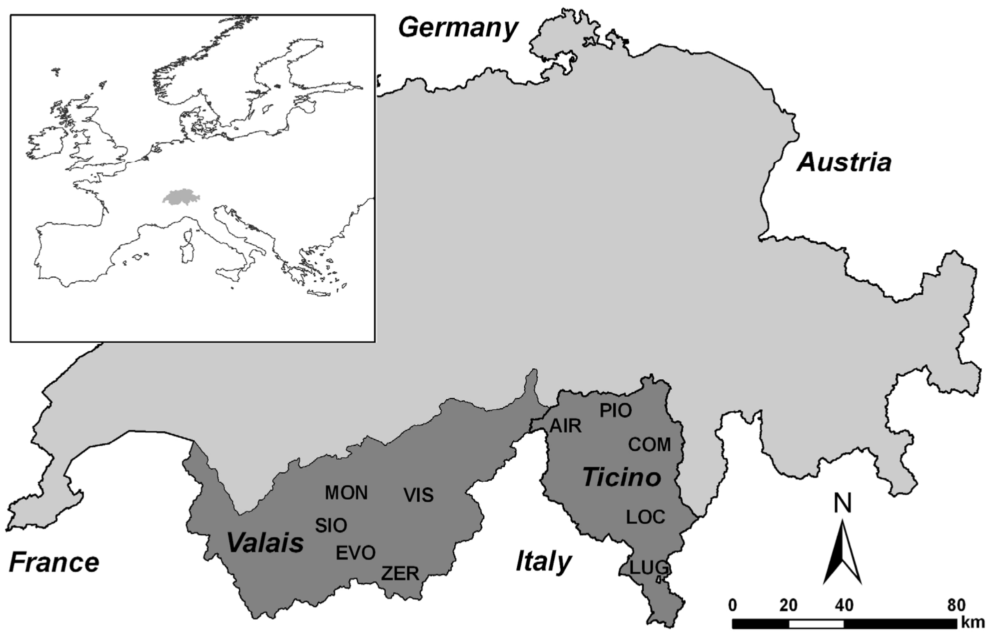

Figure 1. Map of the study regions Ticino and Valais in southern Switzerland (large map) and position of Switzerland in Europe (small map), with acronyms of the weather stations. Weather stations in Ticino: Airolo (AIR), Piotta (PIO), Comprovasco (COM), Locarno-Monti (LOC), and Lugano (LUG); weather stations in Valais: Montana (MON), Sion (SIO), Visp (VIS), Evolène-Villaz (EVO), and Zermatt (ZER).

The TI covers an area of 2 644 km² and is the most fire-prone region in Switzerland. Fires are an important disturbance agent in this partly steep region with forests that provide protection from avalanches, rockfall and landslides. The insubrian climate in TI is characterized by mild winters, warm summers, and mean annual rainfall of more than 1 300 mm, with a very high day-to-day variability, particularly in summer. Forests cover about 50% of the area and consist mainly of deciduous tree species with a significant amount of sweet chestnut (*Castanea sativa* Miller). Human activities are concentrated mainly at the valley bottoms, where residential and industrial areas, highways and railways are located.

The VS covers an area of 5 216 km^2 and is the second most fire-prone region in Switzerland. A recent large fire in 2003 with a burned area of 300 ha underlined the importance of forest fires in this dry inner-alpine region (Moser et al. 2006). The continental climate with cold winters, warm summers and mean annual rainfall of 600 mm (measured at the bottom of the main valley; weather station Sion, cf. Figure 1) provides conditions that are conducive for forest fires. The VS has a forest cover of about 20% mainly consisting of coniferous tree species. Human activities exhibit a similar pattern as in TI.

Table 1. Key environmental differences between the study regions Ticino (TI) and Valais (VS).

	Ticino		**Valais**	
Weather and climate[a]				
Mean annual temperature (°C)		12.2		9.9
Mean annual rainfall (mm)		1 310		608
Climate type		insubrian		continental
Forest composition (ha)[b]				
Coniferous forest	41 503	(29.9%*)	80 046	(82.5%*)
Deciduous forest	69 374	(50.1%*)	13 592	(14.0%*)
Non-classified forest	27 734	(20.0%*)	3 367	(3.5%*)
Total forested area	138 846	(52.5%**)	97 005	(18.6%**)
Forest fires (number)[c]				
Human-induced 1974-1989		675		75
Human-induced 1990-2005		567		168
Lightning-induced 1974-1989		30		10
Lightning-induced 1990-2005		87		19

[a] Information on weather derives from the weather stations Locarno-Monti (TI) and Sion (VS) for the period 1974 to 2005.

[b] Information on forest composition derives from the Swiss land use statistics 1992-1997.
* percent of total forested area; ** percent of total area of the study region.

[c] Information on forest fires derives from the forest fire data base developed by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL).

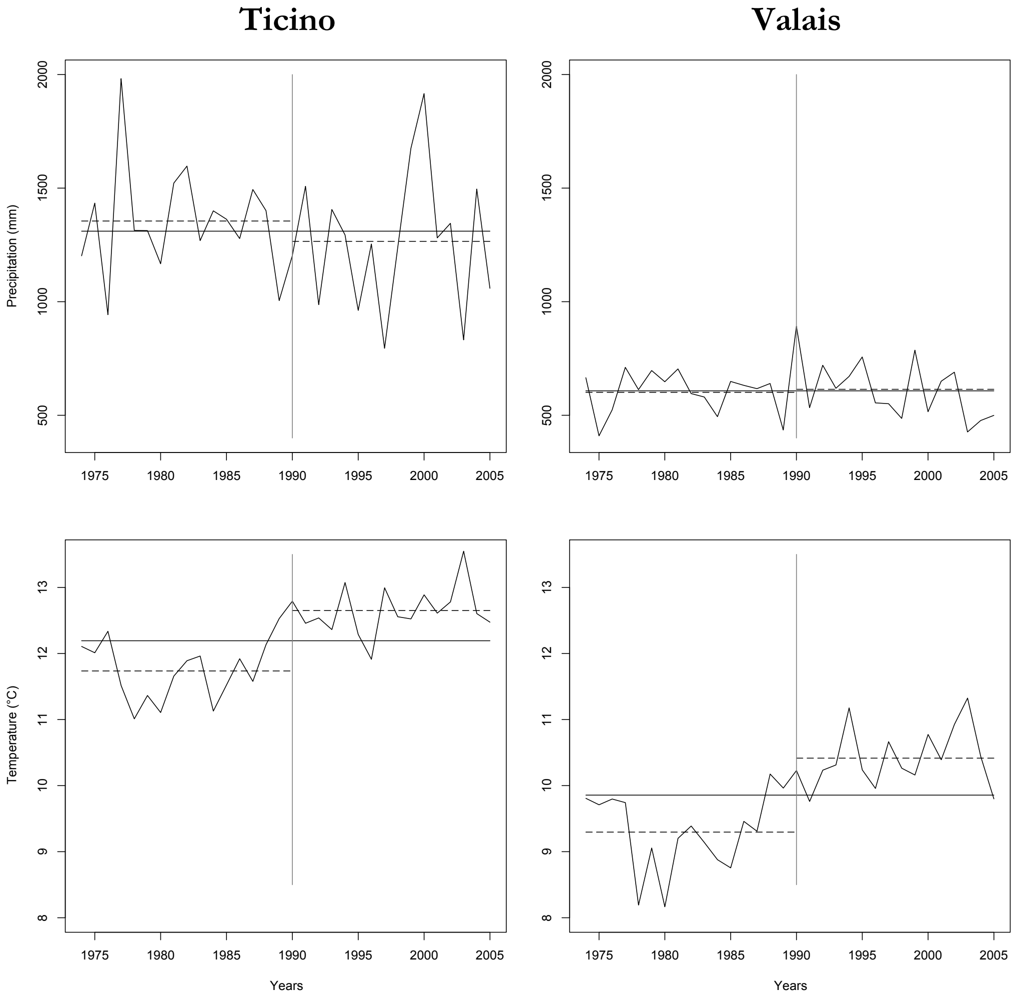

Figure 2. Development of annual precipitation sum (upper graphs) and mean annual temperature (lower graphs) for Ticino (left) and Valais (right). The solid horizontal lines indicate the mean values over the whole period 1974-2005. The long dashed horizontal lines indicate the mean values for the early period 1974-1989 and the late period 1990-2005. In Ticino, the mean annual rainfall slightly declined between the two periods whereas in Valais there is no clear difference. The mean annual temperature increased in both regions between the early and the late period.

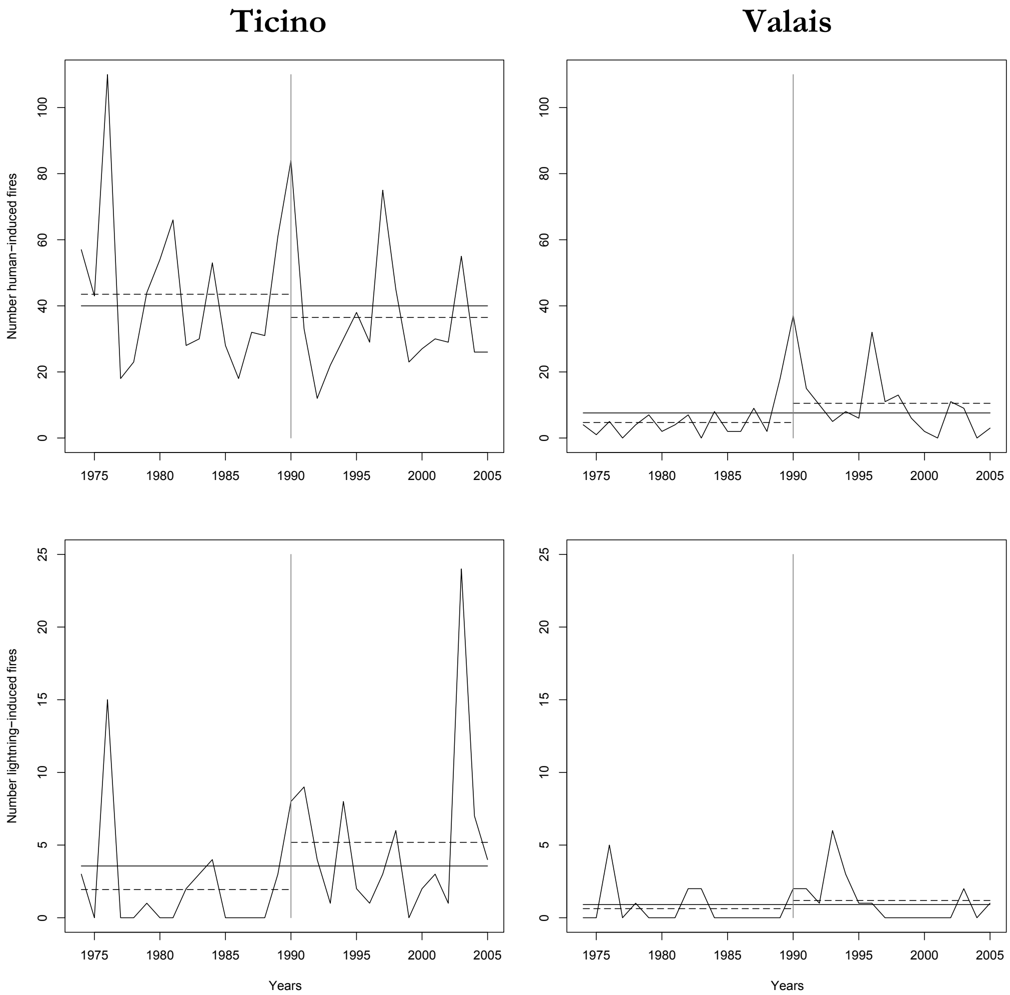

Figure 3. Changes in annual number of forest fires in Ticino (left) and Valais (right) for human- and lightning-induced forest fires. The solid horizontal lines indicate the mean annual number of forest fires over the whole period 1974-2005. The long dashed horizontal lines indicate the mean annual number of forest fires for the early period 1974-1989 and the late period 1990-2005. The annual number of forest fires is increasing between the two periods with one exception in the Ticino for human-induced forest fires. This decline can be explained by a change in legislation in the year 1990 (ban on burning garden rubbish).

Data

We used daily records of forest fire occurrence and weather data, and spatially explicit data on forest composition and human activities for each 100 m x 100 m (1 ha) cell in the two study regions.

Fire occurrence data

The forest fire data base developed by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) provides forest fire data for TI and VS (Pezzatti *et al.* 2005; Zumbrunnen *et al.* 2009). The data were collected systematically based on an extended standard protocol, and they comprise information on ignition cause, geographical coordinates of the ignition point, date and time of the start and end of the fires, topographic parameters (elevation, aspect, slope), area burned, type of forest fire (crown fire, ground fire), damage, forest type, and main tree species of the burnt forest.

Weather data

Time series of weather data were taken from the Swiss Meteorological Agency, using weather stations in central TI (Locarno-Monti, 366 m a.s.l.) and central VS (Sion, 482 m a.s.l.). Elevation adjustments were calculated for the variables temperature, precipitation, and relative air humidity. We used linear lapse rates based on data from five weather stations on different elevations in both regions, including the base stations Locarno-Monti (TI) and Sion (VS). Additional stations for TI were Lugano (273 m a.s.l.), Comprovasco (575), Piotta (1 007), and Airolo (1 139), and for VS Visp (640), Montana (1 508), Zermatt (1 638), and Evolène-Villaz (1 825) (Figure 1). The values of the monthly lapse rates are given in Appendix 2. Wind speed was not adjusted with elevation because local effects are overriding any general elevational pattern.

Land use and land cover data

Data on forest composition and human impacts were taken from the land use statistics of Switzerland, which provides information on 74 land use categories for the 1 ha grid cells, derived from aerial photographs (BFS 2001; Hotz *et al.* 2005).

Forest composition was used as a substitute of fuel type for each hectare cell. We used three classes of forest composition: coniferous forest (>50% coniferous tree species coverage), deciduous forest (>50% deciduous tree species coverage), and non-classified forest resulting from constraints in the classification of aerial photographs (e.g. topographical shading, cloud cover).

We evaluated human impacts on forest fire ignition by pooling 37 land use categories into one single value characterizing a wide range of human activities (settlements, industry, traffic, and leisure time). For the analysis, the intensity of human activities on each forested cell was represented by the absolute distance to the nearest cell with human land use.

The data from the land use statistics of Switzerland used here refer to the period 1992-1997. Rates of change in land use are relatively small, and thus these data represent conditions for the whole study period that we investigated (1974-2005) well enough (BFS 2001; Hotz *et al.* 2005).

Data analysis

We used 14 drought and forest fire danger indices to represent weather conditions (cf. Appendix 3 for a detailed overview): the Canadian Forest Fire Weather Index System (CFFWIS; van Wagner 1987) with 7 indices; the Munger Index (Munger 1916); the Nesterov Index (Nesterov 1949); the Keetch and Byram Drought Index (KBDI; Keetch and Byram 1968), the Fosberg Fire Weather Index (FFWI; Fosberg 1978); the modified Fosberg Fire Weather Index (mFFWI; Goodrick 2002); the Angstroem Index (Skvarenina *et al.* 2003); and the LandClim Drought Index (LCDI; Bugmann and Cramer 1998).

We used logistic regression models (generalized linear models GLM; Menard 1995; generalized linear models GLM; Hosmer and Lemeshow 2000) to distinguish between time-space units (1 day; 100 m x 100 m = 1 ha) with and without forest fire ignitions (presence-absence data sets). In our case, the presence points were given by the fire events. The large number of fire-free time-space units – 0.81 billion in TI and 0.57 billion in VS – necessitated that a random sample was taken. We chose the procedure introduced by Brillinger et al. (2003) and used in Weibel et al. (subm.): The sampling procedure was to collect a random date and cell out of all absence points without replacement. The use of a constant fraction of 0.0025% of all time-space units resulted in 20 030 data points (presence and absence points) for TI and 13 994 data points for VS. Each randomly sampled absence point thus represented a certain number of absence points depending on ignition source, study region and period. We therefore weighted the absence points in the data sets accordingly so as to adequately represent the large number of absence points that were not selected. To distinguish between two study periods, we divided the time series from 1974-2005 into two periods of the same length (1974-1989 and 1990-2005). For both sub-periods, we randomly sampled the required number of absence points.

We calibrated a range of GLMs that distinguish between forest fire ignitions in time and space (presence points) and fire-free time-space units (absence points). The models were built using three environmental factors (Weibel et al. subm.): (1) one of the 14 drought and fire danger indices, (2) forest composition (three categories), and (3) distance to human infrastructure. For the latter factor, we included a non-linear relationship by fitting this variable and the logits of forest fire probabilities using restricted cubic spline (RCS) functions. Models with RCS functions are composed of piecewise third-order polynomials within intervals determined by knots. The connections between the polynomials are forced to be smooth, and the composite function is constrained to be linear in the tails (Stone and Koo 1985; Harrell 2001).

The application of all 14 drought and fire danger indices resulted in 14 different GLMs that were used in both study regions, for both study periods, and for both ignition sources. A total of $14 \cdot 2^3 = 112$ GLMs were thus calculated and evaluated.

For each combination of study region, study period, and ignition source we selected the model with the most suitable drought or fire danger index for the transferability study (determined by the Akaike Information Criterion AIC). Each of these most suitable models was calibrated under insubrian climate (TI) and then tested under continental climate (VS), and vice versa. We also calibrated the models in the early period (1974-1989) and tested them in the later period (1990-2005), and vice versa. In total, 8 transfer constellations were tested. In order to separately evaluate the role of weather conditions, we additionally transferred 8 GLMs with only the most suitable drought and fire danger indices as explanatory variables.

We calculated the percentage of fire events that were erroneously classified as non-fire events as a measure of how many fire events were missed by the transferred models (false negatives), and the percentage of non-fires that were erroneously classified as fires as a measure of how often fire fighting teams would have been on alert on days without fire danger (false positives) using the corresponding thresholds of the training data on the test data (cf. Table 3). In addition, to compare observed vs. simulated numbers of forest fires, we plotted the monthly numbers of forest fires over time for all transfers.

The area under the receiver operating characteristic curve (AUC) value was used to determine model quality on the training data. The transferability of the models between study areas and study periods was assessed by three performance measures: sensitivity (true positive rate), specificity (true negative rate) and the True Skill Statistic (TSS) maximized over the full range of possible probability thresholds on training as well as on test data (Allouche et al. 2006). TSS is calculated as sensitivity plus specificity minus one, and it is a measure of accuracy that does not depend on prevalence (Allouche et al. 2006). Thus, it is highly suitable for evaluating presence-absence models, e.g. in ecology (Manel et al. 2001); in our presence-absence data set we had a highly asymmetric pattern of presence and absence points and thus needed such an accuracy measurement. For the interpretation of the TSS values, we adopted the classification for kappa values proposed by Araujo et al. (2005): "excellent" for TSS ≥ 0.75; "good" for 0.75 > TSS ≥ 0.4; and "poor" for TSS < 0.4.

To assess the causes for transferability problems in time and space, we visually compared histograms of all explanatory variables (drought and fire weather indices, forest composition, distance to infrastructure) for all combinations of study region, period, and ignition source.

All analyses were performed using R, a language and environment for statistical computing (R version 2.8.0; R Development Core Team 2008). Logistic regression models were fitted with the *glm* function, restricted cubic splines (RCS) were calculated using the *Design* package, and AUC values were calculated using the *somers2* function of *Design* (R-package version 2.0-12; Harrell 2005).

Results

Between 1974 and 2005, a total of 1 359 and 272 forest fire events were recorded in TI and VS, respectively (Table 1; Appendix 1 D1/D2 & E1/E2). Humans and lightning ignited on average 42.5 forest fires per year in TI and 8.5 fires in VS. This corresponds to annually 0.98 forest fires per km^2 of forested area in TI and 0.28 fires per km^2 in VS.

The results of our analyses showed that model transferability was restricted to specific conditions: In general, transfer between periods within the same region was possible, whereas transfer between regions during the same period was difficult. The percentage of fires that were erroneously classified as non-fires by transferred GLMs showed a high variability with 3-40% for transfers in time; time-space units without fires that were classified as carrying fires ranged between 11 and 56%. For transfers in space, these percentages were even higher. Therefore, we distinguish between regions, periods, and ignition sources when evaluating the most suitable models below.

Table 2. Overview of the most suitable logistic regression models with the respective drought or fire danger index for all combinations of study region, ignition source, and study period. **Bold values** indicate parameters with p<0.05.

Study area	Ignition cause	Study period	Drought or fire danger index	AUC	(Intercept)	Index	Deciduous forest	Coniferous forest	Distance to infrastructure	Distance to infrastructure'
Ticino	human	**1974-1989**	**FFWI**	0.872	**-3.192**	**0.219**	**0.852**	**-0.859**	**$-5.69 \bullet 10^{-3}$**	**$7.45 \bullet 10^{-3}$**
		1990-2005	**ANGSTROEM**	0.865	**0.555**	**-0.687**	**0.761**	**-0.398**	**$-5.20 \bullet 10^{-3}$**	**$6.96 \bullet 10^{-3}$**
	lightning	**1974-1989**	**LCDI**	0.944	**-109.178**	**105.497**	0.161	-0.351	$-8.38 \bullet 10^{-4}$	$1.08 \bullet 10^{-3}$
		1990-2005	**KBDI**	0.906	**-8.603**	**0.007**	0.399	0.420	**$1.59 \bullet 10^{-3}$**	**$-2.63 \bullet 10^{-3}$**
Valais	human	**1974-1989**	**FFMC**	0.841	-21.512	**0.062**	12.109	13.249	**$-3.07 \bullet 10^{-3}$**	$-2.58 \bullet 10^{-4}$
		1990-2005	**ANGSTROEM**	0.807	-12.736	**-0.891**	12.202	13.575	**$-3.11 \bullet 10^{-3}$**	$2.07 \bullet 10^{-3}$
	lightning	**1974-1989**	**ANGSTROEM**	0.935	-30.401	**-1.200**	12.891	12.691	**$4.59 \bullet 10^{-2}$**	**$-1.11 \bullet 10^{-1}$**
		1990-2005	**LCDI**	0.854	-30.484	**10.234**	13.457	14.062	$4.52 \bullet 10^{-3}$	$-6.73 \bullet 10^{-3}$

Model fitting

The choice of the most suitable models for each region and each period (Table 2) as determined by AIC values was based on AIC differences between 7 and 53 units; in one case the difference was only 2 units (data not shown). Weather indices, forest composition, and distance to human infrastructure were significant ($p < 0.05$) for human-induced forest fires in TI (Table 2). In VS, forest composition was not significant in the models; this is probably because the fraction of deciduous forest stands in VS is quite small (14%), thus lending little predictive power to this variable in VS. A different pattern was characteristic for the models of lightning-induced forest fires: Only the weather indices were significant, with two exceptions in the second period in TI and the first period in VS. In these cases, distance to infrastructure was a significant predictor variable as well.

Hence, the most suitable models for the different combinations of study region, study period, and ignition source include only a few different fire indices. Particularly the Angstroem Index was found to be highly suitable for human-induced as well as – though in one case only – for lightning-induced forest fires. For human-induced fires also FFWI and FFMC – an index from the CFFWIS – were suitable. In the case of lightning-induced forest fires, the models with the drought indices LCDI and KBDI were most suitable.

Transferability of the best models

The GLMs evaluated here were generally transferable in time but much less transferable in space (Table 3), with dramatic changes of TSS values from training data to test data (Figure 4). An almost identical pattern was evident from the GLMs that included only the most suitable drought or fire weather index, with a tendency of lower transferability of the models of human-induced fires and slightly better transferability of the models of lightning-induced fires (data not shown). The percentages of fires that were erroneously classified as non-fires and of non-fires that were erroneously classified as fires are given in Table 4.

Transferability of the GLMs in *time* as measured by the True Skill Statistic (TSS) on the test data was acceptable for human-induced fires and mostly also for lightning-induced fires, with TSS > 0.4 (Figure 4, Table 3). For human-induced forest fires, the transfer of GLMs was good in both directions, i.e. from the early to the late period and vice versa. For lightning-induced forest fires, the transfer pattern was not uniform: the backward transfer from the late to the early period was good in TI and VS, whereas the forward transfer from the early to the late period was good in TI but poor in VS. Transfers of the

Table 3. True Skill Statistic (TSS) values and corresponding thresholds on training and test data for all conducted transfers of logistic regression models. For both human- and lightning-induced forest fires all 8 transfers are listed. The abbreviations are composed of the study area (TI for Ticino and VS for Valais) and the beginning year of the study period (74 for the early period 1974-1989 and 90 for the late period 1990-2005)

				Human-induced forest fires						Lightning-induced forest fires					
	Training data		**Test data**	**Index**	**TSS Training data**	**Threshold**	**TSS Test data with threshold Training data**	**TSS Test data with threshold Test data**	**Threshold**	**Index**	**TSS Training data**	**Threshold**	**TSS Test data with threshold Training data**	**TSS Test data with threshold Test data**	**Threshold**
1	**TI74**	→	**VS74**	FFWI	0.570	10^{-6}	0.120	0.120	10^{-6}	LCDI	0.809	10^{-7}	0.000	0.336	10^{-11}
2	**TI90**	→	**VS90**	ANGSTR.	0.569	10^{-6}	0.186	0.228	10^{-7}	KBDI	0.672	10^{-7}	0.000	0.246	10^{-8}
3	**VS74**	→	**TI74**	FFMC	0.532	10^{-7}	0.316	0.332	10^{-8}	ANGSTR.	0.658	10^{-8}	0.062	0.185	10^{-5}
4	**VS90**	→	**TI90**	ANGSTR.	0.320	10^{-7}	0.385	0.385	10^{-7}	LCDI	0.529	10^{-8}	0.488	0.488	10^{-7}
5	**TI74**	→	**TI90**	FFWI	0.570	10^{-6}	0.545	0.545	10^{-6}	LCDI	0.809	10^{-7}	0.569	0.596	10^{-8}
6	**TI90**	→	**TI74**	ANGSTR.	0.569	10^{-6}	0.550	0.550	10^{-6}	KBDI	0.672	10^{-7}	0.648	0.648	10^{-7}
7	**VS74**	→	**VS90**	FFMC	0.532	10^{-7}	0.393	0.393	10^{-7}	ANGSTR.	0.658	10^{-8}	0.209	0.306	10^{-9}
8	**VS90**	→	**VS74**	ANGSTR.	0.320	10^{-7}	0.414	0.414	10^{-7}	LCDI	0.529	10^{-8}	0.489	0.489	10^{-7}

GLMs in *space* were poor for all models (Figure 4), with TSS < 0.4 on the test data with one exception, i.e. lightning-induced fires from VS to TI in the late period (Table 3). An asymmetric pattern with very low TSS values for transfers from TI to VS and higher TSS values for transfers from VS to TI was evident especially for human-induced fires (Table 3).

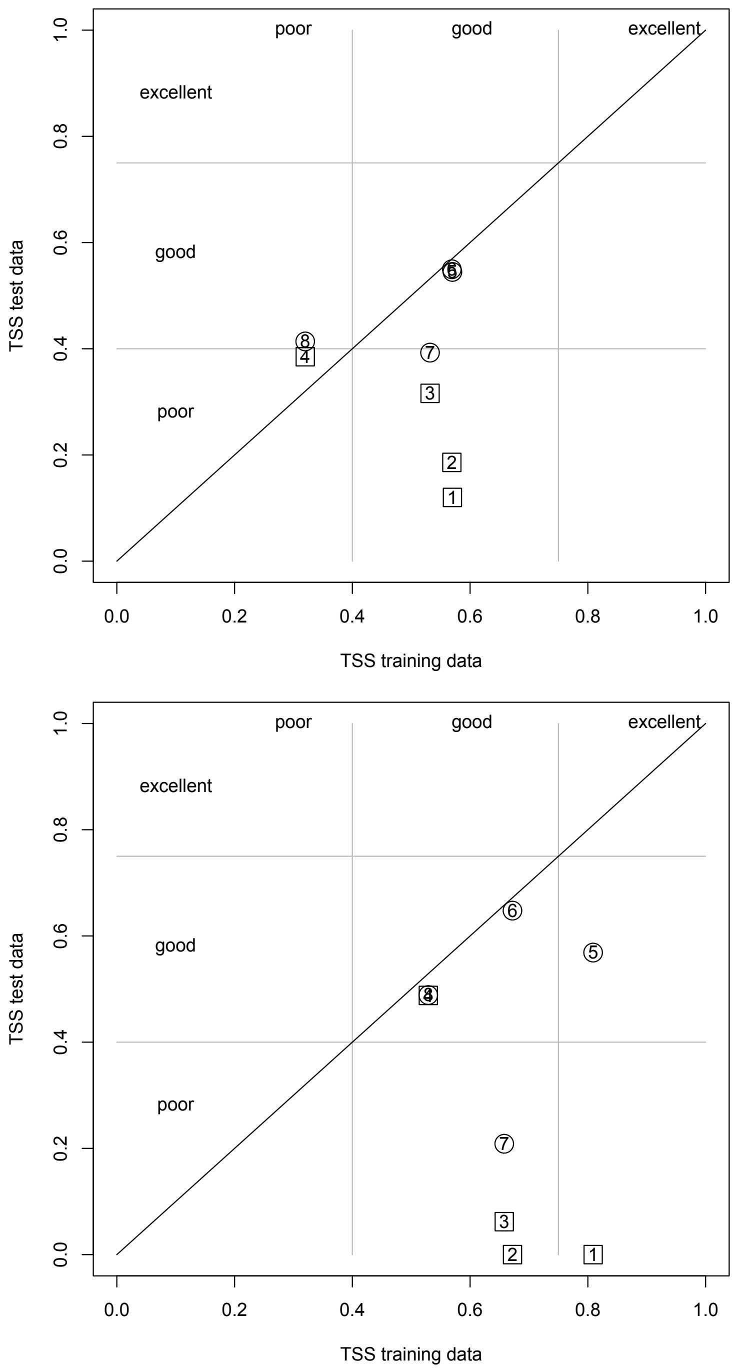

Figure 4. TSS values of the logistic regression models (GLMs) on training and test data for human-induced forest fires (upper graph) and for lightning-induced forest fires (lower graph). The numbers correspond to the numbers in Table 3 and indicate model transfers in space (framed with a square) and time (framed with a circle). In the left figure, the numbers 5 and 6 and in the right figure, the numbers 4 and 8 are nearly congruent.

The percentages of fires erroneously classified as non-fires and of non-fires erroneously classified as fires showed large differences across time and space (Table 4). The percentage of total false classifications ranged between 35 and 69% for transfers in *time* and between 51 and 88% for transfers in *space*, indicating a poor to very poor performance of the models.

Table 4. Overview on the percentages of erroneously classified fires as non-fires and erroneously classified non-fires as fires with the corresponding thresholds on test data. For both human- and lightning-induced forest fires all 8 conducted transfers of logistic regression models are listed.

				Human-induced forest fires				Lightning–induced forest fires			
	Training data		**Test data**	**% Fires erroneously classified as non-fires**	**% Non-fires erroneously classified as fires**	**% Error classifications**	**Threshold test data**	**% Fires erroneously classified as non-fires**	**% Non-fires erroneously classified as fires**	**% Error classifications**	**Threshold test data**
1	**TI74**	→	**VS74**	70.7%	17.3%	88.0%	10^{-6}	50.0%	16.4%	66.4%	10^{-11}
2	**TI90**	→	**VS90**	7.1%	70.0%	77.2%	10^{-7}	0.0%	75.4%	75.4%	10^{-8}
3	**VS74**	→	**TI74**	28.3%	38.5%	66.8%	10^{-8}	70.0%	11.5%	81.5%	10^{-5}
4	**VS90**	→	**TI90**	31.2%	30.3%	61.5%	10^{-7}	26.4%	24.7%	51.2%	10^{-7}
5	**TI74**	→	**TI90**	25.0%	20.5%	45.5%	10^{-6}	13.8%	26.6%	40.4%	10^{-8}
6	**TI90**	→	**TI74**	28.3%	16.7%	45.0%	10^{-6}	20.0%	15.2%	35.2%	10^{-7}
7	**VS74**	→	**VS90**	23.8%	36.9%	60.7%	10^{-7}	26.3%	43.1%	69.4%	10^{-9}
8	**VS90**	→	**VS74**	2.7%	55.9%	58.6%	10^{-7}	40.0%	11.1%	51.1%	10^{-7}

The plots of the monthly numbers of forest fires showed different patterns between observed and predicted values, depending on the transfers conducted (for examples, see Figure 5). The spectrum of relations ranged from zero to good according to the TSS values. The R^2 values for the monthly fire plots supported this valuation (cf. Figure 5). In general, the seasonal pattern of predicted lightning-induced forest fires matched the observed pattern well (cf. Figure 5A). For human-induced fires, the number of forest fires did not show a clear seasonal pattern, and simulated fires occurred also sporadically across the season.

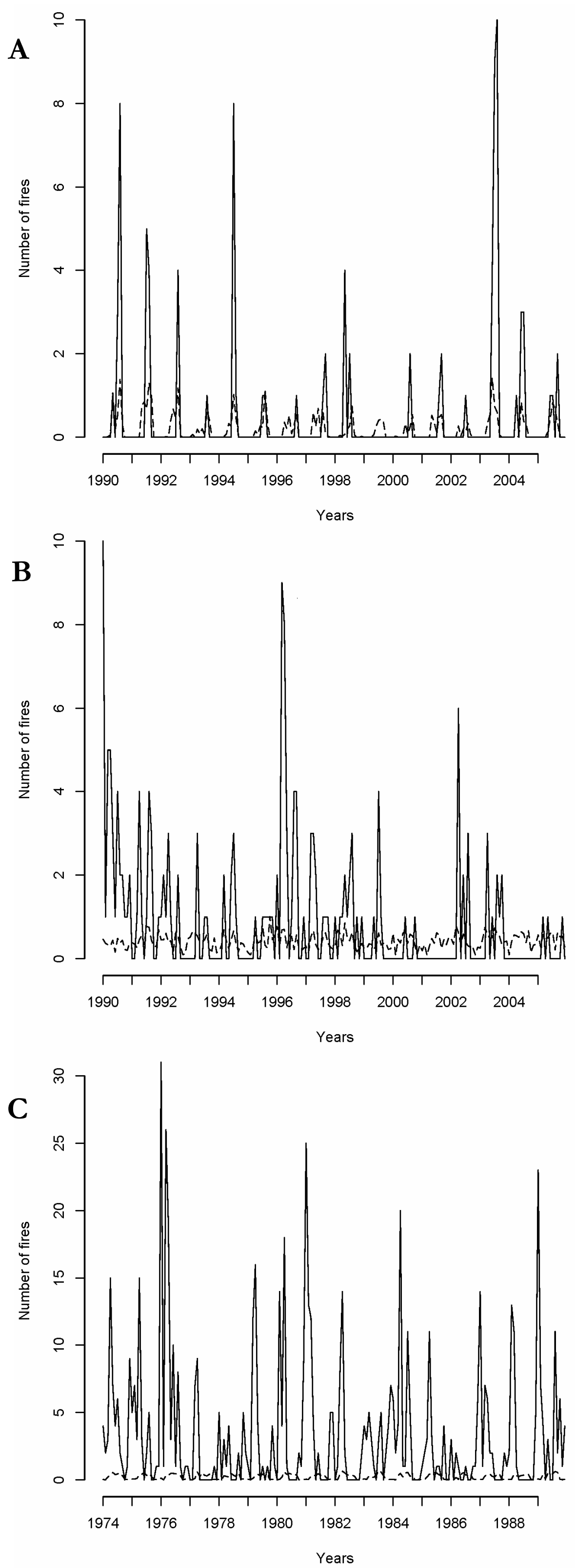

Figure 5. Relations of observed (solid lines) and predicted (dotted lines) numbers of forest fires per month using logistic regression models (GLMs). A: strong relation for model transfer of lightning-induced fires from Ticino 1974-1989 to Ticino 1990-2005 (TSS = 0.6; R^2 = 0.58); B: moderate relation for model transfer of human-induced fires from Valais 1974-1989 to Valais 1990-2005 (TSS = 0.4; R^2 = 0.28); C: weak relation for model transfer of human-induced fires from Valais 1974-1989 to Ticino 1974-1989 (TSS = 0.3; R^2 = 0.07).

The histograms of all explanatory variables for both regions and both periods clearly showed that the drought and fire weather indices were generally higher in VS than in TI, forest composition was obviously different with a domination of coniferous forests in VS and deciduous forests in TI (cf. Table 1), and the frequency distribution of distance to infrastructure was practically identical (results not shown). The histograms of all variables were nearly identical for the two periods within a region.

Discussion

General aspects

The transferability of the logistic forest fire regression models evaluated here is restricted to the temporal domain; transfer in space is not possible. Thus, the assumption that forest fire models are transferable in time *and* space, which is underlying many recent model applications at the regional (e.g. Schumacher and Bugmann 2006) or for coupled climate-carbon cycle models including fire disturbances at the global scale (e.g. Friedlingstein et al. 2006), should be viewed with caution. Among others, climatic change may have consequences for the absolute and/or relative importance of environmental determinants, which would result in changes in the relationships that are captured in statistical forest fire ignition models. Our results clearly demonstrate that differences in climate, weather, forest composition, and human activities result in different patterns of forest fire ignition, suggesting that it is necessary to use different model structures for specific situations. Because models are an important component of ecological research, environmental management, and conservation biology (Morrison et al. 1998), the ability to use models in different regions and under different climatic conditions is a key requirement for assessing the future state and dynamics of ecosystems. Hence, significant research challenges remain in the field of predicting forest fire occurrence.

Our study shows that the most suitable forest fire ignition models include only a few drought and fire danger indices. For human-induced forest fires, the Angstroem index, the FFWI and the FFMC performed best; they are capturing fire weather conditions. For lightning-induced forest fires, however, the drought indices LCDI and KBDI were best; they are based on the concept of soil moisture deficit. These differences in the suitability of the various indices for human- vs. lightning-induced forest fire models have already been established by Weibel et al. (subm.) and thus were confirmed in the present study.

Transfer in time

Our finding of good model transferability in time is supported by other studies, although most of them refer to species distributions. For example, Bonn and Schröder (2001) found a good transfer in time for a habitat model of carabids in an alluvial forest in two periods within two months. Clearly, the absolute length of the period considered in the two studies differs strongly, but this has a biological/ecological background: carabid population processes operate on time scales of weeks, whereas forest fire ignitions are the result of trends in weather (weeks to month), forest succession, and land use (years to decades).

It is important to take into account that the transfer in time assessed here constitutes a mild test for the models, because the two periods are adjacent, they are relatively short and do not feature exceedingly strong changes of climate (but cf. Figures 2 & 3). Transfers between periods that are not consecutive are likely to be much less favorable, but we were unable to test this in our study regions because of the absence of longer records of high-resolution data. Thus, in spite of the apparent success, our results clearly call for caution also with respect to transfers in time, particularly when large changes in climate (and/or land use) are to be expected, such as under anthropogenic global changes in the 21st century (IPCC 2007).

The choice of the calibration period is important, because the fire regime in a specific period may show only a partial aspect of a long-term fire history (de Groot *et al.* 2003; Girardin and Mudelsee 2008). The length of our calibration periods was relatively short. On the one hand, this may be a problem for model robustness; on the other hand, it allowed us to assume that forest composition and human influence remained essentially constant; hence our approach represents a necessary compromise between conflicting requirements in the modelling process.

Without changes in forest composition and human activities (also emergent from the histograms for all predictors; not shown), model transferability in time depends mainly on weather conditions, which are not strongly different in the two consecutive periods per region. The fire and drought indices of the most suitable models represent typical fire weather conditions either for lightning- or human-induced forest fires. As climatic change between the early and the late period has not been drastic in the two study regions, although temperatures have been increasing slightly (cf. Table 2), and particularly the typical seasonal patterns of the insubrian (TI) and continental (VS) climate have not changed over time, the good transferability of the models in time is explained well, and we conclude that these weather indices are highly suitable for capturing regional weather properties and drought conditions.

Models containing only the most suitable drought or fire weather index as explanatory variable showed even a better transferability in the case of lightning-induced fires, whereas the transferability of models for human-induced fires was clearly reduced. This confirms that weather conditions are the most important predictor for lightning-induced fires. For human-induced fires, in contrast, the role of weather is not so essential, and it is mainly the distance to human infrastructure that determines forest fire occurrence.

Transfer in space

The poor transferability of our forest fire ignition models in space indicates seminal differences in weather conditions and forest composition between the two study regions, which is in line with findings by Wotton et al. (2003) for fire models in Ontario, Canada. They used models that depend on weather data only and calibrated them for different areas separately. These models predicted somewhat different regional increases of fire occurrence under future climate. Based on their results, Wotton et al. (2003) predicted a general increase of human-caused fires when disregarding regional differences. With respect to our results, we feel that generalizing the conclusions from different models to larger areas may be misleading. The projections of different models calibrated for different parts of a larger region do not necessarily result in the same conclusion as if one model was calibrated for the entire region. Barbosa et al. 2009 (2009) showed that when a model is applied in the region where it was calibrated, the results are clearly better than under other conditions. Thus, following Parisien and Moritz (2009) it is typically not possible to use models on several different scales, e.g. at stand and landscape scales, without severe restrictions; this is particularly important when an upscaling to larger spatial units is sought.

Our findings of poor spatial transferability conform with results from a study of a multi-scale model for koala bears (McAlpine et al. 2008), which admittedly is not directly comparable to forest fire models. However, the argument of McAlpine et al. (2008) that biogeographical and land-use differences among regions tend to result in a specific validity of statistically derived ecological models is likely to apply to our results as well. Between our study regions, there are very strong environmental differences: an insubrian climate (TI) with mild winters, warm summers, and very high day-to-day variability in precipitation vs. a continental climate (VS) with cold winters, warm summers and much lower annual rainfall; as a consequence, the drought and fire weather index values in VS are generally higher than in TI; the fraction of forested area differs by a factor of 2.5, and forest composition differs as well, with dominance by deciduous tree species in TI vs. coniferous species in VS (cf. Table 1). In addition, sweet chestnut (*Castanea sativa* Miller) is present in TI only. Moreover, *Pinus* species have a high abundance in VS, whereas in TI Norway spruce (*Picea abies* L.) is the most widespread conifer (Ellenberg and Klötzli 1972). Only the influence of human activities is comparable in both regions, with a concentration in the lower parts of the valleys. However, historical impacts of human land use may have caused differences that are not straightforward to detect (Conedera *et al.* 2007; Muster *et al.* 2007; Gimmi *et al.* 2008). Overall, our study clearly shows the pitfalls of applying statistical models beyond the range of their calibration data.

The transferability of models that contain only a drought or fire weather index as predictor is practically identical to the model with all predictors, with one exception for lightning-induced fires in the early period and the transfer from VS to TI. This may indicate that the inclusion of the other predictors (forest composition and distance to infrastructure) is actually detrimental for the predictive power of this model, thus underlining that weather (drought) conditions are most important for predicting the occurrence of lightning-induced fires.

Limitations

The limited spatial resolution and the relatively short period for which daily weather data were available is a critical point for our study. For example, local, short-term extreme events such as thunderstorms that are important for lightning-induced forest fires may not be represented well by daily climatic data from individual weather stations. Additionally, small-scale topographic influences on local weather may have been represented overly simply by elevational lapse rates. Other approaches, e.g. dynamic models such as LANDIS II that have flexible temporal and spatial resolution (Scheller et al. 2007) may provide a better local representation of weather conditions. However, the availability and quality of the input data determines the quality of model output.

When only two study regions are available for the calibration and application of GLMs, the number of permutations for model tests is highly limited. The approach by Parisien and Moritz (2009) shows an example of nested fire models on different spatial scales, suggesting that models transferred to different areas were useful only when they overlapped appreciable in terms of their environmental space; such an approach would be interesting in our case as well, but it is not feasible due to data limitations.

A factor that may limit the transferability in our study could also be the fact that for most combinations of study region, period, and ignition source another drought or fire weather index was most suitable. As each index captures the weather signal differently, the application of a model with an index that is not most suitable under the new conditions (region and period) may lead to lower predictive power. Thus, a standard model with a more generally skillful drought or fire weather index may have a higher transferability, albeit such a model would have lower predictive power when fitted for a certain combination of region and period, as the more general index is not most suitable under the conditions of these combinations. Hence, there may be a trade-off between the regional accuracy of fire models and their cross-regional applicability.

Ecological aspects

Differences of climate/weather and forest composition between our study regions are larger than between periods within the same study area. However, drought as a single factor does not explain the occurrence of forest fires. Ignition sources are very important – without an ignition source, even under the driest conditions no fire will ignite. The higher number of forest fires in TI can be explained by the more extended wildland-urban interface (for conceptual information see Haight *et al.* 2004), and the higher fraction of forests may also be important: the more forested area there is the more potential ignition points are available.

When interpreting the different patterns of human- vs. lightning-induced forest fires (cf. Dickson et al. 2006), the good match of observed and predicted numbers of lightning-induced fires within the seasons indicates that there is a distinct periodicity (cf. Figure 5A). Nevertheless, it is important that the potential danger of natural fires is determined not only by drought conditions, but that the ignition needs a lightning strike. As the simulation of lightning strikes is not included explicitly in our models, this may explain some of the remaining differences between observed and predicted numbers of lightning-induced fires. The intra-annual pattern of human-induced forest fires is much more random, probably because the ignition sources of human activities cover a wide range of causes, including inadvertence, negligence, and arson rather than, as in the case of lightning-induced fires, a seasonally determined cycle of ignition-suitable weather conditions in combination with lightning strikes.

Here, we focus on forest fire prediction at the local to regional scale. For these scales, it is important to capture shifts to drier conditions and longer periods without precipitation. Such conditions are embodied well in the Angstroem Index, the KBDI and the LCDI. When forest fire ignition models for larger areas – on the continental to global scale – are required, however, the level of detail included in the models (e.g. Dynamic Global Vegetation Models) necessarily must be lower (cf. Cramer *et al.* 2001; Friedlingstein *et al.*

2006). Due to the much larger variation in climatic and land surface properties that must be captured with less detail, the transferability of large-scale (i.e. continental to global) models containing fire indices may thus not be warranted, either.

Despite the limitation of only two study regions, we feel that our approach of model transfer between regions with different climatic conditions can to some degree be interpreted as a study of future climatic conditions. As the climatic conditions are strongly different between the two study regions, the test region in this approach is a proxy for potential future climate in the original region. Thus, the lack of spatial transferability found here may lead to serious problems in dealing with forest fire disturbances in the context of climate change. Further research on forest fire models that are applicable under novel conditions of climate and land use is therefore sorely needed.

Management implication

For effective and efficient management, our research yields one main recommendation: Drought and forest fire danger indices can help preparing fire-fighting teams in operational readiness. The information of such indices gives a basic level of general forest fire danger. The fact that in our study 10-50% (in some cases, up to 75%) of the non-fire days were classified as fire days suggest that our models tend to overestimate fire danger to the point where they are not useful any more. More problematic than an overestimation of fire danger, however, is the percentage of fire days that were classified as non-fire days, reaching up to 30% for many cases and sometimes even higher. Fire danger that is not detected by a model that is used operationally may lead to serious problems in the setup of fire fighting strategies.

Regarding lightning-induced forest fires, no special actions have to be taken – at least under the current climate – for the two mountain regions studied here because these forest fires usually remain small due to subsequent precipitation. However, adaptation of forest and fire management to an altered number of forest fires will be necessary, and for this reliable forest fire models will be needed. A development of more integrative and spatially explicit management strategies to decrease the vulnerability of forests to changing fire risk has already been proposed by Le Goff et al. (2005); better knowledge on future forest fire risk would be of key importance also because the ability of fire management agencies to cope with increasing fire activity is limited, and fire managers operate with a very narrow margin between success and failure (Flannigan et al. 2009).

Conclusions

Our study suggests that the transferability of forest fire ignition models is limited to the temporal domain, provided that climatic and land-use conditions do not change strongly. We recommend to rigorously test other models for their transferability in time and space, and to evaluate uncertainties before applying models under novel conditions. New study areas or new climatic conditions may require forest fire models that feature a different structure or at least different parameter values. Based on our study we conclude that the Angstroem Index often captures forest fire danger under different conditions quite well, especially in regions with a human-dominated forest fire regime. In regions with lightning-dominated forest fire regimes, the Keetch and Byram Drought Index (KBDI; Keetch and Byram 1968) and the LandClim Drought Index (LCDI; Bugmann and Cramer 1998) are quite suitable as well.

The reason for the limited transferability in space between our study regions is mainly due to the insufficiency of our models to capture the different weather conditions and the strongly different forest composition. Thus a general trade-off exists between the regional accuracy of a model and its applicability across regions.

The results of our study do not allow for a generalization regarding a broader range of climatic conditions. Further investigations should test the transferability of forest fire models for other climatic conditions, geographical regions, and longer time periods. More generally speaking, the question arises whether a scientific method (the modelling approach) may have reached a limit here, such that a much more detailed representation of the complex interactions between the different systems (weather, forests, and human activities) – which are complex in themselves – would be required. The data for such detailed analyses may not be available in many regions of the world, thus strongly limiting our predictive ability of future forest fire occurrence.

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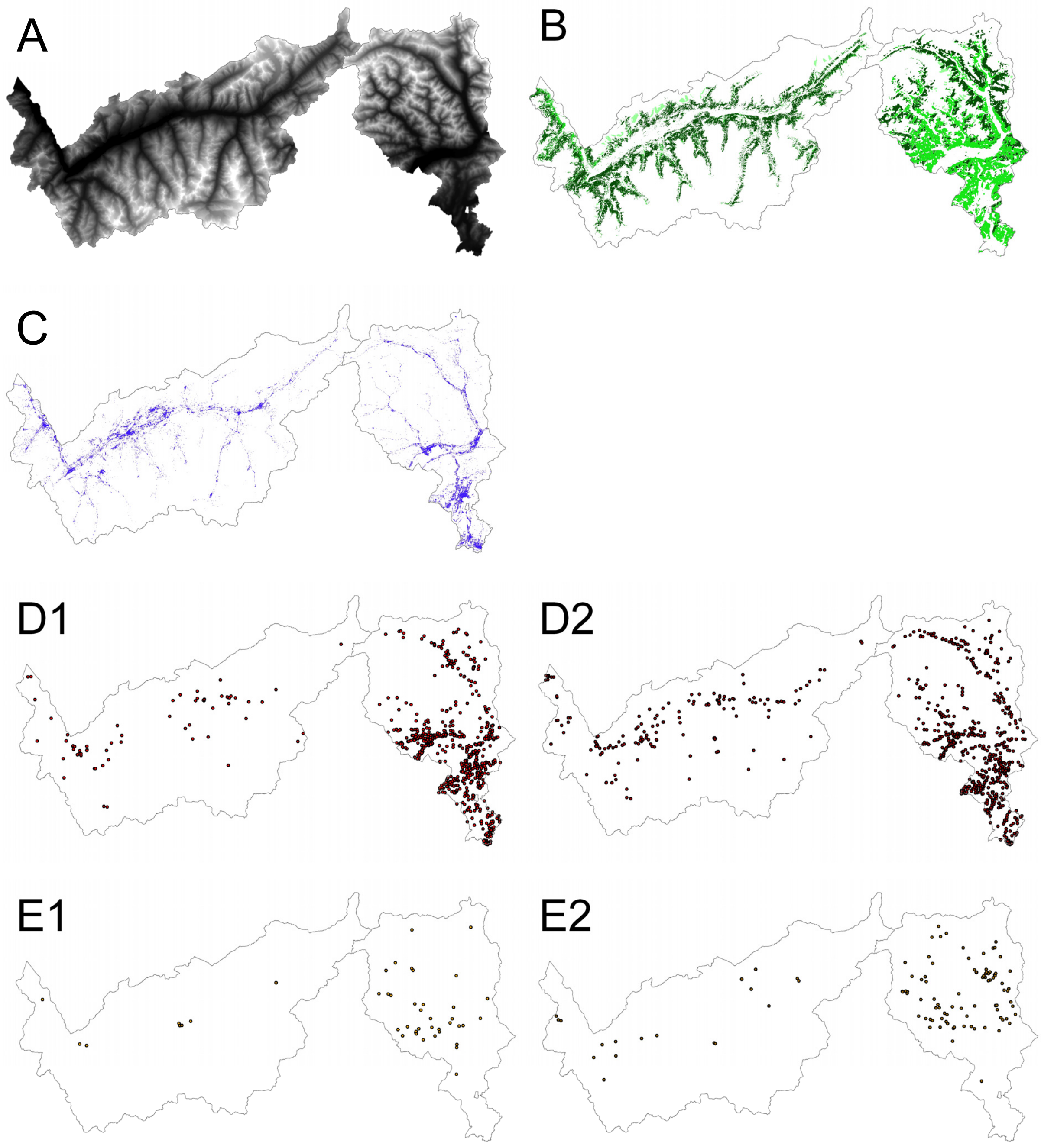
Supplementary material

Appendix 1. Detail maps of both study regions with information on (A) elevation, (B) forest composition, (C) human activities, (D1) human-induced forest fires in the early period 1974-1989, (D2) human-induced forest fires in the late period 1990-2005, (E1) lightning-induced forest fires in the early period 1974-1989, (E2) and lightning-induced forest fires in the late period 1990-2005.



Appendix 2. Monthly lapse rates used for the calculation of elevation-dependent values of precipitation, maximum and mean air temperature, and air humidity for both study regions Ticino (TI) and Valais (VS). The values are calculated for changes in mm, °C, and % per 100 meter of increasing elevation. Underlying data derive from 5 weather stations (cf. Figure 1).

Month	**Precipitation (mm/100 m)**		**Maximum air temperature (°C/100 m)**		**Mean air temperature (°C/100 m)**		**Air humidity (% / 100 m)**	
	TI	**VS**	**TI**	**VS**	**TI**	**VS**	**TI**	**VS**
January	1.10	1.48	-0.600	-0.264	-0.637	-0.210	0.226	-1.323
February	2.37	1.23	-0.634	-0.477	-0.678	-0.373	0.333	-0.766
March	-1.04	1.19	-0.677	-0.707	-0.700	-0.547	0.128	-0.030
April	-1.60	1.44	-0.704	-0.764	-0.723	-0.622	-0.035	0.377
May	-3.41	2.31	-0.591	-0.742	-0.658	-0.603	-0.377	0.393
June	-4.29	2.20	-0.559	-0.704	-0.675	-0.594	-0.403	0.399
July	-3.06	1.79	-0.590	-0.641	-0.700	-0.548	-0.118	0.191
August	-5.93	2.19	-0.603	-0.632	-0.701	-0.513	0.031	0.024
September	-2.90	1.33	-0.586	-0.570	-0.675	-0.451	-0.109	-0.207
October	3.24	1.37	-0.540	-0.475	-0.654	-0.341	-0.197	-0.813
November	2.40	1.06	-0.688	-0.352	-0.695	-0.267	0.125	-1.093
December	1.84	0.81	-0.637	-0.185	-0.651	-0.152	0.305	-1.547

Appendix 3. Overview of the 14 evaluated drought and fire weather indices used in this study, with formula (where sufficiently compact), required input variables, and reference for further information.

Name and Reference	Formula	Input variables	
Munger Munger, T.T. 1916. Graphic method of representing and comparing drought intensities. Monthly Weather Review **44**: 642-643.	$Munger = \frac{1}{2} \bullet w^2$	w	number of days since last daily rainfall >0.05”
Nesterov Nesterov, V.G. 1949. Combustibility of the forest and methods for its determination (in Russian). USSR State Industry Press.	$Nesterov = \sum_{i=1}^{w} (T_i - TD_i) \bullet T_i$	T TD w	temperature (°C) dew point temperature (°C) number of days since last daily rainfall >3mm
KBDI (Keetch and Byram Drought Index) Keetch, J.J., and G.M. Byram. 1968. A drought index for forest fire control. Asheville.	$KBDI = Q + \frac{(800 - Q) \bullet (0.968 \bullet e^{0.0486 \bullet T} - 8.30) \bullet \Delta t}{1 + 10.88 \bullet e^{-0.0441 \bullet PA}} \bullet 10^{-3}$	Q T Δt PA	previous day’s KBDI temperature (°K) time increment (1 day) mean annual rainfall (inch)
FFWI (Fosberg Fire Weather Index) Fosberg, M.A. 1978. Weather in wildland fire management: the fire weather index. *in* Proc. of the Conference on Sierra Nevada Meteorology, South Lake Tahoe.	$FFWI = \frac{\eta \bullet \sqrt{1 + U^2}}{0.3002}$	η U	function of temperature (°F) and relative air humidity (%) wind velocity (mph)
mFFWI (modified FFWI) Goodrick, S.L. 2002. Modification of the Fosberg fire weather index to include drought. International Journal of Wildland Fire **11**: 205-211.	$mFFWI = (0.000002 \bullet KBDI^2 + 0.72) \bullet FFWI$	see FFWI and KBDI	

Angstroem Skvarenina, J., J. Mindas, J. Holecy, and J. Tucek. 2003. Analysis of the natural and meteorological conditions during two largest forest fire events in the Slovak Paradise National Park. Pages 11 *in* International Bioclimatological Workshop, Račková dolina, Slovensko (Slovakia).	$Angstroem = \left(\frac{RH}{20}\right) + \left(\frac{27-T}{10}\right)$	RH relative air humidity (%) T temperature (°C)
LCDI (LandClim Drought Index) Bugmann, H., and W. Cramer. 1998. Improving the behaviour of forest gap models along drought gradients. Forest Ecology and Management **103**: 247-263.	(see reference)	temperature (°C) potential evapotranspiration (mm) precipitation (mm)
FFMC (Fine Fuel Moisture Code), ISI (Initial Spread Index), FWI (Fire Weather Index), DSR (Daily Severity Rating) van Wagner, C.E. 1987. Development and structure of the Canadian forest fire weather index system. 35, Canadian Forestry Service, Ottawa.	(see reference)	precipitation (mm) relative air humidity (%) wind velocity (m/s) temperature (°C)
DMC (Duff Moisture Code), BUI (Buildup Index) (van Wagner 1987)	(see reference)	precipitation (mm) relative air humidity (%) temperature (°C)
DC (Drought Code) (van Wagner 1987)	(see reference)	precipitation (mm) temperature (°C)

Chapter 3

Calibrating and testing a dynamic forest fire model in complex topography

Patrick Weibel, Björn Reineking, Ché Elkin & Harald Bugmann (in preparation).

Abstract

Forest fires are an important disturbance agent in many terrestrial ecosystems, and many goods and services depend on spatial interactions between ecosystems, i.e. they operate at the landscape scale. To investigate terrestrial ecosystems at the landscape scale, dynamic modelling is often used. Most dynamic forest succession models including fire disturbance are based on the concept of a fixed mean fire return interval and a mean fire size, thus making the validation of the fire model not necessary or even not possible. This, however, may cause problems when using such models to study the effects of climate change on forest fire regimes.

In contrast to other dynamic fire models, the fire return interval and the fire size are emerging properties of the landscape model LandClim, which was demonstrated to be appropriate for simulating vegetation properties along an elevational gradient in the Rocky Mountains that is characterized by strongly changing fire regimes.

In this study, we subject the fire module of LandClim to a rigorous test against detailed fire history data from two regions of the Swiss Alps. Model improvements were made, including (1) the daily calculation of drought index values; (2) implementation of the Angstroem fire weather index; and (3) incorporating a new sigmoidal function to convert index values into fire probabilities that has a floor and a ceiling.

The evaluation shows that the simulation results match the observed fire regimes (number of forest fires and fire size distribution) well when using appropriate parameter settings. The model improvements – especially the use of the Angstroem index and the limitation of minimum and maximum fire probabilities – result in appreciable advancements. Thus we conclude that the LandClim model is highly suitable for projecting forest succession under different fire regimes along strong climatic gradients.

Introduction

The temporal and spatial scale of terrestrial ecosystem services such as production of food and fibre, water supply, and carbon storage often precludes using direct observational or experimental studies to assess their fate e.g. under environmental changes. Thus, dynamic landscape models are often employed to examine the importance of ecological processes and to project future ecosystem states (e.g. Groot *et al.* 2004; e.g. Scheller and Mladenoff 2004; Scheller and Mladenoff 2007). Landscape models allow forest succession to be explored as well as the impacts of landscape-level disturbances such as forest fires to be examined. However, only few studies have performed an extensive validation of the disturbance modules that are incorporated in landscape models (cf. Mladenoff and He 1999). This is partially due to the lack of observational data, but also reflects the highly stochastic nature of disturbances that makes them difficult to study (Zumbrunnen *et al.* 2009; Weibel *et al.* in prep.). In the case of forest fires, many fire models are based on the concept of fixed mean fire return intervals and mean, maximum and/or minimum fire sizes that are prescribed by the modeller (e.g. Baker 1995; Bradstock *et al.* 1998; Mladenoff and He 1999; Keane *et al.* 2002). As a consequence, a validation of the fire regime simulated by the model is not needed or even not possible, because it is prescribed by the parameter values that are set as boundary conditions for the simulation. However, this lack of validation and of more mechanistic process representations is problematic, e.g. when evaluating the effects of climate change on forest fire regimes. Under new climatic conditions the fire return intervals and the mean fire sizes are expected to change, but many models are not capable of simulating the fire regime as an emergent property of the modelled processes.

In this study, we focus on the problem of simulating the forest fire regime in complex topography, using the Swiss Alps as a case study. In central Europe, wildfires are expected to occur more frequently and with larger areas burned under changing climatic conditions (higher temperatures, less precipitation, changes in seasonal precipitation patterns; e.g. Schumacher and Bugmann 2006; IPCC 2007). It is important to be able to evaluate forest fire danger and its impacts on forest succession in mountain regions because – among others – forests provide important protection function against avalanches, rockfall, erosion, and landslides. A key concern for the future is that fires often destroy large areas within hours to days, whereas the restoration of disturbed forests takes decades to centuries, thus strongly reducing protection from gravitational natural hazards for extended periods.

Here, we build upon the latest version of the dynamic landscape model LandClim, which allows for investigating forest succession and the influence of forest fire disturbance at the landscape scale (Schumacher and Bugmann 2006). Fire return interval and fire sizes are emerging properties of the process interactions simulated in the model. LandClim was demonstrated to be appropriate for simulating vegetation properties along an elevational gradient in the Rocky Mountains that is characterized by strongly changing fire regimes. However, a rigorous evaluation of the fire module of LandClim against detailed empirical data has not been accomplished yet.

Bond and Keeley (2005) defined fire regimes as the patterns of fire frequency, season, fire type (ground, surface, and crown), severity, and extent of fires in a given landscape over a given time period. Here, we focus on two of these aspects, i.e. the number of forest fires (frequency) and the fire size distribution (extent).

The overall goal of this paper is to simulate the forest fire regime of mountain forests of the Swiss Alps using the landscape model LandClim, and to compare model behaviour (i.e. the number and size distribution of forest fires) at the landscape scale against detailed empirical data. The specific objectives of the paper are (1) to evaluate LandClim by comparing simulated with observed numbers of forest fires and the fire size distributions (as elements of the forest fire regime), and (2) to improve the LandClim forest fire module to the extent that disagreements between simulated and observed properties of the fire regime are no longer evident. We therefore include new model formulations and test a range of parameter settings.

Material and methods

Model description

The forest succession model LandClim {Schumacher, 2004 #44} is a spatially explicit, raster-based, and stochastic model with the purpose to simulate forest succession in combination with disturbance regimes such as forest fires, windthrow and forest management (harvest). It has been developed based on the LANDIS model (Mladenoff *et al.* 1996; He and Mladenoff 1999; Mladenoff and He 1999; He *et al.* 2004) and tested in four landscapes, two in the Colorado Front Range (Schumacher et al. 2006) and two in the Swiss Alps (Schumacher and Bugmann 2006). The LANDIS model family was designed to simulate vegetation dynamics over long time spans (hundreds of years) and on large landscapes (10^3–10^6 ha). Key processes simulated in each raster cell are tree establishment, tree mortality, seed dispersal, and disturbances. Schumacher et al. (2004)

modified and extended the LANDIS formulations at the patch scale in three respects: (1) they introduced a more detailed description of the properties of tree cohorts; (2) they incorporated new formulations for tree growth and competition, thus strongly influencing simulated succession; and (3) they added routines describing the impacts of the physical environment more explicitly (i.e. climatic influences on tree demography). LandClim consists of two main parts: a 'local' succession model that operates on each grid cell with a time step of one year, and a landscape model that contains processes operating over several grid cells in 10-year time steps. Cell size is typically 25 m x 25 m. In the 'local' model, tree establishment, growth, and mortality are modelled under the influence of bioclimatic and biotic variables. In the landscape model, seed dispersal, harvest, windthrow, and forest fires are modelled. A detailed description of LandClim can be found in Schumacher et al. (2004; 2006) and Schumacher {, 2004 #44}.

The structure of the LandClim fire module is based on the assumption that fire occurrence is primarily responsive to climatic conditions as modulated by topography, fuel availability, and fuel state, i.e. moisture content of fuel (e.g. Bessie and Johnson 1995). Climatic conditions are represented by a monthly resolved, but annually aggregated drought index, which mimics average fuel dryness for any given cell. Forest fire occurrence is simulated with a 10-year time step. In each simulation step, several ignitions may occur. The number of potential ignitions is determined by an ignition coefficient that is multiplied by the number of cells in the landscape. The spatial distribution of the potential ignitions is uniform, i.e. each cell in the forested landscape has the same chance to be selected. However, a fire is only simulated if fire spread to a neighbouring cell is possible. Since fire spread probability depends on local conditions, the resulting distribution of fires is not uniform in the landscape. The number of potential ignitions is exponentially reduced with each fire. For each of the simulated fires, a year is selected randomly out of the 10 years of the past decade, and the fire is then simulated using an annual drought index that is calculated from the monthly weather data of this year. This procedure is repeated for each fire occurring within that decade {cf. \Schumacher, 2004 #44}.

Fire spread probability from each ignited cell to any of its eight neighbours is possible only when fuel is present, and it is simulated as a function of the drought index:

$$fireP_{base} = droughtIndex^{fireProbExp} \qquad \text{[Eq. 1]}$$

where $fireP_{base}$ is the fire probability, $droughtIndex$ the LandClim drought index, and $fireProbExp$ the exponent that determines the shape of the curve (cf. Table 1;

Figure 1A). Note that the fire probability influences not only fire spread but also the likelihood of fire occurrence.

Table 1. Parameters used in the LandClim fire module: names, descriptions, and values.

Name	Description	Value(s)
ignition coefficient	Coefficient, fire ignition	0.0001, 0.00014, 0.0002*, 0.00025, 0.0005
$fireP_{base}$	Basic fire probability	[0,1]
$fireP$	Resulting fire probability	[0,1]
$droughtIndex$	Drought Index	[0,1]
sa	Coefficient, slope adjustment	0.001
$\alpha = fireProbExp$	Coefficient, fire probability (Eq. [1] , [4] & [5])	2.0, 2.5, 3.0, 3.5, 4.0
$\beta = fireProbExpBeta$	Coefficient, fire probability (Eq. [4] & [5])	1.0, 2.0
$PMin$	Coefficient, fire probability (Eq. [6])	[0,1]
$PMax$	Coefficient, fire probability (Eq. [6])	[0,1]

Topography also influences fire spread, as fires are typically more likely to burn upslope than downslope (Rothermel 1972). This is taken into account by linearly increasing the basic spread probability ($fireP_{base}$) by a slope adjustment factor sa; the resulting downslope fire probability ($fireP$) is reduced accordingly. However, because burning logs and other debris can roll down steep slopes and thus ignite fire downslope, the fire spread probability ($fireP$) is reduced only up to a slope angle of 30° (Heinimann *et al.* 1998):

$$fireP = \begin{cases} fireP_{base} \bullet \left(1 + sa \bullet slope\right) & slope > -30(^{\circ}) \\ fireP_{base} \bullet \left(1 + sa \bullet -30\right) & else \end{cases} \qquad \text{[Eq. 2]}$$

Preliminary simulations with the original LandClim fire module showed that while it was capable of simulating broad-scale features of forest fires (cf. Schumacher and Bugmann 2006), it had problems to resolve the detailed features of regional fire regimes (Zumbrunnen *et al.* 2009; Weibel *et al.* in prep.). Therefore, we used in our study a modified version of the LandClim fire module, as follows: (1) we calculated the drought

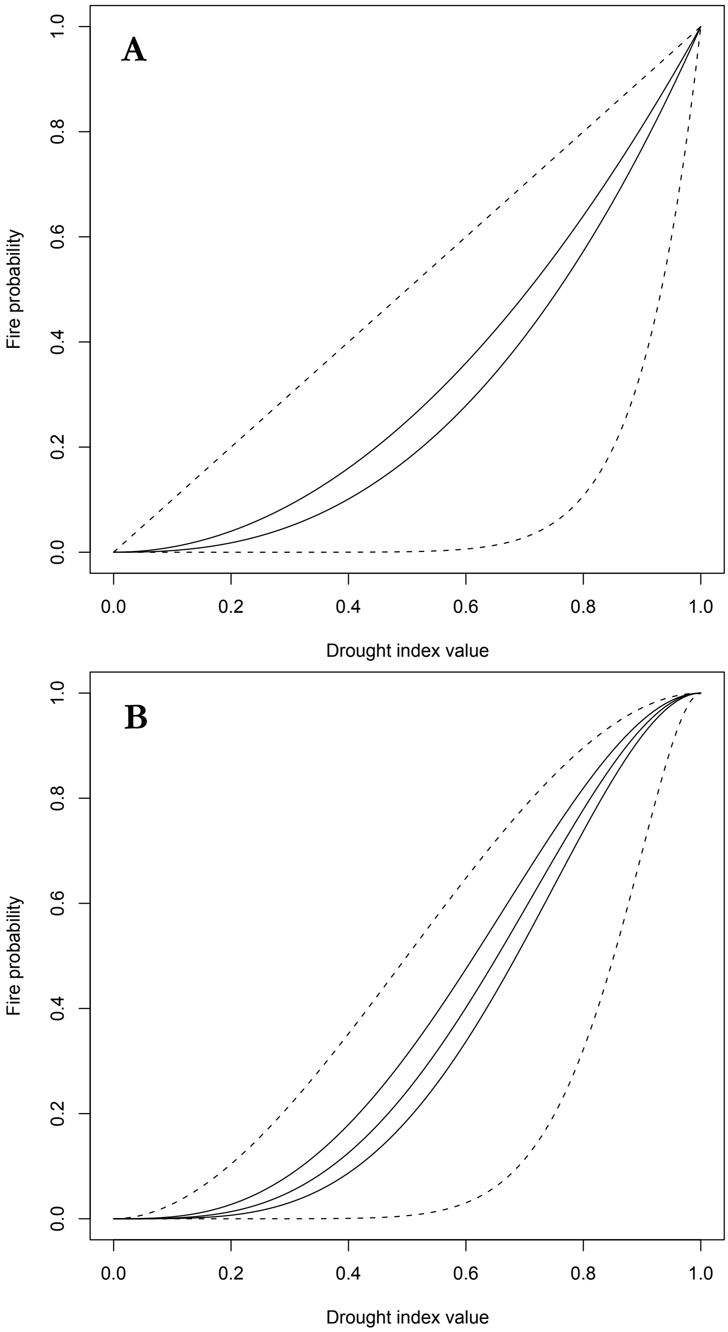


Figure 1. Fire probability as a function of the drought index value: Exponential (A) and sigmoidal (B) curves.

(A) Solid lines: original exponential curves [Eq. 1] from Schumacher (2004) with *fireProbExp* = 2.0 and 2.5; dashed lines: with extreme low *fireProbExp* = 1.0 (upper line) and extreme high *fireProbExp* = 10 (lower line);

(B) Solid lines: sigmoidal curves [Eq. 4] with *fireProbExp* = 3.0, 3.5 and 4.0, and *fireProbExpBeta* = 2.0; dashed lines: with extreme low *fireProbExp* = 2.0 (upper line) and extreme high *fireProbExp* = 10 (lower line).

index values on a daily basis in order to capture short-term variations of weather conditions; (2) we implemented the Angstroem index, which had been found to be highly suitable for determining forest fire danger in mountain forests of the study regions (Weibel *et al.* in prep.; Weibel *et al.* subm.); (3) in addition to the exponential function [Eq. 1], we incorporated an alternative sigmoidal function for translating the index values into fire probabilities so as to better represent this relationship particularly for very low and very high index values, respectively; and (4) we added the possibility to constrain the fire probabilities to a smaller range within the interval [0,1] by prescribing minimum and maximum probabilities. By doing so, we increased the number of very small fires that typically occur under conditions of low drought. These modifications are described in detail below.

Daily drought index values. For the calculation of daily drought index values, daily weather data, i.e. temperature, precipitation, and relative air humidity were necessary. The daily calculation routine randomly chooses data from a particular day to determine the fire probability of each fire ignition. This routine allowed to better capture the fluctuations of short-term weather events. The climate data that were available to us were not spatially explicit, but an elevation adjustment using monthly lapse rates was included based on climate station data.

Angstroem index. The integration of the fire weather index by Angstroem {Skvarenina, 2003 #123} in addition to the LandClim drought index is based on Weibel et al. (in prep.), who found it to be highly suitable for the prediction of fire danger for human- and lightning-induced forest fires in southern Switzerland. The Angstroem index is easy to calculate as it requires information on relative air humidity (RH in %) and temperature (T in °C) only:

$$Angstroem = \left(\frac{RH}{20}\right) + \left(\frac{27-T}{10}\right) \qquad \text{[Eq. 3]}$$

Sigmoidal translation function. In addition to the exponential translation function [Eq. 1] of drought index values into fire probabilities, we implemented a sigmoidal approach as an incomplete beta function that is defined by the integral

$$I_x(x,\alpha,\beta) = \frac{B_x(\alpha,\beta)}{B(\alpha,\beta)} = \frac{1}{B(\alpha,\beta)} \int_0^x t^{\alpha-1}(1-t)^{\beta-1}dt \qquad \text{[Eq. 4]}$$

where α and β are > 0, and $B(\alpha,\beta)$ is the value of the beta function

$$B(\alpha,\beta)=\frac{(\alpha-1)!(\beta-1)!}{(\alpha+\beta-1)!} \qquad \text{[Eq. 5]}$$

The incomplete beta function is defined for drought index values x in the range from 0 to 1. For x = 0, the value of the function is 0, for x = 1, the value of the function is 1. The parameters $\alpha = \mathit{fireProbExp}$ and $\beta = \mathit{fireProbExpBeta}$ (cf. Table 1) determine the shape of the sigmoidal curve (cf. Figure 1B). This new function allows simulating scenarios where the fire probability converges to zero for small and to one for large values of the drought index. For medium drought index values, the new function is steeper than the exponential curve and it translates these values into fire probabilities within a smaller range between the asymptotic tails near zero and one. Figure 1B shows different combinations of *fireProbExp* and *fireProbExpBeta* values and the resulting curves. If *fireProbExpBeta* is one, the curve is identical to the original exponential case of equation [Eq. 1] used by Schumacher et al. (2006).

For the use of the new sigmoidal function, the drought index values need to be scaled between 0 and 1. The LandClim drought index is scaled between 0 and 1 by definition, but the Angstroem index needed re-scaling. Because low Angstroem values indicate a high fire danger and vice versa, we scaled the values by using reciprocal values $1/\mathit{Angstroem}$. This was possible because for the conditions in our study regions, there are no Angstroem values <1, which would have led to values above 1.

Minimum and maximum fire probabilities. With the option to set a minimum and a maximum fire probability, it is possible to cap the function by adding a prefix to the incomplete beta function [Eq. 4]:

$$I_{res} = PMin + (PMax - PMin) \bullet I_x \qquad \text{[Eq. 6]}$$

where I_{res} is the resulting fire probability, $PMin$ is the minimum fire probability and $PMax$ is the maximum fire probability (cf. Table 1). Figure 2 shows different translation curves with different combinations of $PMin$ and $PMax$ values.

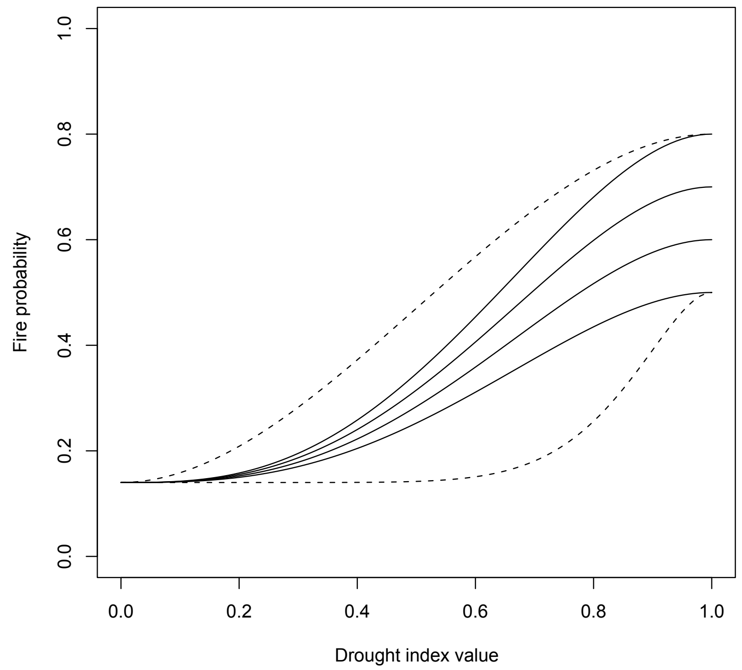


Figure 2. Sigmoidal translation curves for the translation of drought index values into fire probabilities including limitation of minimum and maximum fire probabilities. Solid lines: with *fireProbExp* = 3.0, *fireProbExpBeta* = 2.0, *PMin* = 0.14, and *PMax* ranging from 0.5 to 0.8; dashed lines: sigmoidal translation curves with extreme low *fireProbExp* = 2.0, *fireProbExpBeta* = 2.0, *PMin* = 0.14, and *PMax* = 0.8 (upper line) and extreme high *fireProbExp* = 10, *fireProbExpBeta* = 2.0, *PMin* = 0.14, and *PMax* = 0.5 (lower line).

Study area

Our study regions comprise a part of the cantons Ticino (the Leventina valley) and Valais (the south central Valais region comprising the Val d'Hérens, the Val d'Arolla, the Val de Réchy, the Val d'Anniviers, and the Turtmanntal). Both study regions are located in southern Switzerland and belong to the south-central/southwestern Alps (Figure 3).

The Leventina is the upper main valley of Ticino and covers an area of 319 km^2. The insubrian climate of the Ticino is characterized by mild winters, warm summers, and mean annual rainfall of more than 1 300 mm, with a very high day-to-day variability, particularly in summer. Forests consist mainly of deciduous tree species {Ellenberg, 1972 #224}. Human activities are concentrated mainly at the valley bottom, where residential and industrial areas, highways and railways are located. The Leventina valley is part of the most fire-prone region of Switzerland. Fires are an important disturbance agent in this steep valley because the forests provide protection from avalanches, rockfall and landslides (Conedera *et al.* 1996; Conedera *et al.* 2004). In the Leventina, humans and lightning cause on average three to four forest fires per year, which is equivalent to 0.01 forest fires km^{-2} yr^{-1} (Pezzatti et al. 2005).

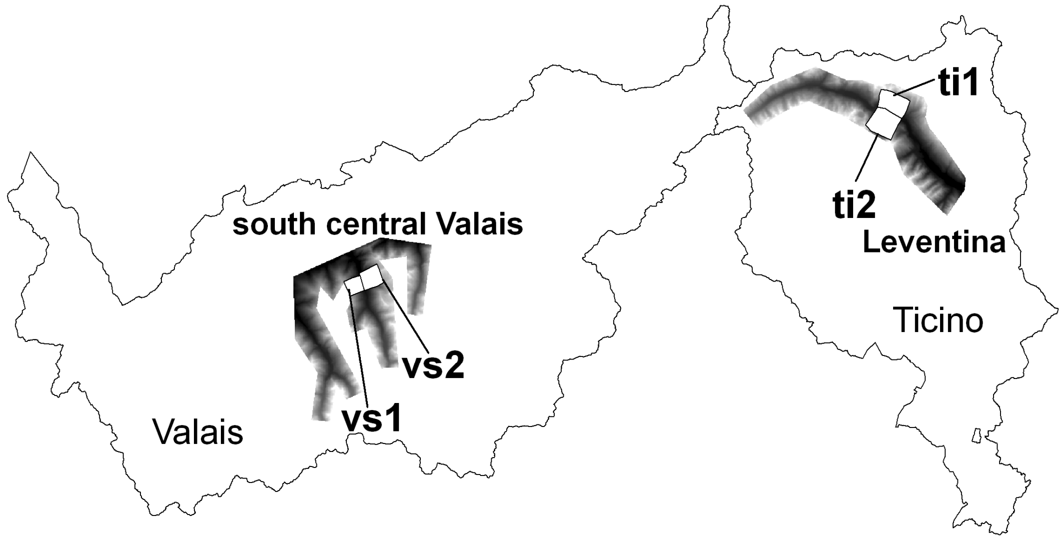


Figure 3. Map of the study regions south central Valais and Leventina in the Ticino. The study plots are labeled vs1 (7.9 km^2) and vs2 (12.1 km^2) in the south central valais, and ti1 (17.3 km^2) and ti2 (21.2 km^2) in the Leventina.

The south central Valais covers an area of 355 km^2 and comprises several of the main side valleys of Valais, the second most fire-prone region in Switzerland. A recent large fire just outside the study region occurred in 2003 and burned an area of 300 ha, underlining the importance of forest fires in this dry inner-alpine region (Moser et al. 2006). The continental climate with cold winters, warm summers, and mean annual precipitation of 600 mm at the valley bottom provides conditions that are conducive for forest fires. Forests consist mainly of coniferous tree species {Ellenberg, 1972 #224}. Like in the Leventina, human activities are most frequent at the bottom of the valleys. Altogether, humans and lightning cause approximately one forest fire per year in the south central Valais, what is equivalent to 0.003 forest fires km^{-2} yr^{-1} (Zumbrunnen et al. 2009).

Within the two study regions Leventina and south central Valais, we selected two study plots each, one on the southwest-facing slope and one on the northeast-facing slope to investigate the influence of aspect on fire occurrence (Figure 3).

Data

We used daily records of weather data from two weather stations operated by the Swiss Meteorological Agency: Locarno-Monti at 366 m a.s.l. in central Ticino and Sion at 482 m a.s.l. in central Valais. Data on observed forest fires in the two study regions were taken from the forest fire database developed by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). These data have been collected systematically based on an extended standard protocol, and they comprised among others information on the ignition cause, geographical coordinates of the ignition point, date and time of the start and end of the fires, and area burned (Pezzatti et al. 2005).

Simulations

To obtain an initial forest state for the four study plots we first simulated forest succession from bare ground using a 1000-yr "spin-up" run. Daily weather data for these runs were taken from the climate database of the Swiss Meteorological Agency for the period 1969 to 2005 by selecting randomly (with replacement) whole year data sets. For the simulation of the fire regimes between 1970 and 2000 we then started with the initial forest state at the end of the "spin-up" period and used the observed daily weather data to drive the model.

We first tested a series of parameter combinations for *fireProbExp*, *fireProbExpBeta*, *PMin*, and *PMax* to get a coarse overview of simulated fire size distributions and the number of fires. We then confined the parameter space to all combinations of the pairs {*fireProbExp*, *fireProbExpBeta*} to {2.0, 1.0}, {2.5, 1.0}, {3.0, 2.0}, {3.5, 2.0}, and {4.0, 2.0} with all combination pairs of *PMin* 0.1, 0.15, and 0.2 with *PMax* 0.5, 0.6, 0.7, and 0.8 as well as the combination {*PMin*, *PMax*} {0.0, 1.0}. The parameter pairs for {*fireProbExp*, *fireProbExpBeta*} of {2.0, 1.0} and {2.5, 1.0} were used for the evaluation of the exponential translation curves; the parameter pairs {3.0, 2.0}, {3.5, 2.0}, and {4.0, 2.0} were used for the evaluation of the sigmoidal curves. All these combinations were simulated using 10 replicates from 1970-2000 to achieve a number of simulated forest fires that equaled at least the number of observed fires. In a second step, we tested values of the *ignition coefficient* that were lower and higher (Table 1) than the default value of 0.0002 used by Schumacher {, 2004 #44}. With this parameter, it was possible to adjust the number of simulated forest fires without notably changing the fire size distribution. All simulations were performed using LandClim version 1.1.1 (revision 294).

Data analysis

We analysed the fire size distributions by combining all replicates per parameter combination. From this combination pool, we randomly selected as many simulated fires without replacement as we had in the observed data. Each simulated fire size distribution was compared with the observed fire size distribution using the Kolmogorov-Smirnov two-sample test.

For the analysis of the simulated number of forest fires during the study period, we compared the mean number of fires of all simulated replicates with the observed number of forest fires and allowed for a ±20% difference to declare a match.

All analyses were performed using R, a language and environment for statistical computing (R version 2.8.0; R Development Core Team 2008).

Results

The model improvements that we implemented allowed the model to be well calibrated against the observed fire regimes in the study plots, especially in the Leventina. The simulations with the Angstroem fire weather index resulted in more accurate numbers of forest fires and fire size distributions than the simulations with the LandClim drought index (Tables 2 & 3).

The simulated number of forest fires and the fire size distribution in the Leventina study plots matched the observation data with the use of appropriate parameter combinations (Tables 2 & 3, Figures 4A & 4B). For the south central Valais the simulated fire size distributions were not significantly different from the observed fire size distributions (Figures 4C & 4D) but the simulated number of forest fires was higher than the observations in most cases (Table 4 & 5). The number of observed forest fires in the Leventina was higher than in the south central Valais, hence a difference of 20% between observed and simulated number of fires could be reached with only a few additional events for the south central Valais whereas some more simulated fire events in the Leventina did not imply a drastic change in the deviation. Thus, the power of this test for the Valais was low due to the low number of fires.

The possibility of setting minimum and maximum fire probability values resulted in a clear improvement of model performance. All simulations with $PMin = 0$ and $PMax = 1$ were not able to simultaneously reproduce the number and sizes of forest fires (Tables 2-5). The most suitable values for $PMin$ and $PMax$ depended on the drought index and on the study region. For the Angstroem index in the Leventina, a $PMin$ value of 0.15 was most suitable, whereas in the south central Valais a $PMin$ value of 0.1 was more appropriate. The optimal $PMax$ values ranged from 0.5 to 0.8. For the LandClim drought index the most suitable $PMin$ value is 0.1 and the $PMax$ values ranged from 0.5 to 0.8 in both study regions.

The use of an exponential vs. a sigmoidal relationship between the drought index and the fire probabilities did not reveal a clear pattern. Depending on the values of the other

Table 2. Simulated numbers of fires in the study plot ti1 (Leventina) with the use of different values for *fireProbExp*, *fireProbExpBeta*, *PMin*, and *PMax*, an ignition coefficient of 0.0002, and for the LandClim drought index (LCDI) and the Angstroem index. Numbers are the number of fires, with **bold** face indicating agreement with observed numbers (5.9 fires) in a range of ±20%, while † indicates those parameter combinations where simulated fire size distributions are not significantly (p=5%) different from observed distributions.

		fireProbExp = **2.0** *fireProbExpBeta* = **1.0**		*fireProbExp* = **2.5** *fireProbExpBeta* = **1.0**		*fireProbExp* = **3.0** *fireProbExpBeta* = **2.0**		*fireProbExp* = **3.5** *fireProbExpBeta* = **2.0**		*fireProbExp* = **4.0** *fireProbExpBeta* = **2.0**	
PMin	*PMax*	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**
0.0	**1.0**	**6.6**	2.6	**5.4**	1.2	**5.7**	1.5	**5.9**	0.8	**5.5**	0.5†
0.1	**0.5**	**6.2†**	**6.0**	**6.6**	**5.0**	**6.7†**	4.4	**6.7†**	**5.5**	**6.1†**	4.3
	0.6	**6.9**	**6.4**	**6.1†**	**5.3**	**6.0**	**5.5**	**6.8**	**6.1**	7.6	**4.9**
	0.7	**7.0**	**6.4**	7.2†	**5.4**	7.9	**5.3**	**6.7**	**6.3**	**6.7†**	**4.9**
	0.8	7.1	**6.5**	**6.5†**	4.7	7.5	**6.7**	7.9	**6.5**	7.5†	**4.9**
0.15	**0.5**	7.2	**5.4†**	7.6	**6.8**	**6.7**	**6.5†**	**6.3**	**6.6**	7.8	7.5†
	0.6	7.5	**6.0†**	**6.7**	**6.8†**	7.5	**6.4†**	7.4	**6.7†**	**6.9**	**6.3†**
	0.7	**6.7**	**6.8†**	8.9	**6.8**	8.4	**5.6†**	7.1	**6.8†**	7.1	**6.3†**
	0.8	8.8	**6.4†**	8.1	**6.9†**	7.9	**6.2†**	7.3	**6.0†**	8.1	**6.8†**
0.2	**0.5**	7.4	**6.6**	7.5	**6.8**	7.8	7.5	7.8	7.3	**6.9**	**6.4**
	0.6	**7.0**	7.6	7.8	7.3	8.5	**6.6**	7.3	7.6	7.5	7.1
	0.7	8.6	7.8	7.2	7.3	**6.9**	8.4	8.4	8.0	7.8	**6.7**
	0.8	8.5	7.4	7.6	7.4	8.4	**6.8**	7.8	7.5	7.2	7.1

Table 3. Simulated numbers of fires in the study plot ti2 (Leventina) with the use of different values for *fireProbExp*, *fireProbExpBeta*, *PMin*, and *PMax*, an ignition coefficient of 0.0002, and for the LandClim drought index (LCDI) and the Angstroem index. Numbers are the number of fires, with **bold** face indicating agreement with observed numbers (7.2 fires) in a range of ±20%, while † indicates those parameter combinations where simulated fire size distributions are not significantly (p=5%) different from observed distributions.

		fireProbExp = 2.0 *fireProbExpBeta* = 1.0		*fireProbExp* = 2.5 *fireProbExpBeta* = 1.0		*fireProbExp* = 3.0 *fireProbExpBeta* = 2.0		*fireProbExp* = 3.5 *fireProbExpBeta* = 2.0		*fireProbExp* = 4.0 *fireProbExpBeta* = 2.0	
PMin	*PMax*	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**
0.0	**1.0**	**8.1**	3.3	**6.9**	2.2	**8.5**	2.6	**7.2**	2.0	**6.8**	1.0
0.1	**0.5**	8.9†	**6.6**	**7.9**†	**6.0**	8.7	**6.5**	**8.4**†	**5.8**	**8.1**	**6.7**
	0.6	**8.1**	**6.8**	**7.3**†	**6.0**	**8.6**	**7.0**	**7.8**†	**5.9**	**8.2**†	**6.8**
	0.7	9.2	**6.4**	9.4†	**6.1**	9.8	**8.0**	**8.4**	**6.5**	**8.2**†	**6.1**
	0.8	9.5	**6.8**	9.1†	**6.0**	9.1	**7.9**	9.3	**6.3**	9.0	**6.1**
0.15	**0.5**	8.7	**8.0**	9.5	**8.0**	8.8	**8.5**†	8.8	**7.6**	9.2	**7.6**†
	0.6	8.9	**8.1**†	9.2	**7.5**	10.2	8.7†	**8.3**	**8.1**	**8.3**	**8.3**
	0.7	9.3	**8.2**†	9.2	**7.4**	9.5	8.8†	8.8	**8.0**†	9.0	8.9
	0.8	9.5	9.0†	8.9	**8.0**†	9.5	**7.9**†	9.2	**8.0**†	8.9	**8.6**
0.2	**0.5**	9.4	9.1	9.0	8.9	9.3	**7.3**	10.7	9.2	9.5	**8.1**
	0.6	9.7	8.7	11.1	9.0	9.8	**8.1**	9.8	9.4	10.8	**8.0**
	0.7	10.8	9.1	10.0	9.0	9.1	**8.3**	10.0	**8.5**	9.3	**8.3**
	0.8	9.4	9.1	9.2	9.1	10.8	**8.4**	9.9	**8.4**	10.1	**8.6**

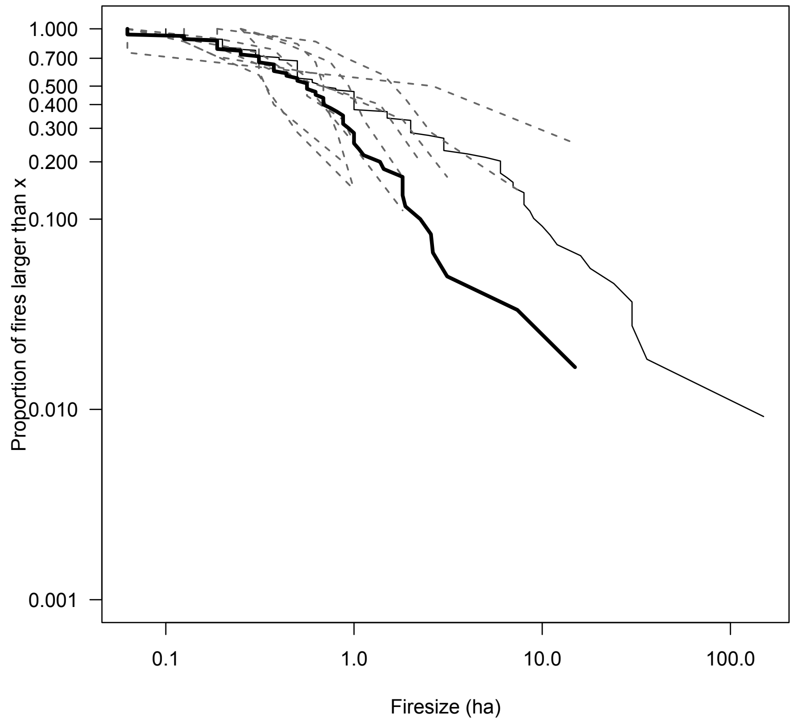


Figure 4A. Example of a fire size distribution using the Angstroem index for study plot ti1. The dashed lines show different simulations with *fireProbExp* = 3.5, fireProbExpBeta = 2.0, *PMin* = 0.15, and *PMax* = 0.8. The bold solid black line shows the sum of all simulations, and the thin solid black line shows the observation.

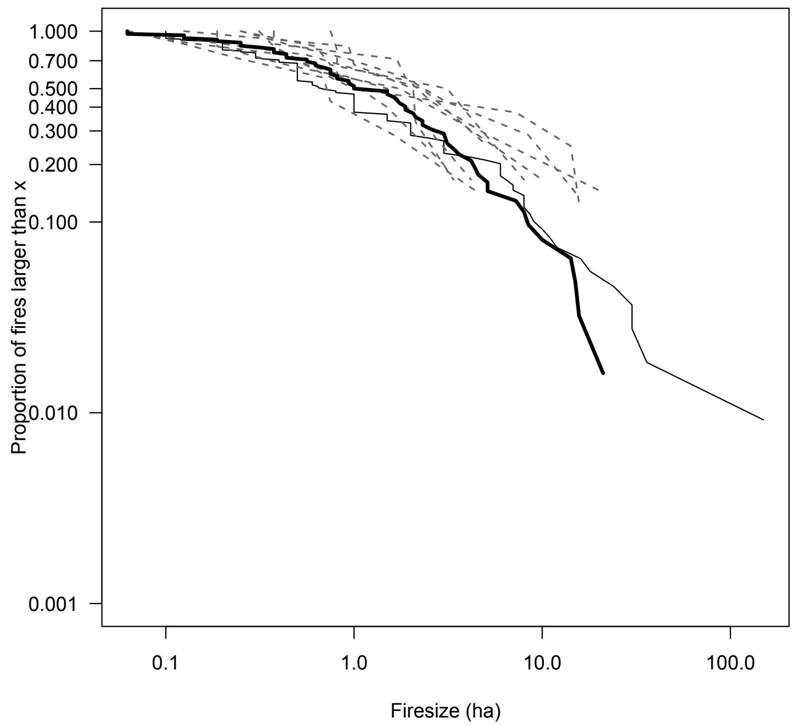


Figure 4B. Example of a fire size distribution using the drought index for study plot ti1. The dashed lines show different simulations with *fireProbExp* = 2.0, *fireProbExpBeta* = 1.0, *PMin* = 0.1, and *PMax* = 0.5. The bold solid black line shows the sum of all simulations, and the thin solid black line shows the observation.

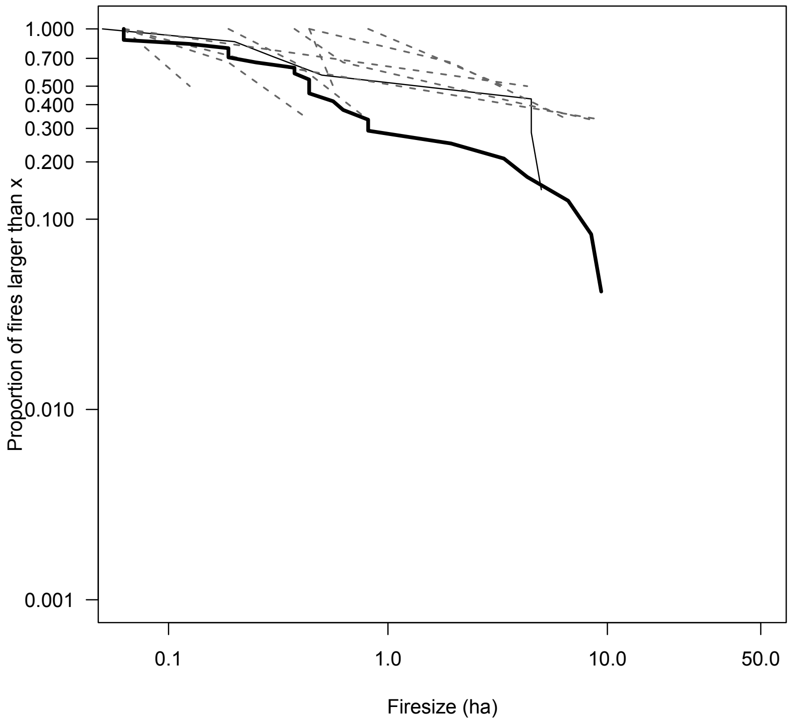


Figure 4C. Example of a fire size distribution using the drought index for study plot vs1. The dashed lines show different simulations with *fireProbExp* = 2.5, *fireProbExpBeta* = 1.0, *PMin* = 0.15, and *PMax* = 0.8. The bold solid black line shows the sum of all simulations, and the thin solid black line shows the observation.

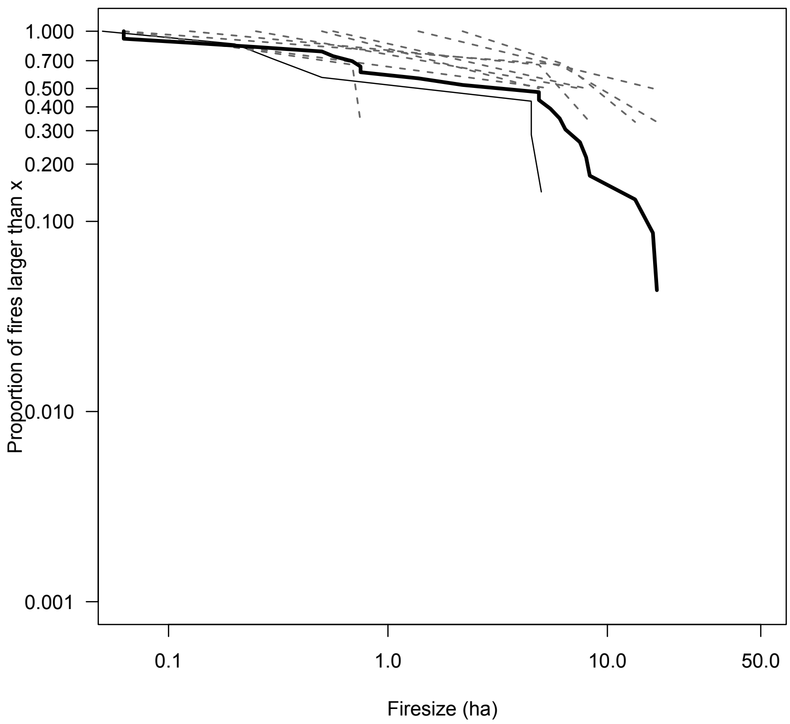


Figure 4D. Example of a fire size distribution using the Angstroem index for study plot vs1. The dashed lines show different simulations with *fireProbExp* = 2.0, *fireProbExpBeta* = 1.0, *PMin* = 0.2, and *PMax* = 0.5. The bold solid black line shows the sum of all simulations, and the thin solid black line shows the observation.

Table 4. Simulated numbers of fires in the study plot vs1 (south central Valais) with the use of different values for *fireProbExp*, *fireProbExpBeta*, *PMin*, and *PMax* an ignition coefficient of 0.0001, and for the LandClim drought index (LCDI) and the Angstroem index. Numbers are the number of fires, with **bold** face indicating agreement with observed numbers (0.8 fires) in a range of ±20%, while † indicates those parameter combinations where simulated fire size distributions are not significantly (p=5%) different from observed distributions.

		fireProbExp = **2.0** *fireProbExpBeta* = **1.0**		*fireProbExp* = **2.5** *fireProbExpBeta* = **1.0**		*fireProbExp* = **3.0** *fireProbExpBeta* = **2.0**		*fireProbExp* = **3.5** *fireProbExpBeta* = **2.0**		*fireProbExp* = **4.0** *fireProbExpBeta* = **2.0**	
PMin	*PMax*	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**
0.0	**1.0**	1.2†	0.4	0.9†	0.1†	1.1†	0.3†	0.9†	0.2†	0.3†	0.2†
0.1	**0.5**	1.9†	1.3†	1.8†	1.4†	1.7†	1.4†	1.7†	**0.9†**	1.1†	**0.9†**
	0.6	2.0†	1.3†	1.9†	1.4†	1.6†	1.4†	1.7†	1.0†	1.1†	**0.9†**
	0.7	2.1†	1.3†	1.9†	1.4†	1.5†	1.4†	1.6†	1.0†	1.0†	**0.9†**
	0.8	1.9†	1.3†	2.0†	1.4†	1.6†	1.4†	1.5†	1.0†	1.0†	**0.8†**
0.15	**0.5**	2.1†	1.9†	2.2†	1.8†	2.1†	1.5†	1.7†	1.4†	1.7†	1.3†
	0.6	2.0†	2.0†	2.1†	1.8†	2.0†	1.5†	1.6†	1.5†	1.6†	1.4†
	0.7	2.1†	1.9†	2.2†	1.8†	2.0†	1.5†	1.7†	1.5†	1.7†	1.4†
	0.8	2.3†	1.9†	2.4†	1.9†	1.9†	1.5†	1.9†	1.5†	1.8†	1.5†
0.2	**0.5**	2.5†	2.3†	2.4†	2.3†	2.1†	1.9†	1.8†	1.7†	1.8†	1.6†
	0.6	2.6†	2.2†	2.3†	2.2†	2.0†	1.8†	2.0	1.6†	1.9†	1.4†
	0.7	2.0†	2.4†	2.0†	2.1†	2.0†	1.6†	2.1†	1.7†	2.0†	1.5†
	0.8	2.6†	2.6†	2.3†	2.1†	2.3†	1.9†	2.1	1.6†	2.1†	1.6†

Table 5. Simulated numbers of fires in the study plot vs2 (south central Valais) with the use of different values for *fireProbExp*, *fireProbExpBeta*, *PMin*, and *PMax*, an ignition coefficient of 0.0001, and for the LandClim drought index (LCDI) and the Angstroem index. Numbers are the number of fires, with **bold** face indicating agreement with observed numbers (1.2 fires) in a range of ±20%, while † indicates those parameter combinations where simulated fire size distributions are not significantly (p=5%) different from observed distributions.

		fireProbExp = 2.0 *fireProbExpBeta* = 1.0		*fireProbExp* = 2.5 *fireProbExpBeta* = 1.0		*fireProbExp* = 3.0 *fireProbExpBeta* = 2.0		*fireProbExp* = 3.5 *fireProbExpBeta* = 2.0		*fireProbExp* = 4.0 *fireProbExpBeta* = 2.0	
PMin	*PMax*	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**	**LCDI**	**Angstroem**
0.0	**1.0**	1.3†	0.3†	0.6†	0.3†	1.2†	0.5	1.1†	0.1†	0.2†	0.1†
0.1	**0.5**	1.8†	1.5†	1.5†	**1.0†**	**1.2†**	1.8†	2.0†	**1.0†**	**1.2†**	1.5†
	0.6	1.7†	**1.3†**	1.5†	**1.0†**	**1.1†**	1.8†	2.1†	**1.0†**	1.5†	1.5†
	0.7	2.0†	1.5†	**1.4†**	**1.0†**	1.7†	1.9†	2.1†	**1.0†**	1.5†	1.5†
	0.8	2.0†	1.7†	**1.4†**	**1.0†**	1.6†	1.9†	2.0†	**1.0†**	1.6†	1.5†
0.15	**0.5**	2.4†	1.8†	1.8†	1.6†	1.7†	2.0†	1.7†	1.5†	1.5†	1.8†
	0.6	2.4†	1.7†	1.9†	**1.3†**	1.9†	2.0†	1.8†	**1.4†**	1.5†	1.8†
	0.7	2.5†	2.0†	1.8†	**1.4†**	2.0†	1.9†	2.0†	**1.4†**	1.5†	1.8†
	0.8	2.4†	2.2†	1.8†	1.5†	2.1†	1.8†	2.2†	**1.4†**	1.6†	1.8†
0.2	**0.5**	2.2†	1.9†	2.4†	1.6†	2.4†	1.8†	2.5†	2.0†	2.2†	1.8†
	0.6	2.3†	2.2†	2.3†	1.6†	2.0†	2.0†	2.3†	2.2†	2.1†	1.8†
	0.7	2.3†	2.1†	2.3†	1.8†	2.1†	1.9†	2.3†	1.9†	2.1†	1.7†
	0.8	2.6	2.0†	2.4†	1.7†	2.3†	1.8†	2.6†	2.0†	2.0†	1.7†

parameters (*fireProbExp*, *fireProbExpBeta*, *PMin*, *PMax*), both curves were generally capable of approximating the number and sizes of fires, although the sigmoidal function was slightly better. The incomplete beta functions with *fireProbExp* values of 3.0, 3.5, and 4.0 combined with a *fireProbExpBeta* value of 2.0 resulted in good matches of observed vs. predicted numbers of forest fires and fire size distributions (Tables 2-5, Figures 4A-4D). However, the simulations using exponential curves were only slightly inferior in their performance.

Discussion

We find that the forest fire regime in the Ticino study region can be reproduced using the improved LandClim model with certain parameter settings. Especially the levelling of minimum and maximum fire probabilities and the use of the fire-specific Angstroem drought index are important improvements.

Model evaluation and calibration

In this study we are interested in how accurately forest fire regimes in mountain forests of the Swiss Alps can be reproduced using the landscape model LandClim. The evaluation and calibration of our simulation results with observations of the number of forest fires and the fire size distribution shows that a rigorous testing of the fire module in a landscape model is possible, and that the calibrated model is useful for simulating the forest fire regimes under current climatic conditions in mountain forests of the Swiss Alps.

There are surprisingly few other studies that have evaluated the behaviour of dynamic landscape fire models. For the DGVM MC1, Lenihan *et al.* (2003) found that validation is difficult on the one hand because the model simulated dynamic ecosystem properties only as a function of climate and soils and did not include the effects of land use practices that modified life-form mixtures, carbon stocks, and fire regimes, but on the other hand they affirmed that validation would constitute an important step for the establishment of a credible model. In a recent study, Bachelet *et al.* (2009) investigated the response of fire regimes in Alaska and in the western conterminous US to climatic variability and tested the MC1 model against observation data. They found a good match of the simulated burned area with observed records of large fires. For Alaska, the higher value of 20% of total area burned in the simulation in comparison to the observation was explained by the lacking number of small fires in the observations and by constraints on ignition. An important difference between MC1 used by Lenihan *et al.* (2003) and Bachelet *et al.* (2005;

2009) and LandClim in our study is the prescribed minimum and maximum fire return interval of MC1. Finally, already Schumacher *et al.* (2006) tested LandClim in two regions of the Rocky Mountains and found broad agreement between simulated and reconstructed fire frequencies.

To the best of our knowledge, for many dynamic landscape fire models an evaluation against independent data has not been attempted (e.g. EMBYR by Hargrove *et al.* 2000). This is understandable for theoretical models that are used to study basic fire properties such as conditions for successful fire spread (e.g. Turner *et al.* 1989), but these models are not usually applied to specific landscapes (e.g. DISPATCH by Baker *et al.* 1991).

In the case of models that were built for specific landscapes, the difficulty of obtaining or the complete lack of long-term series of vegetation data, detailed historical weather and fire data have sometimes been brought forward to explain the absence of rigorous model tests (Thonicke *et al.* 2001; He *et al.* 2005). He (2008) discussed the dilemma of lacking data across time and space for the validation of forest landscape models, suggesting that it was not possible to validate a model in a specific landscape, because each real landscape was non-replicable and unique. Instead, He (2008) proposed three approaches that allow for the validation of simulation results from forest landscape models: (1) comparison of results from different simulation scenarios using the same model, (2) comparison of simulation results from independently developed models for the same purpose (e.g. Cary *et al.* 2006; Yang *et al.* 2007), and (3) – the most widely used approach – comparison of simulation results with data from long-term landscape-scale experiments or specific ecological knowledge (e.g. He *et al.* 2002). We do not dispute the utility of these approaches, but we think that the evaluation of dynamic models for specific landscapes is possible as long as we do not attempt to replicate the exact spatial and temporal distribution and abundance of organisms or disturbances; if instead we evaluate the typical landscape-scale patterns, a quantitative assessment of model performance will be possible, as shown by our study.

Still, there are several examples of applications of dynamic fire models in the absence of prior model tests, such as in DGVMs (Venevsky *et al.* 2002; Scheiter and Higgins 2009), in a dynamic model of cropland and pasture dynamics (Shevliakova *et al.* 2009), in LPJ-GUESS (Lehsten et al. 2009) or the forest landscape model LANDIS (Mladenoff *et al.* 1996; Mladenoff and He 1999; Mladenoff 2004). While for all of these models, overall behaviour of the vegetation part has been tested against some independent data sources (e.g. Scheller and Mladenoff 2004; e.g. Franklin *et al.* 2005), the accuracy of the fire submodel and its relative contribution to the overall signal remain largely unknown.

Although it is reasonable to test a model against broad-scale properties (Bugmann 2001), we maintain that also the components of larger models at landscape to global scales should be subject to rigorous tests.

Model application under future climate

Although we can never prove that a model is suitable for extrapolation to novel climatic conditions such as those imposed by anthropogenic climate forcing (IPCC 2007), model evaluations such as the one described here increase our confidence in the robustness and applicability of the model under changing climatic conditions (for examples cf. Keane *et al.* 1999; Bachelet *et al.* 2005; for examples cf. Schumacher and Bugmann 2006).

The validity of process representations in a model (e.g. fire ignition, spread, fire effects, and the associated interactions which define the fire regime) is not necessarily given under different climate conditions. Interactions among the environmental factors of forest fire regimes may change, and so may their relative importance. This can cause problems for model applications under new conditions without previous model validation, and it is a risk potentially leading to incorrect conclusions of future fire danger conditions. In our study, we were able to show that it is possible to test the behaviour of a dynamic landscape fire model for mountain forests in the European Alps. This should motivate modellers to strive for model evaluation and validation. The analysis of LandClim with observation data from two study regions is an important step for establishing the reliability of the model (Rykiel 1996). Again, we suggest that other fire models should be subject to rigorous tests against empirical data prior to impact studies.

Model improvements

We show that an unlimited increase of the fire probability with increasing drought index values is not a realistic scenario. The implementation of minimum and maximum fire probabilities is a powerful improvement of LandClim. With these additions, the observed fire regimes on the landscape scale can be simulated well.

The increased minimum fire probability ($PMin > 0$) indicates a baseline fire danger even under weather conditions that are not very dry. This is especially important in regions with a high number of human-induced forest fires (like in the southern Swiss Alpine region), as humans provide the ignition energy. In turn, the reduction of the maximum fire probability ($PMax < 1$) can be interpreted as the effect of fire fighting limiting the maximum fire size. Moreover, it may indicate that fires do not spread in any case even under very dry conditions because it is not the general fire weather alone but also small-scale features such as topography, local winds, fuel connectivity, and possibly also stochasticity may be crucial for determining actual fire spread.

The Angstroem index accounts for another important improvement of the results. It was developed specifically for characterizing fire weather {Skvarenina, 2003 #123}, whereas the original LandClim drought index is a measure of soil moisture deficit (Bugmann and Cramer 1998). This may explain why the simulations using the Angstroem index produce fire regimes that match the observations better than simulations using the LandClim drought index. For the consideration of forest fire disturbances in the context of forest succession at the landscape scale, it seems expedient to use a specific fire weather index instead of a general drought index, in spite of the success of the latter in earlier studies (Weibel *et al.* in prep.; Weibel *et al.* subm.). The Angstroem index is easy to calculate as it requires information on temperature and relative air humidity only. In addition, it can be calculated without relying on previous day's weather data.

Limitations and constraints

Although the validation of a model is an important step to increase the confidence in its applicability, we are only able to calibrate LandClim; still, this calibration increases the robustness of LandClim as the model is applicable in two different regions. For the study plots in the south central Valais, we find a discrepancy between the simulated number of forest fires and the simulated fire size distribution. In most cases, only the simulated fire size distribution is close to observations, and only for very few parameter combinations both measures are broadly consistent with observations. This can be explained by the small number of forest fires in the south central Valais, where only about one forest fire occurred per year during the study period, and therefore the power of the test is low. Unfortunately, some forest fires in the data set from Valais do not comprise information about date and location. This fraction, which amounts to about a third of all events, thus could not be included in the analysis, which of course may strongly influence the results.

A limitation of our study also arises from the small case study regions and the small number of different climatic regions. The choice of the two regions Leventina and south central Valais is due to the availability of forest fire and weather data. An expansion to additional regions, e.g. in the European Alps or other fire-prone mountain regions such as the Rocky Mountains could further increase the confidence in the applicability of the model. At the present stage, a generalisation to other climatic regions is not possible.

Conclusions

Our study shows that the evaluation of a landscape fire model with independent observation data is possible. LandClim is a good candidate for further model tests, and its application to study the implications of climate change on forest fire occurrence in mountain forests may be warranted as well.

The improvements of the LandClim fire module by implementing the Angstroem fire weather index and by limiting minimum and maximum fire probabilities lead to reasonable advancements of the simulated number of forest fires and the fire size distribution. We thus conclude that LandClim is highly suitable to reproduce the observed fire regimes in mountain forests of the Swiss Alps.

We recommend that LandClim should be tested in additional regions; if the parameter values of the fire module were stable across regions in the calibration, it would be legitimate to use the model also under future climatic conditions to project future forest fire regimes. This would be not only of scientific interest, but the importance of forest fires as a disturbance agent in mountain forests is crucial e.g. for practical planning of fire fighting management and the identification of dangerous zones affected by landslides, avalanches and rockfall after forest fires. Hence such model applications would be important and relevant for a wide range of stakeholders.

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Synthesis

This thesis aims to assess forest fire regimes in mountain forests of the southern and central Swiss Alps with the help of statistical and dynamic modelling. Here, I discuss ecological interpretations, management implications, methodological aspects, and areas of future research based on the investigations presented in the previous chapters.

The results of this thesis show that forest fire regimes are the product of multiple factors and their interactions, as presented in the conceptual framework in the Introduction section. This conceptual framework links weather conditions, forest type, fuel characteristics, topography, and human activities in an interactive web of influences on forest fire ignition, rate of spread, and effects. My findings suggest that forest fires are a phenomenon strongly depending on local conditions. It is thus not possible to derive generally valid ignition and spread conditions and interaction patterns among all influencing factors. Drought conditions (fuel moisture), forest composition, and intensity of human influence indicate not always the same fire danger depending on the ignition source. Nonetheless, some conditions are a prerequisite for forest fire occurrence: in any case, an ignition source is needed as well as a minimal amount of more or less dry fuel.

The principle findings of my thesis show that models are a powerful but at the same time limited approach to study fire regimes. Only complex models incorporating many different aspects from the conceptual framework are able to accurately portray forest fire ignitions. Simpler models with only one or a few explanatory variables do not have the ability of simulating forest fires properly. In addition, the models seem to be valid only for specific conditions, i.e. when they are restricted to a well-defined geographical range. Still, models allow for investigating forest fires and for detecting relations among influencing factors, and thus the modelling results contribute to a better understanding of parts of the conceptual framework. For a deepened understanding, I propose that a small-scale consideration is needed because forest fire regimes seem to differ with respect to ignition source, forest type, climatic conditions, and probably also regarding topography and patterns of human activities. From this expectation, one can conclude that the use of models to predict forest fire danger under new climatic conditions is strongly limited. From a management point of view, the findings of my thesis suggest using fire danger indices for the evaluation of fire danger and for the organization of fire fighting efforts.

Ecological interpretations

Possible changes in the role of forest fires, especially in mountain forests, are important because forests provide many goods and services to humans, such as production of food and fibre, water supply, carbon storage, protection from gravitational natural hazards, and tourism (e.g. de Groot et al. 2002). In steep mountain regions, protection against avalanches, landslides, and rockfall is particularly important. A better understanding of the current and the possible future forest fire regimes thus supports adaptive resource management in an era of rapid environmental changes.

From Chapter 1, it is evident that lightning- and human-induced forest fires show different relations among the factors of the conceptual framework. The influence of weather conditions on forest fire ignition probabilities greatly depends on the ignition source. In the study areas, lightning-induced forest fires are best predicted by the Keetch and Byram drought index (KBDI, 1968). This index indicates especially drought conditions that are necessary for a natural fire ignition by lightning and is a proxy of soil moisture deficit. For human-induced forest fires, in contrast, the Angstroem index (Skvarenina *et al.* 2003), a measure including temperature and relative air humidity, is most suitable. The ecological interpretation is that lightning-induced forest fires ignite under highly specific weather conditions only. Dry periods with lightning strikes and low amounts of precipitation are necessary. This meteorological phenomenon can be observed during dry, hot periods with convection and thunderstorm build-up. In contrast, human-induced forest fires do not need such restricted weather conditions. Thanks to the initial energy provided by human activities (e.g. agriculture, forestry, military exercises, and arson), the fuel conditions need not be very dry for an ignition.

In the Ticino, coniferous forest stands have a lower probability of being ignited by human activities than deciduous forest stands. The distribution of coniferous and deciduous tree species shows that conifers are predominantly located at higher elevations where human activity usually is rare, whereas deciduous tree species typically dominate in the valleys that are more accessible by humans (Conedera *et al.* 2006). Snow cover that is common in high-elevation conifer stands during the main fire season of human-induced forest fires (in the winter) may also play a role. The spatial pattern of lightning-induced fires is not absolutely clear but it seems that these fires are more frequent in coniferous stands at higher elevations. Cesti et al. (2005) proposed that conifer morphology and their rough-textured bark tend to attract lightning strikes but it appears impossible to draw firm conclusions from the results of this thesis.

Human activities are clearly linked to forest fire ignitions, i.e. human-induced fires are strongly affected by human activities whereas lightning-induced fires occur independently. Anthropogenic activities related to forest fires comprise agriculture, forestry, tourism and, negligence but include also arson. Most of these activities mainly occur at places where forests are adjacent to human infrastructure, representing a well developed wildland-urban-interface (Haight et al. 2004). However, the influence of human activities on forest fires is not restricted to the ignition. Fire extent and fire effects are influenced by suppression activities and human changes in fuel connectivity (Sturtevant *et al.* 2004; Syphard *et al.* 2007). Furthermore, fire regimes are aimed to be controlled by legislation (e.g. Vigilante et al. 2004).

The findings and interpretations for the Ticino (Chapter 1) are confirmed by the analyses in Chapter 2 for Valais and Ticino. The patterns of the influencing factors on forest fire regimes, especially on fire ignition, in these two regions are comparable to the first chapter for both lightning- and human-induced forest fires. An exception exists regarding the forest types that are mainly affected. In the Valais, the fraction of coniferous-dominated forest stands is nearly three times higher, which may explain why forest fires ignite more often in coniferous stands in the Valais than in the Ticino.

The transfer of logistic forest fire regression models between the two regions Ticino and Valais and between the two periods 1974-1989 and 1990-2005 is differently successful (Chapter 2). While transfers between periods are possible, transfers between the regions are not. These differences can be interpreted ecologically with larger differences of climate, weather, and forest composition between the regions than between the periods within the same region. The fundamental climatic differences between insubrian and continental climates become obvious: drought is much higher in the continental Valais. Although there are clear shifts in temperature between the early and the late period, these differences remain small compared to the differences in climatic conditions between the regions.

Generally, fire danger in the sense of forest fire ignition depends on the drought conditions that are also determined by vegetation cover and species distribution, and on ignition sources. The general validity of the logistic forest fire regression models in this thesis is limited. This shows the potential danger of using such models in different ecoregions or under different climatic conditions, e.g. under scenarios of climate change. Thus, the lack of transferability may lead to serious problems in dealing with forest fire disturbances in the context of climate change.

With respect to the analyses in the first two chapters, it is important to keep in mind that the conclusions derive from statistical models combining numerous input variables. Although I included weather conditions, forest composition, human activities, and a change in legislation in these models, other factors such as explicit fuel conditions may be missing. Furthermore, the interpretations are not always unequivocal because of possible correlations of the predictor variables with other factors. Thus the relations that are observable can be a proxy for hidden relations of factors not explicitly included in the models. However, statistical models are useful for studying a phenomenon like forest fire ignitions, and additional factors can be included if needed and if the necessary data are available. A disadvantage of the statistical models used here is the fact that only the ignition part of fire regimes can be investigated. For studying fire ignitions and rate of fire spread at the same time, dynamic models – like the landscape model LandClim – can be used.

The use of LandClim in Chapter 3 thus shows an alternative approach of investigating forest fires by addressing the number of ignitions and the fire size distribution within one single model. The results show that the evaluation of such a model with observation data is possible. The confirmation of appropriate model outcomes is an important step to underpin the validity and the applicability of a model for studying fire regimes under specific conditions.

The improvements of the LandClim fire module have a clear ecological background and interpretation. The use of the fire weather index by Angstroem (Skvarenina *et al.* 2003) instead of the LandClim drought index (Bugmann and Cramer 1998) shows the advantage of an index that was developed for capturing fire weather situations instead of an index that measures soil moisture deficit as a general characteristic of drought, even though the latter index proved to be useful in my earlier analyses. The limitation of minimum and maximum fire probabilities can be interpreted ecologically as follows. The lower limit indicates a baseline fire danger even under weather conditions that are not very dry. Fire danger under such conditions mainly depends on human ignitions that provide the ignition energy. The upper limit is more difficult to explain, as it is probably composed of two effects. On the one hand, it can be interpreted as the effects of fire fighting, leading to limited fire sizes even under very dry conditions. On the other hand, it may indicate that even under very dry conditions fire spread is not guaranteed because it is not the general fire weather alone but also small-scale features such as (1) topography, (2) local wind speed and direction, (3) fuel connectivity, and possibly even (4) stochasticity may be crucial for determining effective fire spread.

As climate change is expected to alter fire regimes (Bowman *et al.* 2009) the question on the altered number of fires and fire sizes arises. The results in Chapter 3 suggest that LandClim is a good candidate for further model tests in other biogeographical regions with other climatic conditions. A model that is able to reproduce the fire regime in different climatic regions may be reliable for projecting future fire regimes under changed conditions.

Management implications

The results of the modelling efforts on forest fire ignitions under different climatic conditions and for different forest types give rise to some management recommendations.

First, the differentiation between lightning- and human-induced forest fire ignitions may lead to better warning systems regarding fire danger. The conditions for elevated fire danger are clearly different and can be captured by appropriate fire weather indices that can help preparing fire-fighting teams in operational readiness. The use of multiple such indices is likely to improve forecasting in regions such as the Valais and Ticino, even if this is not a usual practice in operational fire management systems today.

Second, as the spatial pattern of human activities is important for the location of human-induced fires this information may allow for the derivation of fire ignition probability maps. Such information can be used for the planning of spatial fire fighting infrastructure, e.g. water reservoirs or access roads.

Third, with respect to climate change that influences natural processes, adaptations of forest management to altered numbers of forest fires may be required. Already Le Goff et al. (2005) proposed more integrative and spatially explicit management strategies to reduce the vulnerability of forests to changing fire regimes. Nonetheless, it is important to keep in mind that fire managers operate with a narrow margin between success and failure and thus the ability of fire managers to cope with increasing fire activity is limited (Flannigan et al. 2009).

Methodological aspects

Data sources and study region

The investigation of the fire regimes in the Ticino and the Valais (or in any other region) requires spatially and temporally explicit data on forest fires, weather conditions, forest composition, land use, and topography. Here, these data derive from different sources: data on forest fires from the Forest Fire database developed by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL (Pezzatti *et al.* 2005; Zumbrunnen *et al.* 2009), data on weather conditions from weather stations operated by the Swiss Meteorological Agency, land use information on human activities and data on forest composition from the land use statistics of Switzerland (BFS 2001), and topographic parameters from the digital elevation model of Switzerland. These data come from reliable sources and provide the basis for a thorough analysis of the fire regimes in the study regions. The research approach of this thesis was feasible only with a high spatial resolution (100 m x 100 m = 1 ha) of forest fire ignition points, forest composition, and human activities, and a high temporal resolution (1 day) of the forest fire ignitions and the weather data, which allow for investigating fire regimes at local and daily resolution. In other studies of fire regimes, the fire data derive from observational databases that are managed by the Forest Service (e.g. Krawchuk *et al.* 2006; e.g. Lafon and Grissino-Mayer 2007) or from remote sensing observations (e.g. Diaz-Delgado *et al.* 2004; e.g. Dasgupta *et al.* 2006). The level of detail thus is often relatively low, featuring information on ignition area, extent, and date only, whereas the Forest Fire database of WSL also contains information on forest type, special wind constellations (e.g. foehn wind), the disposition of helicopters, and fire effects. Studies similar to this thesis such as Syphard et al. (2007) include housing density, wildland-urban interface, road net, vegetation type, geology and topography information, and climatic variations on an ecoregion level opening possibilities to refine the definition of human activities used in this thesis. They found the human influence represented by three different aspects to be most influencing fires at intermediate strength. The investigation of large fires using maps of elevation, slope, aspect, topographic roughness, vegetation, precipitation, and road density by Dickson et al. (2006) showed that large fire events are related to environmental factors. These factors were topographic roughness combined with reduced access to these areas. The database used in this thesis covers all aspects of the conceptual framework (cf. Introduction section) with an exception for explicit topographic parameters. Implicitly, however, topography is included in the elevation-adjusted weather data and in the spatial pattern of forest types and human infrastructure. Overall, it appears that the data on forest fires in my thesis are of very high quality. The lack of spatially explicit weather data is a problem because local differences in topographically rough regions are missing. In addition, the representation of human activities and fuel are only coarse.

The Valais and the Ticino are highly suitable by providing the required data. Under the conditions of the Swiss Alps, both regions have frequent lightning- and human-induced forest fires and are well documented (Conedera and Pezzatti 2005; Zumbrunnen *et al.* 2009). Furthermore, they feature pronounced altitudinal gradients in forest composition, diverse dominant forest types, clear geographical patterns of human activities, and divergent climatic conditions with insubrian climate in the Ticino and continental climate in the Valais.

Although the database of my thesis is of good quality for investigating the number and sizes of forest fires, more options would stand open if additional data were accessible. Especially, spatially explicit data on weather conditions would allow for modelling and assessing forest fire regimes under local conditions. Such small-scale conditions are important and determine the fire processes more strongly than general weather conditions as measured at distant climate stations. If even large numbers of stations measuring local data on wind direction and wind speed were available, fire spread could be investigated even more appropriately. However, to the best of my knowledge such data are not measured anywhere, and this may thus be a fundamental problem for the development and testing of models that simulate fire spread. Furthermore, a spatially explicit differentiation of human activities according to sectors, e.g. traffic (e.g. roads, railroads), settlements (e.g. built-up area, population density), the number of employees in the different economic sectors per area, or leisure activities (e.g. hiking trails, fireplaces) could help to better identify the impacts of specific human activities on forest fire ignition. And finally, explicit data on fuel load and on fuel characteristics would allow to model fire effects much more reliably.

Spatial and temporal scales

The spatial and temporal scale on which forest fires are studied can influence the results, as illustrated by the example of heterogeneity in fire frequency in a coniferous boreal forest of eastern Canada (Cyr et al. 2007). The relative importance of fuels, topography, and climate depends on the scale of observation, as also shown by a cross-scale analysis of fire regimes in western North America (Falk et al. 2007).

Fire regimes are studied on different spatial scales from global (e.g. Girardin and Mudelsee 2008; Bowman *et al.* 2009) to regional (e.g. Chertov et al. 2006), and from landscape (e.g. Boychuk and Perera 1997) to local scales (e.g. Amatulli et al. 2006). At large scales, most studies conclude that the spatial patterns of forest fires are highly variable. Fires are able to shape landscapes and to determine stand ages and species distributions. At small scales, the influences of specific local conditions on forest fire regimes can be evaluated. The scale determines also the spatial resolution of units for which fires are investigated. Over five orders of magnitude, Malamud et al. (2005) found a power-law distribution of the area burned. This may indicate that some characteristics of fire regimes are scale-invariant. By focusing on two mountain regions within the Swiss Alps, the spatial scale of this thesis addresses the regional (Chapters 1 & 2) and landscape scales (Chapter 3). These spatial scales have the advantages of distinct properties of weather conditions, forest composition, human activity patterns, and topography. High resolution data are available on a 100 m x 100 m grid (except for weather variables). The main disadvantage that comes with the relatively small size of the case study areas is the lack of a broader range of climatic, forest composition, and topographic conditions. Larger variability would allow for investigating forest fire regimes over broader environmental gradients, thus further enhancing the robustness of forest fire models for application under different conditions.

The temporal variability of forest fire studies ranges from thousands of years (e.g. Tinner *et al.* 1999; Whitlock *et al.* 2003; e.g. Thonicke *et al.* 2005; Tinner *et al.* 2005) and centuries (e.g. Batek *et al.* 1999; e.g. Gromtsev 2002) to the last century (e.g. Veblen *et al.* 2000; Schumacher and Bugmann 2006; Girardin and Mudelsee 2008; Zumbrunnen *et al.* 2009) and the most recent decades (e.g. Stocks *et al.* 2004; Malamud *et al.* 2005; e.g. Dickson *et al.* 2006). Over all temporal scales human influences on forest fires can be observed. In the long term, first traces of settlers using fire were found in charcoal data, and in recent centuries humans became an important ignition agent as well as a suppressor of forest fires. The most important difference among the temporal scales is the effect of fires on the composition of the vegetation: over hundreds of years, fires are able to change species composition by eliminating fire-sensitive plants, whereas over few decades this is only the case for stand-replacing fires that are seldom. With respect to changes in climate and land use, a multitude of forest fire studies project potential future fire regimes (e.g. Flannigan *et al.* 1998; e.g. Whitlock *et al.* 2003; Wotton *et al.* 2003; Bergeron *et al.* 2004; Flannigan *et al.* 2005; Girardin and Mudelsee 2008; Robinson 2009). On the temporal scale, my thesis focuses on the past 30 to 40 years when recent changes in local climatic conditions were recognizable and political efforts for the reduction of the number of forest fires took place. This temporal scale has the advantage that weather variables are available at daily resolution. Furthermore, during the study period no drastic changes in forest composition and human activity patterns occurred.

Research methods to study fire regimes

Fire regimes are intensively investigated by many authors and in many ecoregions of the world. As a consequence, the spectrum of research methods that are being applied is quite broad. In the Introduction, I gave an overview on selected examples of paleo-ecological and historical approaches, as well as on experiments and on modelling, the most widely used approach to study forest fire regimes. With the combination of statistical and dynamic modelling, this thesis allows for a deepened insight into the forest fire regimes of mountain forests in the southern Swiss Alps. The outcomes of this work ask for a critical appraisal of my modelling approach.

Statistical and dynamic modelling show advantages as well as disadvantages. The advantage of logistic regression models is their flexibility. The number of predictors can be changed easily depending on the research question or data availability. In addition, flexible model structures can be integrated, e.g. by using restricted cubic spline functions (cf. Chapters 1 and 2). A disadvantage of logistic regression models is that only one aspect – in my case the question if a forest fire ignites or not – can be investigated. In contrast, the dynamic landscape model LandClim has the advantage that both the number of forest fires and the fire sizes can be simulated at the same time. The embedding of the fire module into the dynamic succession model allows in addition to study interactions between fire occurrence and forest development, although this aspect was not explored in this thesis. A disadvantage of the LandClim fire module is its complexity, especially when changes in the model structure or in the calculation routines have to be conducted.

From the results gained in my investigations with LandClim I conclude that it is possible to evaluate or even to validate a dynamic forest fire model. This depends mainly on data availability. Independent test data are needed, which may be a considerable problem in many regions. In this thesis, LandClim was tested in two regions, but a validation was still not possible because of the lower data quality (much fewer fires and hence lower signal-to-noise ratio) in one region. As the simulation results using minimum and maximum fire probabilities showed reasonable performance but still a considerable potential for model improvements, this approach could be a promising starting point for other dynamic forest fire models. Many models still use predetermined maximum and/or minimum fire sizes (e.g. Baker 1995; Bradstock *et al.* 1998; Mladenoff and He 1999; Keane *et al.* 2002) instead of these variables being emergent properties of the model. This is especially important when models are intended to be used for studying forest fire regimes under climate change.

Continued observations of forest fire regimes are also indispensible for studying forest fires, their origin, and their effects. Observation data collected in my study regions (Conedera *et al.* 1996; Pezzatti *et al.* 2005; Zumbrunnen *et al.* 2009) are the essential basis of my modelling efforts. Often, such observation data are also used for the validation of simulation results (e.g. Li 2000; Alexander and Cruz 2006). For testing and validating models in different biogeographical regions with distinct climatic and topographic conditions, it would be appreciable to gain access to forest fire as well as weather and land use data in different parts of the world.

Over the last years, a new branch of forest fire research has become popular, i.e. the application of remote sensing techniques. Dasgupta et al. (2006) developed a fire susceptibility index based on remote sensing data. Explicitly, they measured live fuel moisture content and fuel temperature for their index. Such approaches can allow for estimating forest fire danger for large areas without the need to measure data at the earth surface or in the direct proximity of forests. An instrument for fuel mapping based on remote sensing was established by Arroyo et al. (2008). In the longer term, the lack of data on the spatial differences in fuel amount in my thesis could be solved by the use of such remote sensing data.

Other weaknesses of my analyses arise from the following aspects. The number of study regions is small with only two neighboring areas. An expansion to other adjacent, fire-prone regions such as the Valle d'Aosta in Italy or the canton of Grisons would have been highly beneficial, but this would have been possible only if the necessary data had been easily accessible. Another limitation is the representation of human influence with the pooled index of all kinds of human activities. Here, a differentiation between different aspects, e.g. settlements, industry, traffic, and leisure time could be a promising advancement, especially when not only using raster but also vector data. Finally, a holistic interpretation of ecological (e.g. species composition), economical (e.g. costs and benefits of goods and services, damage), and societal (e.g. loss of earnings, damage) effects of forest fires is lacking in this thesis.

Areas of future research

The investigations of forest fire regimes in this thesis are restricted spatially to two regions in the southern and central Swiss Alps. To obtain results of more general applicability, fire regimes have to be analyzed under a broader range of climatic conditions, topography, vegetation types, and human dominance, thus in more diverse ecoregions. Especially, testing the transferability of forest fire models needs data from a larger sample and more different geographical regions as well as from longer time periods.

When defining the study regions for this thesis, the expansion to and comparison with the Rocky Mountains were under consideration. But due to difficult data availability and general time constraints this plan could not be implemented. Nevertheless, the Rocky Mountains might provide interesting conditions for model testing as an extension to this thesis, as they show a similar temperature regime with a distinct seasonality but they are considerably drier than the Alps, particularly in summer. A transfer study to the Rocky Mountains could be interpreted as an analogy for tests under changed future climate, which is an important field of research on future disturbance regimes. With this approach, differences in space are used to mimic changes in time since the time span of observed changes of climatic conditions are small to date. Whether this space-for-time approach is acceptable to study potential future fire regimes or not, is an open question that can not be answered here. However, research on forest fire models that are applicable under novel conditions of climate and land use is sorely needed.

The different roles of environmental and human determinants on lighting- and human-induced forest fires ask for the integration of this differentiation in dynamic landscape models. With different disturbance regimes by forest fires of different ignition sources, the resulting successional processes may be different as well. The knowledge gained in this thesis thus allows for more realistic forest succession modelling with respect to forest fire disturbances. In addition, a more differentiated examination of human activities could bring some further improvements.

With regard to LandClim, a specific area of future research is the application of the evaluated model in additional study areas, e.g. the Rocky Mountains, and under potential future climate conditions. This may allow for validating LandClim and to analyze future forest fire danger. With this perspective, the effects of forest fires on important goods and services can be evaluated. Furthermore, information on forest fire disturbances is also important for the planning of fire fighting management and the definition of zones that may be affected by landslides, avalanches and rock fall after a forest fire occurred.

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The path was sometimes broad, sometimes narrow, it went up and down, and I had to climb rocky mountains (although my study regions were the Ticino and the Valais…). It was sometimes exhausting but always informative and never boring. I became acquainted with many aspects of forests and forest fires, with the legendary R, with statistical and modelling knowledge, with research practice, with scientific writing, with posters and presentations, with group meetings and excursions, and so on.

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