Vegetation trends in Switzerland in relation to land cover and climate – A 15-year time series analysis

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Abstract

Vegetation activity analysis through remotely sensed data has been an important field of research during the last decades, because of the important role of the biosphere in contemporary environmental change. Before 2000, global trends indicated greening, i.e. increased vegetation activity, whereas a trend shift to browning has been observed afterwards. The goal of this study was to explore this vegetation-activity shift in Switzerland after 2000 by comparing the global trends with the trends in Switzerland, a country of very diverse land cover and climatologies. Kalman-filtered MODIS NDVI data were used to explore trends and uncover how much, and where greenness has changed. Relationships between vegetation activity and the possible drivers land cover and climatologies, like temperature, precipitation an relative sunshine duration, were investigated. Additionally, the dependence on altitude was studied and for the climatologic research the biogeographic regions of the Alps were emphasized. It was found that in accordance with global development, NDVI in Switzerland has decreased during the 15 years analysed in this study. Areas of positive changes concentrated in the Alps and in the West of Switzerland, negative change was mainly found in the Plateau and the Valais. NDVI changes were positively correlated with altitude with a Pearson's r of 0.4, demonstrating that vegetation activity is decreasing less or even increasing at higher elevations. Concerning land cover types, the largest decrease in NDVI was found in urban areas. Forest and agriculture showed weaker decrease, whereas shrub and open spaces had values close to no change. Temperature increased slightly over the last years, while precipitation and relative sunshine duration decreased. The means vary for the different biogeographic regions, with the South Alps displaying the strongest differences from the other parts of the Alps. Standard deviations where high for all meteorological parameters and illustrate the high diversity all over Switzerland. The Pearson's correlation coefficients of the meteorological parameter trends and the NDVI trends ranged between -0.16 and 0.04 for all of Switzerland and between -0.34 and 0.16 in the alpine regions and therefore show weak relationships, partly attributable to the occurrence of anomalous conditions in some years. Temperature change seemed to be stronger at higher altitudes, precipitation change didn't show any clear patterns in relation

to elevation class and relative sunshine duration seemed to be decreasing with elevation. NDVI change in urban and agricultural areas can mainly be explained by societal development and policies, change in forests by disturbances like droughts, fires and beetles, and in shrubs and open spaces warming had the strongest influence on NDVI change. Temperature appears to be the strongest climatological factor influencing vegetation activity in Switzerland. Precipitation and sunshine duration have stronger seasonal variability their relationship with NDVI was not as straightforward in this study. But especially precipitation might gain significance for future development of vegetation activity, as summer precipitation is predicted to decrease and droughts might become more common.

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List of Abbreviations

ANOVA - Analysis Of Variances

AVHRR - Advanced Very High Resolution Radiometer

CLC - CORINE Land Cover

CORINE - Coordination of Information on the Environment

DAO - Data Assimilation Office

DEM - Digital Elevation Model

DTM - Digital Terrain Model

EVI - Enhanced Vegetation Index

fPAR - fraction of absorbed Photosythetic Active Radiation

FOAG - Federal Office for Agriculture

FOEN - Federal Office for the Environment

GPP - Gross Primary Production

HANTS - Harmonic Analysis of Time Series

IPCC - Intergovernmental Panel on Climate Change

LM - Linear Model

LUE - Light Use Efficiency

MODIS - Moderate Resolution Imaging Spectroradiometer

NDVI - Normalized Difference Vegetation Index

NPP - Net Primary Production

OcCC - Organe consultatif sur les changements climatiques

PAR - Photosynthetically Active Radiation

SFSO - Swiss Federal Statistical Office

SPOT - Satellite Pour l'Observation de la Terre

SRTM - Shuttle Radar Topography Mission

1. Introduction

Vegetation is changing globally. Patterns vary for different regions but several studies have found increasing vegetation activity from the early 1980s until 2000. A study by Nemani et al. (2003), for example, found increasing global terrestrial Net Primary Production (NPP) from 1982-1999. They compared NPP with climate data and concluded that this increase in productivity was mainly climate driven. Ichii et al. (2002) came to a similar conclusion, when they correlated global Normalized Difference Vegetation Index (NDVI) and climate patterns from 1982 to 1990. Especially in northern mid- and high latitudes they found significant climatic effects on vegetation activity, mainly due to temperature. There seems to be a statistically significant link between temperature and NDVI in latitudes between 40°N and 70°N (Slayback et al., 2003; Zhou et al., 2001).

Vegetation activity is relevant for Switzerland as it is heavily reliant on the productivity of the land. Agricultural areas cover around a third of the territory of Switzerland and almost another third is covered by forests and shrubs (SFSO - Swiss Federal Statistical Office, 2013). Due to the ecological and economical importance of vegetation in Switzerland, especially in the form of agriculture, a good understanding of vegetation trends is crucial for planning for the future.

Up to now, vegetation trends in Switzerland have only been marginally analysed with satellite data. Most studies assess vegetation activity at global scale or for larger regions like North America (Neigh et al., 2008) or the African Sahel (Herrmann et al., 2005). There have been a few studies for Europe, one by Julien & Sobrino (2010), who saw increasing NDVI averages over most of Europe during the 1980s and 90s, which they linked to increasing temperature as well as to increasing woodland areas. Despite their coarse resolution, these large-scale studies showed a general greening pattern in Switzerland since 1980.

After 2000 there appears to be a trend shift. A study by Zhao & Running (2010) found decreasing global terrestrial NPP from 2000-2009. They also identified climate as the main driver, as they suggest that the decrease in NPP was induced by droughts, especially in the Southern Hemisphere. Another study by Potter et al. (2012) used a model to estimate NPP values according to Enhanced Vegetation Index (EVI) values from 2000 to 2009. Although they did not find the same negative trend, they identified similar patterns of NPP anomalies in both hemispheres.

A study by de Jong et al. (2013) shows an overview of vegetation trends from 1982 to 2011. The study illustrates increasing global NDVI, and thus greening until 2000 and signs of decreasing NDVI, and thus browning after 2000. It is therefore of interest, how vegetation activity behaved in Switzerland after 2000, and if it corresponds with global vegetation trends.

After identifying the direction and magnitude of change, the challenge is to attribute it to driving factors. Climate change and human induced land cover change are widely accepted as main drivers of global vegetation change. The latest IPCC report (2014) states a global increase in atmosphere and ocean temperature as well as a decrease of snow and ice cover over the past decades. Precipitation has also significantly changed, both in annual mean as well as in seasonal distribution, but it differs strongly from region to region and there is no general global trend as for temperature. In an OcCC (2008) report that evaluated the findings of the preceding IPCC report of 2007, rising temperatures were also verified for Switzerland. Long-term precipitation changes weren't that clear as the detection of trends is more difficult due to strong natural variability and regional differences. Mean annual precipitation has not changed significantly, but there appears to be a tendency to an increase in intense precipitation events in autumn and winter as well as decreasing precipitation in summer.

Warming in Switzerland could, for example, lead to increasing vegetation activity in alpine regions, as the treeline probably moves further up the mountain due to higher temperatures (Cannone et al., 2007; Ozenda & Borel, 1991; IPCC, 1990). This relationship is, however, not straightforward at regional or local scale (Holtmeier & Broll, 2005). Not only climate change can drive treelines to higher altitudes, there is also the possibility that human induced land cover change in the form of land abandonment in mountainous regions leads to more opportunities for forest growth (Gehrig-Fasel et al., 2007). Therefore, processes driving vegetation trends are very complex and interconnected (DeFries et al., 1999; Houghton et al., 1999).

For land cover, major changes have been identified by federal studies. A study by the SFSO (2013) identified some of the main trends from 1985-2009: Urban areas are expanding, wooded areas are increasing in the south and alpine regions and agricultural areas of every type are decreasing. These changes in land cover are linked to vegetation and influence vegetation activity trends.

Most of the time, human induced land cover change stems from policy changes. There has, for example, been a politically induced paradigm shift that led to major structural changes in agricultural policies from 1990 on. Traditional, production oriented subsidies in agriculture were exchanged against direct payments for services that benefit public and ecological interests rather than maximizing production (Bosshard et al., 2011). Land cover change in Switzerland is also influenced by economic structural transformation. The on-going shift from employees in agriculture to increasing numbers of people employed in the service sector (Odermatt & Wachter, 2004) can lead to growth of urban areas and decrease in agricultural or natural areas. It is therefore important to also take political and economical factors into account when analysing vegetation activity.

1.1 Research goals

The main goal of this study was to analyse vegetation trends in Switzerland and investigate possible drivers, especially since 2000. For this, the following research questions were defined:

1. How has vegetation activity in Switzerland changed in the last 15 years?
   - Is the globally observed trend-shift from greening to browning in this timespan also observable in Switzerland?
   - Where are hotspots of vegetation change?

2. Are vegetation trends related to land cover?
   - Are vegetation change patterns different among land cover types?

3. Are vegetation trends related to climatologies?
   - Can statistical relationships with climatologies explain the vegetation change patterns?

To answer these questions, vegetation activity trends were derived from satellite data, as satellites provide consistent long-term measurements of vegetation parameters. The regions with the strongest trends were identified, and the trends were compared with land cover and climatology data to analyse and quantify their co-occurrence with vegetation change.

1.2 Biogeography, climate and land cover in Switzerland

Switzerland is situated in Central Europe and covers an area of just over 41000km^2. The territory can be divided in three main regions: Jura, the Swiss Plateau and the alpine region (Odermatt & Wachter, 2004). Most of the Swiss population lives in the lower areas of the Plateau. The Alps can be broken down further into biogeographic regions: North, East, South and West Alps (FOEN, 2001). Figure 1.1 shows these main biogeographic regions of Switzerland.

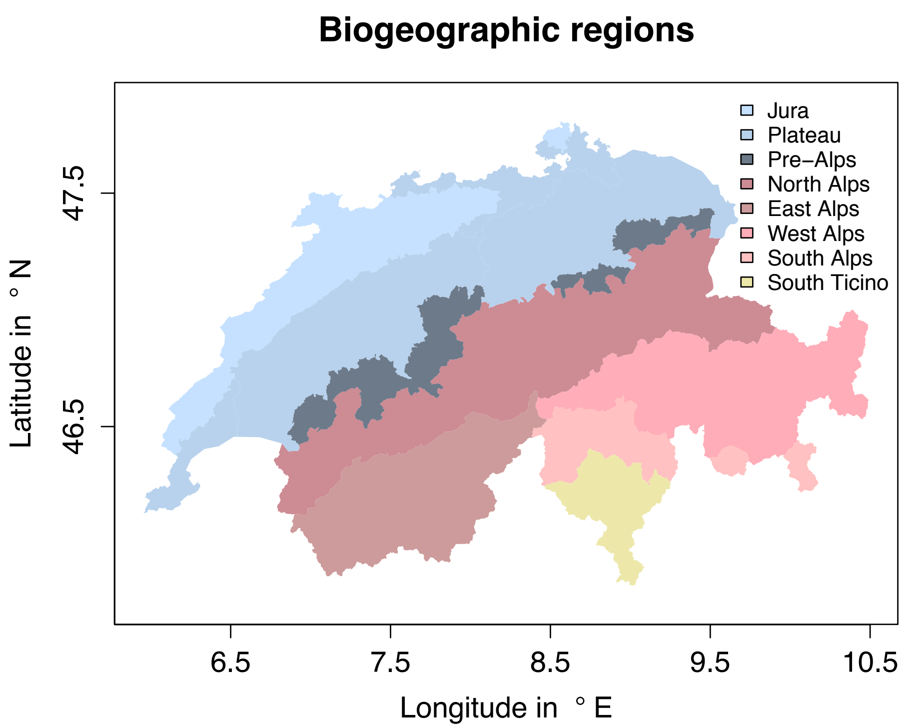

Figure 1.1 Biogeographic regions of Switzerland.

The Swiss Climate ranges from oceanic to continentally influenced regimes. But there are strong regional differences due to the Alps and the unique character of some enclosed areas (Odermatt & Wachter, 2004). South of the Alps, the Climate is influenced by the Mediterranean Sea and winters are milder than in the North. As a complex mountain range, the Alps contain many different climatic areas (Meteo Swiss, 2014b).

Vegetation is diverse and mainly influenced by climate and altitude. Lower areas, below 600 m.a.sl., are to a large degree characterized by human influence, most of the larger vegetated areas are used agriculturally and consist of pastures, vines and arable land. There are also considerable areas of broad-leaf forest, which compose most of the areas between 600 and 1200 m.a.s.l. Above that, deciduous trees dominate the landscape, and above 1900 m.a.s.l., vegetation consists of shrub and summer pastures. There are several regions with very specific and different vegetation types, for example the warmer South, where Mediterranean plant species grow, or the drier Valais in the South-West with steppe vegetation (Odermatt & Wachter, 2004).

In 2009, agriculture and wooded areas each covered around one third of the Swiss territory. Populated areas made up around 7.5%, and the rest is covered by unproductive areas as water bodies, unproductive vegetation or non-vegetated areas (SFSO, 2013). Figure 1.2 shows the CORINE Land Cover (CLC) classification from 2012 (Steinmeier, 2013).

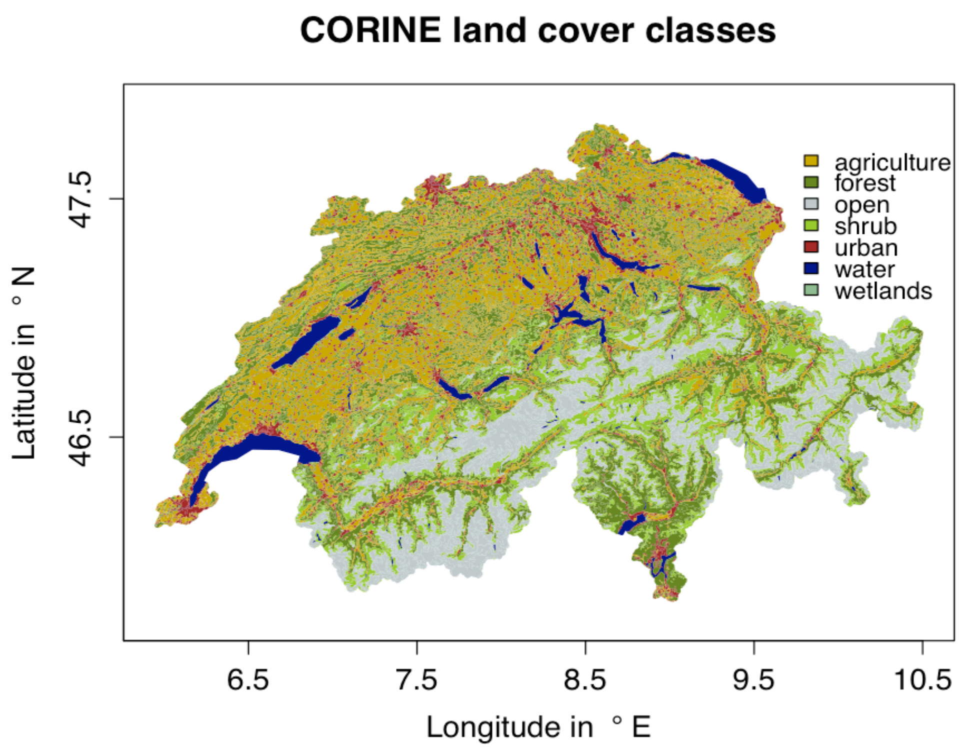

Figure 1.2 CORINE land cover classes 2012.

2. Material and Methods

2.1 Vegetation activity

There are different methods to assess vegetation activity. The closest to the actual photosynthetic process is using measurements of Gross Primary Productivity (GPP), as it combines daytime photosynthesis with night-time respiration (Brinson et al., 1981). According to the concept of Light Use Efficiency (LUE), Monteith (1972) formulated the following equation:

$$GPP = \varepsilon \times \int fPAR \times PAR$$

The equation defines GPP as a relationship between LUE (epsilon), the fraction of absorbed Photosythetic Active Radiation (fPAR) and incident Photosynthetically Active Radiation (PAR). In the GPP equation, fPAR is most variable and can be estimated using remote sensing methods. In fact, the relationship between NDVI and fPAR is almost linear (Asrar et al., 1984).

NDVI is a measure of vegetation greenness and is based on a simple band ratio between reflectances (ρ) of the visible red (RED) and the near-infrared (NIR) part of the electromagnetic spectrum. It is based on the distinctive increase in vegetation reflectance around 700 nm, known as the red edge, and was first formulated in its current form by Tucker (1979):

$$NDVI = \frac{(\rho_{NIR} - \rho_{RED})}{(\rho_{NIR} + \rho_{RED})}$$

Several studies, like Box et al. (1989), suggest that NDVI can be seen as a relatively reliable predictor of productivity. Whereas GPP is a good measure of actual photosynthetic activity, NDVI can be seen as a simple approximation of such. It can be directly and reliably measured from satellites.

NDVI can be obtained from most types of optical satellite imagery, some of which provide time series with high temporal resolution. The Moderate-resolution Imaging Spectroradiometer (MODIS) has been in operation since 2000 and provides different products, which can be used for vegetation trend analysis (Zhang et al., 2003). The spatial resolution of many products is substantially better than the ones obtained using older sensors like the Advanced Very High Resolution Radiometer (AVHRR), which was, and still is, also widely used for remote sensing vegetation analyses (e.g. Goward et al., 1985).

The products used for this study include MOD13A1 for NDVI and MOD17A2 for GPP (LP DAAC, 2000-2014). Both products cover the timespan March 2000 until December 2014. The first two months of 2000 are missing in all MODIS products, as MODIS started delivering data in March 2000. Therefore, in the time series analysis the first months of 2001 were also used for 2000. This is unlikely to introduce artefacts for vegetation analysis, as the missing months are in winter when vegetation activity is low in Switzerland.

The used NDVI product has a 500-m spatial and 16-day temporal resolution. It has been calculated using the Tucker (1979) formula on atmospherically corrected reflectance data, although some aerosol contamination remains (Huete et al., 1999). Studies have confirmed the MODIS NDVI product as a valuable instrument to analyse both temporal and spatial variability of vegetation (Huete et al., 2002).

MOD17A2 has a 1-km spatial and 8-day temporal resolution. It is estimated with Monteith's (1972) equation for GPP. The values for fPAR are acquired from another MODIS product, MOD15A2. PAR is estimated from meteorological data provided by NASA's Data Assimilation Office (DAO) and has a resolution of 1°. LUE is derived from a biome property look up table of different vegetation types (Running et al., 1999).

A Harmonic Analysis of Time Series (HANTS) was carried out on the data. HANTS can remove cloud contamination or processing noise by interpolating the data temporally with a Fourier analysis, making it well suited for analysing time series of remotely sensed data (Jakubauskas et al., 2001; Roerink et al., 2000; Verhoef et al., 1996). In essence, Fourier analysis reduces a complicated curve to a (Fourier) series of sinusoidal waves and fits it to the original data (Rayner, 1971). The NDVI profile can be reconstructed, and outliers are removed, while still accounting for phenological variability (de Jong, 2008; Jakubauskas et al., 2001).

Many studies used Fourier transformation based filtering for NDVI time series (Menenti et al. 1993; Negrón Juárez & Liu, 2001), but fitting harmonics to long periods with missing observations, like winter cloud cover in parts of Switzerland, introduces artefacts that may affect the trend analysis. Other methods, like seasonal Kalman filtering (Kleynhans et al., 2010), can be used to eliminate these artefacts. Kalman (1960) defined an algorithm to separate signals in time series from noise and predict the next state of an observation (i.e. NDVI) based on a linear season-trend function of the current state and process noise. Kalman filtering is computationally more intense and therefore time consuming compared to HANTS. Short-term noise, like occasional cloudiness or corrupted observations, were therefore filtered using harmonics before filling larger gaps using a seasonal Kalman filter.

2.2 Land cover

Land cover describes the composition of the earth surface, whereas land use describes how humans use the land cover (Lambin et al., 2006), but definitions can sometimes overlap. In this study, I will only use the expression land cover for simplicity, as the underlying data were land cover based.

The CORINE Land Cover (CLC) datasets for Switzerland (Steinmeier, 2013) were used to assess vegetation activity in relation to land cover and land cover changes. The Swiss

CLC project uses a large variety of data to create land cover classification maps. Included in the process are for example SPOT satellite images, aerial images and a variety of digital vector (e.g. inventories) and raster (e.g. DTM) data. The resulting classification is a vector dataset with a minimum mapping unit of 25 ha and a minimum mapping width of 100 m (Steinmeier, 2013). For this study, the datasets from 2012 and the change datasets from 2000 to 2006, as well as from 2006 to 2012 were used.

2.3 Climatologies

Monthly gridded data of mean temperature, relative sunshine duration and total precipitation with a spatial resolution of 2.2 km were used to assess climatological influences on vegetation (Meteoswiss, 2014a). These three meteorological parameters are the most important components influencing characteristic weather patterns and ultimately climate (Odermatt & Wachter, 2004), and are also the main climatic resource limitations affecting plant growth (Field et al. 1995). Climate usually describes weather averages of 30 years or more (WMO, 2015), therefore the term climatology will be used in this study, as it can apply to any long-term average of a variable, in this case 15 years.

In 2014, the values for October were missing in all three datasets. To fill the gap in the data, an average of September and November was calculated and used for October. This is not a very accurate estimation of the missing values but considered sufficient for looking at general patterns in a 15-year time series.

To analyse climate in the alpine region, it was separated into the four main biogeographic regions of the Swiss Alps (FOEN, 2001): North, East, South and West Alps.

2.4 Altitude

A 100-m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) by the USGS (2003) was used to compare change in NDVI along an altitudinal gradient and also in relationship with the possible drivers of vegetation change climate and land use.

Elevation classes were created according to natural vegetation boundaries: From 0 m.a.s.l. to the vine boundary at around 600 m.a.s.l., from 600 m.a.s.l. to the deciduous-tree boundary at around 1200 m.a.s.l., from 1200 m.a.s.l. to the coniferous-tree boundary at around 1900 m.a.s.l., and from 1900 m.a.s.l. to 3000 m.a.s.l., where there is almost no vegetation anymore (Odermatt & Wachter, 2004).

2.5 Trend analysis

To determine trends in vegetation activity, a time series analysis was carried out. For this, the MODIS NDVI data were assembled into per-pixel time series, and the dataset was masked to the extent of Switzerland. Then, a season-trend regression model of NDVI against time was applied, where NDVI is the dependent and time the independent variable (e.g. de Jong, 2008; Fensholt et al., 2009). The season-trend model by Verbesselt et al. (2012) was used as a base:

$$y_t = \alpha_1 + \alpha_2 t + \sum_{j=1}^{k} y_j \sin(\frac{2\pi j t}{f} + \delta_j) + \varepsilon_t$$

Where y_t are NDVI observations at time t with $\alpha_1, \alpha_2, y_1, \ldots, y_k$ and $\delta_1, \ldots, \delta_k$ as the unknown parameters. Intercept α_1 and slope α_2 represent a linear trend model, whereas amplitudes $y_1, \ldots, y_k$, phases $\delta_1, \ldots, \delta_k$, as well as the known frequency f describe the invariant seasonality. Finally, ε is defined as the random error at time t.

Simplified, the equation corresponds to:

$$NDVI = linear\ trend\ model + sum\ of\ seasons + error$$

To assess the significance of the trends, a p-value was calculated using an ANOVA on the model, under the null hypothesis that the slope equals zero and the alternative hypothesis that the slope is either larger or smaller than zero. Slopes that significantly deviated from zero (α == 0.05) were considered in the statistics. The final output contained a layer each for total and yearly change in NDVI, as well as a layer for the p-values. The same methodology was used for analysing trends in GPP and in the meteorological data.

2.6 Relationship of NDVI-trends with possible driving factors

To assess their relationship, total change in NDVI over the years was correlated with possible drivers. Pearson's correlation coefficient was used to quantify the correlation. Similar methods have been used in recent remote sensing studies (e.g. Ichii, 2002; Kim, 2013; Raynolds et al., 2008). Using similar methodology, the DEM was correlated with change in NDVI to assess change in vegetation activity along an altitudinal gradient. Trends in climate data of monthly rainfall, relative sunshine duration and mean temperature were also correlated with changes in NDVI.

The results were aggregated according to land cover, to assess potential relationships between vegetation activity change and human influence. The CORINE data were grouped into: urban (artificial surfaces), agriculture, forest and open spaces with little or no vegetation. The agriculture class was further separated into different types: arable land, vine and fruit cultivation (permanent crops), pastures and heterogeneous agricultural land. The forest class was split into a forest and a shrub class (consisting of shrubs and grasslands) and then further broken down into the different forest types: broad-leaved, coniferous and mixed forest. Wetlands and water bodies were left out. Agriculture, forest and shrub classes were further correlated with elevation to investigate the influence of altitude on vegetation more deeply.

3. Results

3.1 Vegetation activity

3.1.1 Vegetation activity trends

Figure 3.1 illustrates the difference between the original data and the Kalman-filtered data according to one exemplary pixel located in the Swiss Plateau. The number of outliers varied geographically from ca. 10% up to ca. 40% of all observations.

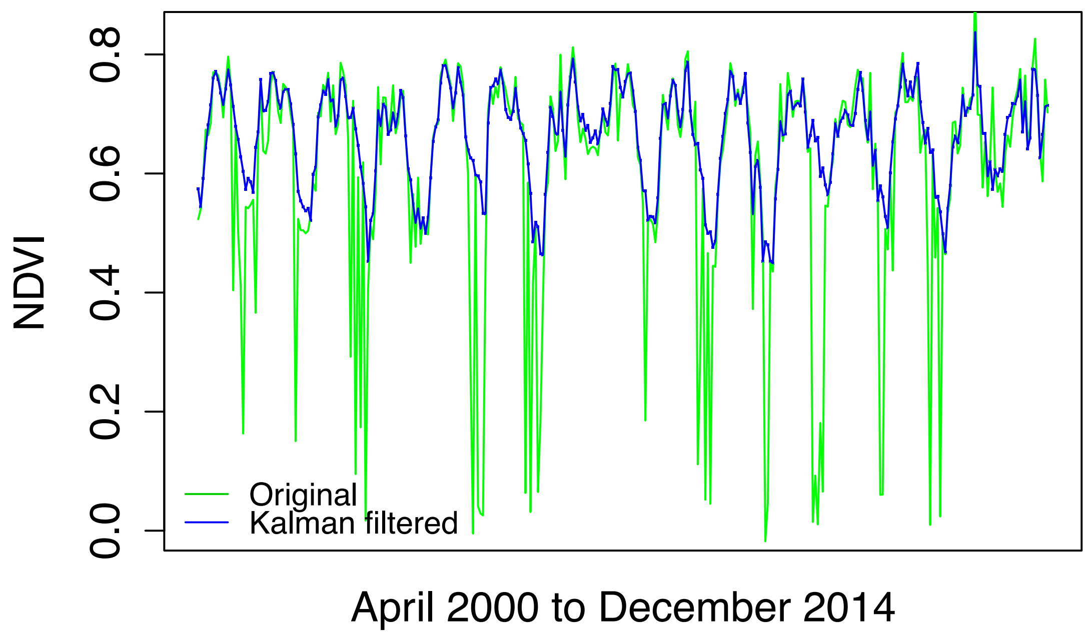

Figure 3.1 Time series of original and Kalman-filtered NDVI values for one pixel located in the Plateau.

The seasonal decomposition and subsequent trend analysis were carried out on the Kalman-interpolated data. Without this interpolation step, the seasonal distribution of the gaps would influence the trend analysis. Figure 3.2 shows the result of the linear model, where green areas indicate an increase in NDVI from 2000 to 2014, while brown areas indicate a decrease.

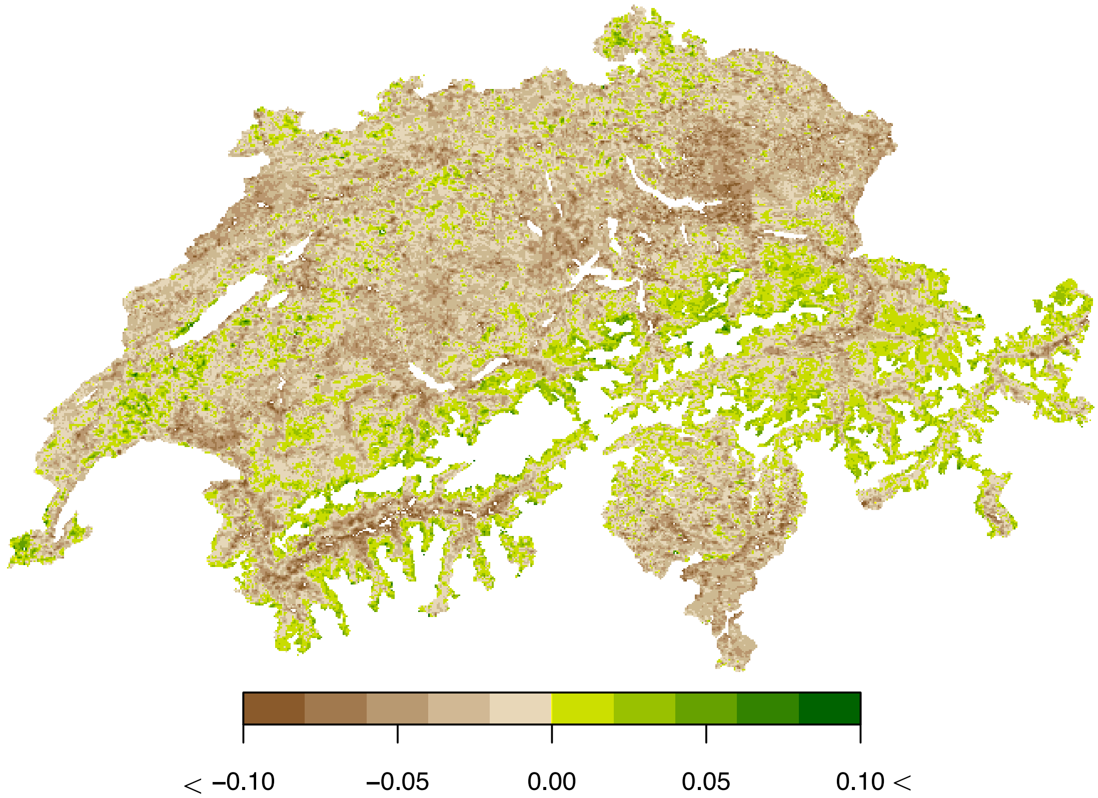

Figure 3.2 Total change in NDVI from 2000 to 2014.

Table 3.1 Mean and standard deviations of change in NDVI in all of Switzerland, the Alps and the four main biogeographic regions of the Alps.

NDVI	*Switzerland*	*Alps*	*North Alps*	*East Alps*	*South Alps*	*West Alps*
Mean	-0.018	-0.011	-0.013	-0.003	-0.012	-0.016
Stdv.	0.027	0.029	0.028	0.024	0.025	0.036

Table 3.1 shows that NDVI has slightly decreased from 2000 to 2014 in Switzerland with a mean of -0.018. The negative trend was weaker in the Alps (-0.011) and even closer to zero (-0.003) in the eastern part of the Alps. The standard deviation lay between 0.024 and 0.036.

3.1.2 Vegetation activity and altitude

The NDVI change values where then correlated with the DEM to assess the relationship between vegetation activity and elevation between 2000 and 2014.

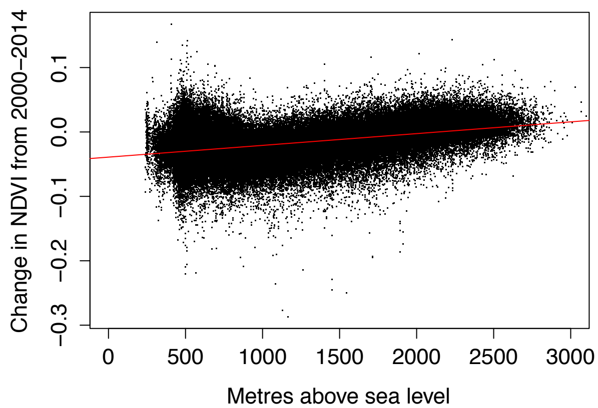

Figure 3.3 Scatter plot of changes in NDVI versus altitude.

The relationship of NDVI and altitude is illustrated in Figure 3.3. Trends in NDVI were generally less negative the higher the altitude. Pearson's correlation coefficient was 0.4, which indicates a moderate positive relationship (Cohen, 1992).

3.2 Land cover

3.2.1 Land cover and vegetation activity

NDVI change was analysed according to CORINE land cover classes. Figure 3.4 illustrates the general relationship between the most basic classes that contain vegetation: urban, forest, agriculture, shrub and open spaces with little or no vegetation. Overall NDVI changed negatively, with similar deviations from the mean in all classes. The decrease in NDVI in urban areas was strongest, with a mean of -0.032. Forest and agriculture decreased less with means of -0.025 and -0.02. The mean of the shrub class was slightly positive with 0.002 and the open spaces class showed the strongest increase with 0.01.

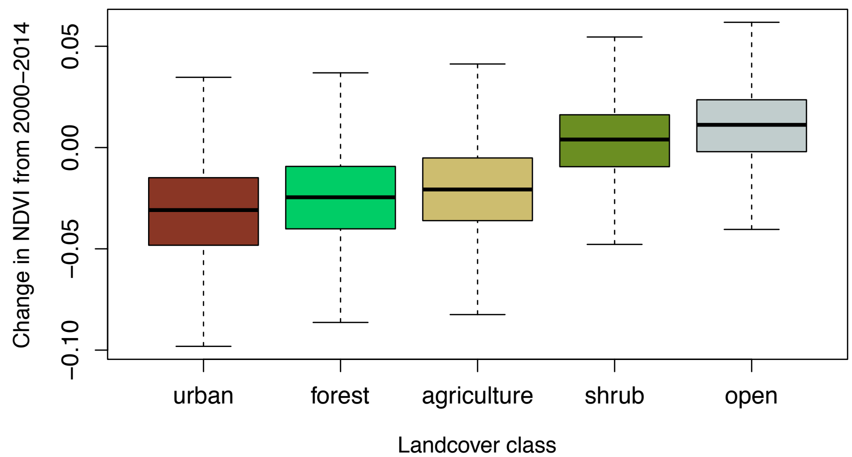

Figure 3.4 Change in NDVI from 2000 to 2014 according to CORINE land cover class.

In Figure 3.5, the distribution of NDVI values in different types of agricultural land is shown. Arable land and permanent crops, like vine and fruit, show the same mean value in NDVI change: -0.019. NDVI decrease is stronger in pastures (-0.023) and heterogeneous agricultural land (-0.027). Standard deviations differ only slightly from class to class, with an exception of the permanent crop class, where values differ more from another.

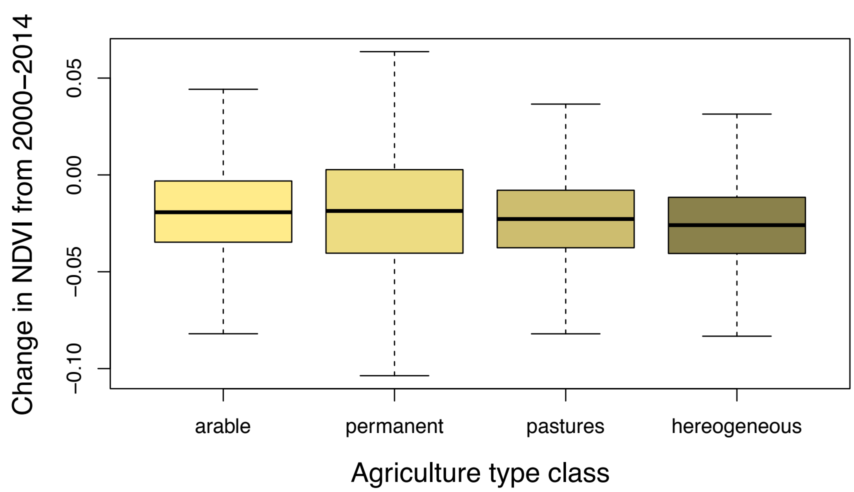

Figure 3.5 Change in NDVI from 2000 to 2014 according to CORINE agriculture class (arable land, permanent crops like vine and fruit, pastures and heterogeneous agricultural areas).

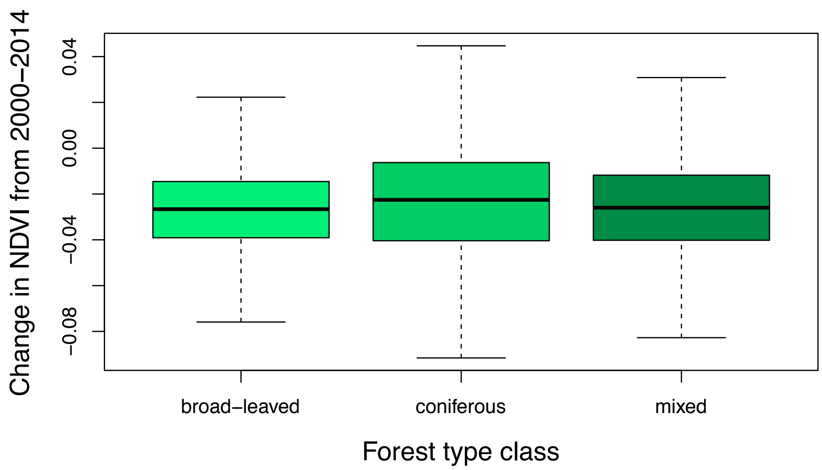

Figure 3.6 Change in NDVI from 2000 to 2014 according to CORINE forest type class (broad-leaved, coniferous and mixed forests).

NDVI changes in different forest types had similar means with -0.027 in the broad-leaved forest class, -0.025 for coniferous forests and -0.026 for mixed forests (Figure 3.6). Broad-leaved forest had a small distribution of NDVI change values, whereas the values in the coniferous forest class varied more and mixed forests showed standard deviation in between the two other forest classes.

3.2.2 Land cover and altitude

The vegetation classes agriculture, forest and shrub were further investigated according to elevation class. As urban areas concentrate mainly at lower elevations and open spaces are more common at higher elevations, they do not show a relationship with altitude. Figures 3.7 to 3.9 illustrate the relationship of NDVI change and elevation class in different land cover types. The pattern was similar for the analysed vegetation types agriculture, forest and shrub: In the lowest elevation class below 600 m.a.s.l. NDVI change values were higher than in the following class of 600 to 1200 m.a.s.l., where the values were lowest for all vegetation types. The values then increased in the class of 1200 to 1900 m.a.s.l. and reached their maximum in the class of 1900 to 3000 m.a.s.l.

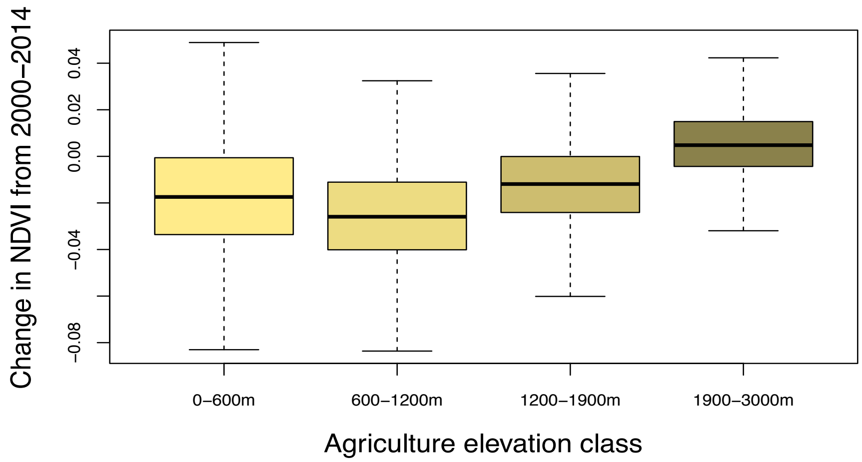

Figure 3.7 Change in NDVI from 2000 to 2014 in the CORINE agriculture class in relation to elevation classes.

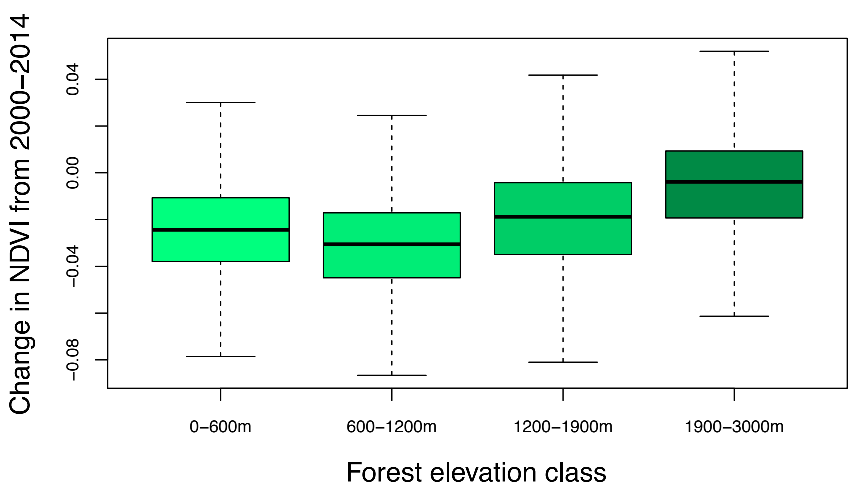

Figure 3.8 Change in NDVI from 2000 to 2014 in the CORINE forest class in relation to elevation classes.

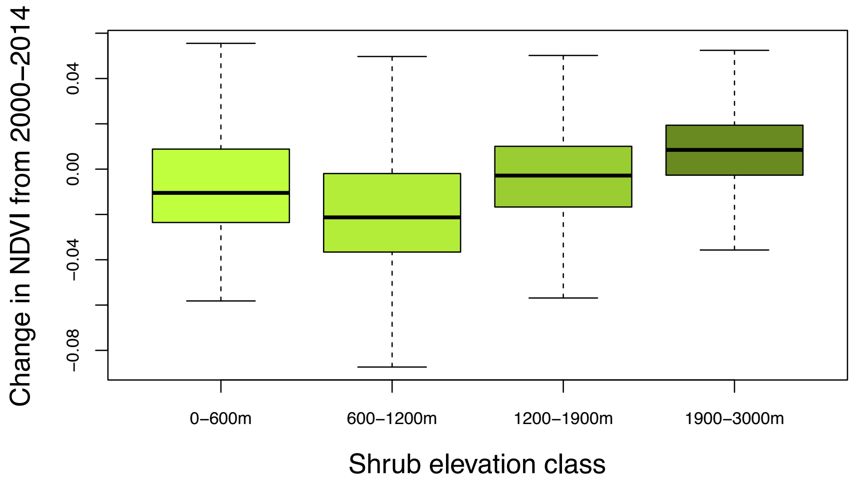

Figure 3.9 Change in NDVI from 2000 to 2014 in the CORINE shrub class in relation to elevation classes .

NDVI change values in the vegetation classes were also correlated with the DEM. Table 3.2 shows the correlation coefficients of the NDVI change values in the three vegetation types with altitude. Agriculture has a correlation coefficient of 0.05, forest of 0.21 and shrub of 0.36.

Table 3.2 Correlations of NDVI change versus altitude in the different vegetation land cover classes.

	Agriculture	*Forest*	*Shrub*
Pearsons r	0.05	0.21	0.36

3.3 Climatology

3.3.1 Climatology trends

Following the same methodology as for the vegetation activity, trends for the climatological parameters mean temperature, total precipitation and relative sunshine duration were calculated. Figure 3.10 illustrates the resulting changes in climatological parameters from 2000 to 2014. Tables 3.3 – 3.5 show the corresponding means and standard deviations for different regions.

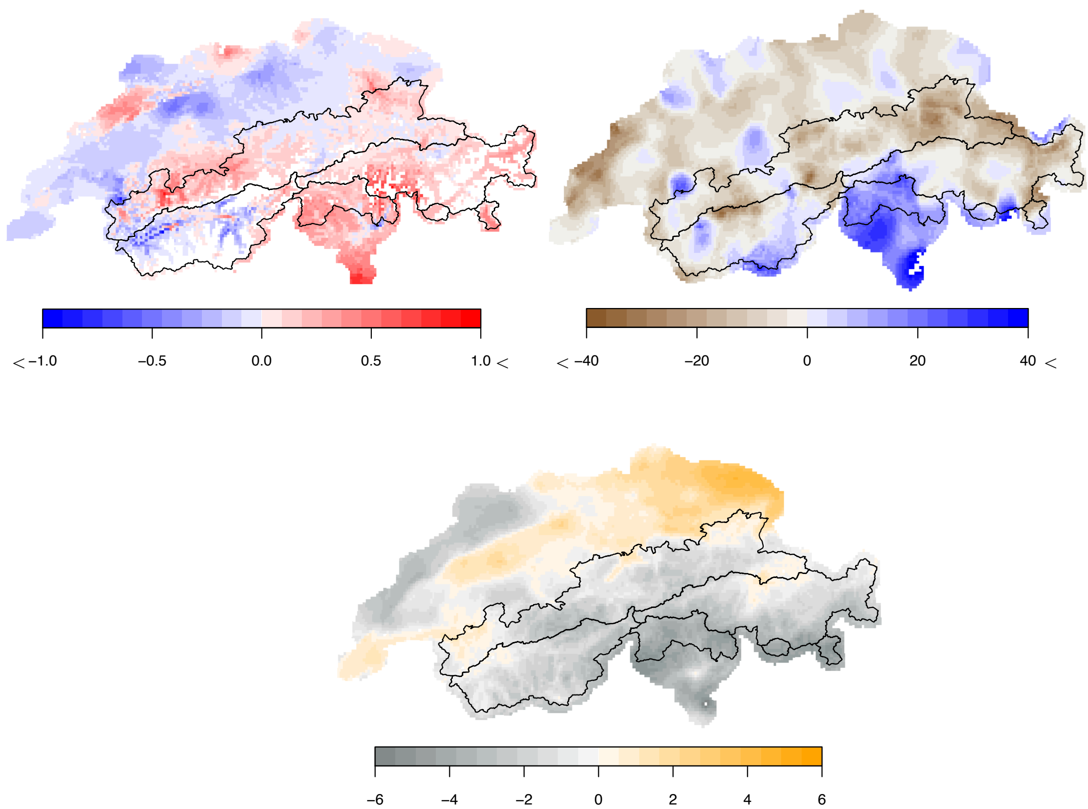

Figure 3.10 Trend maps of change in temperature in °C (upper left), precipitation in mm (upper right) and relative sunshine duration in % (lower middle) from 2000 to 2014 with the borders of the biogeographic regions of the Alps.

As visible in figure 3.10 and table 3.3, temperature has slightly increased on average. The Alps showed stronger trends, with the highest mean value of 0.24 degrees Celsius increase in the South Alps. The West Alps were the only region analysed that showed slightly decreasing temperatures (-0.07°C.) Standard deviation was similar in all alpine regions and lay between 0.13 and 0.18, all over Switzerland it was around 0.24.

Table 3.3 Mean change in temperature for different regions between 2000 and 2014.

Temperature [°C]	*Switzerland*	*All Alps*	*North Alps*	*East Alps*	*South Alps*	*West Alps*
Mean	0.03	0.09	0.07	0.18	0.24	-0.07
Stdv.	0.24	0.18	0.14	0.17	0.13	0.18

Precipitation trends were mainly negative (Figure 3.10 and Table 3.4). Differences between the alpine regions were strong, with high negative change values in the North (-9.5 mm) and high positive values in the South (11.29 mm). Standard deviation was 10.86 mm all over Switzerland, 10.28 mm in the Alps and a little lower in the four alpine regions.

Table 3.4 Mean change in precipitation for different regions between 2000 and 2014.

Precipitation [mm]	*Switzerland*	*All Alps*	*North Alps*	*East Alps*	*South Alps*	*West Alps*
Mean	-3.35	-4.12	-9.5	-4.07	11.29	-1.33
Stdv.	10.86	10.28	7.25	9.12	9.44	8.66

Relative sunshine varied strongly across all of Switzerland with negative trends in the South, Alps and the Jura and positive trends in the Plateau (Figure 3.10). The mean values for the different regions were negative (Table 3.5), whereas all of Switzerland (-0.94%) and the North Alps (-0.97%) had weaker trends than the other parts of the Alps, and the South Alps showed the strongest decrease (-4.04%).

Table 3.5 Mean change in relative sunshine duration for different regions between 2000 and 2014.

Sunshine [%]	*Switzerland*	*All Alps*	*North Alps*	*East Alps*	*South Alps*	*West Alps*
Mean	-0.94	-1.65	-0.97	-1.83	-4.04	-1.66
Stdv.	1.87	1.35	1.1	1.18	0.61	0.9

3.3.2 Climatology and vegetation activity

The changes in climatological parameters were then correlated with changes in NDVI to evaluate the co-occurence between trends in climatologies and in vegetation activity.

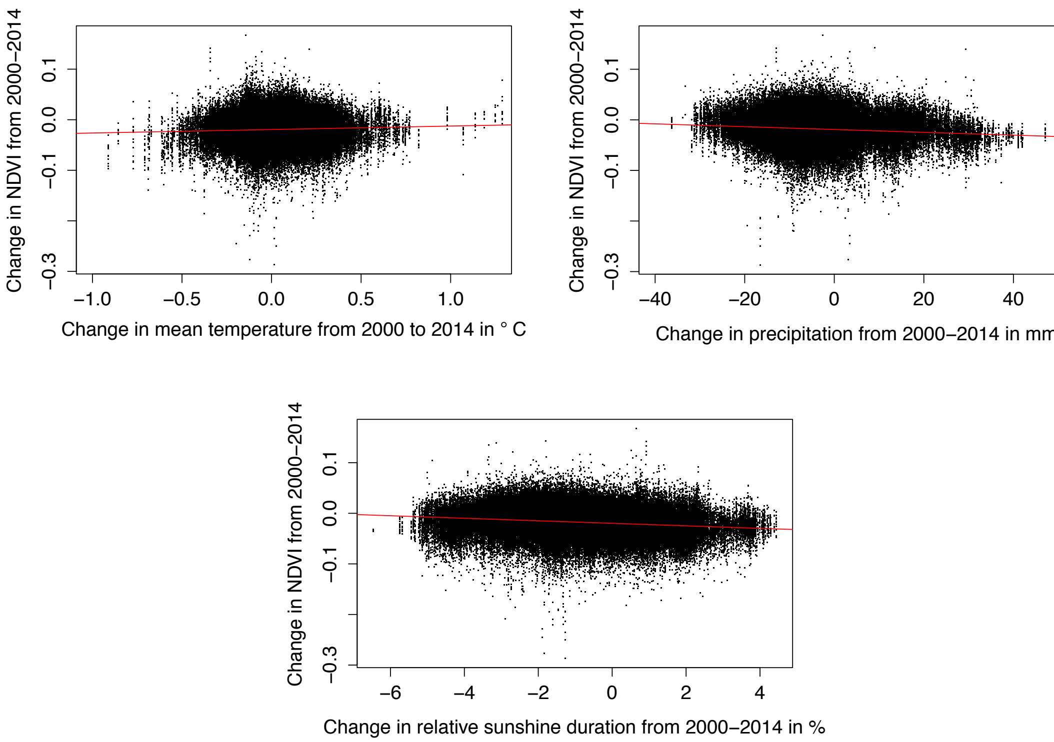

Figure 3.11 Scatter plots of change in NDVI versus change in temperature (upper left), precipitation (upper right) and relative sunshine duration (lower middle) from 2000 to 2014.

Figure 3.11 shows the correlation of change in NDVI and mean temperature, precipitation and relative sunshine duration all over Switzerland from 2000 to 2014 respectively. Table 3.6 contains the corresponding correlation coefficients, as well as correlations for the different regions. Correlation of temperature and NDVI change was positive everywhere. It was strongest in the western part of the Alps, with Pearson's r of 0.16 in comparison to 0.02 to 0.05 in all other regions. Rain and NDVI change correlated mainly negatively, with an exception of the Eastern Alps (0.03). The relationship was strongest in the West Alps with Pearson's r of -0.34. The correlation of sunshine duration and NDVI change was mostly negative, except in the South Alps, where it was slightly positive (0.04). The strongest negative relationship was found in the North Alps (-0.33) and in the East Alps (-0.26).

Table 3.6 Pearson's correlation coefficient for changes in NDVI and changes in meteorological parameters in Switzerland and the biogeographic regions of the Alps.

	Temperature	*Precipitation*	*Sunshine*
Switzerland	0.04	-0.1	-0.16
Alps	0.11	-0.05	-0.19
North Alps	0.02	-0.14	-0.33
East Alps	0.02	0.03	-0.26
South Alps	0.05	-0.06	0.04
West Alps	0.16	-0.34	-0.18

3.3.3 Climatology and altitude

To link climatology with altitude, classes of 100 m.a.s.l. were created for the alpine regions and applied on the changes in climatological parameters. Figures 3.12 shows changes in temperature from 2000 to 2014 according to elevation class in the different alpine regions. When looking at all of the Alps (Figure 3.12, upper left), temperature mainly increased with increasing altitude. Especially in the South Alps (Figure 3.12, lower left) positive temperature change generally got stronger with higher altitudes. In most regions, lower elevation classes between fewer than 500 and 900 m (classes a to e) show higher variability and different patterns than higher elevation classes.

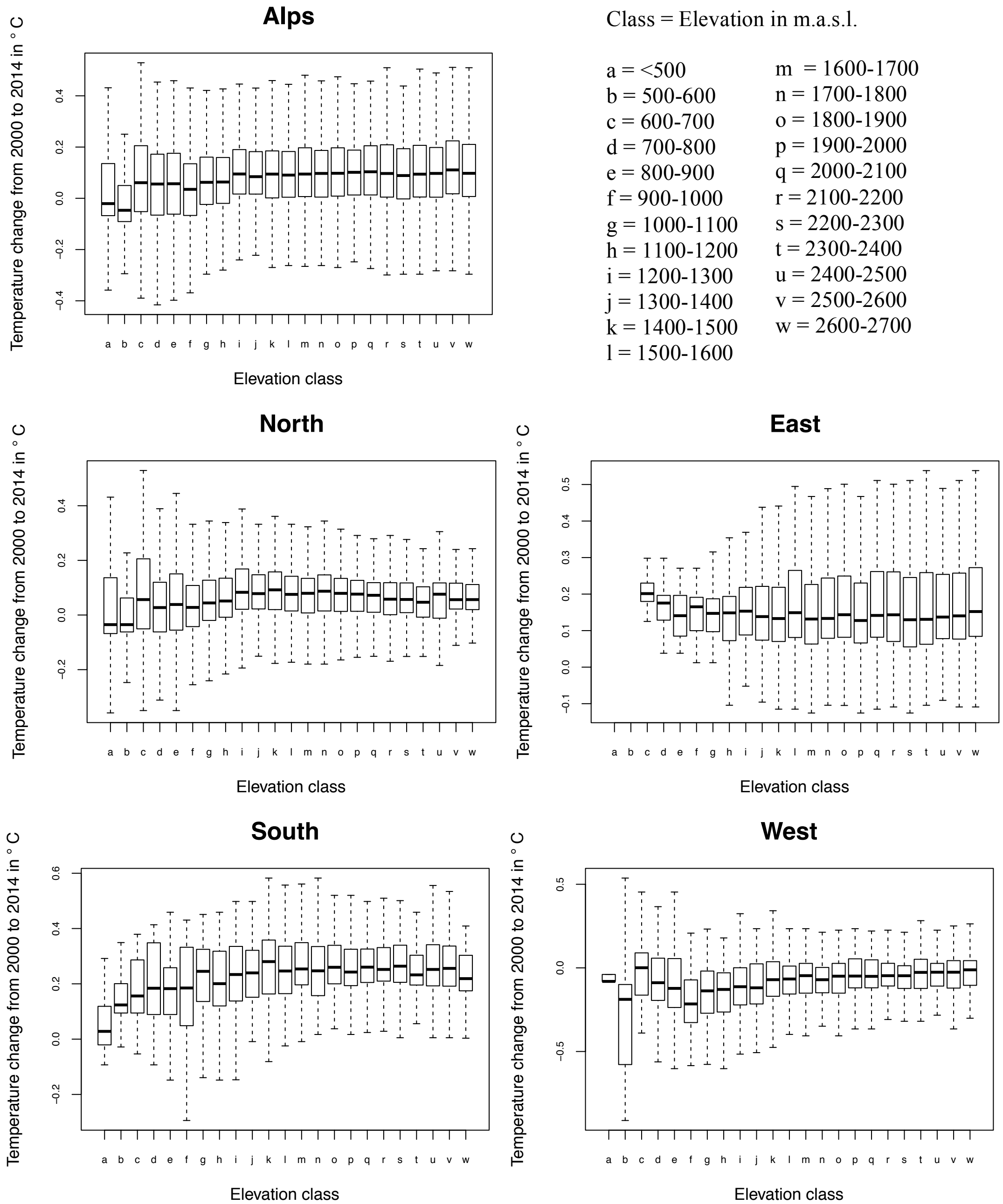

Figure 3.12 Change in temperature from 2000 to 2014 in the Alps (upper left), the North Alps (middle left), East Alps (middle right), South Alps (lower left) and West Alps (lower right) in relation to elevation class.

Figure 3.13 illustrates precipitation changes from 2000 to 2014 according to elevation class in the different alpine regions. In all regions, precipitation varies strongly in most elevation classes. A slightly positive trend is visible for all of the Alps.

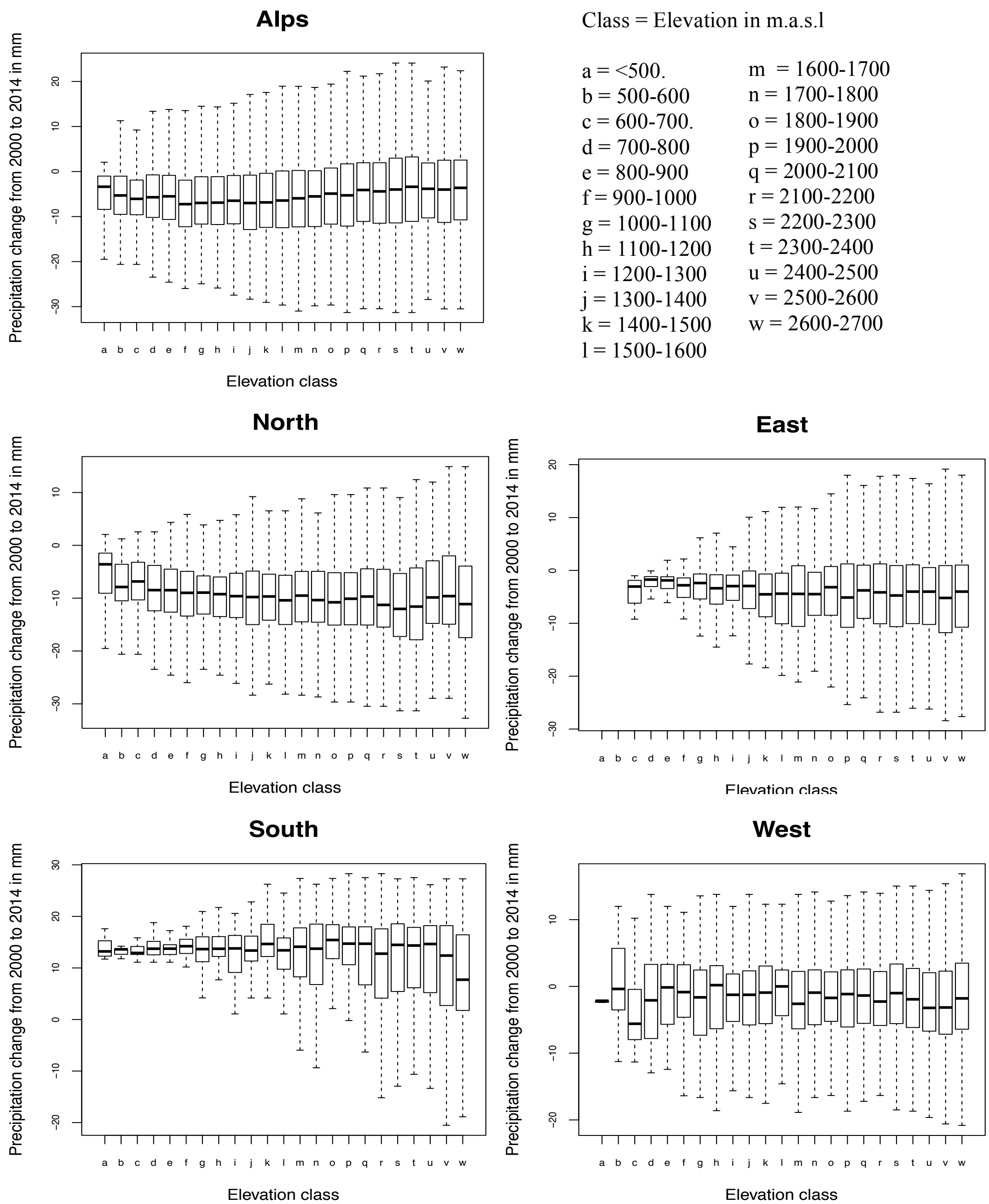

Figure 3.13 Change in precipitation from 2000 to 2014 in the Alps (upper left), the North Alps (middle left), East Alps (middle right), South Alps (lower left) and West Alps (lower right) in relation to elevation class.

In figure 3.14 changes in relative sunshine duration from 2000 to 2014 according to elevation class in the different alpine regions are shown. With an exception of the South Alps (Figure 3.14, lower left), relative sunshine duration decrease is clearly stronger with increasing altitude in all alpine regions.

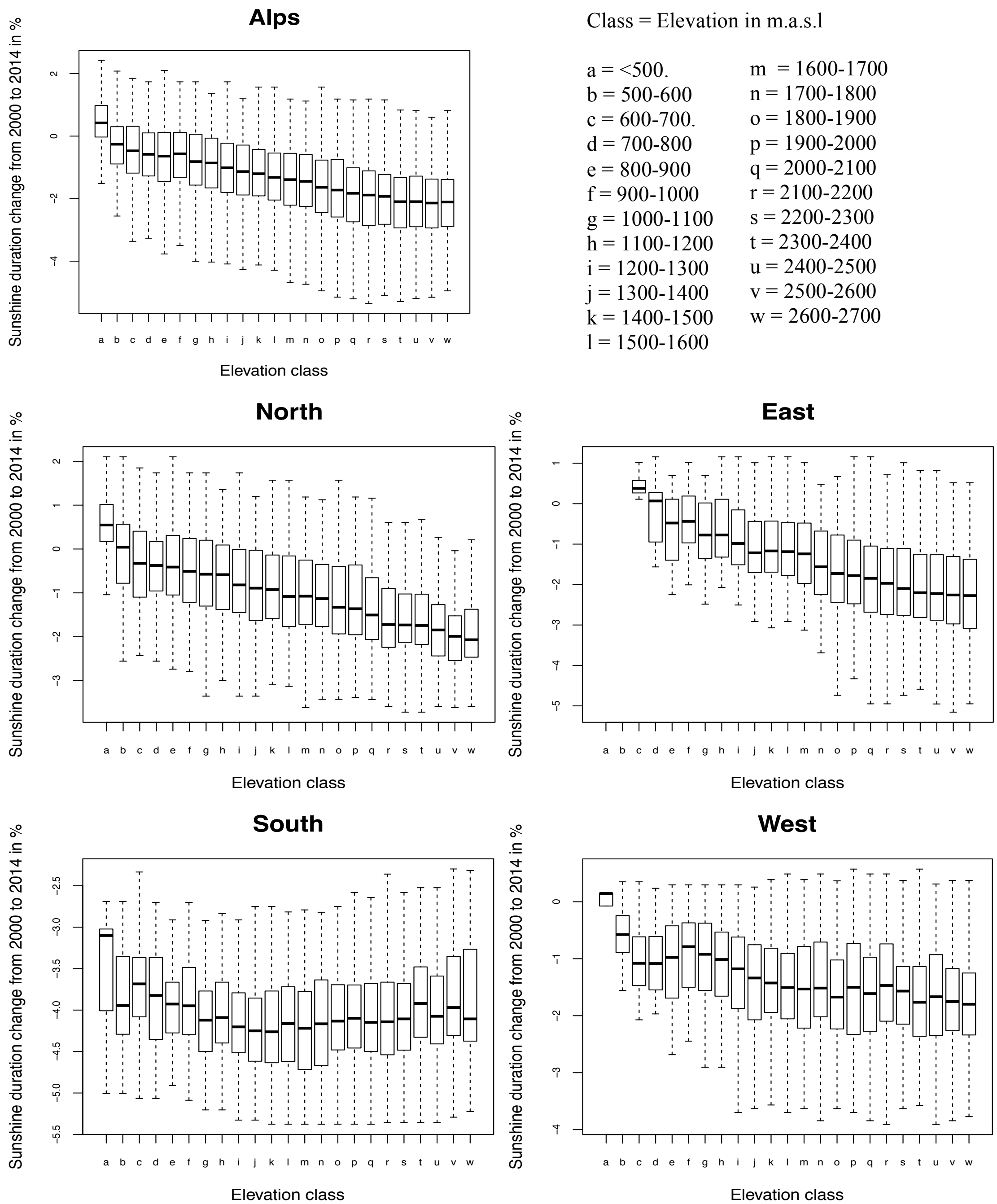

Figure 3.14 Change in relative sunshine duration from 2000 to 2014 in the Alps (upper left), the North Alps (middle left), East Alps (middle right), South Alps (lower left) and West Alps (lower right) in relation to elevation class.

3.3.4 Weather extremes

To study the impact that weather extremes could have on the trend model, I ran the linear model on the temperature data again while excluding 2003, a year with a strong summer heat wave and therefore the most anomalous year in the time series. The mean values for temperature change rose significantly in all regions, whereas standard deviation remained similar (Table 3.7). The difference became visible on the change map (Figure 3.15): Almost all of Switzerland now showed increasing temperature.

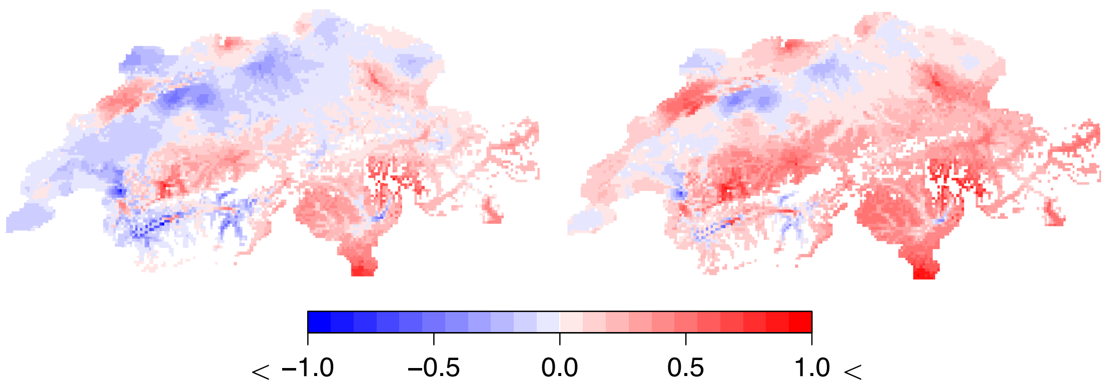

Figure 3.15 Comparison of temperature change in °C from 2000 to 2014 with (left) and without (right) 2003 in the model.

Table 3.7 Mean change in temperature for different regions between 2000 and 2014, excluding 2003.

Temperature [°C]	*Switzerland*	*All Alps*	*North Alps*	*East Alps*	*South Alps*	*West Alps*
Mean	0.17	0.27	0.26	0.34	0.37	0.1
Stdv.	0.25	0.17	0.13	0.17	0.13	0.17

4. Discussion

4.1 Vegetation activity

4.1.1 Vegetation activity trends

The Kalman filter removed outliers from the data and smoothed the time series, while keeping natural variability intact. The time series of the uncorrected data showed how much cloud cover was still present in the atmospherically corrected MODIS NDVI product. This is partly because the aerosol product used for the correction has a coarse resolution of 20 km (Huete et al., 1999). Consequently, for smaller areas with frequent cloud cover, like Switzerland, filtering of the NDVI product is crucial.

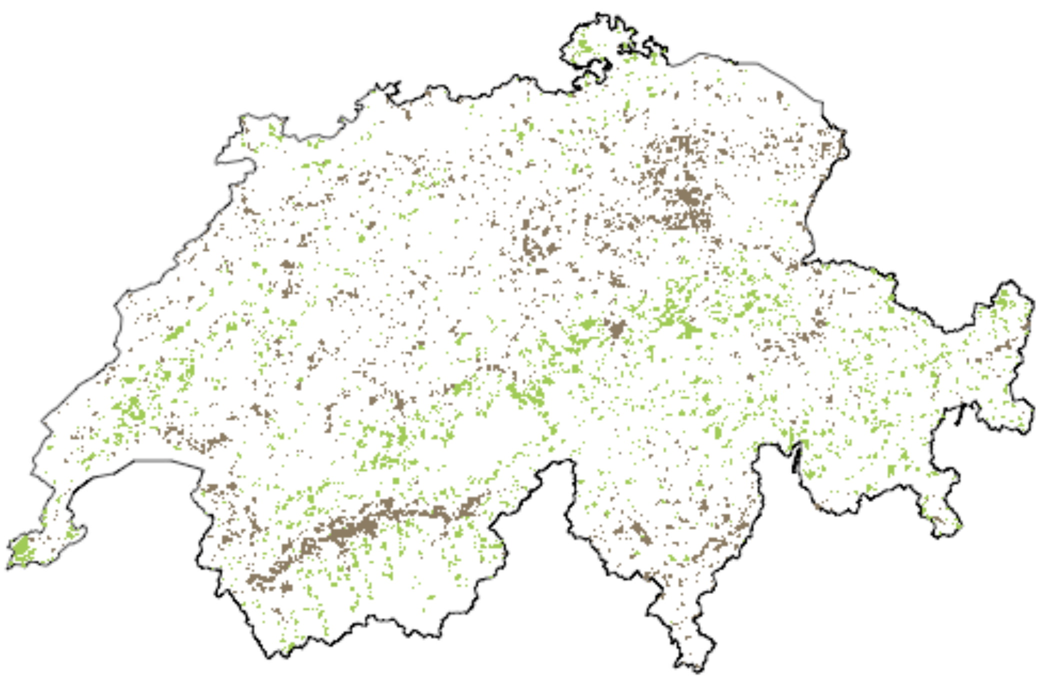

Figure 4.1 Highest (green) and lowest (brown) 5% of NDVI change values.

The on average negative vegetation activity trend found in this study for Switzerland corresponds to general global vegetation dynamic patterns of browning in the past 15 years. In figure 4.1, the lowest and highest five percent of the NDVI change values from the LM are highlighted to improve the visibility of the areas with strongest change.

Strong negative change is mainly visible in the Valais, the South and in the Plateau whereas positive change concentrates in the Alps and in the West of Switzerland.

The strong decrease of NDVI in the more densely populated Plateau is probably caused by other factors than climate: growing urban areas, decreasing agricultural land and policies influencing land cover are more likely to have an influence than limiting climatic controls. Significantly decreasing NDVI in the Valais and the South shows the potential impact of droughts on vegetation in Switzerland. As the Valais and the South are some of the driest areas in Switzerland, they are the first places to show drought caused vegetation changes. Especially the Valais experienced particularly negative change that was probably caused by heat waves in some years and/or decreasing precipitation in general.

4.1.2 Vegetation activity and altitude

NDVI decrease is weaker at higher altitudes, as the positive correlation between NDVI change and altitude suggests. There are several factors that could be responsible for this: As temperature change is positive in the alpine regions, with an average value of almost +0.1°C, it influences the locations where plant growth is possible. When average temperature over several months is over 0°C it can be assumed that plants start to grow, as there is probably no more snow cover and it is warm enough for plants to germinate. Below 0°C the water in plant structures can freeze and hinder growth, like in tree saps, where temperatures between -1 and -2°C lead to ice formation (Zimmermann, 1964). Temperature in the Alps decreases with around 0.5°C per 100m (Odermatt & Wachter, 2004); with increasing temperatures, this decrease shifts, and the elevation zone of average 0°C moves further up. Therefore the vegetation range shifts to higher altitudes (Walther et al., 2002) and NDVI increases with altitude. This can explain the stronger correlation of temperature with NDVI change in the alpine regions as well.

Land cover also influences changes in NDVI at higher altitudes. Shrubs and open spaces are mainly found in alpine regions and their land cover classes have considerable potential of growth, as shrub vegetation can mature into forest and open spaces can become vegetated under the right conditions. A typical succession of abandoned (agricultural) land consists of the development of grasslands, then shrubs and finally forest (Graf Pannatier, 2005). Also, the agricultural policies in the Alps encourage farmers there to facilitate increasing biodiversity and landscape maintenance (FOEN & FOAG, 2008) which can lead to more vegetation activity in all land cover classes. This is supported by the fact that NDVI shows the strongest relationship of increase with altitude in the shrub class, but the two other vegetation classes, forest and agriculture, also show a positive relationship.

4.2 Land cover

4.2.1 Land cover and vegetation activity

The land cover class with the strongest decrease in NDVI were urban areas. The forest and agriculture classes showed weaker decrease than urban areas but still had negative values. In contrast, the shrub class had slightly positive mean, while the mean of the open spaces class was even more positive.

There are many different factors that can influence land cover, for example biophysical factors, like climate or weather extremes, economic and technological factors, demographic factors, institutional factors or cultural factors (Geist & McDonnell, 2006).

Several land cover trends for Switzerland were already observed by federal studies: Population is increasing in Switzerland, primarily because of immigration. This, in combination with increasing need for space leads to an increasing demand in residential areas. In the Plateau, agriculture is pushed back and in mountainous regions rural exodus leads to increasing shrub and forest (Hotz & Weibel, 2005). In regions where urban areas are developing, forest growth is stagnating or wooded areas are decreasing slightly (Ginzler et al., 2011)

Forests have been growing in Switzerland for 150 years, reclaiming territory that they had lost before to clear cutting (Graf Pannatier, 2005). From 1985 to 2009 a strong increase in forested areas at higher altitudes has been observed (SFSO, 2013). This increase of forest and shrub was mainly due to abandonment of agricultural land, which was caused mostly by a decline in economic profitability (Rutherford et al., 2008). An explanation why forests have shown decreasing NDVI values in the time period between 2000 and 2014 could be that growth might have stagnated and the forest area has not been growing as much in the last 15 years. On the other hand, droughts, forest fires and beetle infestations could also be responsible for negative NDVI change. Forests provide important ecosystem services and protect settlements in the Alps from natural threats like landslides. Swiss forest law regulates forest management according to the principle of sustainability, and extensive cutting is restricted (Graf Pannatier, 2005). After storms or heat waves, forests are often threatened by bark beetle, benefitting from warm and dry conditions and weakened trees (Meier et al., 2003). Between 2000 and 2006, bark beetle infestations in Swiss forests where at a very high level (WSL, 2015), which could be linked to damages by storm Lothar in 1999 and the 2003 summer heat wave. This could be an aspect causing NDVI decrease in the forest class despite rising temperatures. Heat waves like the one in 2003 can also negatively impact tree growth for several years after, as droughts can damage the smaller roots, and the weakened trees are more susceptible to different kinds of diseases. Forest fires are primarily a problem in the drier regions of Switzerland, thus the Valais and the South are affected the most. But in general, forest fires are not a big threat to Swiss forests (Graf Pannatier, 2005).

The on-going shift to a service and leisure society and less people working in the first and second sector lead to an on-going decline of agricultural land. Many farmers sold their land as building land for more financial profit (Flury et al., 2005). Decreasing NDVI in agricultural land could also be caused by consolidation and erosion of soil (Bosshard et al., 2011). But NDVI in agricultural areas is not decreasing as strongly as in forests and there are several possible causes: New spatial planning policies have been developed (FOAG, 1992) and implemented into the federal spatial planning law (RPG, 2014) to stop increasing decentralisation and building on agricultural land. Policies like this have slowed the abandonment of agricultural land and weakened the structural change, although it is still in progress (FOAG, 2015). Also, several kinds of subsidies for alpine farming could be a reason for decreasing pressure on agricultural land (Mann & Mack, 2004). Subsidies for standard agricultural production were cut, which in the Alps mostly consisted of animal production and summering (Mack & Flury, 2008). But more subsidies were granted for environmental services, like the improvement and care of grasslands or shrubs (FOEN & FOAG, 2008). Land classified as agricultural could therefore also be natural vegetation growing back. So even though agricultural land has decreased, there are some areas where vegetation quality has been improved and NDVI has increased.

The shrub and open spaces classes showed only slightly negative, as well as increasing values, which could be explained by the increase in growth at higher altitudes. This can be mainly attributed to open spaces, sparsely vegetated areas, shrubs and grasslands, where growth has increased due to possible factors like warming or policy changes. Another factor, which is likely to have influenced positive changes in NDVI in open spaces are retreating glaciers and decreasing snow cover that open up potential new habitats for plants. As open spaces are mainly found at higher altitudes and they are the class with the strongest increase in NDVI, it is very likely that areas formerly covered by snow or glaciers are starting to become vegetated.

The different agriculture types show similar mean values, but in the permanent crop class, variability is much larger. This could be caused by the larger sensitivity of permanent crops to climate and weather influences (Olesen et al., 2011), as well as pests and diseases (Salinari et al., 2006). Warm springs without frost reduce the risk of damage in fruit trees, grapevine profits from warm temperatures in general, or extreme weather events like storms can have large negative impacts on yield (Olesen et al., 2011).

The forest types show a similar pattern, with close average values. Coniferous forest values vary more, a reasonable interpretation could be that coniferous trees can grow to higher altitudes but also grow at lower altitudes and as vegetation trends vary with elevation, the variability for coniferous forests increases. Mixed forests display values that lie in between broad-leaf and coniferous forest and therefore provide expected results.

Land cover changes were not as abundant in the CORINE datasets and were therefore only marginally analysed. The main changes in land cover from 2000 to 2012 were decreasing areas of glaciers and decreasing snow, which could be an indicator of rising temperatures, but could also be influenced by an early acquisition of CORINE data in 2006, when there was still non-permanent snow cover (Steinmeier, 2013). Nevertheless, this corresponds with the observed increase in vegetation in open spaces.

4.2.2 Land cover and altitude

In all vegetation classes, the positive correlation between elevation and NDVI was detectable. NDVI change in the agriculture class had only a weak correlation with elevation. As agricultural land is decreasing at all altitudes and it cannot naturally advance to higher altitudes, the altitude dependency is weak. Forests and specifically shrubs and grasslands have a stronger correlation, so that even positive values in NDVI change can be found at higher altitudes, indicating vegetation growth in the Alps. This could be another indicator that some forests are reclaiming old territory, primarily by shrubs maturing into forests (Rebetez, 2006). Additionally treelines and vegetation lines could have moved to higher altitudes, shifting the range of trees and other plants and resulting in positive change values in the highest elevation class.

4.3 Climatology

4.3.1 Climatology trends

Generally, changes in meteorological parameters were stronger in the alpine regions. This corresponds to several studies (e.g. Beniston, 2005a; Böhm et al., 2001) discovering changes in climatologies to be more extreme in mountainous areas. Therefore the meteorological trends were analysed in more detail for the alpine region and the four sub-regions.

Temperature trends suggest that warming took place primarily at higher altitudes, with the most substantial positive changes in the East and South Alps, and cooling in Plateau along the Alps into the West and the Valais. Correlations with NDVI were especially strong in the West Alps (including the Valais), where both temperature and NDVI appear to have considerably decreased. Precipitation generally shows negative change, with several patches of increase in some areas and especially strong increase in the South. Changes in sunshine duration are caused by differences in air pressure resulting in clouds or fog. Relative sunshine duration change was on average negative, with positive change located in the Plateau and along the Alps into the West. Negative change concentrated in the Alps, the South and the Jura. Sunshine duration has strong seasonal differences: The Alps have more sun than the rest in winter because of fog at lower elevations, whereas in summer there is more sun in the Plateau. Precipitation also shows strong seasonal variations. Although these two meteorological parameters are difficult to analyse on an annual basis, some general trends can lead to a better understanding of climatologic influences on vegetation.

4.3.2 Climatology and vegetation activity

Correlation between NDVI and temperature, precipitation or relative sunshine duration should be positive, as all these factors can facilitate plant growth. However, temperature is the only meteorological parameter actually showing a positive relationship with NDVI. This is a sign that neither rain nor sunshine duration are strong limiting factors for vegetation growth in most parts of Switzerland. Furthermore, less precipitation can also mean less snow, which would be another factor facilitating vegetation increase.

Vegetation dynamics are a combination of growing season length and total amount of vegetation (Roerink et al., 2003). Change in NDVI shows how much the greenness has increased or decreased, but the length of the growing season can have an influence on the trend. Longer growing seasons can lead to more overall vegetation activity and greenness, but not all plant species show increasing growth with longer growing seasons (Keller et al., 2005). This seems to be accurate, as growing season probably is getting longer in Switzerland due to warming but NDVI is decreasing anyway. Different forest types or plant species in general react differently to climate influences, they can be more or less adaptive and have different sensitivities (Park et al., 2015). Therefore, not all vegetation types show the same reaction to changing climatologies and relationships between them are not as straightforward as one would first expect.

Studies have shown that photoperiod (daylength) is the main factor limiting plant growth for most parts of Western Europe, defining the potential growing season, and that during the growing season water availability is the main limiting factor (Jolly et al., 2005). As photoperiod is invariant, changes in growing season length relate to temperature changes. Therefore climatically induced NDVI change in Switzerland stems from changes in growing season length, caused by temperature changes, and precipitation change influencing water availability. The decrease in precipitation doesn’t seem to be strong enough to cause a large-scaled negative impact on plant growth. Temperature is most important for the growing season in most of Switzerland, as the following figure (4.2) by Garonna et al. (2015) suggests:

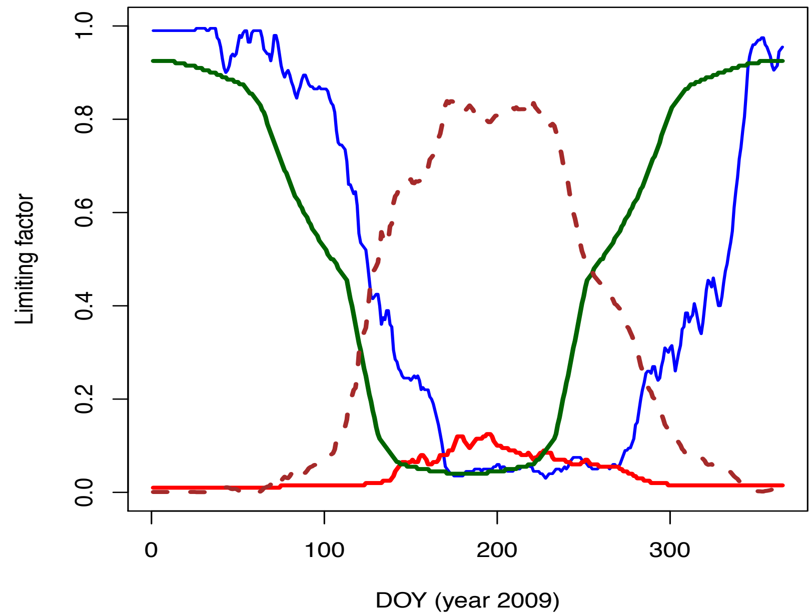

Figure 4.2 Modeled influence of climatic growth limitation for a 50 x 50 km area in central Switzerland. Blue represents temperature, green photoperiod, red water availability (vapour pressure deficit) and the dashed line the resulting growth potential. After Garonna et al. (2015).

As photoperiod is not variable, minimum temperature is the only factor influencing the length of the growing season in the area. During the growing season water availability influences growth more, but the influence is strongest at the end of growing season, where there isn't much growth anymore. This is confirmed by a study by Ichii et al. (2002) who identified temperature rise as the main driver of NDVI rise in mid- and northern latitudes and Xiao & Moody (2005) who did not find a relationship between increasing greenness and precipitation in the majority of the world. But, strongly decreasing NDVI values in the driest regions of Switzerland suggest that there are some places were reduced water availability may start to limit vegetation activity (e.g. in the Valais). This is supported by the fact that several tree species in Switzerland are already suffering from drought (Eilmann & Rigling, 2012). The decrease in both NDVI and precipitation in parts of Switzerland does not seem coincidental, even though correlations aren't positive in general, and should be further investigated. The lack of positive correlation could also be caused by the fact that precipitation is very variable and doesn't show strong long-term trends yet (OcCC, 2008), although a decreasing tendency seems to be apparent. Also, precipitation varies with season and scenarios for the future predict that precipitation will decrease in summer and increase in winter (OcCC, 2008). So annual trends might show an increase in precipitation, even though summer precipitation, which influences vegetation growth more than winter precipitation does, could be decreasing. The same could be true for sunshine duration, as it also shows different patterns for summer and winter, although it could also be possible that the changes in sunshine duration were not strong enough to have a detectable impact on vegetation.

The impacts of changes in climatologies are hard to quantify, especially in mountainous regions, due to co-varying factors like the complex topography (Beniston, 2005b). However, with the expectedly continuing warming in the Alps, vegetation will move up even further, several species will go extinct or be exchanged with different species, and biodiversity will be strongly influenced (OcCC, 2008; Pauli, et al., 2007; Keller et al., 2005). This can have impacts on vegetation activity, which are difficult to foresee. It is also important to note that although climate influences vegetation, it is also possible that vegetation influences climate in reverse, for instance by changing surface albedo, soil temperature or CO_2 and H_2O fluxes (Richardson et al., 2013). Furthermore, climate can be influenced by land cover (Verburg et al., 2011). All these factors make it challenging to attribute possible drivers to vegetation change.

4.3.3 Climatology and altitude

The dependence of climatologies and altitude becomes visible when looking at the relationship of elevation with temperature and elevation with relative sunshine duration. Temperature seems to be increasing with altitude in the Alps, especially in the South. This is an indication that alpine regions are impacted more by warming or temperature change in general than lower areas. Sunshine duration seems to be decreasing with altitude, except the South, where the trend isn't as clear. More clouds and fog moving up to higher altitudes probably cause this decrease. The trend could also be linked to increasing temperatures at higher altitudes, as clouds tend to increase warming in the

Alps (Marty et al., 2002). Precipitation shows no clear altitudinal trends and very strong variability inside the elevation classes.

Increasing NDVI at higher altitudes can be indirectly caused by temperature increase. First, snow can melt earlier if spring temperatures increase and therefore plants have the opportunity to start growing earlier. This could be happening in the Swiss Alps, where according to Beniston (2012) snow cover seems to be receding. So longer growing seasons seem to lead to more vegetation in higher altitudes. Secondly, warming leads to retreating glaciers, which opens up new possible habitats for plants, and this also seems to be the case in Switzerland (OcCC, 2008).

4.3.4 Weather extremes

The meteorological trend models showed high p-values, indicating low significance, and the difference between the model with all years and the one without 2003 illustrates that in climatologically short time periods, the trend can be strongly influenced by one single extreme year. For climate-related analyses, 15 years is a relatively short period and can bias the results. Weather extremes, like a heat wave in a single year, can strongly influence the outcome of the linear regression. The climatological trends were therefore not as accurate as they probably would have been if a longer time period had been available.

Droughts are not yet a substantial problem; there have been only single years where large-scale droughts have occurred all over Switzerland. But according to scenarios of future temperature and precipitation trends, droughts might become an increasing complication (OcCC, 2008). Also heat waves, like the one that occurred 2003, are predicted to become more frequent in the future (Beniston, 2004) and can also lead to recurring and more severe droughts in more areas of Switzerland. The impact of droughts on vegetation will very likely become more severe as well and possible outcomes will have to be investigated.

4.4 Limitations & Outlook

4.4.1 Vegetation activity

The first important decision in the data preparation was to choose a method to pre-process the data. With the HANTS algorithm, the Fourier series accuracy is dependant on frequency (Rayner, 1971) and it is always a balancing act between smoothing too much and potentially eliminate seasonality or not smoothing enough and keeping cloud covered dates and outliers in. Even though the Kalman filtering method is computationally more intensive, it was decided to use it to improve the quality of the NDVI data.

The GPP approach has limited application in a small and heterogeneous country like Switzerland because of spatial-resolution problems. The coarse resolution of the underlying MODIS data, mainly the 1° resolution of the meteorological reference caused the GPP trend model to have many uncertainties and high p-values. It could not reproduce vegetation activity trends demonstrated with the NDVI model; even showing opposite trends in some parts of the country (Figure 4.3). This indicates that the spatial resolution of the MODIS GPP product, which might be working well on a global scale, is not well suited for analysing smaller regions like Switzerland. I would therefore advise for future studies to calculate a suitable GPP product using meteorological data from MeteoSwiss or other national databases to improve results at a regional scale.

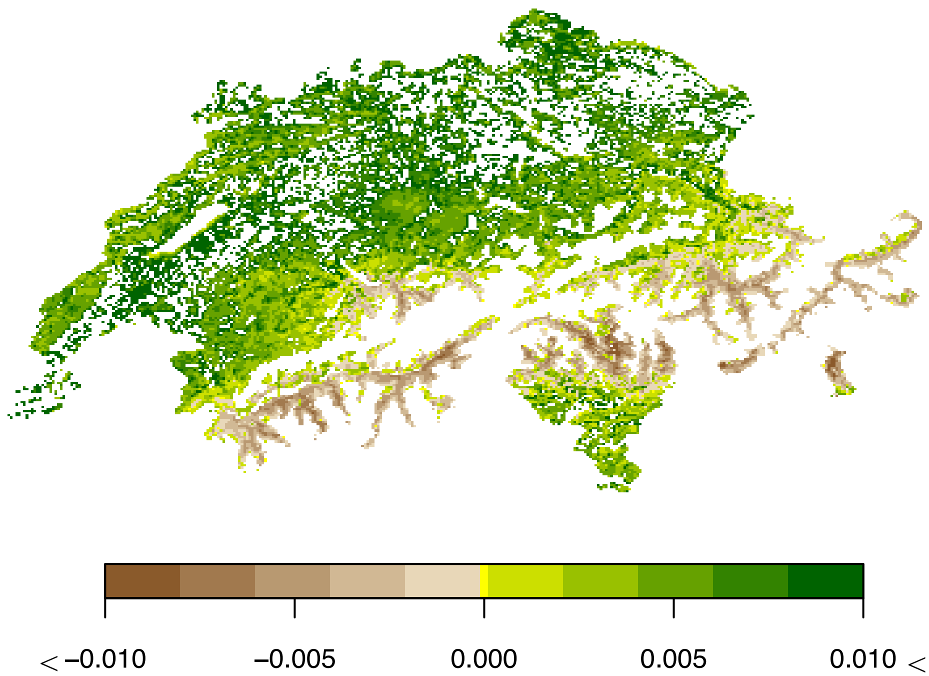

Figure 4.3 Change in GPP from 2000 to 2014 in kgC/m^2.

Another factor leading to a decrease in accuracy could be resampling, which influences data strongly (Raptis et al., 2003). The main problem was that all data used were at different scales and in different projections and in the process of resampling much information gets lost or distorted. This problem can't be eliminated completely and it has to be taken into account that uncertainties in the data increase.

4.4.2 Land cover

CORINE showed a limited area with land cover change. This is in strong contrast to other data collected concerning land cover in Switzerland, as for example the Swiss land use statistics by the SFSO (2013). Due to the relatively large pixel size of 500m, there might have been some changes inside the classes that contribute to the changes in NDVI, even though most classes remained the same in the CORINE data from 2000 to 2012. CORINE was applied as it seemed well suited due to the many inputs used in the calculation as well as the comparability as European standard. But to further investigate land cover change, other data like the Swiss land use statistics would probably be better suited. It would be interesting to know if not only land cover change results but also results for land cover analysis in general would improve.

4.4.3 Climatology

To decrease the influence of single extreme years on climatologic trends, a 30-year analysis including AVHRR data for the time before MODIS was in operation could give more insights on the relationship between climatologies and NDVI. For precipitation and sunshine duration it would also be interesting to study seasonal rather than annual trends and see if it improves correlations to NDVI change and if stronger relationships can be detected.

The biogeographic regions used to look at separate trends might still have been too heterogeneous. For example the decrease in the West Alps is not stronger than anywhere else but the region contains the area with strongest decrease. This might be another reason why correlating climatology with NDVI change did not yield clearer results. The complexity of the different regions with different vegetation types, local climatologies, soil properties, scale dependences and topographies make it hard to identify suitable stratifications.

5. Conclusion

In this study, the development of vegetation in Switzerland from 2000 to 2014 was investigated and linked to land cover and climatologies. The research questions formulated in the beginning can be answered as follows:

1. How has vegetation activity in Switzerland changed in the last 15 years?
    - Is the globally observed trend-shift from greening to browning in this timespan also observable in Switzerland?
    - Where are hotspots of vegetation change?

Similar patterns to global trends can be found in Switzerland. NDVI values were decreasing on average, which indicates a reduction in vegetation activity. Drought effects weren't a large influence like in other regions but might well be in the future. Vegetation dynamics are mainly influenced by temperature at the moment but long-term changes in precipitation could shift the importance of different drivers. Especially around urban areas, in the West and in the mountains change has happened. Lower, more densely populated areas experienced a stronger decrease in vegetation activity whereas areas of increasing activity concentrated in the Alps and in the West of Switzerland. The negative NDVI trends got significantly weaker at higher altitudes indicating a link between change in vegetation activity and elevation in Switzerland.

2. Is land cover related to vegetation trends?
    - Are vegetation change patterns different among land cover types?

Land cover type has a strong influence on the behaviour of vegetation activity. NDVI change had the largest negative values in urban areas, which is mainly caused by growing urban areas and building on natural and agricultural land. Forests showed negative change as well, even though forests have been re-growing for over a century. This could be because of stagnating growth and an increase in heat waves, droughts, fires and beetle infestations. Agricultural areas had weaker negative change, which could be caused by a slowing of land abandonment and less converting of agricultural land to building land. This was mainly achieved by policies, especially by subsidiaries granted for environmental services, which restored some economic profitability and aided growth of natural vegetation. Also, new policies to stop decentralisation and building on agricultural land have weakened urban growth. Shrubs and open spaces had mainly positive change values. Firstly, this could be because shrubs and open spaces have large potential for growth, as shrubs can grow into forests and open spaces can become new habitats for vegetation. Secondly, due to their concentration at higher altitudes, increasing temperatures favour growth in shrubs and open spaces by melting snow and glaciers or shifting the contour line where vegetation growth is possible. Land cover is also influenced strongly by climate, so attributing only one cause to the patterns is difficult.

3. Are climatologies related to vegetation trends?
    - Can statistical relationships with climatologies explain the vegetation change patterns?

In relation to NDVI change, all meteorological parameters displayed weak correlations. Only temperature correlated positively with changes in NDVI, but also precipitation and sunshine duration were anticipated to show a positive relationship. There are several possible explanations for this: Firstly, temperature was probably the main factor influencing vegetation in Switzerland during the last years. Secondly, precipitation varies strongly during the year and rain in summer is more important for plants than in winter. Also, precipitation can be in the form of snow and less snow leads can lead to increased plant growth. Lastly, sunshine duration differs with season as well and could also be just not as influential as temperature. Due to different species reacting differently to changes in climatologies and the complexity of relationships between the various climatic systems of Switzerland, especially in the Alps, the relationship between climatologies and NDVI is not very straightforward and difficult to analyse.

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Bibliography

Asrar, G., Fuchs, M., Kanemasu, E. T., & Hatfield, J. L. (1984). Estimating Absorbed Photosynthetic Radiation and Leaf Area Index from Spectral Reflectance in Wheat. *Agronomy Journal*, *76*(2), 300–306.

Beniston, M. (2004). The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. *Geophysical Research Letters*, *31*, L02202.

Beniston, M. (2005a). An Overview of Extreme Climatic Events in Switzerland: Implications for Assessing Economic Damages and Costs. In: Haurie, A. & Viguier, L. (eds.), *The Coupling of Climatic and Economic Dynamics* (Volume 22). Dordrecht: Springer. 321-340.

Beniston, M. (2005b). Mountain climates and climatic change: An overview of processes focusing on the European Alps. *Pure and Applied Geophysics*, *162(8)*, 1587–1606.

Beniston, M. (2012). Is snow in the Alps receding or disappearing? *Wiley Interdisciplinary Reviews: Climate Change*, *3(4)*, 349–358.

Böhm, R., Auer, I., Brunetti, M., Maugeri, M., Nanni, T., & Schöner, W. (2001). Regional temperature variability in the European Alps: 1760-1998 from homogenized instrumental time series. *International Journal of Climatology*, *21(14)*, 1779–1801.

Bosshard, A., Schläpfer, F., & Jenny, M. (2011). *Weissbuch Landwirtschaft Schweiz - Analysen und Vorschläge zur Reform der Agrarpolitik* (2nd ed.). Bern: Vision Landwirtschaft, Haupt Verlag.

Box, E. O., Holben, B. N., & Kalb, V. (1989). Accuracy of the AVHRR vegetation index as a predictor of biomass, primary productivity and net CO2 flux. *Vegetatio*, *80*(2), 71–89.

Brinson, M. M., Lugo, A. E., & Brown, S. (1981). Primary Productivity, Decomposition and Consumer Activity in Freshwater Wetlands. *Annual Review of Ecology and Systematics*, 12, 123-161.

Cannone, N., Sgorbati, S., & Guglielmin, M. (2007). Unexpected impacts of climate change on alpine vegetation. *Frontiers in Ecology and the Environment*, *5(7)*, 360–364.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112(1)*, 155–159.

De Jong, R. (2008). *Analysis of vegetation-activity trends in a global land degradation framework*. Wageningen University, The Netherlands.

De Jong, R., Verbesselt, J., Zeileis, A., & Schaepman, M. E. (2013). Shifts in global vegetation activity trends. *Remote Sensing*, *5*(3), 1117–1133.

DeFries, R. S., Field, C. B., Fung, I., Collatz, G. J., & Bounoua, L. (1999). Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. *Global Biogeochemical Cycles*, *13*(3), 803–815.

Eilmann, B., & Rigling, A. (2012). Tree-Growth Analyses to Estimate Tree Species' Drought Tolerance. *Tree Physiology*, *32(2)*, 178–187.

Fensholt, R., Rasmussen, K., Nielsen, T. T., & Mbow, C. (2009). Evaluation of earth observation based long term vegetation trends - Intercomparing NDVI time series trend analysis consistency of Sahel from AVHRR GIMMS, Terra MODIS and SPOT VGT data. *Remote Sensing of Environment*, *113*(9), 1886–1898.

Field, C.B., Randerson, J. T. & Malmström, C. M. (1995). Global net primary production: Combining ecology and remote sensing. *Remote Sensing of Environment, 51(1),* 74-88.

Flury, C., Zgraggen, K., Giuliani, G., & Gotsch, N. (2005). Flächen- und Landnutzung in der Schweiz – eine ökonomische Betrachtung. *Festschrift Zu Ehren von Professor Peter Rieder*, 65–82.

FOAG - Federal Office for Agriculture. (2015). *Agrarbericht 2015*. Bern.

FOAG - Federal Office for Agriculture. (1992). *The sectoral plan for cropland protection.* Bern. Accessed January 12, 2016 at http://www.are.admin.ch/sachplan/04910/index.html?lang=en

FOEN - Federal Office for the Environment. (2001). Die biogeographischen Regionen der Schweiz - Erläuterungen und Einteilungsstandard. Umweltmaterialien UM. Accessed October 30 , 2015, at http://www.bafu.admin.ch/publikationen/publikation/00207/index.html?lang=de

FOEN & FOAG - Federal Office for the Environment & Federal Office for Agriculture. (2008). Umweltziele Landwirtschaft - Hergeleitet aus bestehenden rechtlichen Grundlagen. *Umwelt-Wissen*, 221 S.

Garonna, I., Schenkel, D., De Jong, R. & Schaepman, M.E. (2015). Linking Land Surface Phenology and Growth Limiting Factor Shifts over the Past 30 Years. AGU Fall Meeting. San Francisco, USA.

Gehrig-Fasel, J., Guisan, A., & Zimmermann, N. E. (2007). Tree line shifts in the Swiss Alps: Climate change or land abandonment? *Journal of Vegetation Science*, *18(4)*, 571–582.

Geist, H., & McDonnell, W. (2006). Causes and Trajectories of Land-Use/Cover Change. In: Lambin, E.F. & Geist, H. (eds.), *Land-Use and Land-Cover Change: Local Processes and Global Impacts* (pp. 41–69). Berlin: Springer. 41-69.

Ginzler, C., Brändli, U.-B., & Hägeli, M. (2011). Waldflächenentwicklung der letzten 120 Jahre in der Schweiz. *Schweizerische Zeitschrift Fur Forstwesen*, *162,*(9), 337–343.

Goward, S. N., Tucker, C. J., & Dye, D. G. (1985). North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. *Vegetatio*, *64(1)*, 3–14.

Graf Pannatier, E. (2005). *Wie steht's um unseren Wald?*. Bern: Haupt.

Herrmann, S. M., Anyamba, A., & Tucker, C. J. (2005). Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environmental Change*, *15*(4), 394–404.

Holtmeier, F. K., & Broll, G. (2005). Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales. *Global Ecology and Biogeography*, *14*(5), 395–410.

Hotz, M., & Weibel, F. (2005). *Arealstatistik Schweiz, Zahlen – Fakten – Analysen*. Neuchâtel: Bundesamt für Statistik (BFS).

Houghton, B. R. A., Woods, T., Box, P. O., & Hole, W. (1999). The annual net flux of carbon to the atmosphere from changes in land use 1850 – 1990. *Tellus B*, *51(2)*, 298–313.

Huete, A., Justice, C. & van Leeuwen, W. (1999). MODIS vegetation index (MOD13) - Algorithm Theoretical Basis Document, version 3.0. (http://modis.gsfc.nasa.gov/data/atbd/atbd_mod13.pdf), accessed January 12, 2016 at https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod13a1

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, *83(1-2)*, 195–213.

Ichii, K., Kawabata, A., & Yamaguchi, Y. (2002). Global correlation analysis for NDVI and climatic variables and NDVI trends: 1982-1990. *International Journal of Remote Sensing*, *23*(18), 3873–3878.

IPCC - Intergovernmental Panel on Climate Change. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri R. K. & Meyer L.A. (eds.). IPCC, Geneva, Switzerland.

IPCC - Intergovernmental Panel on Climate Change. (1990). Climate change: The IPCC Impacts Assessment. Report prepared for Intergovernmental Panel on Climate Change by Working Group II. Tegart, W.J. McG. , Sheldon, G.W. & Griffiths, D.C. (eds.). Australian Government Publishing Service, Canberra, Australia.

Jakubauskas, M. E., Legates, D. R., & Kastens, J. H. (2001). Harmonic analysis of time-series AVHRR NDVI data. *Photogrammetric Engineering and Remote Sensing*, *67(4)*, 461–470.

Jolly, W. M., Nemani, R., & Running, S. W. (2005). A generalized, bioclimatic index to predict foliar phenology in response to climate. *Global Change Biology*, *11(4)*, 619–632.

Julien, Y., & Sobrino, J. A. (2010). Comparison of cloud-reconstruction methods for time series of composite NDVI data. *Remote Sensing of Environment*, *114(3)*, 618–625.

Kalman, R. E. (1960). A New Approach to Linear Filtering and Prediction Problems. *Transactions of the ASME-Journal of Basic Engineering*, *82(1)*, 35–45.

Keller, F., Goyette, S., & Beniston, M. (2005). Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain. *Climatic Change*, *72(3)*, 299–319.

Kim, Y. (2013). Drought and elevation effects on MODIS vegetation indices in northern Arizona ecosystems. *International Journal of Remote Sensing*, *34(14)*, 4889–4899.

Kleynhans, W., Olivier, J. C., Wessels, K. J., Van Den Bergh, F., Salmon, B. P., & Steenkamp, K. C. (2010). Improving Land Cover Class Separation Using an Extended Kalman Filter on MODIS NDVI Time-Series Data. *IEEE Geoscience and Remote Sensing Letters*, *7(2)*, 381–385.

Lambin, E. F., Geist, H., Rindfuss, R.R. (2006). Introduction: Local Processes with Global Impacts. In: Lambin, E.F. & Geist, H. (eds.), *Land-Use and Land-Cover Change : Local Processes and Global Impacts.* Berlin: Springer. 1-8.

LP DAAC - Land Processes Distributed Active Archive Center. (2000-2014). MOD13A1 & MOD17A2. Version 5. NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov), accessed February 10, 2015, at reverb.echo.nasa.gov/

Mack, G., & Flury, C. (2008). *Wirkung der Sömmerungsbeiträge*. ART - Agroscope Reckenholz-Tänikon. Ettenhausen.

Mann, S., & Mack, G. (2004). *Wirkungsanalyse der Allgemeinen Direktzahlungen*. Agroscope - FAT Tänikon. Ettenhausen.

Marty, C., Philipona, R., Fröhlich, C. & Ohmura, A. (2002). Altitude dependence of surface radiation fluxes and cloud forcing in the alps: results from the alpine surface radiation network. *Theoretical and Applied Climatology, 72,* 137-155.

Meier, F., Gall, R., & Forster, B. (2003). Ursachen und Verlauf der Buchdrucker-Epidemien (Ips typographus L.) in der Schweiz von 1984 bis 1999. *Schweizerische Zeitschrift Für Forstwesen*, *154(11)*, 437–441.

Menenti, M., Azzali, S., Verhoef, W., & Vanswol, R. (1993). Mapping agroecological zones and time-lag in vegetation growth by means of Fourier-analysis of time-series of NDVI images. *Advances in Space Research*, *13(5)*, 233-237.

Meteo Swiss - Federal Office of Meteorology and Climatology. (2014a). Räumliche Daten. Accessed November 20, 2015, at http://www.meteoswiss.admin.ch/home/services-and-publications/produkte.html

Meteo Swiss - Federal Office of Meteorology and Climatology. (2014b). Klima der Schweiz. Accessed December 3, 2015, at http://www.meteoschweiz.admin.ch/home/klima/vergangenheit/klima-der-schweiz.html

Monteith, J. L. (1972). Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology*, *9(3)*, 747–766.

Negrón Juárez, R. I., & Liu, W. T. (2001). FFT analysis on NDVI annual cycle and climatic regionality in northeast Brazil. *International Journal of Climatology*, *21(14)*, 1803–1820.

Neigh, C. S. R., Tucker, C. J., & Townshend, J. R. G. (2008). North American vegetation dynamics observed with multi-resolution satellite data. *Remote Sensing of Environment*, *112(4)*, 1749–1772.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., … Running, S. W. (2003). Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, *300(5625)*, 1560–1563.

OcCC - Organe consultatif sur les changements climatiques (2008). Das Klima ändert – was nun? Der neue UN-Klimabericht (IPCC 2007) und die wichtigsten Ergebnisse aus Sicht der Schweiz. Bern.

Odermatt, A., & Wachter, D. (2004). *Schweiz - Eine moderne Geographie* (4th ed.). Zürich: Verlag Neue Zürcher Zeitung.

Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, a. O., Seguin, B., Peltonen-Sainio, P., … Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, *34(2)*, 96–112.

Ozenda, P., & Borel, J. (1991). *Les conséqeunces possibles des changements climatiques dans l'arc alpine - Rapport FUTURALP 1991*. ICALPE: Centre international pour l'environnement alpin.

Park, H., Jeong, S., Ho, C., Kim, J., Brown, M. E., & Schaepman, M. E. (2015). Nonlinear response of vegetation green-up to local temperature variations in temperate and boreal forests in the Northern Hemisphere. *Remote Sensing of Environment*, *165*, 100–108.

Pauli, H., Gottfried, M., Reiter, K., Klettner, C., & Grabherr, G. (2007). Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994-2004) at the GLORIA master site Schrankogel, Tyrol, Austria. *Global Change Biology*, *13(1)*, 147–156.

Potter, C., Klooster, S., & Genovese, V. (2012). Net primary production of terrestrial ecosystems from 2000 to 2009. *Climatic Change*, *115(2)*, 365–378.

Raptis, V. S., Vaughan, R. A., & Wright, G. G. (2003). The effect of scaling on land cover classification from satellite data. *Computers and Geosciences*, *29(6)*, 705–714.

Rayner, J. N. (1971). *An introduction to spectral analysis*. London: Pion Limited.

Raynolds, M. K., Comiso, J. C., Walker, D. A., & Verbyla, D. (2008). Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI. *Remote Sensing of Environment*, *112(4)*, 1884–1894.

Rebetez, M. (2006). *Helvetien im Treibhaus*. Bern: Haupt.

Richardson, A. D., Keenan T. F. , Migliavacca M., Ryu Y., Sonnentag O., & Toomey M. (2013) Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology, 169*, 156-173.

Roerink, G. J., Menenti, M., Soepboer, W., & Su, Z. (2003). Assessment of climate impact on vegetation dynamics by using remote sensing. *Physics and Chemistry of the Earth*, *28(1-3)*, 103–109.

Roerink, G. J., Menenti, M., & Verhoef, W. (2000). Reconstructing cloudfree NDVI composites using Fourier analysis of time series. *International Journal of Remote Sensing*, *21(9)*, 1911–1917.

RPG - Raumplanungsgesetz. (2014). Art. 3. Accessed January 12, 2016 at https://www.admin.ch/opc/de/classified-compilation/19790171/index.html

Running, S. W., Nemani, R. R., Glassy, J. M., & Thornton, P. E. (1999). MODIS daily photosynthesis (PSN) and annual net primary production (NPP) product (MOD17). Algorithm Theoretical Basis Document, version 3.0. (http://modis.gsfc.nasa.gov/data/atbd/atbd_mod16.pdf), accessed January 12, 2016 at https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod17a2

Rutherford, G. N., Bebi, P., Edwards, P. J., & Zimmermann, N. E. (2008). Assessing land-use statistics to model land cover change in a mountainous landscape in the European Alps. *Ecological Modelling*, *212(3-4)*, 460–471.

Salinari, F., Giosuè, S., Tubiello, F. N., Rettori, A., Rossi, V., Spanna, F., … Gullino, M. L. (2006). Downy mildew (Plasmopara viticola) epidemics on grapevine under climate change. *Global Change Biology*, *12(7)*, 1299–1307.

SFSO - Swiss Federal Statistical Office. (2013). *Land use in Switzerland*. Neuchâtel.

Slayback, D. A., Pinzon, J. E., Los, S. O., & Tucker, C. (2003). Northern hemisphere photosyntetic trends 1982-1999. *Global Change Biology*, *9(1)*, 1–15.

Steinmeier, C. (2013). CORINE Land Cover 2000/2006 Switzerland. Final Report. Birmensdorf, Swiss Federal Institute for Forest, Snow and Landscape Research WSL. (http://www.wsl.ch/publikationen/pdf/12359.pdf), accessed March 5, 2015, at http://www.wsl.ch/fe/landschaftsdynamik/projekte/corine_landcover_update/index_DE

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, *8*(2), 127–150.

USGS - U.S. Geological Survey. (2003). STRM Documentation. EROS Data Center, Sioux Falls. Accessed November 4, 2015 at http://dds.cr.usgs.gov/srtm/version2_1/SRTM30/srtm30_documentation.pdf

Verbesselt, J., Zeileis, A., & Herold, M. (2012). Near real-time disturbance detection using satellite image time series. *Remote Sensing of Environment*, *123*, 98–108.

Verburg, P. H., Neumann, K., & Nol, L. (2011). Challenges in using land use and land cover data for global change studies. *Global Change Biology*, *17(2)*, 974–989.

Verhoef, W., Menenti, M., & Azzali, S. (1996). Cover A colour composite of NOAA-AVHRR-NDVI based on time series analysis (1981-1992). *International Journal of Remote Sensing*, *17(2)*, 231–235.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., … Bairlein, F. (2002). Ecological responses to recent climate change. *Nature*, *416*, 389–395.

WMO - World Meteorological Office. FAQs. Accessed December 2, 2015 at http://www.wmo.int/pages/prog/wcp/ccl/faqs.php

WSL - Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft. Borkenkäfer-Prognose. Accessed December 23, 2015 at http://www.borkenkaefer.ch/kaeferholz/index_DE

Xiao, J., & Moody, A. (2005). Geographical distribution of global greening trends and their climatic correlates: 1982–1998. *International Journal of Remote Sensing*, *26(11)*, 2371–2390.

Zhang, X., Friedl, M. A., Schaaf, C. B., Strahler, A. H., Hodges, J. C. F., Gao, F., … Huete, A. (2003). Monitoring vegetation phenology using MODIS. *Remote Sensing of Environment*, *84(3)*, 471–475.

Zhao, M., & Running, S. W. (2010). Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, *329(5994)*, 940–943.

Zhou, L., Tucker, C. J., Kaufmann, R. K., Slayback, D., Shabanov, N. V, & Myneni, R. B. (2001). Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *Journal of Geophysical Research, 106(D17), 20069-20083.*

Zimmermann, M. H. (1964). Effect of Low Temperature on Ascent of Sap in Trees. *Plant Physiology*, *39*(4), 568–572.

Declaration

Personal declaration: I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis

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