Wildfires in Switzerland

An Extreme Value Analysis

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Abstract

The objective of this thesis is to analyse the fire regime of the Swiss cantons of Ticino, Valais and Grisons from 1940 until 2018. The main focus is on large events. Three central questions are discussed. How large fires may become in each canton, if these sizes change over time and if so, which are the driving forces. Extreme value statistics is applied to address the special requirements of extreme events. The risk for large fires is expressed by calculating return levels for different scenarios. Two different approaches are applied to take non-stationary effects into account: First, the data is split into quasi-stationary subsets. Second, covariates are included into the model parameters. The second approach additionally allows to test which variables lead to changes in the return levels. The data of Ticino and Valais is split into three periods. In both cantons an increase of the return levels is found from period one to two, followed by a decrease in period 3. The 10 year events for Ticino reach sizes of roughly 250 ha in period 1, 600 ha in period 2 and 250 ha in period 3. The values for Valais are 31 ha, 65 ha and 31 ha for periods 1, 2 and 3 respectively. Several covariates improve the model fit significantly. The best combinations include the population density in all cantons. In Ticino, the relative humidity and in Grisons the precipitation sum are used additionally. The effect of each covariate is estimated by using the full data set together with the respective combination of covariates. All covariates but one are kept fixed while the remaining is specified with the lowest and highest values observed. This reveals that a higher population density is related to a decrease of the return levels in all cantons as well as higher relative humidity in Ticino and a higher monthly precipitation sum in Grisons. The effect of the climatic variables exceeds that of the population density considerably. Measures taken by the canton of Ticino to reduce the threat of fire are found to lead to a reduction of the return levels. The effect is small though compared to the other factors. The main conclusions of the thesis are that following: Applying extreme value theory to fire data provides new insights into the development of the fire regime that complements the existing literature on the general fire regime. Changes in the risk for large fires are the result of a combination of socioeconomic and climatic factors. The largest impact on the return levels is via the climate. Nevertheless, anthropogenic variables are important too. The largest potential for prevention seems to be avoiding the ignition of a fire. All catastrophic events were caused by human action. While this would not reduce the size of extreme events, it would lower their frequency.

Contents

1 Introduction

1.1 Motivation

In 1973, a single fire destroyed 1,600 hectares of forest near Bogno in the canton of Ticino. To date, this is the largest forest fire ever recorded in Switzerland. The same year should set another record: A total of 7,000 ha of forest fell victim to the flames in Ticino, the largest annual sum of any year (Conedera, Corti, and Ambrosetti 2004). 30 years later, in 2003, a fire above Leuk in the canton of Valais destroyed 300 hectares of forest. It is the largest fire recorded in Valais. Fire suppression activities lasted for three weeks. More than 100 persons from fire brigades, police, rescue services, civil protection, forestry service, mountain rescue and helicopter crews were deployed (Moretti et al. 2003). In the same year, an extraordinary number of forest fires were recorded in the canton of Grisons. On the 26^{th} of June, a lightning strike triggered a fire near Sta Maria. At 39 ha, the fire did not reach catastrophic proportions. However, due to the difficult terrain and weather conditions, fire suppression activities lasted for several weeks and could only be completed on the 6^{th} of September. The cost of the intervention amounted to more than 2 million Swiss francs. In 1997, a catastrophic fire destroyed 390 ha of forest in the Misox. Firefighting operations cost 5 million francs (Wald und Naturgefahren 2003).

Wildfires are classic examples of extreme events. Small fires occur quite often. Most of them can be contained and are harmless. Occasionally though, fires grow out of control and reach extremely large sizes. Such fires consume vast areas of forest and endanger human beings, their assets and important infrastructure. It is typical for extreme events that a small fraction of all incidents cause a disproportionately large share of the total damage. "One percent of the fires do ninety-nine percent of the damage", is an often-heard statement among fire management personnel. It contains more than just a grain of truth: Strauss et al. (1989) find that in three USDA forest fire jurisdictions, just one percent of all fires caused 96%, 94% and 80% of the total damage. Jiang et al. (2011) state that in Canada, fires with a size larger than two square kilometers represent only three percent of all incidents but cause 97% of the total damage.

Wildfires are not only a threat though. Quite the opposite is true. Fires have different facets and can be perceived in various ways. They are a natural part of many ecosystems. Some species depend on periodic fires. Also, humans have used fire for millennia. So called "slash and burn" practices have been used to clear land for agriculture or for hunting grounds to give just one example. In some regions of the world, this practice is used to this day. On the other hand, wildfires are a great peril for flora, fauna and human society. Large fires can destroy natural habitats of plants and animals. Soil erosion is increased strongly on burnt surfaces during heavy precipitation. Fires damage or destroy human settlements and infrastructure. Some forest have a protective function. They shield buildings from natural hazards such as rockfall and avalanches. If they are destroyed, homes and infrastructure become more exposed. Fires result in substantial damage if productively used forests are destroyed. Emissions of fires benefit the production of tropospheric ozone. This can lead to smog-like conditions with adverse effects for human health (BAFU 2015). The diverese ecological and societal impacts make wildfires a relevant public policy issue (Zea Bermudez et al. 2010).

1.2 Study objectives

The aim of this work is to contribute to the understanding of large forest fires in Switzerland. Three central questions are discussed. First, to which extent extreme fires can occur in Switzerland. Second, whether the danger of extreme fires has changed, and third, which factors are responsible for this. Extreme value theory is applied to incorporate the special requirements of extreme events.

1.3 The dynamics of wildfires

Wildfires are not static phenomena. Fire regimes depend on a variety of factors. Changes in these factors can induce changes in the fire regime. Simply put, a sufficient amount of fuel and an ignition source are needed to start a fire. Both of these components are influenced by natural and anthropogenic factors. In the short term, the weather determines the condition of the fuel. Wood is easier to ignite when it is dry. Thus, more and possibly larger fires are to be expected during hot and dry weather. The climate has the same effect in the long term. Additionally, changes in the mean state of the climate can change the availability and composition of the potential fuel. Plant growth can increase or decrease. Also, the composition of the vegetation can be altered. Humans can influence the availability of fuel as well. Forestry is an obvious example. Also, humans can be an ignition source. Changing human behaviour can therefor lead to changes in the fire regime (Pyne et al. 1996). Since fires are strongly influenced by the underlying natural and societal conditions, the fire regimes are under constant evolution (Conedera and Pezzatti 2005). The densely populated southern part of Switzerland is an excellent illustration of the complex interaction of human interest and this natural phenomenon. The fact that fire occurrence and behaviour is influenced by a multitude of factors of natural and anthropogenic origin that act on different timescales adds a great deal of complexity. It is thus difficult to attribute a change in the fire activity to a specific variable (Conedera 1996).

In the early Holocene before the emergence of anthropogenic pressure, the fire regime was mainly driven by the climate. High seasonality favoured wildfire activity in southern Europe. Later in the Neolithic, humans began to have a noticeable impact on the fire regime. With increasing human pressure, the determinants of the fire regime evolved to a complex interplay of natural and anthropogenic factors. The relative importance of the factors altered as natural and socioeconomic conditions shifted over the centuries. In the past few decades, pronounced changes in the structure of the economic activity, the way of life of the general public along with changes in the climate affected the fire regime (Ganteaume et al. 2013). Today, Europe can be split into a northern and southern part regarding its fire regime. Most fires develop in the southern part of the continent. In the north, they are rare. The alps broadly speaking, form the border between the two regions (Tinner et al. 2005). Switzerland's location at the boundary between the two regions gives the country a unique fire regime. The division of the European continent regarding its fire regime is reflected in a smaller scale on the national level. Fires are practically non-existent north of the Alps. South of the Alps however, especially in Ticino but also in parts of Valais and Grisons, they are frequent (Zumbrunnen, Pezzatti, et al. 2011).

The connection between dependent variables such as the annual number of fires or the average fire size and explanatory variables is anything but self-explanatory. On the one hand, many factors play a role. In addition, the relative importance of these factors can vary from region to region. Non-linear relationships are possible and add a great deal of complexity. As a result, the relative importance of several variables in a given region can change over time. The weather, and in the long-term the climate, are key variables. Favorable weather alone is in most cases not sufficient to ignite a fire but it is a necessary precondition. Wastl, Schunk, Lüpke, et al. (2013) find a correlation between the weather type and fire outbreak. Most fires occur at the end of a drought period. Drought conditions are recurring states of the local climate and appear every year south of the Alps. Such conditions have been occurring at an increasing rate between 1971 and 2003 due to a decrease of the precipitation, especially in the winter months and an abrupt increase in temperatures in the middle of the 1980s. Also, relative humidity declined and the monthly hours of sunshine increased. The combined effect of these changes is an increase in fire proneness due to drought conditions (Reinhard et al. 2005). The impact of the weather on fire danger is often expressed by using fire weather indices (Zumbrunnen, Pezzatti, et al. 2011). The connection between fire weather indices and fire occurrence is not straightforward though. The correlation between the two measures is weaker in Ticino than in Valais. It improves if winters and summers are analyzed separately. The particular fire regime of Ticino is reflected in these results. In Ticino, most fires occur in winter, whereas in Valais the majority appears in summer. Fire weather indices show lower values in winter than summer because they are strongly influenced by temperature (Wastl, Schunk, Leuchner, et al. 2012).

Forest cover increased from 27% to 52% of the surface in Ticino and from 28% to 42% in Valais during the 20^{th} century. In Ticino, the increase in forest cover correlates positively and significantly with the number of forest fires. In Valais on the contrary, there is no significant correlation. It is presumed that the location of the forest cover increase is the reason for the unequal impact of the two variables in Ticino and Valais. In Ticino, most forest increase materialized at low altitude which is a much more fire prone area than places at higher altitude. In Valais on the other hand, the majority of the increase of the forest cover emerged at high altitude. This setting is characterized by a cold and wet climate. Hence, fires are very unlikely. The explanatory power of the increase in forest area is not large though (Zumbrunnen, Pezzatti, et al. 2011).

Ganteaume et al. (2013) find a positive correlation between the number of fires and the population density. At the same time, they find a negative correlation between the fire size and the population density. This fact leads the authors to conclude that the relation between land abandonment and the fire regime is unclear. While there are more fires, in our context at least in Ticino, they mainly occur because humans ignite them. Only few fires were recorded in sparsely populated regions. In Valais, the population density, the road density, the livestock density, and wood harvest are related to fire occurrence. The population density is positively correlated with fire occurrence. Contrary to other studies, a linear relation was found. In several other studies, the relation appeared to be non-linear. In that case, increasing human presence starting from a low level would first increase fire occurrence. The effect levels off with an increasing population density and becomes negative for high values. Aldersley et al. (2011) find that on a global scale, the burnt surface increases with an increasing population density until a value of 30 persons per km^2 is reached. For higher values, the relation becomes negative. The reasoning behind this is that humans can both initiated and suppress fires. The GDP density is negatively related to fire occurrence. The authors argue that regions with higher GDP can afford more effective fire suppression. Also, the GDP could be a proxy for land fragmentation. The higher the GDP is, the more fragmented the land becomes, hindering in turn the spread of fire. A connection between human presence and the fire regime is found in a number countries. GDP is positively associated the burnt surface in Turkey, Spain and Greece. Livestock density correlates positively with the burnt surface in Italy, France, Portugal and Cyprus. A positive correlation between burnt surface and population density is found in Israel and Cyprus. The degree of the correlation and the significance vary with the countries (Koulelis et al. 2010). In Galicia, a number of socioeconomic variables is found to have an impact on fire occurrence alongside biophysical factors. Population density, road density, the share of agriculture, the unemployment rate, rural exodus and the share of densely built areas influence, among others, fire occurrence. Somewhat contrary to what Aldersley et al. (2011) found, human presence is associated with a higher number of fires. The impact is not primarily via the population density but through the access to the forests. The road density has a greater impact on fire occurrence than the population density. Also, a positive relation between the unemployment rate and fire occurrence was established. The effect seems to act indirectly by what the authors call rural exodus. They argue that owing to unemployment, people move away and leave behind uncultivated land that is more susceptible to fire. However, the authors point out that it remains unclear if the effect of unemployment is larger than that of continued agricultural practice. Additionally, rapid urban growth is positively related to fire occurrence (Chas-Amil et al. 2015). Lekakis (1995) express the view that tourism and recreational activities are related to fire occurrence. The more time people spend in forests, the more fires result. They find that car and population density are positively related to fire occurrence.

As already indicated, the effect of an explanatory variable can change over time. For example, Zumbrunnen, Bürgi, et al. (2010) find a negative correlation between the Thornthait Index, a moisture index, and the annual number of fires in the canton of Valais during the period 1904-1955. This means that more fires are counted in dry years. For the period 1956-2008, however, the authors find a positive correlation with a three year lag. This suggests that there is an increased plant growth, especially of highly flammable herbs, in wet years. Three years later this leads to a larger number of fires. Changes are also found for the relationship between moisture and the annual area burned. In the first period the correlation is negative, in the second it no longer exists. The disappearance of the correlation is explained by improved fire fighting, prevention and legal changes.

The functional form of the independent variables and the question whether a causal effect really exists can also cause problems. Zumbrunnen, Menéndez, et al. (2012) find for Valais that the temperature has higher explanatory power in the period of 1956-2006 than in the previous period from 1904-1955. A possible cause is the shift of the fire activity to lower lying, more fire-prone parts of the canton. There, the climate has a greater effect on the fire regime. Additionally, a negative effect of livestock density on fire occurrence is found in the first period. In the second period there is an inverted u-shaped connection. Here, however, the question of causality arises. The correlation is strongest in the eastern part of the canton. This is also the driest region of Valais. It is therefore possible that the effect of the dry climate rather than that of the livestock density is measured. A similar problem arises when testing the effect of wood harvesting as a proxy for the removal of biomass from forests. There is a stronger negative correlation in the first period than in the second. However, the effect is strongest in the wettest region of the canton. Therefore, there is the risk that instead of the desired effect, that of the climate is be measured.

2 Method and Data

2.1 Extreme Value Theory

Wildfires are typical examples of extreme events. Small incidents take place frequently. Large events are rare but cause a large fraction of the damage. The statistical analysis of wildfires is complicated by this characteristic. Standard statistical tools, such as the ordinary least square method, are well suited to analyze typical values. They are inappropriate though to analyze extreme values. Extreme value models were developed to address this limitation of standard approaches (Holmes et al. 2008). Understanding the entire distribution of fire damage would be invaluable knowledge. Modelling the distribution of fire damage has proven to be a difficult task though. Necessary assumptions about the behaviour often are too restrictive, especially concerning the upper tail of the distribution. Such unrealistic constraints can to a certain degree be relaxed if the focus of the analysis is only on extreme values. Extreme value theory can be applied in this case (Katz, Brush, et al. 2005).

Extreme value theory (EVT) is unique in the sense that it is used to analyze the extreme rather than the usual. The fundamental idea of EVT is that if the statistical distribution of a random variable X_i is known, the corresponding behaviour of the maxima M_n can be estimated. In practice however, the distribution X_i is unknown. EVT allows to model the approximate distribution of the extremes M_n, under certain assumptions.

$M_n = max\{X_1, ..., X_n\}$ is the maximum of a sequence of independent random variables with a common distribution F. F is unknown. X_i is the measurement of a certain variable. In the context of this thesis it is burnt area in hectares. M_n is the maximum of a specified period of time. Often, annual maxima are used. F could be estimated by using observational data. However, small inaccuracies in the estimation could result in substantial differences between the modelled and the real distribution of the data. This issue can be avoided by estimating F^n based on extreme data only. If M_n is linearly renormalized to $M_n^* = \frac{M_n/b_n}{a_n}$ and there exists a sequence of constants $a_n > 0$ and b_n such that $Pr\{(M_n - b_n)/a_n \leq z\} \rightarrow G(z)$ as $n \rightarrow \infty$, where G is a non-degenerate distribution function, then G belongs to one of three families.

$$\text{I} \quad G(z) = exp\{-exp\big[-(\tfrac{z-b}{a})\big]\}, -\infty < z < \infty;$$

$$\text{II} \quad \text{G(z)} = \begin{cases} 0, & z \leq b, \\ exp\{-(\frac{z-b}{a})^{-\alpha}\}, & z > b; \end{cases}$$

$$\text{III} \quad \text{G(z)} = \begin{cases} exp\{-(\frac{z-b}{a})^{\alpha}\}, & z < b; \\ 1, & z \geq b, \end{cases}$$

The three distributions are jointly referred to as extreme value distribution. Distribution one is known as Gumbel, two as Fréchet and three as Weibull family. The three families can jointly be expressed in one family of models. It is termed the generalized extreme value distribution (GEV).

$$G(z) = exp\{-\big[1 + \xi(\frac{z-\mu}{\sigma})\big]^{-1/\xi}\}$$

The model is characterized by the location parameter μ, the scale parameter σ, and the shape parameter ξ. They can be distinguished on the basis of their shape parameter. The Gumbel family has a shape parameter of 0, the Fréchet family > 0, and the Weibull family < 0. Each family has a distinct upper tail behaviour. Gumbel and Fréchet families have no upper limit. They feature an exponential and a polynomial decrease respectively. The Weibull family has an upper limit.

The GEV distribution is the basis for the block maximum approach. A block is a specified time interval, one year for example. The maxima of the blocks are used to model the distribution. This approach is appropriate if one is interested in the single most extreme event within a block. The drawback of this method is the fact that all other observations are disregarded. This leads to a loss of possibly valuable data. The loss of useful data can be avoided by using the peak over threshold (POT) approach. The concept of POT is to regard all values that exceed a high threshold u as extreme events. As before, if the underlying distribution F of the data was known, the probability of exceeding u could be calculated.

The POT approach is similar to the BM method in the sense that the model is an approximation of the real distribution of large values. Again, $M_n = max\{X_1, ..., X_n\}$ is the maximum of a sequence of independent variables with a common distribution F. For large n, $Pr\{M_n \leq z\} \approx G(z)$ with

$$G(z) = exp\{-[1 + \xi(\frac{z-\mu}{\sigma})]^{-1/\xi}\}$$

For μ, $\sigma > 0$ and ξ holds. The distribution function of $(X - u)$, given a sufficiently large u and that $X > u$, can be approximated by

$$H(y) = 1 - (1 + \frac{\xi y}{\widetilde{\sigma}})^{-1/\xi}$$

defined on $\{y : y > 0 \text{ and } (1 + \frac{\xi y}{\widetilde{\sigma}}) > 0\}$, where $\widetilde{\sigma} = \sigma + \xi(u - \mu)$

The expression defines a family of distributions that are known as the generalized Pareto family. If an approximating distribution G for BM exists, exceedances over u have a corresponding approximate distribution within the generalized Pareto family. The generalized Pareto distribution (GPD) is defined by the same set of parameters as the corresponding GEV distribution. They share the same shape parameter ξ. ξ determines the behaviour of the distribution, as in the case of the GEV. If $\xi < 0$, the distribution has an upper limit of $u - \frac{\widetilde{\sigma}}{\xi}$. For $\xi > 0$ and $\xi = 0$, there is no upper bound (Coles et al. 2001). The interpretation of the parameters is the same as in the case of GEV. The location parameter defines the center of the distribution, the scale parameter describes the size of the deviation around the center and the shape parameter governs the decay of the upper tail (Katz 2010).

The selection of an adequate threshold u is delicate and to some degree subjective. On the one hand it should be set as low as possible to include as many observations as feasible. On the other hand, if it is set too low, the assumption that the exceedances can be approximated with a GPD might be violated. The benefit of having plenty of observations by setting a low threshold must be traded against the cost of possibly violating the assumption that the exceedances of u can be approximated as a GPD. This trade-off is the major drawback of the POT approach. If we assume that y has a GPD with parameters σ and ξ, it follows that

$$E(y) = \frac{\sigma}{1-\xi}$$

given that $\xi < 1$ (otherwise $E(y) = \infty$). If we assume that GPD is a valid model for the excess of a given threshold u_0 generated by a series $X_1, ..., X_n$, again under the assumption that $\xi < 1$,

$$E((X-u)|(X>u)) = \frac{\sigma_u}{1-\xi}$$

Because GPD is a valid assumption for the excess of u_0 the expression above is true not just for one specific threshold but, in a adjusted form, for any that exceeds u_0.

$$E((X-u)|(X>u)) = \frac{\sigma_u}{1-\xi} = \frac{\sigma_{u0} + \xi u}{1-\xi}$$

Consequently, for $u > u_0, E((X-u)|()X > u))$ is a linear function of u. In order to set a threshold, the mean value of the excesses over u of a sequence of thresholds $_0, ..., u_m$ are plotted against u. The result is called the mean residual life plot (MRL). The MRL is defined as

$$E((X-u)|(X>u)) = \frac{\sigma}{1-\xi} + \frac{\xi}{1-\xi}u$$

The standard procedure to set a threshold is the visual inspection of the MRL. The optimal threshold is set at the lowest point above which the plot becomes linear. The fit of the model can by judged using a Q-Q plot. The quantiles of the input data are plotted against those of the model. If the model fits well, a straight line results (Coles et al. 2001).

A third method exists, that is called the point process approach. It is a hybrid concept of BM and POT so to speak. $X_1, X_2, ...$ are again assumed to be a series of independent and identically distributed random variables with a common distribution function F. If the X_i are well behaved in an extreme value sense with $M_n = max\{X_1, ..., X_n\}$, there exist sequences of constants $\{a_n > 0\}$ and $\{b_n\}$ such that $Pr\{(M_n - b_n)/a_n \leq z\} \rightarrow G(z)$ with

$$G(z) = exp\Big\{-[1+\xi(\frac{z-\mu}{\sigma})]^{-\frac{1}{\xi}}\Big\}$$

The lower and upper endpoints of G are donted by z_- and z_+. For any threshold $u > z_-$ on regions of $(0, 1)$ x $[u, \infty)$, the sequence of point process

$$N_n = \{\frac{i}{n+1}, \frac{X_i - b_n}{a_n} : i = 1, ..., n\}$$

converges to a Poisson process with intensity measure on $A = [t_1, t_2]$ x $[z, z_+)$ given by

$$\Lambda(A) = (t_2 - t_1)\big[1 + \xi\frac{z - \mu}{\sigma}\big]^{-\frac{1}{\xi}}$$

.

The methodological approach is the same as in the case of POT appart from the tool that is used to set the threshold. For PP, a Z-plot is used. The interpretation remains the same as for the QQ-plot (Coles et al. 2001). A key difference to POT is the fact that the observations that exceed the chosen threshold are assumed to follow a GEV distribution as in the case of BM. The advantage of PP over POT is that, unlike in the case of POT, the scale parameter is independent of the threshold choice. This means that time-varying thresholds are possible. It also implies that the scale parameter can more easily be modelled by including covariates. Accordingly, the PP approach allows to model all parameters (Katz, Parlange, et al. 2002).

Two assumptions are made, when POT or PP is applied. The data is assumed to be independent and stationary. Independence implies that one observation must not depend on another. Data on rainfall is an illustrative example. Independence is an unrealistic assumption if the amount of rainfall at a given point in time should be analyzed. It will depend on the weather some time before the observation. Thus, it is typical for extreme values to appear in clusters. The extremal index is a generally used diagnostics tool. The index can take a value between zero and one. A value of one indicates independence, zero the opposite. There is no general theory of how to deal with them. Declustering is a frequently used approach to address dependence. The challenge here is to define an empirical rule to detect clusters. The cluster size should be large enough to guarantee independence between the different clusters. At the same time, it should be small enough to avoid the loss of too much valuable data. Jiang et al. (2011) note that dependence normally is not a big issue in medium and large fires. They often are independently and identically distributed. Stationarity is the second assumption. The statistician Emil Gumbel expressed this assumption as follows:

> "In order to apply any theory we have to suppose that the data are homogeneous, i.e. that no systematical change of the climate and no important change in the basin have occurred within the observation period and that no such change will take place in the period for which extrapolations are made." (Gumbel 1941, p. 187)

In other words, the distribution of the data that is explored must not change over time. This assumption might not hold in the long term. The problem of such non-stationarity can however be circumvented by including covariates in the model parameters. Typically, the location parameter is modelled. If the issues of dependence and stationarity can be addressed, the likelihood of encountering certain extreme events can be calculated. The return period $\frac{1}{p}$ of an event is the expected waiting time until another event with a certain magnitude and probability occurs again. Associated to this are return levels y_p which are expected to be exceeded once every $\frac{1}{p}$ years (Coles et al. 2001).

PP is used in the statistical analysis. Since the focus is of this thesis is on all large events, not just the largest within a block, a threshold exceedances approach is more suitable than BM. PP furthermore offers more flexibility to include covariates than POT.

2.2 Methodology

The assumption of stationarity is one of the central requirements of extreme value theory. It is also one of the central challenges. As Jiang et al. (2011) state, it can be assumed that long time series of fire data are not stationary. There are two approaches to address this problem. The model parameters can be modelled with covariates. Thus it is possible to consider non-stationary effects. The advantage of this approach is that the total number of observations is available for the estimation. Furthermore, the covariates can be manipulated to test certain scenarios. However, this requires that the processes leading to non-stationarity are known. They must also be measurable. Furthermore, these data must be available for the entire period. Another approach is explained by AghaKouchak et al. (2012) and applied by Evin et al. (2018). If it is known when significant changes have occurred and no significant changes occur in the meantime, the data can be divided into several sections. The advantage of this approach is that no covariates are needed. However, there are some disadvantages as well. Since the data are divided into sections, only a small part of the total available data is used for the estimation. This can be problematic if there are only few observations. In addition, the timing of the subdivision must be well chosen. This requires that the point in time when the distribution changes is known approximately.

On the basis of these considerations, the following procedure is applied: With the help of common descriptive statistics the fire regime of the three regions is presented. Subsequently, the data is divided into 10-year sections. For each decade the 5, 10, 20 and 50 year return levels are calculated. This allows a first view on the development of the extreme fire regime. In the next section the results of the attempt to improve the model fit with covariates are presented. In the following section, the data are divided into three periods. The division is based on the work of Pezzatti, Zumbrunnen, et al. (2013). The authors analyzed the development of the fire regime of the cantons Ticino and Valais and identified several points in time when the fire regime changed significantly. The present analysis supplements the already available results on the development of typical fires with the changes of extreme events. In the following and final part, the entire time series is used. This allows the calculation of different scenarios and shows the influence of the covariates used on the results.

2.3 Data

2.3.1 Fire data

The Swiss Federal Institute on Forest, Snow and Landscape Research Institute WSL at Cadenazzo provided a data extract of the Swissfire data base. The data bank was developed to archive data on wildfires in Switzerland. The data set contains 6,418 observations in total. Included are information on the location, the damage, the cause, and the time when the fire appeared. The location is specified by the canton and municipality in which the fire took place. Temporal information that is available includes the year, the month, and the season, either summer for the months from May to October or winter for the other months. Damage is measured in hectares that were burnt. The cause of the fire is reported as anthropogenic if humans were responsible, lightning if it was ignited by a lightning or unknown (Pezzatti, Michael Reinhard, et al. 2010).

2.3.2 Meteorological data

Meteorological data is used to control for weather and climate variation , a possible source of non-stationarity. To this end, untreated meteorological data is used as well as a set of drought and fire danger indices. The meteorological data is obtained from MeteoSwiss (Meteoschweiz 2019). Daily observational data from one station for each canton is used. The stations are Locarno-Monti for Ticino, Sion for Valais and Davos for Grisons. Homogeneous data on the temperature and the precipitation sum are available for the entire period. For Locarno and Davos mean, maximum and minimum temperature is accessible. For Sion, only daily mean temperature is available. To calculate most drought indicators, information od relative humidity and/or wind speed is needed. Such data is available for all years in Ticino and Davos. At Sion, relative humidity is available only from 1959 and wind speed from 1978. Data on these variables come with the limitation that they were not homogenised. This implies that the reliability of these variables is confined. The ”firebehavioR” R package (Ziegler 2019) is used to calculate the fine fuel moisture code (FFMC), duff moisture code (DMC), drougt code (DC) and fire weather index (FWI) of the Canadian Forest Fire Weather Index System. The Angström, fuel moisture and Fosberg indices are calculated by using the ”fwi.fbp” R package (Wang et al. 2016). The Munger and Nesterov indices are calculated using the code that is provided by Atriplex (2019). All indicators could be calculated for the entire period for Locarno and Davos. Indicators that require data on wind speed and relative humidity are available from 1978 at Sion. The drought code and the munger index are the only indices that can be calculated by exclusively using homogenised data. They are also the only indices that are available for the full data set. The Angström and Nesterov indices are available from 1959 and the remaining indices begin in 1978.

2.3.3 Socioeconomic data

Variables for the population and the population density are constructed by using data of the Federal Statistical Office (BfS 2010; BfS 2019c). Data is available for the years 1930, 1941 and from 1950 to 2000 in 10 year intervals. The values in between are generated by linear interpolation. There is annual data from 2010 until 2018. The population density is simply the total population of the cantons divided by their area.

Land use changes are incorporated by considering changes in the forest cover, the agricultural area and the built-up area. Data on the forest cover is obtained from the Statistical Atlas of Switzerland for the years 1935, 1945, 1955 and 1965. These numbers are based on the "Statistisches Jahrbuch". Annual data is available from 1975 in the Swiss Forest Statistics (BfS 2019b). Data on government owned land is described as reliable. Information on privately owned forest is less accurate, sometimes only estimated. This should not be a major concern since most of the forest is state owned (BfS 2016). 91% of the forested area was owned by the state in Ticino and Valais and 79% in Grisons in 2018. Missing values are again calculated by using linear interpolation. Data on the amount of agricultural land and the built-up area is available in the Statistical Atlas of Switzerland for the years 1923/24, 1952, 1972 (BfS 2019d) and in the "Arealstatistik der Schweiz" for the periods 1979-85, 1992-97 and 2004-09 (BfS 2015). As before, the missing values are calculated by linear interpolation. The units for the total amount of surface is hectares. The share of the surface that is covered is measured in hectares per kilometer squared.

Statistical surveys on the life stock inventory have been conducted since 1922. The results are publicly available on the web page of the Swiss Farmer's Union (Bauernverband 2019). Annual data is available for recent years. For the 20^{th} century, numbers are publicized in 5-year intervals. The missing values are filled by using linear interpolation.

Data on income is provided by the Federal Tax Administration (ESTV 2019). The Swiss Confederation has been taxing income since 1941. Records are available until 2016. The records contain data on the total taxable income and the number of taxpayers. The average income per person is calculated by dividing the total taxable income by the number of taxpayers. The resulting average income is adjusted for inflation by using the "Landesindex der Konsumentenpreise (LIK)" (BfS 2019a). Income is expressed in 2018 prices. The missing values are replaced by setting them equal to the closest available number. 1940 is set to the value of 1941 and the missing values of 2017 and 2018 are replaced with the value of 2016.

2.4 Study region

2.4.1 Ticino

The canton of Ticino is located in the south of Switzerland. It covers an area of 2,812 km^2 and had a population of about 353,700 people at the end of 2017. This results in a population density of 129 persons per km^2. About half of the canton's surface is covered with forest. The topography of the canton is characterized by a strong vertical gradient ranging from as low as 200 to 3,400 meters above sea level. Ticino has a exceptional climate that is referred to as insubrian. Winters are dry and mild, summers are warm and, unlike in the Mediterranean, relatively wet. Annual precipitation amounts to 1,600 to 2,000 mm/m^2 at low elevations. A large share of this, 800 to 1,200 mm, falls in the summer months between June and September. Drought conditions occur frequently in summer, despite the otherwise abundant precipitation. Drought episodes often end with violent thunderstorms accompanied by strong precipitation. A particularity are the Föhn winds. These are warm and dry winds that are blowing from the north. A Föhn event can quickly lower the relative humidity to 20% (Telesca et al. 2010). Of all cantons of Switzerland, Ticino is the most affected by wildfires. The majority of the fires appear in winter. A second, though less distinct peak is in summer. (Conedera and Pezzatti 2005).

Traces of the use of fire to clear land for pastures and hunting grounds are found dating back to 5,000 years before Christ. That practice ended with the introduction of the chestnut tree by the Romans. It appears that fire was no longer used as a tool but rather viewed as a threat. Regulations on the proper conduct of fire existed already in the middle ages. After the first world war, a consensus was reached in Europe that more research on wildfires is needed (Moretti et al. 2003). Factors that influence the occurrence and the size of wildfires were under continuous evolution during the 20^{th} century. Especially the anthropogenic influence changed drastically (Conedera, Corti, and Ambrosetti 2004). Reliable data is available from 1930. In 1931 the first standardized report protocol for wildfires was introduced. Until about 1960, the fire regime remained fairly constant. During this period, the economy in Ticino was dominated by agriculture. After the end of the second world war, in the 1950s und 1960s, the number of the fires and the area burnt increased dramatically. The development coincides with warmer and dryer weather than usual. The main reason for the more active fire regime is however assumed to be the remarkable socioeconomic changes that were taking place. The 1960s were a period of economic expansion. Agricultural activity was declining and people moved to urban centres. Formerly productively used areas were given up and forest began to regrow. The forested area increased and already existing forests started to build up fuel since the amount of biomass was no longer reduced by animals that used to be pastured inside forests or at their edges (Conedera 1996; Conedera and Pezzatti 2005). After the catastrophic year of 1973, in which more than 7,000 ha of forest were destroyed, several improvements were undertaken. Fire brigades were reorganized as well as better trained and equipped. In general it can be said that major improvements were normally undertaken after sever incidents had occurred. The most important legal, organizational and technical changes that occurred are listed in tables 1 and 2. Changes that are thought to have had a major impact are marked in colour. Assessing the impact of a certain measure is difficult though. In the early 20^{th} century, not enough data is available. Generally speaking, especially the efforts that were undertaken from about 1980 proved to be effective (Conedera, Corti, Piccini, et al. 2004).

Pezzatti, Zumbrunnen, et al. (2013) test the data for pronounced shifts. From 1955 until 1968, they find a transition towards a more active fire regime. It is characterized by an increase in the annual burnt surface. The change in the fire regime is explained mainly by an increase in the forested area, and strong socioeconomic changes. The fire weather was partly more favourable for fires, however, this was of minor importance compared to the other changes. Period two includes the transition phase and the following more active period. The second major change in the fire regime took place in the late 1970s. The second shift most likely is the result of a package of legal and organizational changes that were approved and introduced in 1976 and 1978. Firefighting was reorganised fundamentally. The responsibility of organizing and maintaining a fire brigade was transferred from the communities to the canton. Additionally, fire fighting practices were improved and equipment was upgraded. Groups that are dedicated to suppress fires in mountainous areas, the so called "pompieri di montagna" were created. Also, aerial fire suppression by using helicopters was introduced during that time.

In what manner the fire regime will develop cannot be said with certainty. The future development depends on a multitude of factors. Since the introduction of the chestnut tree about 2,000 years ago, the fire regime was moderate. Human pressure on forests is gradually diminishing. A fire regime that resembles the natural regime more closely could be the result. This would imply more fires. But, as discussed already and in more detail in the following sections, the development depends to a large degree on how human pressure will change and in what way the climate, extreme events such as drought and heatwaves especially, will evolve in the future (Conedera 1996).

2.4.2 Valais

Valais is located in the south of Switzerland, west of Ticino. The canton covers an area of 5,224 km^2. It had a population of roughly 341,500 by the end of 2017. The population density is 65.5 persons per km^2, which is about half as much as in Ticino (*Statistischer Atlas der Schweiz* 2019). About a quarter of the surface is covered by forest. The climate of Valais is exceptional for Switzerland. It is not only remarkably different to the climate in Ticino, but to most other parts of the country as well. The climate is of a continental type. Annual and diurnal temperature fluctuations are large. Winters are relatively cold, and summers are hot. In summer, temperatures above 30 degrees Celsius are frequent at low elevations. Valais is in general very dry. At Sion, the typical annual precipitation sum is about 600 mm/m^2. At Visp, the annual precipitation sum can be as low as 400 mm/m^2. This is only about a quarter of what is normal in Ticino. Summers are usually dry and drought conditions occur frequently. Despite low precipitation, water is normally abundant even during drought conditions thanks to a continuous supply of melt water from snow and glaciers at high elevation. However, with a warming climate, glaciers are retreating, and snow melt is occurring earlier in the year, leading to less water supply in later months. Additionally, higher evaporation is expected if temperatures continue to rise. This will lead to more pronounced drought conditions in the already driest region of Switzerland (Wohlgemuth et al. 2012).

Large forest fires are rare in Valais, but occurred repeatedly. In 2003, 300 ha of forest including 70 ha of protective forest that guarded a busy road from rockfall, erosion, hill slide and avalanches were destroyed. It took three weeks to suppress the fire. In 1921, 165 ha were destroyed at Ochsenboden; in 1944, 65 ha were

Table 1: Legal changes in Ticino during the 20^{th} century. Based on Pezzatti, Zumbrunnen, et al. (2013)

Year	**Legislative Act**	**Comment**
1949	Cantonal fire policy law	Ban of fires during drought and strong wind period
1956	Federal decree	Up to 70% of the cost of technical prevention measures may be financed by the Swiss Confederation
1958	Executive cantonal decree	Cantonal authorities may financially support preventive measures such as training of fire brigades
1958	Executive cantonal decree	Up to 50% of the cost of technical preventive measures may be financed by the canton
1975	Modification of the Executive cantonal decree of 1958	Fire prohibition periods are decided by MeteoSvizzera and broadcast in media
1976	Cantonal fire policy law	Any activity related to fire danger is prohibited during drought and strong winds
1978	Application rules of the cantonal fire policy law	Rules prohibiting fires confirmed by MeteoSvizzera
1987	Executive cantonal decree	Ban on burning garden debris
1990	Executive cantonal decree	Fire ban extended to fireworks and bonfires
1992	Partial revision of the cantonal executive decree of 1987	Open fires allowed for phytosanitary reasons
1995	Partial revision of the cantonal executive decree of 1987	Ban issued by communities
1996	Cantonal fire policy law	Any activity related to fire danger is prohibited durning drought and strong winds
1998	Partial revision of the cantonal executive decree of 1987	Burning garden debris allowed in regions above 600 m above sea level
1998	Application rules of the cantonal fire policy law	Fire prohibition periods are decided by MeteoSvizzera and broadcast in media
1998	Cantonal forest law	Wildfires for the first time included in the list of natural hazards that are to be avoided
2002	Application rules of the cantonal forest law	Forest service in charge of fire prevention. Collaborates with MeteoSvizzera in deciding fire ban and organizes stand-by service

lost in the Aletschwald; and in 1962, 42 ha burnt down in the Pfynwald (Gimmi, Bürgi, and Wohlgemuth 2004). Fires develop in the entire canton. Unlike in Ticino, most fires arise in the summer months. Most occur between March and October, with a peak in July and August (Zumbrunnen, Bürgi, et al. 2010).

Pezzatti, Zumbrunnen, et al. (2013) find similar changes in Valais as in Ticino. There are some difference though. In the 1940s, the fire regime intensified. There was an unusually warm and dry period that ended in the beginning of the 1950s. The result was an increase in area burnt and fire frequency. In the beginning of the 1960s, a decrease in the burnt area and the fire frequency is noted in the subalpine part of the canton. There are two likely causes. First, the weather was less fire prone. Especially summer temperatures were low from the middle of the 1950s and stayed low until the beginning of the 1980s. Second, there was a slow down in the increase of the forested area. An increase of the fire frequency was noted in 1985 and 1989, most likely due to favourable fire weather and land abandonment. The dominant factors in Valais appear to be

Table 2: Technical and organizational changes in Ticino during the 20^{th}century. Based on Pezzatti, Zumbrunnen, et al. (2013)

Year	Organizational Act
1940	Two previously existing fire brigade associations merged into one. Represents all fire brigades of the canton
1945	Creation of forest fire commission with the aim to integrate civil fire brigades into fighting forest fires
1958	Expenses for fire guard, fire alarm service, fire fighting and purchase of equipment will be payed by the cantonal authority
1958-	Construction of hydrants togehter with new forest roads Civil fire brigade facilities may be used to control wildfires
1961-1967-	Introduction of radio communication within fire brigades
1962-	Introduction of aircraft for transport and fire fighting
1967-	Hydrants and water reservoirs possible for new plantations
1968	Organization of three fire watching points
1974	Swiss army helicopters may be used for fire fighting
1974-	Introduction of fire prevention rules withing the Swiss army
1974-1990	Construction of spark barriers along the Gotthard railway
1975	Preparation of a fire fighting field book for fire brigades including a map with flying obstacles
1975-	Introduction of automatically refilling water tanks for helicopters
1978	Creation of mountain forest fire brigades in addition to urban fire brigades
1982	Organization of a helicopter stand-by in case of high fire danger during week ends
1987-	Introduction of new and lighter fire fighting tools
1987-	Introduction of Super Puma helicopter into fire fighting. These aircraft have an increased water capacity compared to previously used helicopters.
1998	Better integration of mountain fire brigades into fire brigade organization Collaboration rules with army and civil service
2001-	Permanent stand-by of private and army helicopters in case of fire danger
2002	Permanent stand-by of foresters in case of fire danger

socioeconomic factors and the climate. Unlike in Ticino, organizational and legal changes are not found to have had an impact on the fire regime. Imporant legal and organizational changes are noted in table 3.

The impact of several variables on the fire regime changed with time (Zumbrunnen, Bürgi, et al. 2010). Socioeconomic conditions shifted distinctively after the end of the second world war, quite similar to Ticino. The economy that used to be dominated by agriculture transformed to industry and services. People moved to urban centers. This led to a growth of cities and a decline in population in remote areas combined with large scale land abandonment. By the end of the century, the population had grown to roughly 300,00 people, which is almost twice the size than 100 years earlier. Together with stronger protective regulation, land abandonment led to an increase of the forested area from 75,000 to 95,000 ha from the beginning to the end of the 20^{th} century. The result is, as in Ticino, an increase in the forest area and a build-up of fuel (Zumbrunnen, Menéndez, et al. 2012).

Table 3: Legal, organizational, and technical changes in Valais during the 20^{th}century. Based on Pezzatti, Zumbrunnen, et al. (2013)

Year	**Event**	**Comment**
1933	Cantonal executive decree	Burning of grass and shrubs prohibited
1938	Application rules of the cantonal fire policy law	Burning of grass and shrub lands in open land prohibited; starting fires in open land prohibited, except for forest officials in certain areas; bonfires prohibited, except authorized by the police and only at high altitude
1976	Cantonal executive decree	Setting fires in open lands, forests and alps prohibited (with some exceptions), selling and using pyrotechnical articles and materials prohibited (with some exceptions)
1977	Cantonal law concerning the protection against fire and natural hazards	Individual responsibilities for setting fires in open lands. Municipalities define conditions for burning grasslands
1985	Cantonal forest law	Every action that can cause fire damage in forest prohibited. Fires in forests only allowed at specific locations, must be extinguished before leaving. Fires can be interdicted by forest service. Prevention measures can be prescribed by cantonal government if necessary.
1990	Application rules of the cantonal forest law	Burning waste in open land prohibited, exception for natural waste in remote areas
2001	Cantonal executive decree	Burning of grass and shrub land prohibited
2001	Application rules of the cantonal law concerning the protection against fire and natural hazards	Mandatory cleaning of grass and shrub lands by pasturing or cutting, areas defined by municipalities
2007	Cantonal executive decree	Burning of any kind of waste in open land prohibited

2.4.3 Grisons

The canton of Grisons is located in the south-east of Switzerland. It covers 7,105 km^2. The population amounts to about 197,900 people. This results in a population density of 27.9 persons per km^2 by the end of 2017. 27% of the surface is covered by forest (*Statistischer Atlas der Schweiz* 2019). The climate of Grisons is characterized by strong spatial variation due to the complex local topography. The canton incorporates areas at altitudes from 250 to 4,000 meters above sea level. There are about 20 fires per year in Grisons, mostly on the southern slope of the Alps. As before, damages in most years are moderate. From time to time extremely large fires and years with an increased fire activity occur. In 1997 for example, an especially devastating fire burnt 390 ha in the Misox and Calanca valley. Expenses for fire fighting and reconstruction were estimated to around 9.2 million Swiss Francs (Kaltenbrunner 2013). In 2003, a very hot and dry year, 46 fires were counted. For the future, more but not necessarily larger fires are expected. An important cause is seen in the past changes in socioeconomic circumstances that have led to a decline in agriculture and a less intense use of forests. The processes are analog to those that took place in Ticino and Valais. In forestry, additionally, more biomass is left in the forests due to operational and ecological considerations. In some areas, reserve like conditions have developed (Wald und Naturgefahren 2003). This is clearly visible in the Swiss National Park. A century of strong protection caused the forest to change to conditions that are similar to a primeval forest. This allows a natural fire regime (Arpaci et al. 2010). The warming climate is regarded as another important driver (Kaltenbrunner 2013).

The economic significance of timber is negligible; however many forests are protective forests that guard important infrastructure and settlements form natural hazards such as avalanches and rockfall. If such forests are damaged or destroyed, these assets are more strongly exposed to natural perils. About three quarters of all incidents are caused by humans. This corresponds well to what is observed in Ticino and Valais. Anthropogenic fires occur mainly in the months of March and April. In Ticino, the majority of the anthropogenic fires occur about one month earlier. That difference is explained with the higher altitude where fires typically are located in Grisons. Anthropogenic fires normally occur at altitudes where there is human settlement. Natural fires predominantly occur in June to August (Koutsias et al. 2002).

Measures have also been taken in the canton of Grisons to improve the suppression of forest fires. In 1994, wildfire bases were constructed across Grisons. Equipment dedicated to suppress wildfires is stored in these bases and can be accessed by the fire brigades. In 1996, a new cantonal forest law was passed that put the state office for forest and natural hazards in charge of informing the public about wildfire danger and issue fire bans if necessary. Since 1997, the cantonal authorities use the INCENDI software to forecast and judge the fire danger. In the course of the 1990s, a map with water access points was created for the fire brigades with the purpose of making interventions easier and quicker (Kaltenbrunner 2010). Until 2030, the canton of Grisons intends to construct additional water access to further reduce intervention times (Costa 2019).

3 Results

3.1 Descriptive Statistics

3.1.1 Fire data

Between 1940 and 2018, a total of 6,418 fires were recorded. Information on the area burnt is available for 5,105 events. In Ticino, fires were observed every year. There were no fires in Valais in the years 1940 - 41, 1977, 1986 and 2017. For Grisons there are no entries for the years 1940 - 41, 1945 - 46, 1955 - 59, 1964, 1979 and 1993. It is possible that some fires were not recorded, especially small fires in early years (Gimmi, Bürgi, and Wohlgemuth 2004). In addition, the data for Grisons are not yet complete. Of the 5,105 fires, a good three quarters (78% or 3,969 events) took place in the Canton of Ticino. The remaining fires are divided equally between the Cantons of Valais and Grisons. A total area of 52,836 hectares was burnt. 89.5% of this is located in Ticino, 4.7% in Valais and 5.8% in Grisons.

Summary statistics of the fire sizes are shown in table 4. The average size of the fires is 11.9 ha in Ticino, 4.3 ha in Valais and 5.4 ha in Grisons. The median is 1.3 ha in Ticino, 0.5 ha in Valais and 0.1 ha in Grisons. Fires, which fall into the largest percentile of the distribution, caused 31 % of the damage in Ticino, 49 % in Valais and 45 % in Grisons. This corresponds to 40 events in Ticino, 2 in Valais and 6 in Grisons. The largest five percent of the events caused 63 % of the total burnt area in Ticino, 74 % in Valais and 84 % in Grisons. Only 2.5 % (99 fires) were larger than 100 ha in Ticino, 0.1 % (4 fires) in Valais and 0.2 % (8 fires) in Grisons. 81 % of the events were smaller than 10 ha and 41 % smaller than 1 ha in Ticino. In Valais 94 % were smaller than 10 ha and 62 % were smaller than 1 ha. In Grisons, 93 % of all fires remained smaller than 10 ha and 75 % smaller than 1 ha.

Table 4: Summary statistics of the fire size per canton

Canton	n	Median	Mean	Max
Ticino	3,969	1.3 ha	11.9 ha	1,600 ha
Valais	572	0.5 ha	4.3 ha	500 ha
Grisons	564	0.1 ha	5.8 ha	477 ha

The uneven distribution of the damage is further accentuated when the different sizes of the cantons are taken into account. During the entire period, 1.4 fires per km^2 occurred in Ticino and an area of 16.8 ha per km^2 was burnt. 0.1 fires per km^2 and 0.47 ha burnt area occurred in Valais. In Grisons, there are 0.08 fires per km^2 and a damage of 0.4 ha per km^2. The distribution over the year is shown in figure 1. In Ticino, most fires occur in the winter months (71%). In Valais and Grisons, however, the majority of the fires occur in summer (53.8 % and 64.7 %). The losses are also unevenly distributed over the year. 27.3 % and 27.1 % of the losses in the Canton of Ticino occurred in March and April respectively. The months with the largest losses in Valais are January, April and August with shares of 23.7 %, 25.2 % and 8.4 % respectively. The main months in Grisons are April with 28.7 % and August with 18.4 %. The fires are mainly caused by humans. In Ticino, the proportion of anthropogenic fires is 85.9 %, in Valais 71.2 % and in Grisons 69.2 %. 5.4% of the fires in Ticino, 8.9 % in Valais and 22.9 % in Grisons are caused by lightning, i.e. they are of natural origin. The cause of the remaining 8.7 % in Ticino, 19.3 % in Valais and 7.8 % in Grisons is unknown.

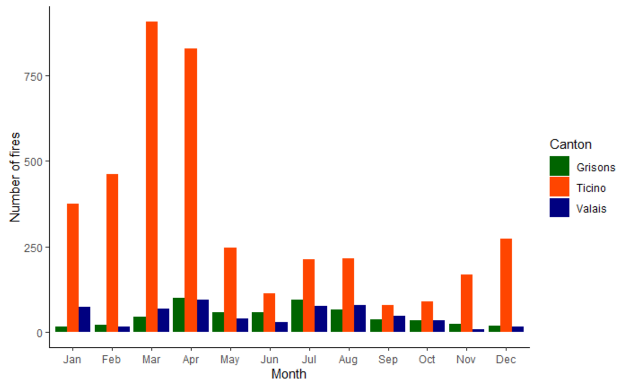
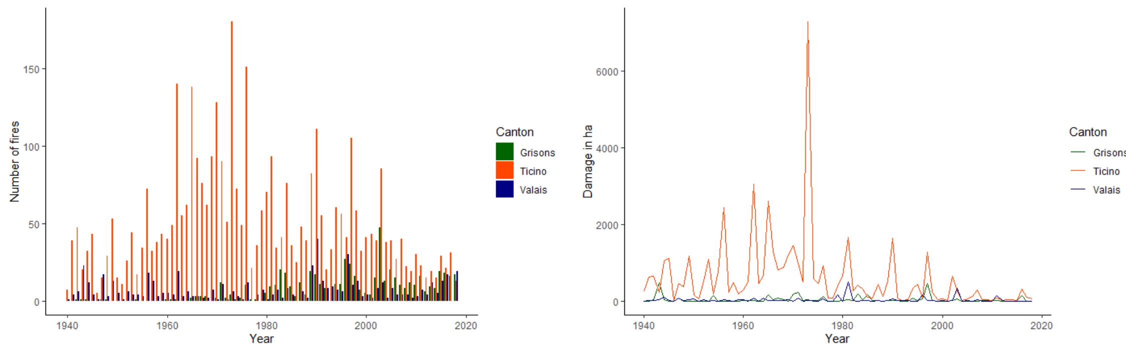


Figure 1: Number of fires per month

Figure 2 shows the annual totals of the burnt surface and the number of events. Clearly visible are the strong annual fluctuations of the burnt surface as well as the number of events. Especially the graphs for Ticino seem to show trends. From the beginning of the data series until about the end of the 1970s, the number of the fires and the burnt surface seem to increase followed by a decrease. The data was checked for trends by regressing different subsets against time. For Ticino, inverted u-shaped trends are found for the number of annual fires, the number of fires in the winter and summer months, and fires with human triggers. The maxima are roughly around the year 1980, or shortly before. A positive trend is found for the number of lightning induced fires, and a negative trend for fires with unknown cause. Negative trends for the annual burned area were found for all subsets except lightning fires. Four significant trends are identified for the canton of Valais: An u-shaped trend of the annual sum of events with a minimum around 1970, an increase of the number of fires caused by lightning, a decrease of the average size of fires with unknown triggers and an inverted u-shaped trend for the mean fire size in summer. For Grisons, an increase of the annual number of fires is found. When different subsets of the data are considered, increases of the number of fires in summer, winter, and fires caused by humans are found. The burned area decreases throughout the year and limited to the summer months. The average size of fires in winter has a slight inverted u-shaped curvature.



(a) Sum of events

(b) Total burnt surface

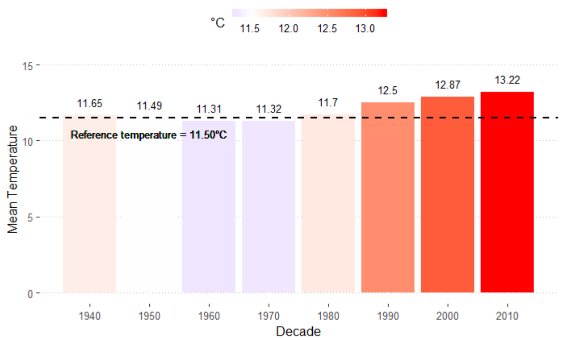
Figure 2: Annual sum of events and burnt surface

3.1.2 Meteorological data

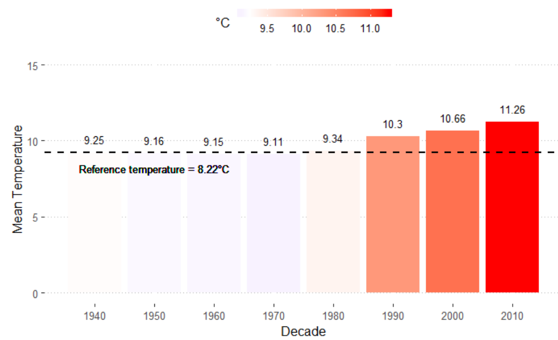
Several tests are carried out to establish if meteorological variables had changed from 1940 until 2018. Since the fire data is in a monthly format, averages of the daily mean temperatures as well as the monthly precipitation sums are calculated for the measurments at Locarno, Sion and Davos. First, it is tested if these values differ significantly from decade to the next. Then, it is tested if there is a significant difference between the values of the 10 year intervals and the reference periode of 1961-1990 as defined by the World Meteorological Organization (WMO 2019). Finally, it is tested, if there is a trend of the data.

Detailed results can be found in tables A 2, A 3 and A 4 and figure B 1. The results of the individual stations are qualitatively similar. A graphical representation of these findings is shown in figure 3. A t-test is used to determine if the mean values are significantly different from each other. A p-value of 0.05 is used as threshold. Starting with the transition of 1980 to 1990, each subsequent decade shows significantly higher temperatures at all stations. At Locarno, the warming sets in a decade earlier in 1970. If only winter temperatures are analysed, we find significantly higher values for the transition of 1970/80 and 2000/10 for all stations. Additional significant warmings are found at Locarno for 1950/60 and Davos for 1960/70. The results for the summer data are slightly different. A cooling is found for all stations from the 1940s to the 1950s. At Locarno and Davos, a sustained warming is found, starting in the 1970s. At Sion, the process starts already in the 1960s. Significantly different monthly precipitation sums are found for the transition of 1940 to 1950 at Locarno and Sion. In both cases, the values increase.

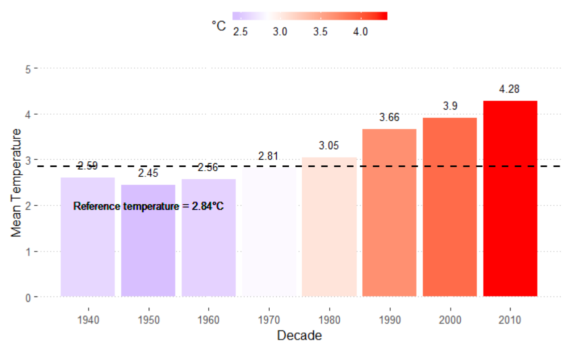
As above, a t-test is used to determine if the mean of the temperature variables or precipitation sum of each decade and station is significantly different from the reference period at the 5 percent level. The annual average temperatures of the 1990s, 2000s and 2010s are higher than the reference temperatures at all stations. At Davos, the annual temperatures of the 1950s and -60s are lower than the reference temperature. The results are similar when the analysis is limited to winter or summer. Annual winter temperatures exceed the reference at all stations in the decades of 1990 to 2010. At Davos, another positive anomaly can be found in the 1970s and a negative one from the 1940s until the 1960s. For summer temperatures we find increased values at Locarno from 1980 to 2010 and lower temperatures in 1960 and -70. At Sion, temperatures are higher in 1940 as well as from 1990 to 2010. They are lower in 1970. Finally, mean temperatures at Davos are significantly higher from 1980 until 2010 and lower in 1950 and in 1970. The only significant difference of the mean of the monthly precipitation sum is found at Locarno in 1940. More detailed results can be found in tables A 5, A 6 and A 7.



(a) Locarno



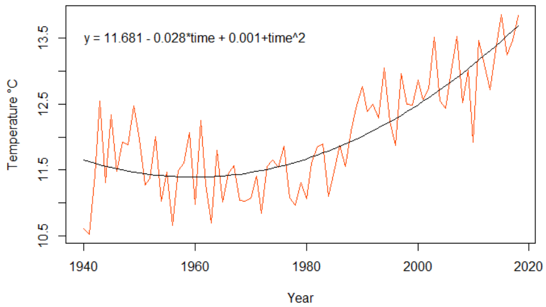
(b) Sion



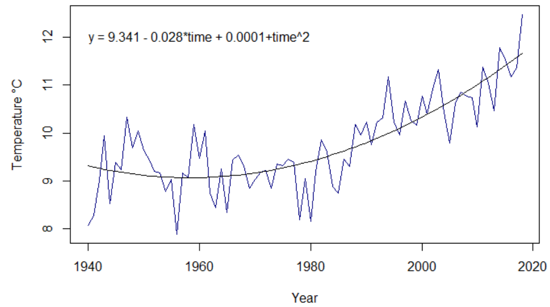
(c) Davos

Figure 3: Mean temperature per decade compared to the reference period

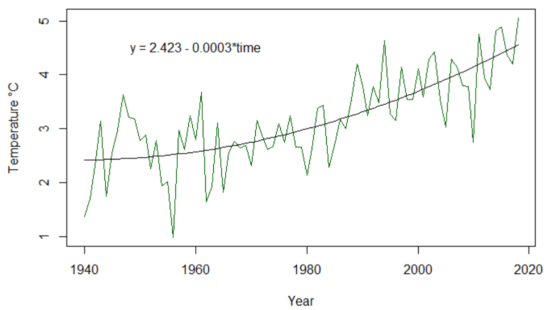
Significant time trends are found in all temperature variables. Again, the results for the different stations are similar. The best fitting functional form was either a quadratic expression of time or a combination of a linear and a quadratic term. As figure 3 shows, the mean temperatures decreased slightly but were rather stable until the 1970s at Locarno and Sion and until 1960 at Davos. The same development can be seen from figure 4. This graph shows the warming that set in after the stable phase and the accelerating magnitude of it during the second half of the observation period. The lowest annual mean temperatures that were measured are 10.5 C in 1941 at Locarno, 7.9 C in 1956 at Sion and 1.0 C also in 1956 at Davos. The highest values all occured in the current decade: 13.9 C were measured at Locarno in 2015. 2018, the last available year turned out to be the warmest in the records at Sion and Davos. 12.5 C were measured at Sion and 5.1 C at Davos. No significant trends are found in the precipitation data.



(a) Locarno



(b) Sion



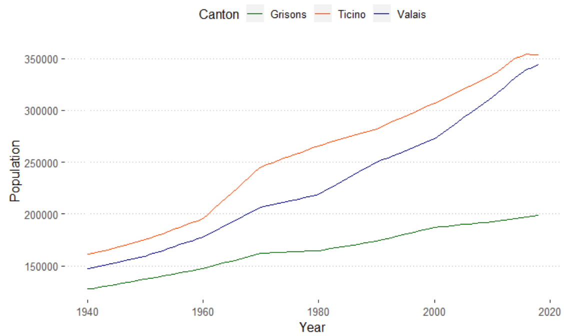
(c) Davos

Figure 4: Trends in annual mean temperature

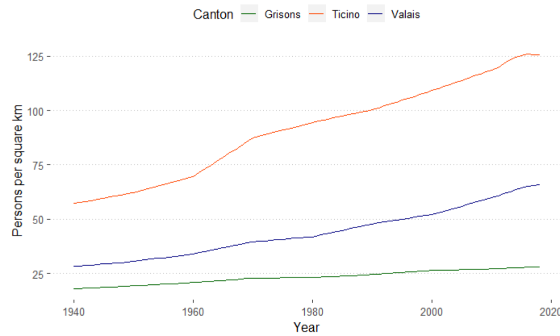
Significant trends are also found in the most fire prone months of the year. The graphs of the results are found in figure B 3. Qualitatively speaking, the results are the same as before. Significant, increasing trends can be found at all stations. Monotonically increasing trends in mean temperatures are found for March at Locarno, January at Sion and August at Davos. For April at Locarno, March and August at Sion and April at Davos, a u-shaped curve fits the data best. The negative curvature is not very pronounced for the observations during August at Sion. In the other three cases, the temperatures show a decreasing trend until the late 1970s. After this point, the trend becomes positive.

3.1.3 Socioeconomic data

Figure 5 shows the development of the total population and the population density from 1940 until 2018 in the study regions. A pronounced increase of the population size occurred in all cantons. Unsurprisingly, the minimum is in 1940 in all cantons. The maximum occurred in 2016 in Ticino and in 2018 in Valais and Grisons. The increases in Ticino and Valais was stronger than in Grisons. In Ticino, the population grew by 119% from a low of 161,640 to 353,343 in 2018. In Valais it incresed by 134% (147,235 to 343,955) and in Grisons by 55% (128,074 to 198,379). The population density is remarkably different between the regions due to the different size of the cantons. It changed from 57.5 to 126.0 persons per km^2 in Ticino, from 28.2 to 65.8 in Valais and from 18.0 to 27.9 in Grisons. The population density is roughly twice as high in Ticino as in Valais from 1940 through 2018. Compared to Grisons, the population density of Ticino was 3.2 times larger in 1940 and 4.5 times larger in 2018.



(a) Total population

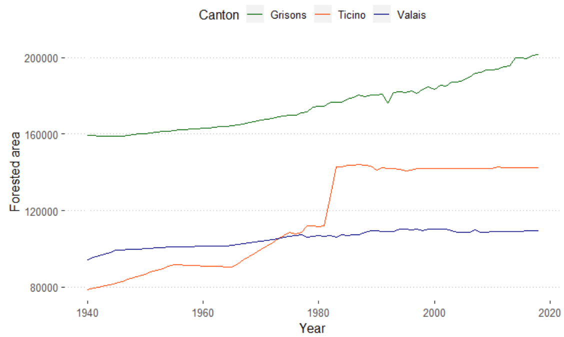


(b) Population density

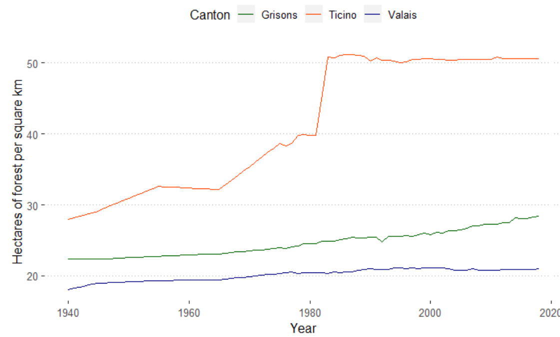
Figure 5: Population and population density

Figure 6 a) shows how the area that is covered by forest changed from 1940 until 2018. It expanded in all cantons. In Ticino, it increased from 78,674 ha to 142,310 ha which is an increase of 80.9%. In Valais, an increase of 16.0% (94,442 ha to 109,584 ha) occurred, and in Grisons one of 26.6% (159,280 ha to 201,585 ha). In Ticino and Valais, the values of 1940 are also the lowest in the records. In Grisons, the minimum occurred several years later, in 1945 with a value of 158,735 ha. The maxima are in 1987 (143,927 ha) in Ticino, 1999 (110,386 ha) in Valais and in 2018 in Grisons.

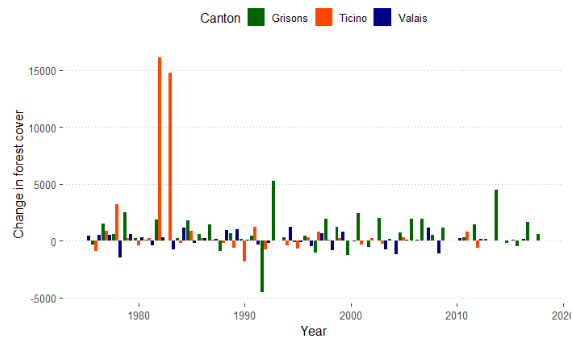
Figure 6 b) shows the forest cover in hectares per square kilometer. Ticino has the largest forest area per km^2, followed by Grisons and Valais. Between 1940 and 2018 the values increase from 28.0 to 50.1 in Ticino, from 18.1 to 21.0 in Valais and from 22.1 to 28.4 in Grisons. Figure 6 c) shows the annual change in forest cover for the period for which annual data is available.



(a) Surface covered by forest



(b) Hectares of forest cover per square km



(c) Annual change in forest cover, 1975-2018

Figure 6: Forest cover

Gimmi, Bürgi, and Stuber (2008) note that it used to be common practice to pasture animals in forests in the canton of Valais. Mainly goats were kept that way, to a lesser extent cows and sheep as well. Goats were kept near villages for milk production. The animals grazed in the nearby forests leading of biomass. Cows and sheep used to be grazed on alpine pastures during the summer months. Figure 7 shows the reported numbers of goats for each canton. The highest numbers are found at the beginning of the observation period. In Ticino and Valais, the peak is in 1941 with 37,417 and 30,917 animals respectively. The peak in Grisons is in 1947 with 42,104 goats. Until the end of the 20^{th} century, that number declines. A large share of this occurs during the time when fire occurrence and the annually burnt surface increase which is roughly from the beginning of the observation period until the late 1970s. The lowest values in Ticino is in 1998 (10,202 animals), in Valais and Grisons in 1993 (3,586 and 2,933 animals). Between 1940 and 2018 the number of goats decreased by 72 % (TI), 80 % (VS) and 71 % (GR).

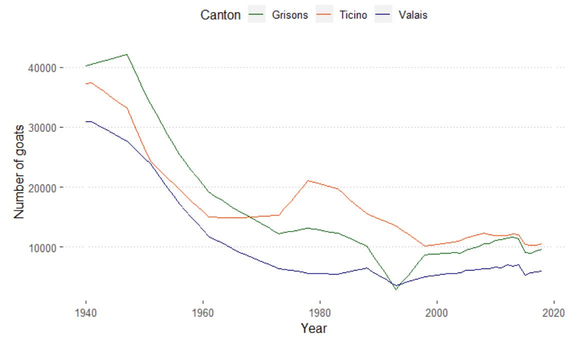
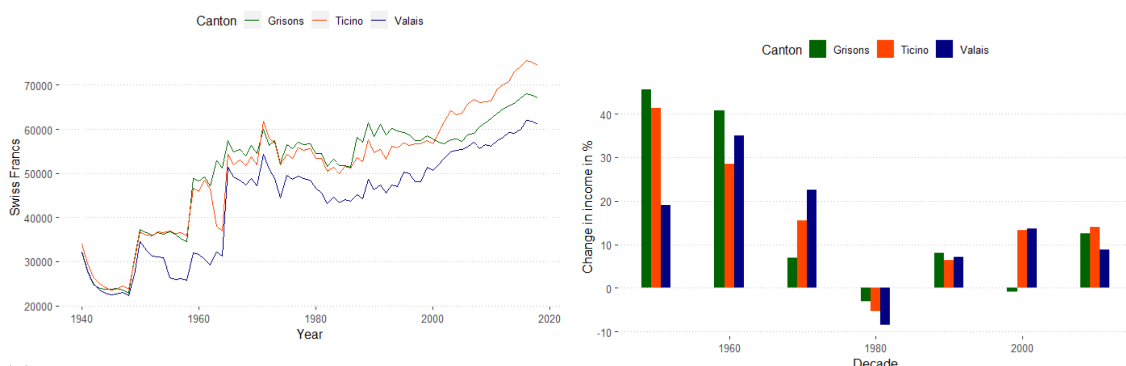


Figure 7: Number of goats

Figure 8 a) shows the development of the real taxable income. Incomes increased substantially since 1940. The lowest values are recorded in 1945 in Ticino and in 1948 in Valais and Grisons. Compared to 2016, the last year for which data was available, incomes increase from 23,656 SFr to 75,589 SFr per year (220%) in Ticino, from 22,330 SFr to 62,089 SFr (178%) in Valais and from 22,905 SFr to 68,097 SFr (197%) in Grisons. Figure 8 shows that the incomes did not grow at the same rate throughout the entire observation period. Figure 8 b) shows the relative increase in income compared to the previous period, average per decade. Incomes grew strongly in the 1950s and 1960s, a little less in the 1970s. In the 1980s, incomes declined, followed by a slower increase in the 1990s. The growth in the following two decades was again at the level of the 1970s. The only exception is Grisons during the 2000 which experienced declining incomes.



(a) Average per capita income adjusted for inflation in 2018 Swiss Francs

(b) Relative change to previous decade

Figure 8: Changes in taxable income

3.2 Analysis per decade

The median fire size declined in the course of the roughly 80 years in all cantons. A Wilcoxon rank sum is applied to test for significant changes. In Ticino, a significantly smaller median value at the 5 % level is found with each new decade until 2000. The median falls from 5 ha in the 1940s to 0.1 ha in the 2010s. In Valais, the median declines from 1 ha in the 1940s to 0.035 ha in the 2010s. From the transition of 1970/80 all changes are significant. Significant changes are found also for Grisons beginning with the transition of

1970/80. Earlier years do not return meaningful results due to the small amount of the observations. Detailed summary statistics for all decades are shown in table A 1 in the appendix.

Figure 9 shows the 5, 10, 20 and 50 year return levels for Ticino and Valais. More detailed results can be found in the appendix in tables A 8 and A 9. It was possible to calculate the return levels for all decades in Ticino. However, due to the smaller amount of observations, the estimates after the 1970s might not be very reliable. For the same reason, the return levels for Valais could only be calculated until the 1970s. For Grisons, no estimation at all was possible.

Qualitatively, all return periods developed the same in Ticino, so the discussion is limited to the 10 year return levels. The level of the chosen threshold varies between 5 ha for 2010 and 30 ha for 1970. The resulting distribution is of a Fréchet type in all cases. A reasonable model fit is obtained until the estimation of 1970. The following estimates do not fit the data well. An increase of the return levels is visible until 1970. The values increase from 314 ha in 1940, 445 ha in 1950, 515 ha in 1960 to 1,190 ha in 1970. Afterwards, the return levels decrease to 278 ha in 1980, 562 ha in 1990, 223 ha in 2000 and 102 ha in 2010.

The thresholds for the estimates of the Canton of Valais vary only slightly and have values between 2 ha and 3.5 ha. In most years, the number of observations exceeding the threshold is small. The resulting model fit is not good in all cases. As in Ticino, all resulting distributions are of a Fréchet type. The expected fire size increases until 1970. The 10 year events have a size of 30 ha in 1940, 29 ha in 1950, 50 ha in 1960, 71 ha in 1970.

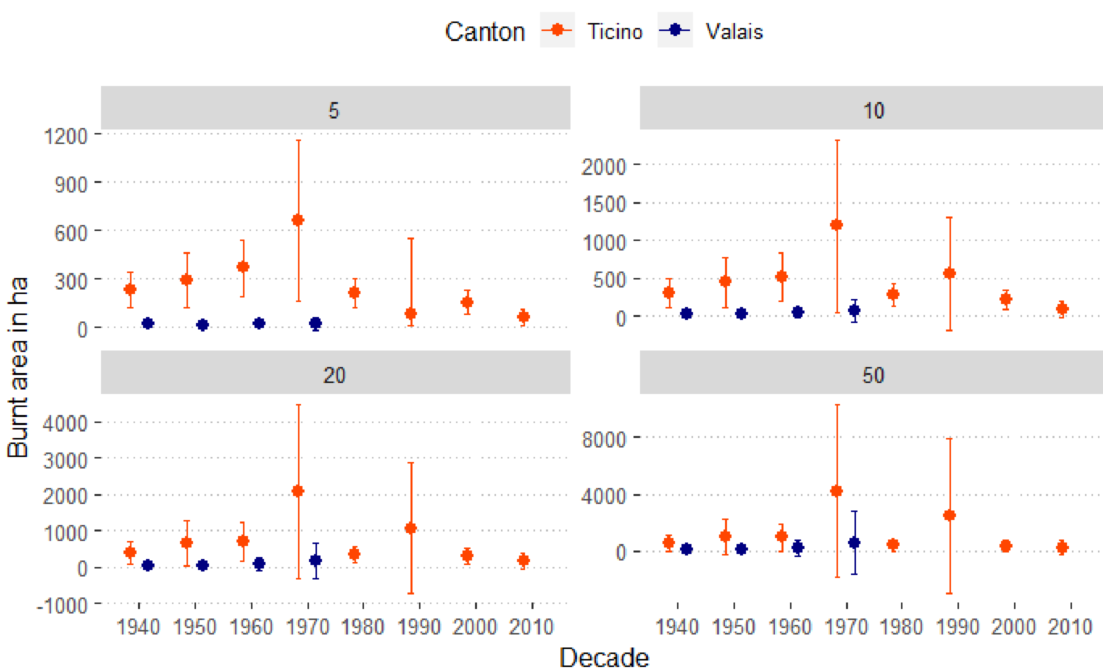


Figure 9: Return levels per decade for Ticino and Valais

3.3 Covariates

The available covariates are used to take into account non-stationary effects. Different functional forms of the covariates are tested in the location, scale and shape parameters. The Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) as well as the linear likelihood test are used as decision criteria. An improvement of 0-2 of the BIC is considered "not worth a bare mention", 2-6 as "positive", 6-10 as "strong" and more than 10 as "very strong", as suggested by Neath et al. (2012). A p value of 5 % is used as threshold for the linear likelihood test. If more than one functional form significantly improves the model fit, the one that leads to the greatest improvement in AIC and BIC values is selected. In a second step, an attempt is made to construct a model that achieves the best possible model fit from the various covariates that significantly improve the model fit. Different combinations of the existing covariates are tested. If several functional forms enabled significant improvements, again the one that led to the greatest reduction in AIC and BIC values is used.

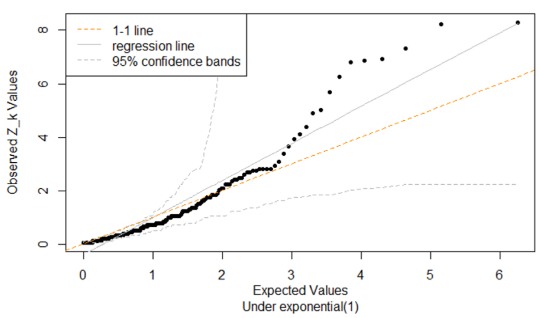
Table 5: Significant covariates in Ticino

Covariable	Paramater	Functional form	BIC	BIC difference
none			2735.4	
time	location	quadratic	2666.0	-69.4
	scale	quadratic	2683.5	-51.9
	shape	linear	2702.4	-33.0
temperature	location	linear and quadratic	2726.8	-8.6
relative humidity	location	quadratic	2725.8	-9.5
wind speed	location	linear and quadratic	2702.8	-32.6
	scale	linear and quadratic	2719.7	-15.7
FWI	location	linear	2715.1	-20.3
	scale	linear	2730.0	-5.4
Fosberg index	location	linear and quadratic	2701.4	-34.0
	scale	linear and quadratic	2722.3	-13.1
summer	location	linear	2731.5	-3.9
broad season	location	linear	2731.5	-3.9
population density	location	quadratic	2670.9	-64.4
	scale	quadratic	2688.8	-46.6
	shape	linear	2704.8	-30.5
forest density	location	linear	2673.5	-61.9
	scale	linear	2675.7	-59.7
	shape	linear	2704.7	-30.7
goat density	location	linear	2702.1	-33.2
	scale	linear	2710.8	-24.6
	shape	linear	2722.3	-13.1
income	location	linear	2687.9	-47.5
policy 1978	scale	linear	2687.5	-47.9
	shape	linear	2702.1	-33.2
	location	linear	2707.9	-27.4

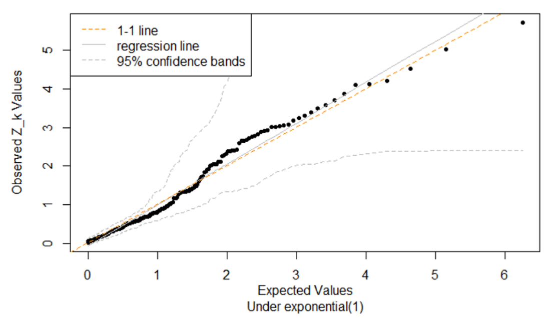
A threshold value of 35 ha is used for the data of Ticino. This results in 259 exceedances. Detailed results are shown in table 5. Among the physical variables, the average temperature, the relative humidity, the wind speed, the fire weather index, the Fosberg index and dummy variables for the summer months and the broad fire season are significant. Among the socio-economic variables, the population density, the forest density, the goat density, the income and a dummy for policy changes allow significant model improvements.

If only one covariate is used, the greatest model improvement is achieved with the population density. The BIC decreases by 64. An almost identical improvement is achieved with the forest density: A reduction of the BIC by 62 results. This is followed by the policy changes of 1976/78 with an improvement of the BIC of 48 and the variable for income with almost the same value. The Fosberg Index, goat density and wind speed are the next variables in the ranking. All three covariates allow a reduction of the BIC of slightly more than 30, while the fire weather index reduces the BIC by 20 units. The relative humidity improves the BIC by 10 and the average temperature by 9, and the dummies for the summer months and the broad fire season by 4 units each. The Population density correlates strongly with the other socioeconomic variables. The correlation coefficients between the population density and the forest density, the goat density and the income are 0.93, -0.80 and 0.94.

The best model for Ticino is a combination of a quadratic term of the population density and the relative humidity in the location parameter and a linear term of relative humidity in the scale parameter. Compared to the base model without covariates, the BIC is reduced by 85 units. The improvement of the model fit is visible in the Z plot shown in figure 10. Without covariates the model fit is not good. It is greatly improved by adding the covariates.



(a) No covariates



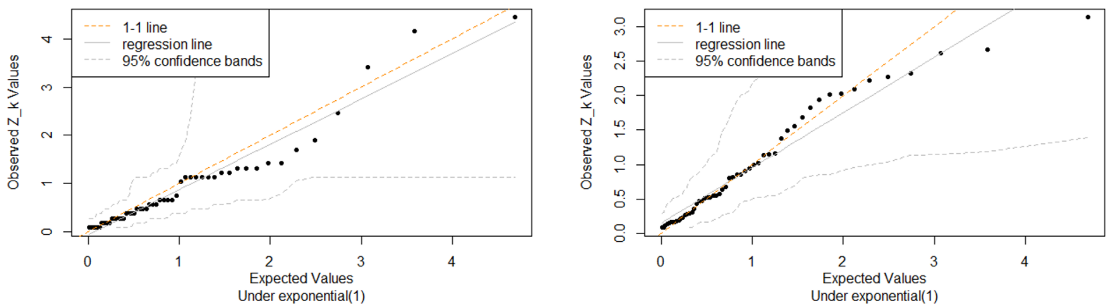
(b) Population density and relative humidity as covariates

Figure 10: Z plots for Ticino without and including covariates

Table 6: Significant covariates in Valais

Covariable	Paramater	Functional form	BIC	BIC difference
none			595.0	
time	location	linear	581.1	-13.9
		quadratic	578.9	-16.1
temperature	location	linear and quadratic	593.5	-1.5
population density	location	linear	579.7	-15.3
		quadratic	578.7	-16.4
forest density	location	linear	584.0	-11.1
goat density	location	linear	587.4	-7.6

A threshold value of 5 ha is set for the data of the Canton of Valais. 54 observations that exceed the threshold remain. As only data for the temperature and the precipitation sum are available for the whole period, only the drought code and the Munger index can be calculated. The results are shown in table 6. Of the physical variables only the temperature allows a significant improvement of the model fit. However, the BIC value only decreases by 1.5 units. The effect is therefore negligible. Larger improvements can be achieved with the socioeconomic variables. The population density allows a reduction of the BIC by 16 units, the forest density by 11 and the goat density by 8. As in Ticino, the population density correlates strongly with the variables for the forest density, the goat density and the income. The correlation coefficients are 0.89, -0.74 and 0.89. The best model for the Canton of Valais uses a quadratic term of the population density in the location parameter. This allows a reduction of the BIC of 16. The model fit is slightly better compared to the model without covariates, but it remains poor. The corresponding Z plots are shown in figure 11.



(a) No covariates

(b) Population density as covariate

Figure 11: Z plots for Valais without and including covariates

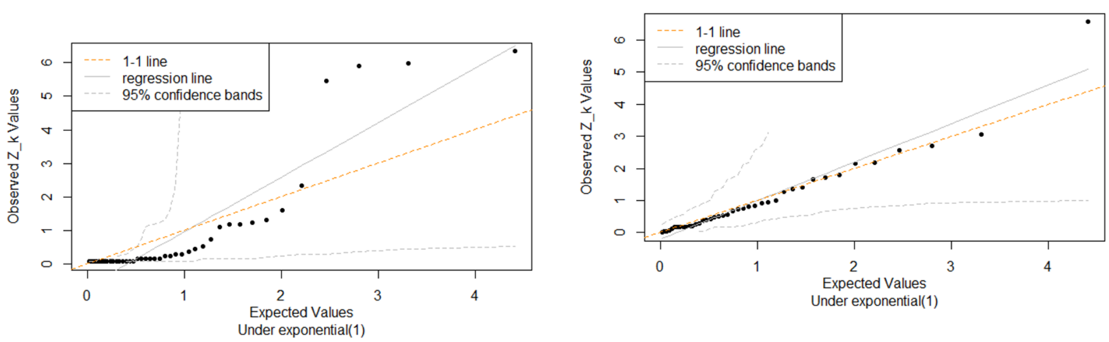
Table 7: Significant covariates in Grisons

Covariable	Paramater	Functional form	BIC	BIC difference
none			555.7	
time	location	linear	514.3	-41.4
	scale	linear and quadratic	538.4	-17.3
temperature	location	linear	546.8	-8.9
precipitation	location	quadratic	543.4	-12.3
windspeed	location	linear	544.0	-11.7
FFMI	location	quadratic	553.3	-2.4
Drought Code	location	linear	554.7	-1.0
FWI	location	linear	551.9	-3.8
Angstrom index	location	linear	549.2	-6.5
FMI	location	quadratic	553.6	-2.1
Fosberg Index	location	linear	544.8	-10.8
summer	location	linear	548.2	-7.5
population density	location	quadratic	521.5	-34.1
	scale	linear	541.2	-14.5
forest density	location	linear and quadratic	516.2	-39.4
	scale	linear	544.0	-11.7
goat density	location	linear and quadratic	526.5	-29.2
	scale	quadratic	546.0	-9.6

For the canton of Grisons, a threshold of 8 ha is set. This results in 41 exceedances. The results are shown in table 7. The physical variables that lead to the greatest model improvements are the precipitation sum, the wind speed, the Fosberg Index and the average temperature. Of the available socio-economic variables, forest density, population density and goat density lead to improvements.

The greatest improvement is achieved with the forest density. The BIC value decreases by 39 ha. The population density allows a reduction of the BIC by 34 units, the goat density by 29. The precipitation sum, the wind speed, the Fosberg index and the average temperature lead to a reduction of the BIC of 9 to 12 units. Improvements of the BIC by 8 and 7 units are achieved with the dummy for the summer months and the Angstrom Index. Marginal improvements are achieved with the fire weather index, the fine fuel moisture index, the fuel moisture index and the drought code. The population density has a correlation coefficient with the forest density of 0.96, -0.87 with the goat density and 0.90 with the income.

The best model for the Canton of Grisons uses linear terms of the population density and the temperature in the location parameter and a linear term of the population density in the scale parameter. This allows to improve the BIC by 37 units compared to a model without covariates. The addition of the control variables improves the model visibly. Apart from very high values, the fit model is quite good. The Z plots for a model without and including covariates are shown in figure 12.



(a) No covariates

(b) Population density and temperature as covariates

Figure 12: Z plots for Grisons without and including covariates

3.4 Analysis per period

3.4.1 Ticino

The data of Ticino is split into three periods according to the findings of Pezzatti, Zumbrunnen, et al. (2013), covering the years from 1940-1955, 1956-1979 and 1980-2018. The averages of the annually burnt surface of periods 1, 2, and 3 are 542 ha, 1,158 ha and 278 ha. The average number of fires per year develops in a similar way. There are 27 in period 1, 76 in period 2, and 44 in period 3. The mean of the fire size decreases with every period. They are 19.9 ha in period 1, 15.2 ha in period 2, and 6.4 ha in period 3. The largest observed fires have a size of 340 ha, 1,600 ha and 550 ha in periods 1, 2 and 3 respectively. We also find changes in the variables that are used to express socioeconomic conditions. The population density increases from 61.2 to 82.4 and 106.0 people per km^2. The number of goats that are kept declines from 30,176 in period 1 to 16,762 in period 2 and 13,178 in period 3.

Two models are fitted to the data of each period. One does not use covariates, the other includes those that are found to improve the model fit. Square terms of the population density and relative humidity are used in the location parameter and a linear term of the relative humidity is used in the scale parameter. The covariates are specified with the average values of the respective variable for each period. Thresholds of 45, 35 and 38 are used for periods 1, 2, and 3 respectively. This leaves 45, 57, and 56 observations that are larger than the threshold to model the distribution. The extremal index is 0.88 for period 1, 0.74 for period 2 and 0.82 for period 3. Dependence should not be a problem since the index is always close to 1.

Figure 8 shows the parameters of the extreme value distribution. The location parameter increases from 130.2 in period 1 to 175.6 in period 2 and drops to 61.9 in period 3. The scale parameter decreases from 49.1 to 40.6 from period 1 to period 2, and increases to 78.6 in period 3. The shape parameter shifts from -0.2 in period 1 to 0.4 in period 2 to 0.0 in period 3.

Table 8: Location, scale and shape parameters of the estimates per period in Ticino

	Periode 1		Periode 2		Periode 3	
	Estimate	95 % CI	Estimate	95 % CI	Estimate	95 % CI
Location	130.2	(-416.1-676.5)	175.6	(-99.5-450.6)	61.9	(-387.6-511.4)
Scale	49.1	(-254.4-352.6)	40.6	(-381.6-462.7)	78.6	(-206.1-363.3)
Shape	-0.2	(-0.5-0.1)	0.4	(0.2-0.6)	0.0	(-0.3-0.4)

The addition of the covariates improves the model fit. The AIC and BIC values of the models including the covariates are lower and the LR tests return significant differences. Additionally, the Z plots show a better fit. The model for period 1 fits the data moderately well. A good model fit is achieved for periods 2 and 3. The covariates lead to narrower confidence intervals of the estimated return levels. The return levels are plotted in figure 13. The return levels of period 2 are the largest, followed by those of period 3 and then period 1. The 10 year events are estimated at 247 ha in period 1, 600 ha in period 2 and at 246 ha in period 3. The 20 year events are estimated at 274 ha, 849 ha, and 308 ha in periods 1, 2 and 3 respectively. The 50 year events have a size of 305 ha, 1,301 ha and 391 ha, and the 100 year events are estimated to reach a size of 324 ha, 1,801 ha and 455 ha. The 95 percent confidence interval of the estimated return levels overlap for all return periods. The estimation for the different periods differ significantly in several cases. The 10 year events of periods 1 and 2, as well as 2 and 3 differ significantly. Further significant differences are found between the 20 and 50 year events of periods 1 and 2.

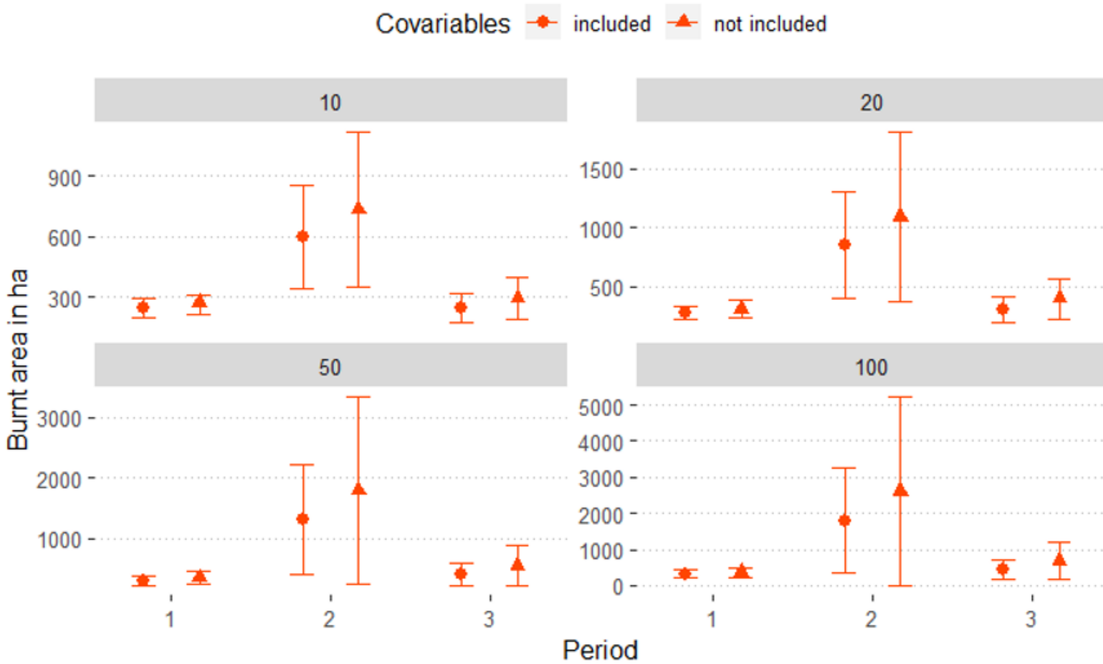


Figure 13: Return levels for models with and without covariates in Ticino.

3.4.2 Valais

The data of Valais is split into three periods based on the findings of Pezzatti, Zumbrunnen, et al. (2013): 1940-1960, 1961-1985, and 1986-2018. The separations are set at the point when the shift in the fire regime of both subregions of the cantons are found to be completed. These changes are found in the data when we look at the annual average of the number of fires. 7.2 events occur on average each year in period 1, 4.8 in period 2, and 9.1 in period 3. The average of the annually burnt surface develops differently: There is an increase from 24 ha in period 1 to 44 ha in period 2, followed by a decrease to 26 ha in period 3. The average fire size follows this pattern. The values for periods 1, 2, and 3 are 3.4 ha, 9.2 ha, and 2.9 ha. The largest fires that are observed in each period have a size of 65 ha in period 1, 500 ha in period 2, and 310 ha in period 3. The population density increases from 31 persons per km^2 in period 1 to 40 and 55 in periods 2 and 3 respectively. The number of goats in the canton decreases from 23,554 in period 1 to 7,639 in period 2 and 5,646 in period 3.

Two models are assessed: One including and one missing covariates. A square term of the population density in the location parameter is used as covariable. The threshold is set to 2 hectares for all periods. This leads to 45, 35, and 32 threshold exceedances in periods 1, 2, and 3 respectively. The model fit is mediocre for periods 1 and 2. The model for period 3 fits the data well. The extremal index in above 0.8 in every case. Dependence should therefore not be a problem.

Table 9 shows the extreme value parameters of all three periods. The location parameter decreases from 6.1 in period 1 to 4.7 in period 2 to 1.3 in period 3. The scale parameter increases from 6.6 in period 1 to

7.8 in period 2 and drops then to 2.6. The shape parameter for the three periods are 0.4, 0.9 and 1.1. This means that the distributions are of a Fréchet type in all periods.

Table 9: Location, scale and shape parameters of the estimates per period in Valais

	Periode 1		Periode 2		Periode 3	
	Estimate	95 % CI	Estimate	95 % CI	Estimate	95 % CI
Location	6.1	(-46.8-59.0)	4.7	(-31.3-40.6)	1.3	(-25.2-27.8)
Scale	6.6	(3.9-9.3)	7.8	(3.2-12.4)	2.6	(0.8-4.5)
Shape	0.4	(0.0-0.8)	0.9	(0.4-1.5)	1.1	(0.5-1.6)

Adding the covariate leads to an improved model fit in period 3 only. The AIC and the BIC show lower values, the LR test returns a significant result and the Z plot indicates a better fit of the data. The confidence interval of the estimations for period 3 is narrower after the addition of the covariable. The effect is only noticeable for larger return periods such as the 50 and 100 year events. But even then, the effect is not large.

Figure 14 shows the return levels for each period. The values are the largest for period 2, followed by periods 3 and 1. The estimations for period 3 are larger than those of period 1, with the exception of the 10 year events. The size of the 10 year event increases from 31 ha in period 1 to 65 ha in period 2, and then declines to 26 ha. The 20 year events have a size of 45 ha in period 1, 131 ha in period 2, and 59 ha in period 3. The results for the 50 year event are 70 ha, 319 ha and 162, those of the 100 year event are 97 ha , 618 ha, and 344 ha. The confidence intervals of the different return periods within a given period overlap. Also, there is no significant difference between the return levels for given return periods across periods 1, 2, and 3.

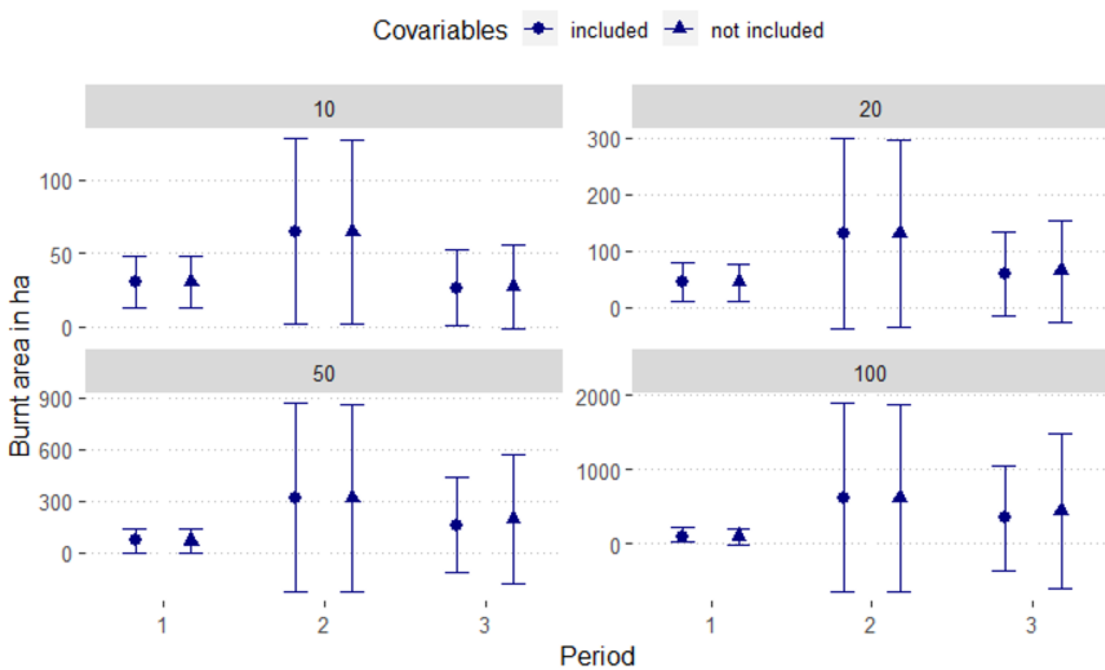


Figure 14: Return levels for models without and including covariates in Valais.

3.4.3 Grisons

The data of Grisons is divided into two periods: Before and after 1980. Similar as in Valais, fire prevention measures were undertaken, however not in the scale as in Ticino. No large change of the fire regime was so far attributed to this. It is therefore assumed that the fire regime developed similarly to that in Valais. A second subdivision in earlier years is not possible due to the low number of observations. Furthermore, the literature on Grisons is less extensive than on Valais and Ticino. For these reasons this section is less detailed and only serves to determine whether there have been strong changes in Grisons as well.

In period 1, 3 fires appeared on average per year. In period 2, 13 are observed. The annually burnt surface increases from 46 ha in period 1 to 64 ha in period 2. The average fire size decreases from 16.8 ha in period 1 to 2.2 ha in period 2. The largest fire in period 1 has a size of 477 ha, and 293 ha in period 2. The population density increases from 21 persons per square kilometer in period 1 to 26 in period 2. The number of goats drops by almost a third from and average of 23,125 to 8,843.

Thresholds of 5 ha and 2 ha are used for the data of periods 1 and 2 respectively. 33 observations are larger than the threshold in period 1, 29 in period 2. The extremal index equals 0.74 and 0.73. Dependence should therefore not be a problem. The model fit is reasonably well, even without covariates. It is improved by the addition of linear terms of the population density and temperature in the location parameter. Temperature is significant only in the second period though. Also, the confidence intervals become narrower, especially in period 2. Different covariates are used compared to the model for the entire year because the model fit, as judged by the Z plot, could be improved that way.

Table 10 shows how the estimated extreme value parameters changed. The location parameter decreases from 6.8 to -0.7. The scale parameter decreases from 30.8 to 6.9. The shape parameter changes from 0.4 to 0.8.

Table 10: Location, scale and shape parameters of the estimates per period in Grisons

	Periode 1		Periode 2	
	Estimate	95 % CI	Estimate	95 % CI
Location	6.8	(-368.9-382.5)	-0.7	(-96.3-94.9)
Scale	30.8	(10.1-51.5)	6.9	(1.9-12.0)
Shape	0.4	(-0.1-0.8)	0.8	(0.3-1.3)

The resulting return levels for the models including and without covariates can be found in figure 15. The model including the covariates has narrower confidence intervals and the estimates change to some degree. The estimations for the 10, 20, and 50 year events decline from period 1 to 2. The value of the 10 year event drops from 113 ha to 43 ha, the one of the 20 year event from 169 ha to 84 ha, and the one of the 50 year event from 266 ha to 188 ha. The 100 year event is estimated at 363 ha in period 1 and 335 ha in period 2. The 95 percent confidence intervals overlap, so none of the periods differ significantly.

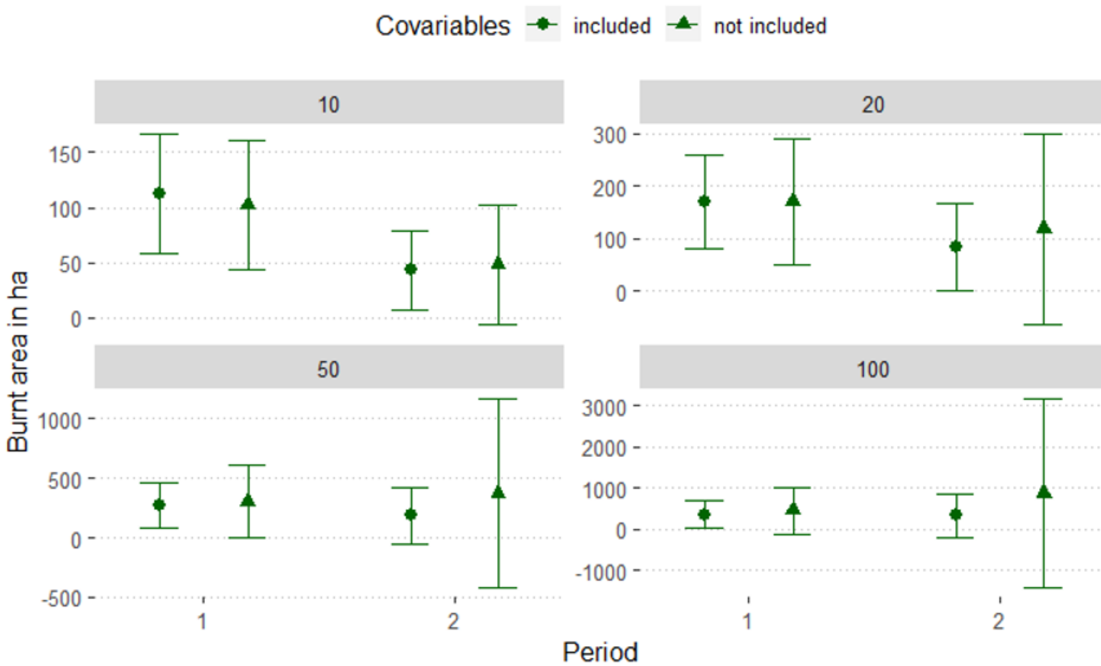


Figure 15: Return levels for models without and including covariates in Grisons.

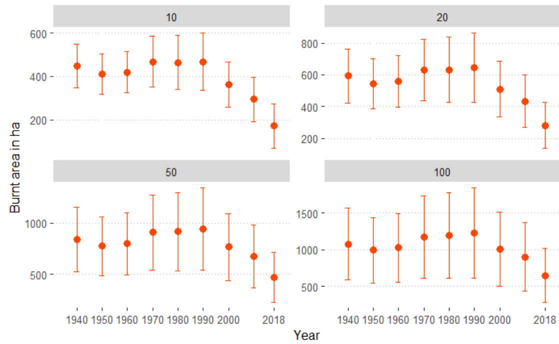
3.5 Full data set

In this section the results of the analysis of the complete data sets of the respective regions are presented. The focus is on the analysis of the effect that the covariates have on the return levels. For this purpose, the same covariates as in the previous section are used: The population density and relative humidity for Ticino, the population density for Valais, and the population density and summer temperature for Grisons. To determine the effect of the covariates, the return levels for the lowest and highest value of each covariate as well as some values in between while the other variable is fixed at the median are calculated.

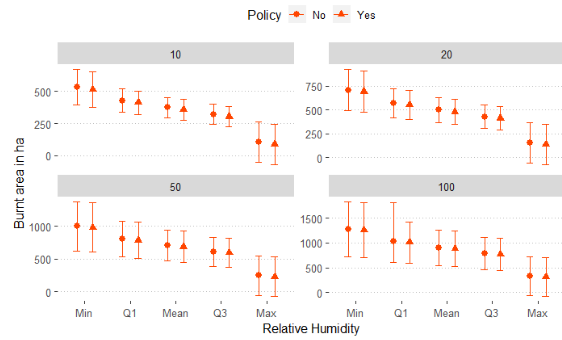
3.5.1 Ticino

The resulting return levels for Ticino are shown in figure 16. Figure 16 a) shows the results of the estimation for certain years. The first year of each decade is calculated, i.e. 1940, 1950 and following, and 2018, the last year for which data is available. The covariates are assigned the corresponding average values of that year. The values for the years 1940, -50 and 60 are slightly lower than those for 1970, -80 and 90, but there are no major changes. All 10 year return levels for the years 1940-1990 are between 410 ha and 470 ha. Subsequently, the return levels start to decrease. The results for 2000, 2010 and 2018 are 360 ha, 295 ha and 173 ha respectively. The value for 2018 is significantly lower than the results for 1940-1990.

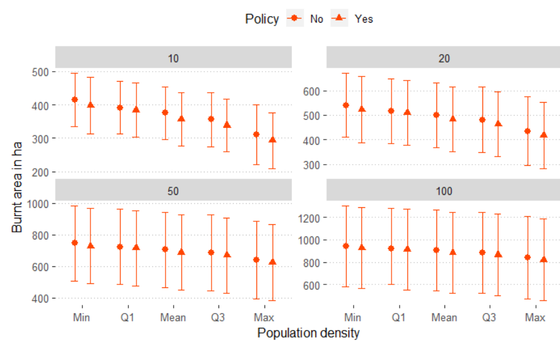
Figure 16 b) shows the effect of the relative humidity on the return levels. The effect of relative humidity on the return levels is large. With otherwise constant parameters, the 10 year return levels for the lowest and highest relative humidity values differ by about 430 ha: 534 ha for the minimum relative humidity and 105 ha for the maximum. Figure 16 c) shows the effect of the population density on the estimates. The difference between the lowest and highest value of the population density is about 100 ha. With the lowest population density, the 10 year return level takes on a size of 415 ha, with the highest a size of 310 ha. A dummy variable is included to take into account policy changes. Assuming that these changes are put in place reduces the return levels by 30-40 ha. In a further step, a variable with values from 0 to 5 was used for the measures instead of a dummy. For the period before 1976 the value 0 was used, which means that no measures were in force. The value increases in regular steps to 5 from 1976 to 1990, which is intended to include a gradual implementation of the measures against forest fires in the model. The variable is significant. The effect on the return levels is roughly the same as when a simple dummy variable is used. The return levels decrease by about 40 ha in all cases.



(a) Return levels for specific years



(b) Fixed population density and varying relative humidity



(c) Fixed relative humidity and varying population density

Figure 16: Return levels for Ticino with varying parameters

3.5.2 Valais

For Valais, only the population density is used as covariate. In figure 17 the return levels for different years are shown. The return levels of all return periods decrease over time, i.e. with increasing population density. However, the differences are not large. The values of 2018 are about 20 ha smaller than those of 1940. The size of the 10 year events decreases from 53 ha to 29 ha, the 20 year events from 96 ha to 72 ha, the 50 year events from 204 to 180 and the 100 year events from 357 ha to 334 ha.

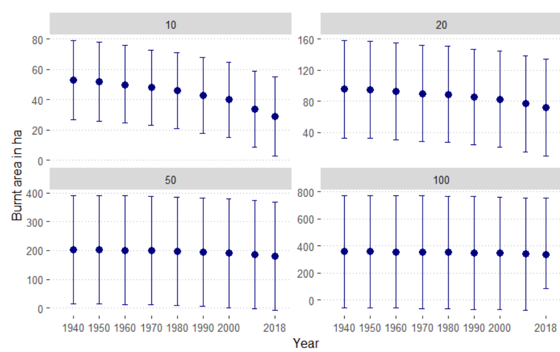
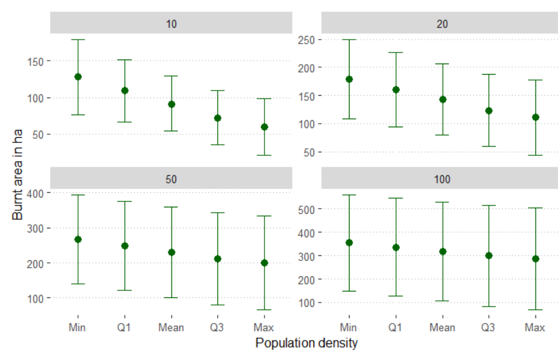


Figure 17: Return levels for Valais for specific years

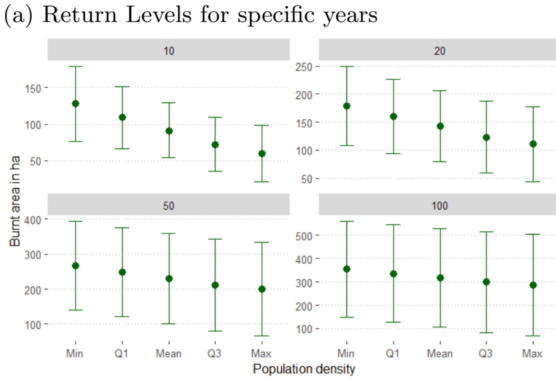
3.5.3 Grisons

Figure 18 a) shows the return levels for different years. The results become smaller over the years. The results of 2018 are about 70 ha smaller than those of 1940. 10 year events decrease from 126 ha to 50 ha, 20 year events from 177 ha to 101 ha, 50 year events from 260 ha to 190 ha and 100 year events from 353 ha to 276 ha. The effect of the population density on the return levels is shown in figure 18 b). The difference in the return levels between the lowest and highest values of the population density is about 70 ha for all return periods. The 10 year events decrease from 126 ha to 50 ha, the 100 year events from 353 ha to 276 ha. The same procedure with a fixed population density and varying temperature leads to almost identical results. The results are shown in figure 18 b). Smaller fires with higher temperatures make little sense though. This is discussed in more detail in the next section. Figure 18 d) shows the effect of the monthly precipitation sum on the estimates. If the precipitation is used instead of the temperature, lower return levels for higher values of the rainfall sum result. All estimates decrease by about 110 ha. The 10 year event deceases from 127 ha to 16 ha and the 100 ha from 355 ha to 243 ha.

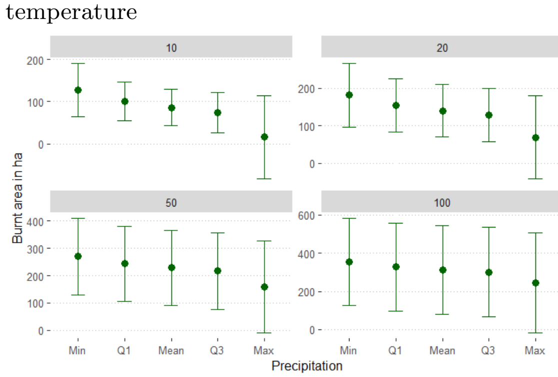
(a) Return Levels for specific years



(b) Fixed population density and varying temperature



(c) Fixed temperature and varying population density



(d) Fixed population density and varying monthly precipitation sum

Figure 18: Return levels for Grisons with varying parameters

4 Discussion

4.1 Descriptive Statistics

4.1.1 The fire regime

The fire regimes of the three cantons differ considerably. Both, the number of the fires and the resulting damage are distributed very unevenly across the cantons. Ticino in particular stands out. The largest fires are observed in there. The average fire size, the median value, the number of fires reaching a size of more than 100 ha and the area burnt per square kilometre of cantonal territory per year are larger in Ticino than in Valais and Grisons. The total damage in Ticino for example exceeds that of the Canton of Valais by a factor of nineteen and is about sixteen times greater than the damage in the Canton of Grisons. In Ticino, moreover, most fires occur in the winter months. In Valais and Grisons, most fires occur during the summer months. All cantons have two things in common: the vast majority of fires are caused by humans. In Valais and Grisons, the proportion of human fires is roughly 70 %, and in Ticino as high as 86 %. A similar distribution results if the total burnt area is allocated to the trigger types: In Ticino and Valais, a good 90 % of the damage is caused by anthropogenic fires. In Grisons, the proportion is 80 %. Most of the fires are small. Nevertheless, the rare but large fires are responsible for a large part of the total damage. The saying that one percent of fires cause 99 percent of the damage is admittedly exaggerated in this context. It does get to the heart of the problem though. These findings are important from a methodological point of view and also for the research question of this thesis. The difference in fire regimes requires an individual analysis per canton. The fact that a large majority of both the events and the resulting damage were caused by humans shows the strong anthropogenic influence. The skewed distribution of the damages shows that wildfire damages are extreme value problems.

The different time trends show two things. First, changes have taken place in all regions. The situation in Ticino can be roughly summarized as follows. The fire regime intensified until about the mid-1970s. After that, the number of fires decreased, as did the annually burnt area. The number of fires caused by humans is decreasing. However, an increase in fires caused by lightnings is found. Secondly, there are differences between the cantons. Approximately at the time when the maximum annual number of events is reached in Ticino, a minimum is found in Valais. In Grisons, a continuous increase in the number of events is observed. However, the lack of data up to the 1960s most likely plays a major role here. These findings imply two important points for the analysis of large fires. First, the cantons must be considered separately, as they differ in many respects. Second, the assumption of stationarity does not seem justified due to the various changes in the fire regime.

4.1.2 Covariates

The meteorological variables, above all temperature, develop similarly at all three locations: towards the end of the 20^{th} century, a marked increase of the average temperature is observed. Since temperature, together with other meteorological variables, is a central factor in a fire regime, there is the potential for a non-stationary effect.

Pronounced changes are also observed in the socioeconomic variables. The population density, the forest area and the incomes have increased significantly during the 20^{th} century. The number of goats, as an indicator for biomass reduction, on the other hand, decreased sharply. Due to the strong anthropogenic influence on the fire regime, it cannot be excluded that these changes had an impact on the regime of very large fires. Thus, the potential for non-stationary effects exists here as well.

4.2 Analysis per decade

The analysis of the return levels per decade provides several insights: First, the comparison of the results between the cantons of Ticino and Valais shows that in the former, larger fires are to be expected. Second, there is a considerable variation in the return levels of the different decades. In Ticino, a strong increase of the 10 year return levels from a little over 300 ha in the 1940s to 1,190 ha in the 1970s is found, followed by an equally pronounced drop to roughly 220 ha in 2000 and 100 ha in 2010. An increase in return levels until 1970 is also found for Valais, but it is less pronounced and at a much lower level. The 10 year return levels increase from 30 ha in the 1940s to 70 ha in the 1970s. These findings indicate that the risk for large fires broadly speaking followed that of the typical fires. Splitting the data into decades allows to avoid the problem of the non-stationary effects. With this approach, however, the methodological limits of extreme value theory are quickly reached. On the one hand, only a small part of the available observations is used for modelling. This is problematic if only a few events are available. This made an estimate for the canton of Grisons and for Valais for the decades after 1970 impossible. Furthermore, it is not possible to make a statement about the possible causes of the changes.

4.3 Covariates

The model fit is greatly improved by including covariates. Socioeconomic variables allow the largest model improvement if only one single variable is used. The population density is the preferred covariate for two reasons. First, the data are reliable. Second, the hypothesis that the population density has an impact on the fire regime is widespread in the literature. Direct measurement data and more complex fire hazard and drought indicators also allow to improve the model fit. The results of the attempt to construct a model that achieves the greatest possible improvement of the model fit leads to different results depending on the canton. For the Canton Ticino, a combination of the population density and the relative humidity is used.

The humidity is used in both the location and the scale parameter. This shows that not only the centre of the distribution shifts, but also its variance. For the Canton Valais, only the population density is used in the location parameter. Thus only the center of the distribution shifts. For Grisons, the population density and the average temperature are used in the location parameter. The population density is also used in the scale parameter. As in the case of Ticino, this suggests that both the centre and the variance of the distribution have changed. As a conclusion to this section it can be said that it is possible to improve the model fit. In all cantons socioeconomic variables are the most important factor. In Ticino and Grisons physical variables lead to a further improvement.

4.4 Analysis per period

4.4.1 Ticino

The results of the analysis per period suggest that the risk for extreme fires has changed substantially in Ticino. The change of the location parameter from 130 to 176 indicates that the center of the distribution shifted to the right, to larger fires. Then in period 3, the location parameter takes a value of 62, which much smaller than the others. The scale parameter expresses the degree of variability of the distribution. In decreases slightly from period 1 to 2, but is highest in period 3. The distribution is of a Gumbel type in period 2 and Fréchet in periods 1 and 3.

The calculated return levels can be compared in two ways. We can look at how the estimates of the different return periods, the 10, 20, 50 and 100 year events, compare to each other. We can also compare how the estimate of a given return period changes from one period to another. In period 1, there is not much difference between the return periods. The 100 year event has a size of 324 ha which is only roughly 80 ha larger than the 10 year event that has a size of 274 ha. The spread between the return periods is much greater in period 2. The 100 year event is estimated at 1,800 ha. It exceeds the 10 year event by a good 1,200 ha. The differences are substantially smaller again in period 3 but still larger than in period 1. The 100 year event reaches a size of 455 ha. This is roughly 210 ha larger than the 10 year event with a size of 246 ha. It seems that the spread between the different return periods increased, not only the estimates. This is worded cautiously because the confidence intervals always overlap. Therefore, not too much should be read into these findings. More compelling insights are gained by comparing the return levels of given return periods across the three periods. All return levels increase by a great amount from period 1 to 2. The increases are significant with the exception of the 100 year event. The second shift from period 2 to 3 leads to a pronounced decrease in the risk for large fires. Only the change in the 10 year event from 600 ha to 246 ha is significant. These findings have two implications. First of all, the findings for large fires match those of the literature which is more concerned with the typical fire. A moderately active stage is followed by a period with strongly increased fire activity that is in turn succeeded by a much calmer phase. Second, it shows that both shifts in the risk for large fires were substantial. A comparison with observed events illustrates the extent of the shift from period 1 to 2. The size of the 50 year event increases by 1,000 ha, from 305 ha to 1,300 ha. Only the largest fire in the data set with a size of 1,600 ha is larger than this increase. The 10 year event changed from 247 ha to 600 ha. This means that once per decade in period 2, a fire has to be expected that burns a larger area than what is lost to fire on average during an entire year (542 ha) in period 1. It is more than twice the average of the annually burnt surface of period 3 (278 ha). From period 2 to 3, only the size of the 10 year event changed significantly. It decreased from 600 ha to 246 ha.

The available results do not allow to determine the causes of the changes. For this reason, the discussion is based on the findings of the literature, in particular on the results of Pezzatti, Zumbrunnen, et al. (2013). Qualitatively speaking, the results of this analysis seem to correspond to those of the existing literature. The regime of the extreme fires develops in the same way as the regime of the typical fires. This would imply that the increase in return levels from the first to the second period is due to the socio-economic changes after the Second World War and to the higher fire risk at that time. For typical fires, the correlation of meteorological drought and fire hazard indices with measures like the amount of fires and the fire size is weak (Wastl, Schunk, Leuchner, et al. 2012). The intensification of the fire regime is therefore mostly attributed to social changes. This implies that the abandonment of traditional agriculture and the depopulation of the valleys has led to an expansion of the forests and an accumulation of potential fuel within the forests. These two factors thus seem to have influenced the regime of extreme fires. However, the results of this analysis do not allow to say which process was more important for the extreme fire regime. The third period shows a significantly lower risk for extreme fires compared to the second. This is remarkable because this period shows a much higher annual number of days with high fire risk compared to the previous one. The increase in the meteorological fire risk is due to progressive climate change and the higher temperatures associated with it (Wastl, Schunk, Leuchner, et al. 2012). The question arises as to what caused the decline in return levels. Pezzatti, Zumbrunnen, et al. (2013) attribute the decrease in burned area to improved fire fighting. The reason for the decrease in the number of fires is seen in the changed legal basis such as fire bans. The largest natural fire in the data for Ticino reached a size of 130 ha. 73 events were larger, 69 of which were caused by humans. In the second period the largest non-human fire destroyed 289 ha. 39 fires were bigger, 3 of which have an unknown origin. In the third period the biggest natural fire burned 130 ha. 20 fires were bigger, all of them were caused by humans. A large share fires are caused by humans. Large fires are almost exclusively ignited by humans.

4.4.2 Valais

The analysis per period shows that the regime of extreme fires has changed also in Valais. Table 9 shows the model parameters for the three periods. The center of the distribution declined with each period. The variability, indicated by the scale parameter increased first from period 1 to 2, and declined from period 2 to 3. The distribution is of a Fréchet type in all periods. The changes in the parameters indicate that the regime of extreme fires changed first to a distribution with a smaller center but a higher variability. The second change was a shift to a distribution with an again smaller center but this time also with a reduced variability.

As in Ticino, the relative sizes of the different return periods change. In period 1, the 100-year event is about 3 times as large as the 10-year event (97 ha and 31 ha). In period 2, the 100 year event is 9.5 times as large as the 10 year event (618 ha and 65 ha). In period 3 the 100 year event is about 13 times as large as the 10 year event (344 ha and 26 ha). The return levels of given return periods are also subject to change. Unlike in Ticino, there are no significant differences though. The risk for extreme fires increases from period 1 to period 2 and then decreases again to a level slightly above that of period 1.

Compared to the results of the Canton of Ticino, the comparison with the results of the summary statistics is somewhat more difficult. In Valais, the fire frequency decreases from an average of 7.2 fires per year in period 1 to 4.8 in period 2. Subsequently, there is an increase to 9.2 fires per year in period 3. The average size of the fires increases from 3.4 ha in period 1 to 9.2 ha in period 2 and then decreases again to 2.9 ha in period 3. The average annual burnt area follows the same pattern. It increases from 24 ha per year in period 1 to 44 ha in period 2 and then decreases to 27 ha in period 3. The results of the return levels follow the results of the average fire size: They are lowest in period 1, increase strongly in period 2 and reach a level between that of period 1 and 2 in period 3.

The interpretation of these results using the findings of Pezzatti, Zumbrunnen, et al. (2013) is not as simple as in the case of Ticino. In Ticino, the frequency and size of the fire develop in same way. This is not the case in the Canton of Valais. While similar changes take place in general, there are some differences. In the 1940s and 1950s, a tendency towards a more active fire regime was found. This was likely due to high temperatures, especially in summer. Also in the 1950s, widespread land abandonment started, which led to an expansion of the forest area and an increase of the available fuel. In contrast to Ticino, a change towards smaller burnt areas is found in the subapline area of Valais around 1960 (Pezzatti, Zumbrunnen, et al. 2013). The results of the extreme value analysis however show a shift towards larger fires form period 1 to 2. The decrease in burnt area in higher areas is therefore not reflected in the risk of extreme fires in relation to the whole canton. The return levels in the third period are lower than in the second and are slightly higher than in the first period. This is remarkable, as the meteorological fire hazard has also increased in Valais. However, in Valais, as in Ticino, the correlation between the meteorological fire hazard and the observed number of fires and burnt area is weak (Wastl, Schunk, Leuchner, et al. 2012). The increased risk of fire due to climate change is seen as the cause for the rising number of fires (Pezzatti, Zumbrunnen, et al. 2013). Interestingly, this seems to affect only the number of fires, but not their size nor the danger of extreme fires. In Valais, too, fire prevention laws have been passed and improvements in fire-fighting have certainly taken place, such as the use of helicopters. However, Pezzatti, Zumbrunnen, et al. (2013) conclude that these changes have not had a major impact on the fire regime. This may explain why no significant reduction in return levels from period 2 to period 3 is found. Finally, the absence of significant differences may also be due to the fact that the fire regime in Valais is generally less active than in Ticino.

4.4.3 Grisons

The apparent increase of annual number of fires is likely explained by the incomplete data of the first roughly 20 years in the data set. Presumably, only large fires were registered. This would also explain why the average fire size decreases from 16.8 ha to just 2.2 ha. The value of the first period, 16.8 ha, is unrealistically high. It exceeds the value of period 1 in Ticino (15.2 ha), which has the most active fire regime. The increase of the annually burnt surface from 46 ha in period 1 to 64 ha could also be explained by the more complete data of the later years. An increase in the burnt area is certainly possible. However, the changes found in the data seem implausible in comparison to the other cantons.

Table 10 shows the parameters of the distributions of both periods in Grisons. The location and scale parameters are lower in period 2 than in period 1. According to the shape parameters, both distributions are of a Fréchet type. It is questionable if these values are trustworthy for several reasons. First, the shift in the parameters is large. The location parameter shifts much more than in Valais. The shift of the scale parameter is almost as large as in Ticino. Second, a negative value for the location parameter does not make sense for an application that cannot lead to negative realisations.

The divison of the data into two periods allows a good model fit, which is further improved by the addition of covariates. From period 1 to 2, all return levels decrease. The 10 year event is estimated 70 ha smaller, the sizes of the 20 and 50 year events decrease by 80 ha, and the 100 year event is estimated 60 ha smaller. A shift to slightly smaller fires seems to have taken place. This finding corresponds to those of Valais and Grisons. However, the question arises as to what proportion of the result is due to the missing data at the beginning of the data series.

4.5 Full data set

4.5.1 Ticino

As seen in the previous section, the return levels first increase and then decrease towards the end of the 20^{th} century. The decrease in the expected fire sizes falls in the period after various measures have been taken to reduce the number and size of fires. Changes of the dummy variable lead to only small variations of the return levels. The fluctuations are in the range of 30 hectares. Thus, the measures lower the expected size of large fires. The effect is however not large. If the dummy is replaced with a variable that increases gradually, the return levels vary in a comparable magnitude. This indicates that the effect of the measures is not immediate but continuous. Much larger fluctuations of return levels result from changes in relative humidity and population density. The effect of the relative humidity is the greatest. Under otherwise identical circumstances, the return levels decrease by 430 ha when the relative humidity is set to the lowest and the highest value. The same test applied to population density results in a decrease of about 100 ha if the lowest value of the population density is replaced by the highest.

The population preventable fraction (PPF) is a concept from the field epidemiology that expresses the effect of a measure against, for example, a disease. The PPF indicates the proportion of the decrease in the number of cases that can be attributed to the measure (Shield et al. 2016).

$$PPF = \frac{Cases_{obs} - Cases_{cf}}{Cases_{obs}}$$

Stone et al. (2005) suggest to apply the concept in a similar form to questions related to climate change. The concept is used here to illustrate the effect of the various factors that influence the fire regime in a more intuitive way. For this purpose, different scenarios are calculated, similar to the above. The 10 year return level of a model for which all covariates are specified with the median value serves as reference scenario. As alternative scenarios the return levels using the dummy variable for the policy changes and the maximum values of the population density and the relative humidity are calculated. The PPF for the policy changes is 5%, that of the increased population density is 17% and that of the highest value of the relative humidity is 72%.

The following conclusions can be drawn from the available results. The return levels have decreased in the last third of the data series. This decline can be attributed to a combination of several factors, which together have a strong effect on the expected size of extreme fires. The increase in population density and the measures taken towards the end of the 1970s together lead to a reduction in return levels of about 130 hectares. This goes in line with Ganteaume et al. (2013) who find a decrease in the burnt area with increasing population density and Aldersley et al. (2011) who find a decrease of fire occurance with an increasing GDP. It is important to point out that a high correlation between the population density, the variable for the taxable income and the forest area is found. This implies that the effect that is attributed to the population density could also be the result of changes in either of these variables or of a combination of them. However, the variable with the greatest effect on return levels, relative humidity, is beyond human control. The direct benefit of the measures on the return levels is small. However, this is not to say that they were useless. The change in the return levels seems to be the result of the changing frequency rather than their size. Figure 19 shows the number and the size of all fires that exceed the threshold of 35 ha. Their mean size never changes significantly. However, the average number of the occurances per year changes from 3.6 in period 1 to 6.0 in period 2 and 1.5 in period 3. As explained above the reduction of the fire frequency is attributed to the measures that were taken in response to the sever fires in the 1970s. Since about 90 % of all fires and virtually all catastrophic fires are caused by humans, the risk of extreme fires has been reduced. However, it is a reduction in the risk of a fire starting, not its size. Once a fire has been lit, the risk of it reaching extreme proportions is reduced due to increased population density and to a lesser extent due to the measures taken. However, it should be noted that this possibility still exists. The most important factor for the risk of an extreme fire, the humidity is outside the influence of society.

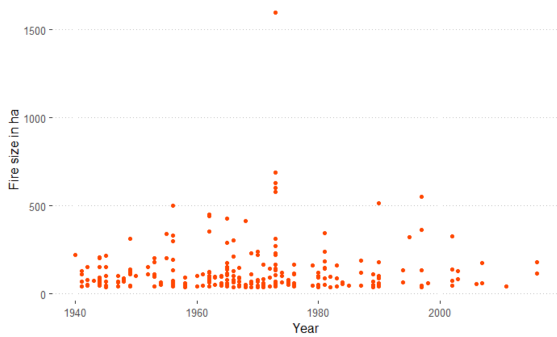


Figure 19: Number and size of fires larger than the threshold in Ticino

4.5.2 Valais

The findings for the anthropogenic influence coincide with those for Ticino. For Valais, a continuous decrease in return levels over time is found. Since only the population density is used as a covariate, the differences in the estimates are attributed to this variable. As in the case of the Canton of Ticino, a higher population density leads to a decrease in the size of the extreme fires. In absolute terms the differences are not dramatic. Replacing the lowest value for the population density with the highest leads to a reduction of the 10 year return level from 53 ha to 30. The result of the PPF, calculated as above by comparing the median and the highest value for the population density leads to a result of 37 %. This is more than twice the effect of Ticino which shows a PPF of 17%. Since fewer climatic variables are available than in Ticino, it cannot be excluded that other variables also play a role. The increase of the return levels found in the modelling per period cannot be confirmed here. This might be an indication, that climatic influences are also important.

4.5.3 Grisons

The results for the Canton of Grisons are similar to those for Ticino and Valais. If the return levels are estimated for individual years, a decreasing risk of extreme fires is observed. This leads to the question of possible causes. If the temperature is kept fixed and the population density is varied, lower return levels is found for high values of the population density. Thus, as in the other two cantons, an increasing population density seems to lead to a lower risk for extreme fires. If the population density is fixed and the temperature is varied, the results seem to make little sense. Lower temperatures would therefore lead to larger fires. At the very least, this raises the question of whether temperature is indeed a suitable variable. If the temperature is replaced by the precipitation sum, the results that are obtained are more credible. A higher precipitation sum is accompanied by lower return levels. The PPF for the difference between the median and maximum value of the population density amounts to 26% and that for the variation of the precipitation sum to 84%. As in Ticino, the effect of a variation in the climatic variable on the return levels is much greater that that of the population density. The results for the canton of Grisons allow some valuable conclusions. Firstly, they mostly correspond to those of Ticino. Changes in the risk of extreme fires cannot be attributed to a single factor. The human influence is certainly important. Climatic factors also seem to play a role. The contradictory results caused by the variables for the temperature and the precipitation sum show on the one hand that climate probably has an important influence. On the other hand, they show that the choice of covariates must be made carefully.

4.5.4 Costs and benefits of prevention - A ”back of the envelope” calculation

Table 11: Annual economic value of various market and non market goods provided by forests.

Function	Value (million SFr)	Source
protective function	4,000	
forestry	380	
carbon capture	300	
honey production	52	
game	20	
mushroom production	11.5	WaldSchweiz (2018)
christmas trees	5	
recreaction	1,900 - 3,900	Grünigen et al. (2014)
water purification	80	David (2009)
Total	6,748.5 - 8,748.5	

Table 12: Valuation of damages

Average annual damage			Difference	Valuation of difference
	Period 2	Period 3		
all fires	1,158 ha	278 ha	880 ha	4.64m - 6.02m SFr
$<$ 100 ha	566 ha	140 ha	426 ha	2.25m - 2.91m SFr
$<$ 20 ha	235 ha	70 ha	165 ha	0.87m - 1.13m SFr
$<$ 10 ha	142 ha	44 ha	98 ha	0.52m - 0.67m SFr

Ticino operates an extensive fire control program for which detailed information is available. Several studies found that the program is effective. At the time of writing, no complete assessment of the economic value of Swiss forests exists, thus the assessment is done in the style of a ”back of the envelope calculation”. Available estimates of the value of forests are presented in table 11. Every year, forestry in Switzerland generates about 380 million SFr. Forests fulfil a variety of other functions that are not compensated by markets. They serve to protect important infrastructure, are used as recreational areas and provide ecosystem services (Rigling et al. 2015). In total, the benefits of Swiss forest are estimated at an annual value of 6.7 to 8.7 billion SFr. With a forest area of 1.28 million hectares of (WaldSchweiz 2018) this corresponds to a value of 5,270 - 6,840 SFr per hectare per year. The canton of Ticino spends between 500,000 and 1,000,000 SFr. per year on preventive measures such as the construction of fire water basins and the installation and maintenance of humidity sensors (Gobbin 2020). In addition to that roughly 280,000 SFr are spent on training and equipment of the ”pompieri di montagna” (Ghiringhelli et al. 2016). This corresponds to an annual sum varying between 780,000 and 1,280,000 SFr. The decrease in the annual burned area and the size of "typical" fires is mostly attributed in the literature to improved fire fighting and prevention. The results of the extreme value analysis suggest that the expected size of large fires is also decreasing, but largely for other reasons. Table 12 shows the average annual burned area caused by all fires, as well as fires smaller than 100, 20 and 10 ha. All values decrease from period 2 to 3 as defined in the previous section. The average size of the individual events has also decreased significantly in all cases. No significant decrease is found for the average size of fires larger than 100 ha. Table 12 also shows the difference in the average annual loss amount between the two periods. This is multiplied with the value of the forest. The result can be interpreted as the economic value of the avoided damage. The limit for extreme fires was set at 100 ha. The average annual burnt area caused by fires smaller than 100 ha decreased by 426 ha from period 2 to period 3. This area corresponds to an economic value of about 2.3 - 2.9 million Swiss francs. In contrast, annual expenditure on prevention amount to 0.8-1.3 million. From an economic point of view, this program therefore appears to be very sensible. This expenditure is also justified if only the damage caused by fires smaller than 20 ha is considered. The avoided damage amounts to a sum of 0.9m - 1.1m SFr. The costs of fire fighting is not included in these calculations. These costs are highly variable and can be high, especially in comparison to the value of the forest used here. Ghiringhelli et al. (2016) provide three examples. The costs of the fire fighting activities are between 7,500 and 17,300 SFr per hectare. In 2 cases helicopters of the Swiss Air Force were used. Their costs are not included. The expenditure on prevention therefore pays off for the typical fires. If fire suppression costs are considered, a break even between the benefit of saving forests and the cost of it is achieved earlier. The results for large fires only are not that favourable. As shown above, the expected damage is reduced by about 40 ha. In order to estimate the economic benefit of the measures, the present value of the savings thanks to the prevention measures is compared with the present value of the expenditure over 10 years (Žižlavsk 2014). A discount rate of 3% is used (Zhuang et al. 2007). This results in savings of only 161,600 to 209,700 SFr depending on the value of the forest. Even including fire fighting costs of 17,300 SFr per hectare, the present value is only 740,100 SFr. This corresponds roughly to the investment of one year. The present value of the investments over 10 years, on the other hand, amounts to 6.9 to 9.1 million SFr. To achieve a net present value of 0, the size of a 10-year event would have to be reduced by more than 1,000 ha without any intervention expenditures. In the "most expensive" scenario, taking into account fire suppression costs of 17,300 SFr per hectare, the area would have to be reduced by 290 ha. This exceeds the combined effect of the measures and the increased population density about twofold. Thus, the benefit of the measures in terms of large fires is limited.

5 Conclusion

The goal of this thesis is to apply extreme value theory to wildfire damage data in the Swiss cantons of Ticino, Valais and Grisons. The central question is how much the danger of extreme wild fires has changed between 1940 and 2018 and what has caused these changes. Since changes have undoubtedly taken place, the assumption of stationarity, which is central to extreme value statistics, is violated. Two approaches are used to deal with this: The subdivision of the data into quasi-stationary sequences and the consideration of non-stationary effects by covariates. This work supplements the existing knowledge about typical fires with an assessment of the development of the size of extreme fires and make it possible to view the phenomenon from a new perspective.

First, return levels are calculated for each decade. This allows to assess if the expected size of extreme fires changes over time. This comes at the cost of using only a small subset of the data. The results for Ticino show a steady increase of the return levels until they peak in the 1970s. After this turning point, they decrease. This finding confirms the expectation that there are changes in the regime of extreme fires. Due to a lack of data, the approach did not lead to satisfactory results for Valais and Grisons.

Third, the data of each canton is divided into several periods. The subdivision is made on the basis of existing evidence about changes in the fire regime. This allows a good model fit. It is further improved by including the previously tested covariates. The problem of non-stationarities can be avoided thanks to the subdivision of the data into several periods. The subdivison according to known changes in the fire regime allows the use of the longest possible sections of the data. Earlier studies showed that in Ticino, as in Valais, socio-economic changes led to the decline of traditional agriculture and forestry. This led to more fires and an increase in the area burnt. The results of this work show that at the same time an increase in the expected size of extreme fires took place. In Ticino significantly higher return levels are found. Increases are also found in Valais, but the differences are not significant. The insufficient amount of data does not allow a subdivision of the data for Grisons for this time. The second significant change in the fire regime in Ticino is attributed to improved fire fighting and fire prevention. The results of this study are in line with these findings. Significantly lower return levels are found for the period from 1980 onwards. The results for Valais are less clear. The period from 1980 onwards is characterized by an increase in the number of fires. In Ticino the opposite happened. The rise is most likely the result of the increased fire risk due to the higher temperatures towards the end of the 20^{th} century. The mean size, as well as the annual burnt area and return levels have decreased. This in turn corresponds to the findings for Ticino. Lower return levels are also found for Grisons for the period after 1980. As in Valais, however, the differences are not significant.

Fourth, the entire data set is used in combination with covariates. Using the entire data set allows to identify the driving forces behind the changes in the fire regime. Two things can be said about the measures taken to combat forest fires in Ticino. First, they have an effect. However, this effect is small. The return levels are lowered by 30 hectares. Second, the effect does not seem to be immediate, but rather to have occurred over several years. This makes it more difficult to include them in the modeling process. The greatest variation of the return levels in Ticino is caused by the relative humidity. The population density follows at some distance. Replacing the lowest value of the relative humidity with the highest value leads to a reduction of the 10 year return levels of roughly 400 ha. The increased population density leads to a reduction of the return levels of about 100 ha. The danger of extreme fires has thus decreased considerably due to the anthropogenic influence. However, the variable with the greatest influence on the return levels is not within the sphere of human influence. Therefore, extreme fires are still to be expected, albeit at a lower level. The lower return levels are mostly a consequence of a lower fire frequency rather than of a decline of their size. Once a fire has been started, there is still the danger that it will develop into a catastrophic event. For the Canton of Valais, it can be said that population density has the same effect on return levels as in Ticino. The increasing values of the covariate lead to a reduction of the return levels by about 20 ha. Over the available period of time, there are therefore few changes in Valais with regard to the regime of extreme fires. However, it cannot be excluded that other variables may play an important role. Declining return levels are also observed for the canton of Grisons. The main reason for this is probably once again the increased population density. It is evident that the covariates must be chosen with care. High temperatures led to a reduction of the return levels, which does not seem to make much sense. Either a more complex functional form is necessary or the temperature correlates with another variable. Using the precipitation sum instead of the temperature leads to a decrease of the return levels as expected. Also in Grisons the effect of the anthropogenic variable is not as strong as the climatic one. This suggests the conclusion that the expected magnitude for extreme fires is reduced by the increasing population. However, catastrophic events cannot be excluded due to the strong influence of the climatic variables. Since the population density correlates with the income per capita and the forest size, the effect on the return levels cannot be unequivocally assigned to one of these variable. It seems quite possible that a combination of these variables lead to the observed changes.

The results of the cost-benefit calculation for the Canton of Ticino show that fire prevention pays off financially. The decline of the area burnt at the end of the 20^{th} century is mostly attributed to the fire prevention policy. The value of the annual loss of forest area prevented by these measures exceeds the costs of fire prevention. The expected damage from large fires is only slightly reduced by the measures though. Thus, the annual investments and a hypothetical 10-year event one decade in the future also result in a strongly negative net present value. Even if the high fire-fighting costs are taken into account, there is no positive balance. Other approaches seem to be necessary to reduce the risk of large fires than of the typical fires. That being said, the results raise the question if it is even possible since the climatic variables exert the greatest influence on the regime of extreme fires. The frequency of such events has declined. The potential for large fires still exists though.

The thesis is subject to some limitations, which provide opportunities for further research. This concerns on the one hand the covariates used. It cannot be ruled out that more complex functional forms would be more suitable. Also, since some of the socio-economic variables correlate with each other it would be interesting to assess in more detail which has the strongest causal relation to the development of large fires. Furthermore, a more extensive economic interpretation could lead to valuable results. The presented cost-benefit calculation could be more detailed if a better estimation of the economic value of the forest were available. A more detailed quantification of the damage would also be interesting. In addition to the costs of fire suppression, this could also include expenditures for reforestation after a fire or the possible impairment of the people affected by the fires.

The findings of this work can be well summarized in the words of John Holdren, the Senior Scientific Advisor to the White House during president Obama's administration:

> "Wildfires are a result of temperature conditions, of soil moisture conditions, and of course something has to start it. It may be lightning. It may be a stray match or a cigarette. But the point is, when it is drier and hotter, you get more wildfires, ... " (Goodman 2008)

Forest fires are a complex phenomenon whose origin and course depends on the interaction of a multitude of factors, both natural and human. Humans are on the one hand triggers of fires, but they also suppress them. Both of these aspects are clearly visible in Switzerland. Almost all major fires were caused by humans. Overall, however, the number of the fires caused by humans is steadily decreasing. The increased population density is causing a decrease of the return levels in all cantons. In Ticino, the countermeasures taken also have a moderate alleviating effect. Overall, however, climatic factors have a greater influence on the return levels. How the risk of major events will develop therefore depends to a large extent on how the climate will change in the future.

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7 Appendix

Table A 1: Summary statistics per decade. Damage is reported in hectares.

Decade	n per year			Damage per year			Median			Mean			Max		
	TI	VS	GR	TI	VS	GR	TI	VS	GR	TI	VS	GR	TI	VS	GR
1940	29.0	8.4	0.5	591	29	63	5.0	1.0	40	20.4	3.5	126.6	310	65	477
1950	33.2	6.2	0.1	609	19	15	4.5	1.0	150	18.3	3.0	150	500	40	150
1960	80.7	5.4	1.4	1177	27	33	3.0	1.0	9.7	14.6	5.0	23.7	450	60	153
1970	83.6	4.6	3.5	1271	32	58	1.6	1.0	2.0	15.2	6.9	16.5	1,600	90	165
1980	54.4	5.7	10.9	451	59	47	1.0	0.3	0.5	8.3	10.3	4.3	345	500	150
1990	57.1	13.9	13.2	412	29	62	0.5	0.5	0.1	7.2	2.1	4.7	550	127	293
2000	39.3	8.0	14.9	155	38	10	0.1	0.3	0.08	3.9	7.7	0.6	325	310	39
2010	21.8	5.6	13.2	106	16	18	0.1	0.04	0.03	3.3	1.8	1.5	180	130	119

Table A 2: Meteorological data on a decadal basis for Locarno. Color marks changes that are singificant at the 5 percent level. Orange indicates an increase, blue a decrease. Temperature is sensible temperature in degrees celsius, precipitation is in mm.

Transition	**Mean temperture**		**Min Temperature**		**Max Temperature**		**Precipitation sum**	
	before	after	before	after	before	after	before	after
				Entire year				
1940/50	11.65	11.49	7.96	7.94	16.08	15.86	148.47	165.97
1950/60	11.49	11.31	7.94	7.97	15.86	15.61	165.97	158.86
1960/70	11.31	11.32	7.97	8.04	15.61	15.65	158.86	156.75
1970/80	11.32	11.70	8.04	8.37	15.65	16.02	156.75	158.31
1980/90	11.70	12.50	8.37	9.01	16.02	16.74	158.31	155.67
1990/2000	12.50	12.87	9.01	9.28	16.74	17.22	155.67	155.59
2000/10	12.87	13.22	9.28	9.61	17.22	17.59	155.59	150.97
				Winter				
1940/50	6.03	6.09	2.28	2.59	9.92	9.87	84.84	124.36
1950/60	6.09	5.77	2.59	2.74	9.87	9.56	124.36	108.83
1960/70	5.77	5.96	2.74	3.05	9.56	9.79	108.83	125.03
1970/80	5.96	6.01	3.05	3.04	9.79	9.87	125.03	105.38
1980/90	6.01	6.95	3.04	3.81	9.87	10.87	105.38	98.00
1990/2000	6.95	7.06	3.81	3.87	10.87	11.01	98.00	120.03
2000/10	7.06	7.47	3.87	4.36	11.01	11.35	120.03	128.69
				Summer				
1940/50	17.18	16.81	13.55	13.22	22.16	21.77	212.10	207.59
1950/60	16.81	16.76	13.22	13.12	21.77	21.56	207.59	208.90
1960/70	16.76	16.61	13.12	12.96	21.56	21.43	208.90	188.46
1970/80	16.61	17.30	12.96	13.62	21.43	22.08	188.46	211.23
1980/90	17.30	17.97	13.62	14.12	22.08	22.52	211.23	213.34
1990/2000	17.97	18.61	14.12	14.60	22.52	23.34	213.34	191.15
2000/10	18.61	18.88	14.60	14.78	23.34	23.73	191.15	173.25

Table A 3: Meteorological data on a decadal basis for Sion. Color marks changes that are singificant at the 5 percent level. Orange indicates an increase, blue a decrease. Temperature is sensible temperature in degrees celsius, precipitation is in mm.

Transition	**Mean temperture**		**Precipitation sum**	
	before	after	before	after
		Entire year		
1940/50	9.25	9.16	43.74	49.83
1950/60	9.16	9.15	49.83	49.12
1960/70	9.15	9.11	49.12	48.15
1970/80	9.11	9.34	48.15	49.96
1980/90	9.34	10.3	49.96	54.76
1990/2000	10.3	10.66	54.76	47.48
2000/10	10.66	11.26	47.48	45.94
		Winter		
1940/50	2.82	2.96	44.12	52.04
1950/60	2.96	2.93	52.04	52.04
1960/70	2.93	3.15	52.04	52.64
1970/80	3.15	3.13	52.64	49.19
1980/90	3.13	4.18	49.19	53.12
1990/2000	4.18	4.33	53.12	44.26
2000/10	4.33	4.93	44.26	46.29
		Summer		
1940/50	15.59	15.26	43.36	47.61
1950/60	15.26	15.27	47.61	46.2
1960/70	15.27	14.97	46.2	43.67
1970/80	14.97	15.45	43.67	50.72
1980/90	15.45	16.32	50.72	56.4
1990/2000	16.32	16.91	56.4	50.71
2000/10	16.91	17.49	50.71	45.6

Table A 4: Meteorological data on a decadal basis for Davos. Color marks changes that are singificant at the 5 percent level. Orange indicates an increase, blue a decrease. Temperature is sensible temperature in degrees celsius, precipitation is in mm.

Transition	**Mean temperture**		**Min Temperature**		**Max Temperature**		**Precipitation sum**	
	before	after	before	after	before	after	before	after
				Entire year				
1940/50	2.59	2.45	-2.28	-2.25	8.48	8.18	78.63	81.11
1950/60	2.45	2.56	-2.25	-2.21	8.18	7.84	81.11	81.03
1960/70	2.56	2.81	-2.21	-2.00	7.84	7.79	81.03	84.91
1970/80	2.81	3.05	-2.00	-1.71	7.79	8.20	84.91	84.70
1980/90	3.05	3.66	-1.71	-1.01	8.20	8.83	84.70	85.72
1990/2000	3.66	3.90	-1.01	-0.69	8.83	9.19	85.72	85.20
2000/10	3.90	4.28	-0.69	-0.32	9.19	9.61	85.20	88.39
				Winter				
1940/50	-3.31	-3.18	-7.96	-7.70	2.27	2.28	62.10	60.03
1950/60	-3.18	-3.07	-7.70	-7.56	2.28	1.72	60.03	60.73
1960/70	-3.07	-2.45	-7.56	-7.03	1.72	2.12	60.73	61.38
1970/80	-2.45	-2.66	-7.03	-7.15	2.12	2.16	61.38	61.22
1980/90	-2.66	-1.93	-7.15	-6.30	2.16	2.94	61.22	63.49
1990/2000	-1.93	-1.97	-6.30	-6.24	2.94	2.95	63.49	60.84
2000/10	-1.97	-1.38	-6.24	-5.73	2.95	3.63	60.84	60.39
				Summer				
1940/50	8.41	7.99	3.31	3.11	14.60	13.98	95.17	102.19
1950/60	7.99	8.12	3.11	3.06	13.98	13.88	102.19	101.33
1960/70	8.12	7.98	3.06	2.96	13.88	13.37	101.33	108.44
1970/80	7.98	8.66	2.96	3.65	13.37	14.16	108.44	108.18
1980/90	8.66	9.16	3.65	4.21	14.16	14.63	108.18	107.96
1990/2000	9.16	9.69	4.21	4.77	14.63	15.34	107.96	109.56
2000/10	9.69	9.85	4.77	5.01	15.34	15.50	109.56	116.39

Table A 5: Temperature and precipitation anomaly in Locarno. Temperature is sensible temperatrue, measured in degrees celsius. Precipitation is measured in mm. Orange indicates a positive, blue a negative anomaly from the reference value. The reference value is calculated based on data from 1961 to 1990.

Decade	**Mean temperature**		**Min temperature**		**Max temperature**		**Precipitation sum**	
	measured	anomaly	measured	anomaly	measured	anomaly	measured	anomaly
				Entire year				
1940	11.65	0.15	7.96	-0.22	16.08	0.24	148.47	-5.17
1950	11.49	-0.01	7.94	-0.24	15.86	0.02	165.97	12.33
1960	11.31	-0.19	7.97	-0.21	15.61	-0.23	158.86	5.22
1970	11.32	-0.18	8.04	-0.14	15.65	-0.19	156.75	3.11
1980	11.70	0.20	8.37	0.19	16.02	0.18	158.31	4.67
1990	12.5	1.00	9.01	0.83	16.74	0.90	155.67	2.03
2000	12.87	1.37	9.28	1.10	17.22	1.38	155.59	1.95
2010	13.22	1.72	9.61	1.43	17.59	1.75	150.97	-2.67
Reference	11.5		8.18		15.84		153.64	
				Winter				
1940	6.03	0.08	2.28	-0.69	9.92	0.12	84.84	-27.06
1950	6.09	0.14	2.59	-0.38	9.87	0.07	124.36	12.46
1960	5.77	-0.18	2.74	-0.23	9.56	-0.24	108.83	-3.07
1970	5.96	0.01	3.05	0.08	9.79	-0.01	125.03	13.13
1980	6.01	0.06	3.04	0.07	9.87	0.07	105.38	-6.52
1990	6.95	1.00	3.81	0.84	10.87	1.07	98.00	-13.9
2000	7.06	1.11	3.87	0.90	11.01	1.21	120.03	8.13
2010	7.47	1.52	4.36	1.39	11.35	1.55	128.69	16.79
Reference	5.95		2.97		9.80		111.9	
				Summer				
1940	17.18	0.21	13.55	0.25	22.16	0.37	212.1	16.72
1950	16.81	-0.16	13.22	-0.08	21.77	-0.02	207.59	12.21
1960	16.76	-0.21	13.12	-0.18	21.56	-0.23	208.9	13.52
1970	16.61	-0.36	12.96	-0.34	21.43	-0.36	188.46	-6.92
1980	17.30	0.33	13.62	0.32	22.08	0.29	211.23	15.85
1990	17.97	1.00	14.12	0.82	22.52	0.73	213.34	17.96
2000	18.61	1.64	14.6	1.30	23.34	1.55	191.15	-4.23
2010	18.88	1.91	14.78	1.48	23.73	1.94	173.25	-22.13
Reference	16.97		13.3		21.79		195.38	

Table A 6: Meteorological data on a decadal basis for Sion. Color marks changes that are singificant at the 5 percent level. Orange indicates an increase, blue a decrease. Temperature is sensible temperature in degrees celsius, precipitation is in mm.

Decade	**Mean temperature**		**Precipitation sum**	
	measured	anomaly	measured	anomaly
		Entire year		
1940	9.25	0.03	43.74	-6.10
1950	9.16	-0.06	49.83	-0.02
1960	9.15	-0.07	49.12	-0.72
1970	9.11	-0.11	48.15	-1.69
1980	9.34	0.12	49.96	0.12
1990	10.30	1.08	54.76	4.92
2000	10.66	1.44	47.48	-2.36
2010	11.26	2.04	45.94	-3.90
Reference	9.22		49.84	
		Winter		
1940	2.82	-0.25	44.12	-9.32
1950	2.96	-0.11	52.04	-1.39
1960	2.93	-0.14	52.04	-1.39
1970	3.15	0.08	52.64	-0.79
1980	3.13	0.06	49.19	-4.24
1990	4.18	1.11	53.12	-0.31
2000	4.33	1.26	44.26	-9.17
2010	4.93	1.86	46.29	-7.14
Reference	3.07		53.43	
		Summer		
1940	15.59	0.30	43.36	-3.88
1950	15.26	-0.03	47.61	0.37
1960	15.27	-0.02	46.2	-1.04
1970	14.97	-0.32	43.67	-3.57
1980	15.45	0.16	50.72	3.48
1990	16.32	1.03	56.4	9.16
2000	16.91	1.62	50.71	3.47
2010	17.49	2.2	45.6	-1.64
Reference	15.29		47.24	

Table A 7: Meteorological data on a decadal basis for Davos. Color marks changes that are significant at the 5 percent level. Orange indicates an increase, blue a decrease. Temperature is sensible temperature in degrees celsius, precipitation is in mm.

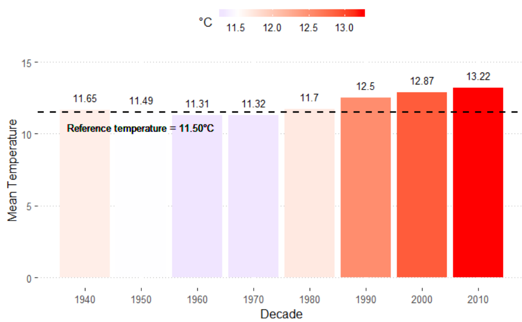
Decade	**Mean temperature**		**Min temperature**		**Max temperature**		**Precipitation sum**	
	measured	anomaly	measured	anomaly	measured	anomaly	measured	anomaly
				Entire year				
1940	2.59	-0.25	-2.28	-0.33	8.48	0.50	78.63	-4.60
1950	2.45	-0.39	-2.25	-0.30	8.18	0.20	81.11	-2.12
1960	2.56	-0.28	-2.21	-0.26	7.84	-0.14	81.03	-2.20
1970	2.81	-0.03	-2.00	-0.05	7.79	-0.19	84.91	1.68
1980	3.05	0.21	-1.71	0.24	8.20	0.22	84.70	1.47
1990	3.66	0.82	-1.01	0.94	8.83	0.85	85.72	2.49
2000	3.90	1.06	-0.69	1.26	9.19	1.21	85.20	1.97
2010	4.28	1.44	-0.32	1.63	9.61	1.63	88.39	5.16
Reference	2.84		-1.95		7.98		83.23	
				Winter				
1940	-3.31	-0.60	-7.96	-0.72	2.27	0.25	62.10	-0.06
1950	-3.18	-0.47	-7.70	-0.46	2.28	0.26	60.03	-2.13
1960	-3.07	-0.36	-7.56	-0.32	1.72	-0.30	60.73	-1.43
1970	-2.45	0.26	-7.03	0.21	2.12	0.10	61.38	-0.78
1980	-2.66	0.05	-7.15	0.09	2.16	0.14	61.22	-0.94
1990	-1.93	0.78	-6.30	0.94	2.94	0.92	63.49	1.33
2000	-1.97	0.74	-6.24	1.00	2.95	0.93	60.84	-1.32
2010	-1.38	1.33	-5.73	1.51	3.63	1.61	60.39	-1.77
Reference	-2.71		-7.24		2.02		62.16	
				Summer				
1940	8.41	0.10	3.31	0.05	14.60	0.74	95.17	-9.13
1950	7.99	-0.32	3.11	-0.15	13.98	0.12	102.19	-2.11
1960	8.12	-0.19	3.06	-0.20	13.88	0.02	101.33	-2.97
1970	7.98	-0.33	2.96	-0.30	13.37	-0.49	108.44	4.14
1980	8.66	0.35	3.65	0.39	14.16	0.30	108.18	3.88
1990	9.16	0.85	4.21	0.95	14.63	0.77	107.96	3.66
2000	9.69	1.38	4.77	1.51	15.34	1.48	109.56	5.26
2010	9.85	1.54	5.01	1.75	15.50	1.64	116.39	12.09
Reference	8.31		3.26		13.86		104.30	

Table A 8: Return levels per decade for Ticino. 95 % confidence interval in brackets.

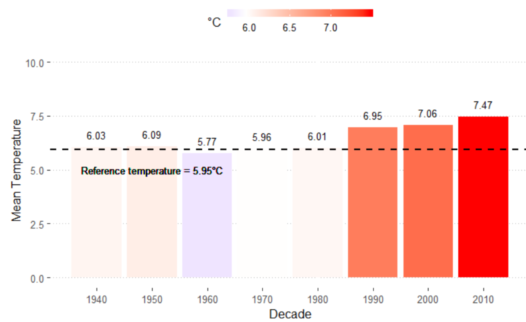
Decade	5 year		10 year		20 year		50 year		μ	σ	ξ	n	u	n > u
1940	234	(125-342)	314	(123-505)	409	(100-719)	565	(19-1110)	114.8	63.7	0.3	290	13	83
1950	299	(129-469)	445	(107-782)	637	(19-1255)	995	(-274-2,264)	118.3	85.3	0.4	332	22	118
1960	373	(198-549)	515	(201-829)	688	(163-1,213)	984	(22-1,947)	117.2	100.8	0.3	807	30	74
1970	666	(166-1,165)	1,119	(54-2,326)	2,069	(-333-4,470)	4,212	(-1,845-10,269)	199.7	166.6	0.8	836	15	127
1980	214	(126-301)	278	(130-425)	345	(111-578)	441	(46-836)	103.5	66.8	0.1	544	20	39
1990	85	(14-557)	562	(-174-1,298)	1070	(-742-2,881)	2,451	(-2,997-7,898)	69.8	68.8	0.9	571	18	35
2000	156	(81-232)	223	(73-353	286	(72-501)	369	(2-735)	2.4	8.8	0.0	393	24	11
2010	62	(12-112)	102	(-4-208)	159	(-54-371)	272	(-218-763)	16.5	19.9	0.5	196	5	19

Table A 9: Return levels per decade for Valais 95 % confidence interval in brackets.

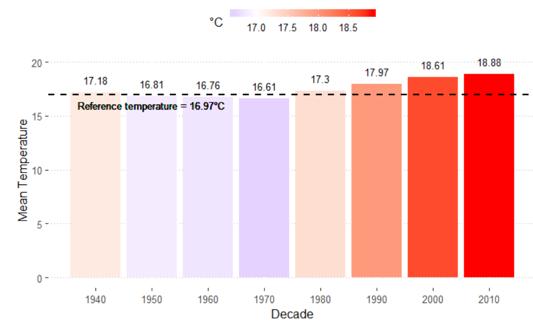
Decade	5 year		10 year		20 year		50 year		μ	σ	ξ	n	u	n >u
1940	20	(8-32)	30	(8-52)	42	(3-82)	65	(-14-143)	7.4	6	0.4	84	2	32
1950	18	(5-32)	29	(3-55)	42	(9-93)	64	(-50-178)	3.8	7.3	0.3	62	2.5	13
1960	26	(0-52)	50	(-22-123)	93	(-92-278)	205	(-367-776)	5.9	6.7	0.8	54	3	18
1970	28	(-10-66)	71	(-72-214)	177	(-311-665)	580	(-1621-2,780)	4.9	5.0	1.3	46	3.5	14



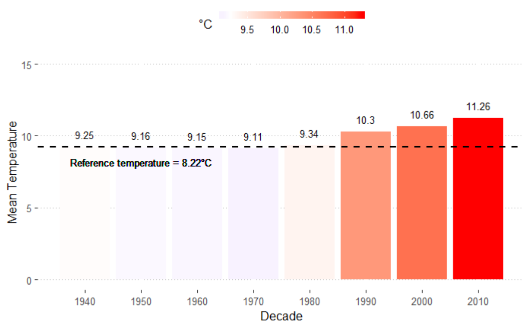
(a) Locarno entire year



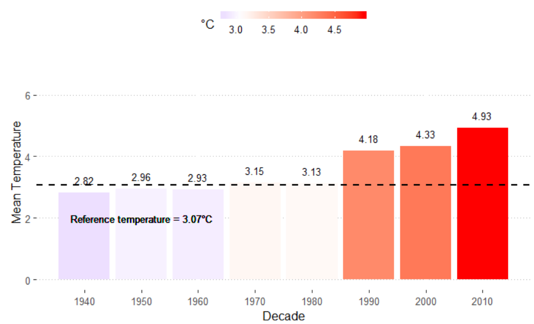
(b) Locarno winter



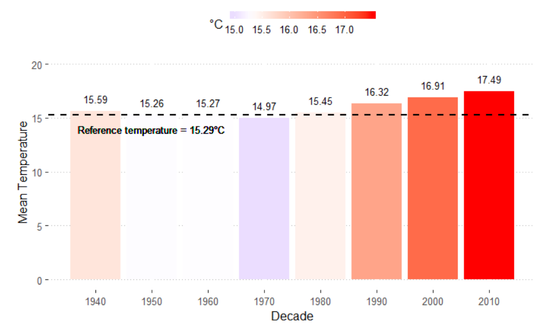
(c) Locarno summer



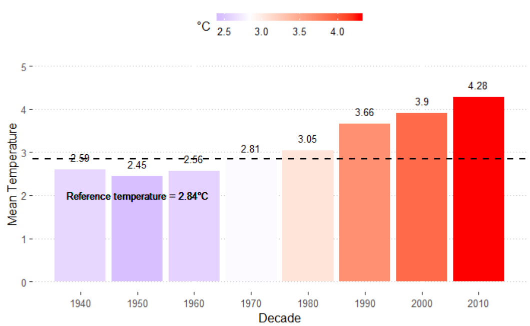
(d) Sion entire year



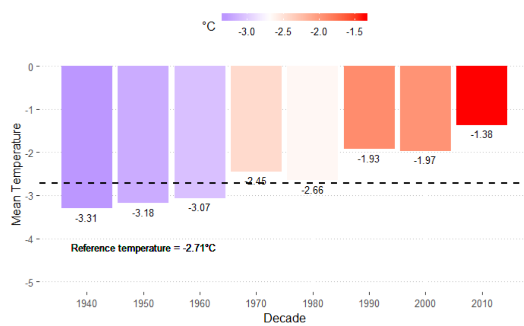
(e) Sion winter



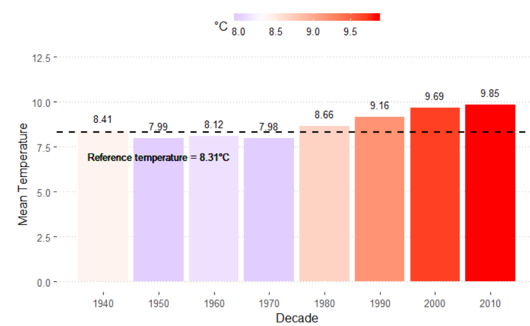
(f) Sion summer



(g) Davos entire year

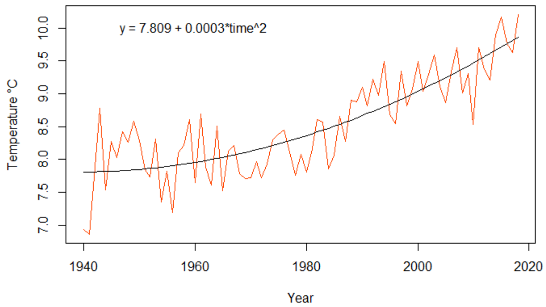


(h) Davos winter

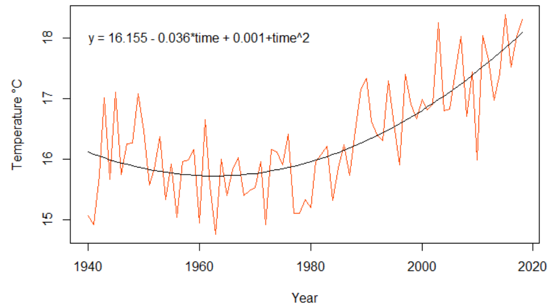


(i) Davos summer

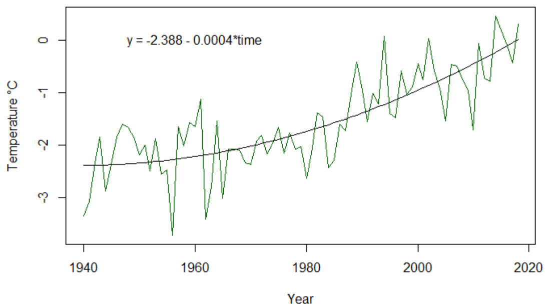
Figure B 1: Anomalies in mean temperature relative to the reference period of 1961 - 1990



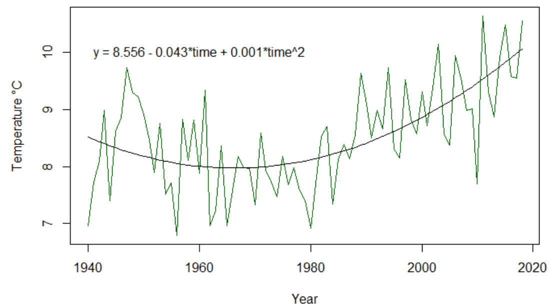
(a) Minimum Temperature in Locarno



(b) Maximum Temperature in Locarno

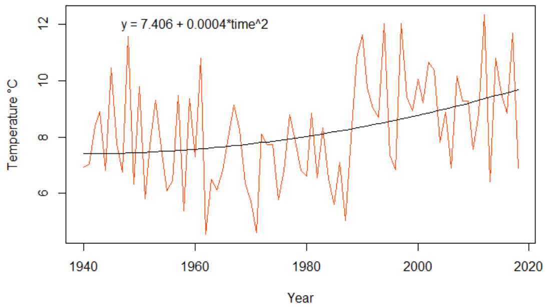


(c) Minimum Temperature in Davos

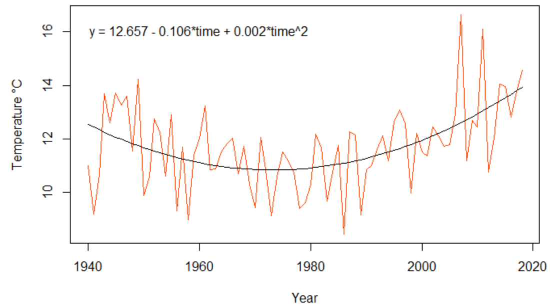


(d) Maximum Temperature in Davos

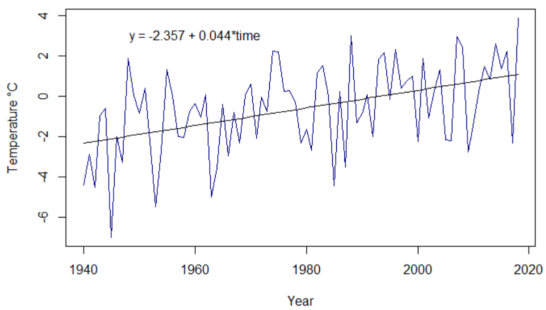
Figure B 2: Trends in meteorological data



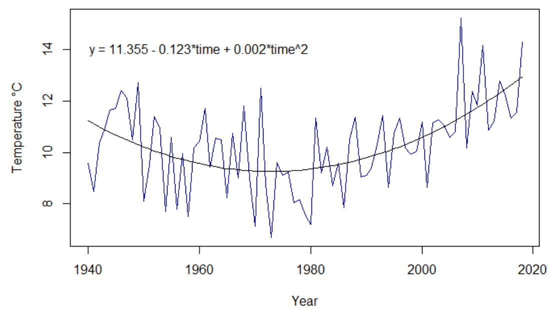
(a) Mean temperature in March at Locarno



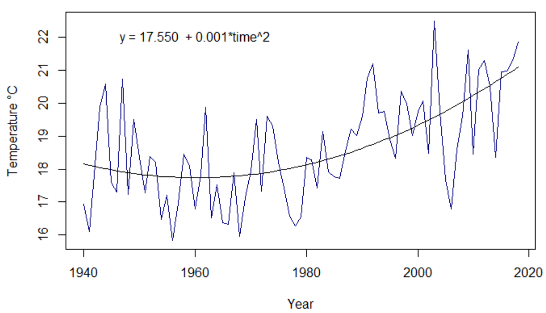
(b) Mean temperature in April at Locarno



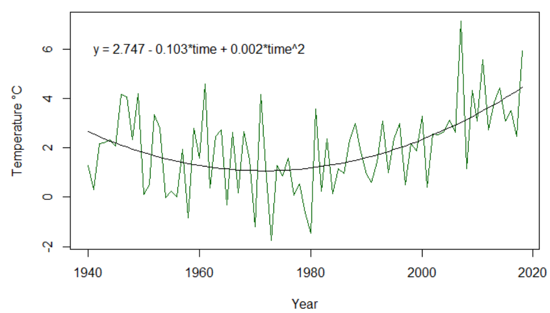
(c) Mean temperature in January at Sion



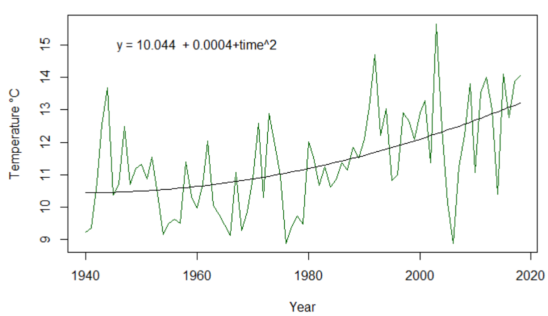
(d) Mean temperature in March at Sion



(e) Mean temperature in August at Sion



(f) Mean temperature in April at Davos



(g) Mean temperature in August at Davos

Figure B 3: Trends in meteorological data in fire prone months

8 Acknowledgements

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Declaration of consent

on the basis of Article 30 of the RSL Phil.-nat. 18

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Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: Wildfires in Switzerland - An Extreme Value Analysis

Supervisor: Prof. Dr. Eric Strobl

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