CLIMATIC AND HUMAN IMPACTS ON MOUNTAIN VEGETATION AT LAUENENSEE (BERNESE ALPS, SWITZERLAND) DURING THE LAST 14000 YEARS

Master's Thesis

Faculty of Natural Sciences

University of Bern

Author:

Fabian Rey

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Supervisor:

Prof. Dr. Willy Tinner

Institute of Plant Sciences

Oeschger Centre for Climate Change Research

Advisor:

Christoph Schwörer

Institute of Plant Sciences

Oeschger Centre for Climate Change Research

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Preface

My master's thesis presents the results of lake sediment analysis of Lauenensee. This lake is located at 1381 m a.s.l. in the Bernese Alps. With its exceptionally old age (14200 cal. years BP) for this altitude, it is possible to give new insights into Late Glacial vegetation dynamics. This thesis is also part of the tree line project at the Institute of Plant Sciences (Christoph Schwörer's PhD project). Located at the transition between the montane and subalpine vegetation belts, Lauenensee is the lowest lake analyzed so far for this purpose. The other lakes of the tree line project are Iffigsee (2065 m a.s.l.) and Lac d'Emines (2288 m a.s.l.). These lakes mainly focus on Holocene tree line dynamics. The aim of this thesis is to focus on the tree line and timber line position during the Bølling-Allerød interstadial and the Younger Dryas cooling.

Another topic of this thesis is human impact on vegetation in the Northern Alps during the last 6000 years. My study shows results from two high-resolution contiguously sampled pollen and macrofossil sequences. The first sequence is covering the Neolithic (5700-5200 cal. BP) and the second is focusing on the Bronze Age (4100-2900 cal. BP). With quantitative time series analysis it is possible to show the different reactions among species or taxa before and especially after a fire. In Switzerland similar high temporal resolutions permitting time series analyses are only available at few sites (e.g. Lago di Origlio in Ticino; Tinner *et al.* (1999; 2005), Soppensee in Central Switzerland (Lotter 1999) and Lej da San Murezzan in the

Engadine (Gobet *et al.* (2003)). The aim of the second part of the thesis is to explain the influence of human disturbances on vegetational composition. Of special interest are the decline of *Abies alba* and the mass expansions of *Picea abies* after 5500 cal. BP and of *Alnus viridis* during the Bronze Age – phenomena that are recorded everywhere else in the Swiss Alps and were so far only poorly investigated (e.g. Markgraf 1970; Welten 1982b; Gobet *et al.* 2003).

Manuscript

Climatic and Human Impacts on Mountain Vegetation at Lauenensee (Bernese Alps, Switzerland) during the Last 14000 years

Fabian Rey, Christoph Schwörer, Erika Gobet, Daniele Colombaroli, Jacqueline van Leeuwen, Willy Tinner

Institute of Plant Sciences, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland

Oeschger Centre for Climate Change Research, University of Bern, Zähringerstrasse 25, CH-3012 Bern, Switzerland

Abstract

Lake sediments from Lauenensee, a small lake in the Bernese Alps, were analyzed to reconstruct the vegetation and fire history. Lauenensee is located at the transition between the montane and subalpine vegetation belts. The chronology, which consists of 11 calibrated radiocarbon dates on terrestrial plant macrofossils, suggests a basal age of 14200 cal. years BP. Our data suggest that tree line never reached the lake catchment during the Bølling-Allerød interstadial. Pollen and macrofossil analyses show that afforestation with tree *Betula* and *Pinus sylvestris* started after the Younger Dryas 11600 cal. years ago, when glaciers expanded and almost reached the study site. Tree *Betula* and *Pinus sylvestris* forests were replaced by *Abies alba* forests around 7500 cal. BP. The first signs of human activity, such as increasing charcoal concentrations and grazing indicators, occurred during the Neolithic at ca. 5700-5200 cal. BP. After 4100 cal. BP anthropogenic activities increased during the Bronze Age. Cross-correlation analysis on high-resolution pollen sequences shows that the expansion of *Alnus viridis* and the replacement of *Abies alba* through *Picea abies* was most likely a consequence of human disturbance. *Abies alba* responded very sensitively to a combination of fire and grazing disturbance. Our results imply that the current dominance of *Picea abies* in the upper montane and subalpine belts where it forms almost pure stands today, is not natural but a consequence of anthropogenic activities through the millennia.

Introduction

Mountain vegetation is considered to be particularly affected by climate change, due to steep ecological gradients. Warmer temperatures are expected to lead to a shift of vegetation ranges and composition. A process that is already observable in the Alps and other mountain ranges (Walther *et al.* 2005; Gottfried *et al.* 2012). In the Alps vegetation is not only affected by climate but also by human land use since millennia. Therefore, to realistically assess future vegetation changes in mountain ecosystems it is crucial to study and disentangle the impacts of climate and human land use on mountain vegetation in the past.

The expansion of *Picea abies* and *Alnus viridis* in the second half of the Holocene is well documented since the early days of Alpine paleoecology (Welten 1952; 1982a). It has been suggested that *Alnus viridis* expanded mainly due to land use including pastoral farming and fire (Welten 1982a; Tinner *et al.* 1996; Wick & Tinner 1997; Gobet *et al.* 2003; David 2010). Similarly it has been hypothesized that the current dominance of *Picea abies* in the Northern Alps is mainly a consequence of human impact (Markgraf 1969; 1970) but in contrast to the case of *Alnus viridis* where one multiproxy quantitative time series is available (Gobet *et al.* 2003), unambiguous high-resolution multiproxy evidence is still lacking for *Picea abies* (Tinner *et al.* 2005).
Paleoecological studies in the Alps have a long tradition (Welten 1952; 1982a; 1982b; Zoller 1960; Bortenschlager 1977; Lang & Tobolski 1985, Burga 1980) but only a few studies are available for the montane-subalpine transition zone in the northern Swiss Alps (1100 m – 1500 m a.s.l.) which cover the Bølling-Allerød interstadial, the Younger

Dryas and the Holocene (Welten 1952; Welten 1982a; Welten 1982b; Wegmüller & Lotter 1990). Most of the older studies lack a proper radiocarbon chronology and are based on pollen data only (Welten 1952; 1982a; 1982b). To gain a better understanding of the environmental changes in the catchment of the lake, it is important to consider several proxies from the same sediment record (Birks & Birks 2006) and it is of particular importance to consider plant macrofossil assemblages to confirm the local presence of tree species at the site.

In this study we present a new, well dated multiproxy reconstruction of the vegetation in the montane-subalpine belt from Lauenensee (1381 m a.s.l.), covering the last 14200 years. Our time series includes the first two contiguous high-resolution pollen, spore, charcoal and macrofossil sequences from the Northern Alps. The first of our high-resolution sequences covers a part of the Neolithic period (5700-5200 cal. BP) while the second sequence focuses on the Bronze Age (4100-2900 cal. BP). We use cross-correlation analysis to investigate the different reactions of individual key taxa to fire. From previous multiproxy studies in other areas in the Alps and their forelands it is known that fire was widely used to open the landscape during both periods (Tinner *et al.* 2005).

The primary aim of this study is to reconstruct the timing of afforestation and to assess the causes of the mid to late Holocene expansions of *Picea abies* and *Alnus viridis* as well as the decline of *Abies alba*. We pay special attention to provide direct evidence of land use (pollen and spores of crops, weeds and fungi), while climatic causes are addressed by comparison with pollen independent evidence such as chironomid, cladocera and oxygen isotopes series.

Study site

Lauenensee is a small montane lake in the Bernese Alps near (3 km) the village of Lauenen, the literal translation from Alemannic means "avalanche or land-slide lake". The lake is located on 1381 m a.s.l. at the coordinates 46° 23′ 49′′ N, 7° 19′ 53′′ E (Fig. 1). Today, the lake consists of two basins that are connected by a small channel. Its total surface area is 8.78 ha (Guthruf *et al.* 1999). For this study, lake sediment from the larger basin was analyzed. The lake has a maximal depth of 3.5 m (Guthruf *et al.* 1999).

The mountains around Lauenensee belong to the Helvetic domain of the Alps, with limestone dominated nappes (Schmid *et al.* 2004). Today, there are several small streams that flow into the lake or the surrounding mire and a single outflow on the eastern side. However, Hauri (1981) suggests that there had been a major inflow into the lake in the Late Glacial, leading to massive silt depositions. During the Bølling-Allerød interstadial, the glacier retreated to elevations higher than the lake, while they re-advanced to reach a plateau just above the lake (1823 m a.s.l., 1.5 km distance) during the Younger Dryas (Geologischer Atlas der Schweiz 1962).

The mean annual temperature today is 4.9 °C and the mean annual precipitation is about 1535 mm (data source: DAYMET model, Swiss Federal Institute for Forest, Snow and Landscape Research WSL). The highest mean temperatures are reached in July with 13.5 °C and the lowest in January with -3.1 °C (data source: DAYMET model, WSL). The highest precipitation rates are measured during the summer months June to August (see Fig. 2).

The lake is located in the inner part of the Northern Alps at the transition between the montane and the subalpine vegetation belts (Landolt 1992). The predominant tree in the forests is *Picea abies* (Fig. 1). However, deciduous tree species such as *Alnus incana*, *Acer pseudoplatanus* and *Betula pubescens* are also occasionally present. The flat areas around the lake are mostly covered by mires or meadows. The farming activity around the lake is rather moderate, since the area belongs to the nature reserve Gelten-Iffigen. On the Western slope, *Alnus viridis* is growing together with other shrubs (e.g. *Rhododendron ferrugineum*) in avalanche gullies. In fact, a huge avalanche reached the lake in 1978, uprooting trees and depositing them in the lake (Hauri 1979).

Methods

Coring and radiocarbon dating

Two parallel sediment cores were taken one meter apart with a modified Streif-Livingstone piston corer from a small platform in May 2011. Both cores (LAUA and LAUB) originate from the deepest part of the lake. The water depth there was 3.5 m and 3.4 m respectively. In the laboratory, these two cores were joined to one master sequence of 1385 cm according to their lithography. The precision of the lithostratigraphic correlation is ca. ± 0.5 cm.

The age-depth model used for the pollen diagrams and the cross-correlation analysis is based on 11 radiocarbon dates from terrestrial plant macrofossils (Tab. 1). The ages of the terrestrial macrofossils were measured at the Poznań Radiocarbon Laboratory in Poland using accelerator mass spectrometry (AMS). With the program CALIB 6.1.0 (Stuiver & Reimer 1993), the radiocarbon dates (conv. ^{14}C yr. BP) were transformed into calibrated dates (cal. BP). The program *clam* (Blaauw 2010) with a 2σ confidence envelope was employed to produce the final age-depth model, based on Monte Carlo sampling with 1000 iterations.

Pollen, charcoal and loss on ignition analysis

A total of 126 samples for pollen and charcoal analysis were retrieved from the sediment core. Usually, samples of 1 cm^3 were taken every 16 cm. From 334 to 142 cm, where (according to the radiocarbon chronology) the sedimentation rate was expected to be low, the resolution was one sample of 1 cm^3 every 8 cm. In the lowest part of the core, the pollen concentration was expected to be exceptionally low and the sedimentation rate to be very high. Here, samples of 3 to 8 cm^3 were taken approximately every 120 cm. 70 samples belong to one of the two high-resolution sequences, where samples of 1 cm^3 were taken every centimeter. The first high-resolution sequence (HR1) consists of 25 samples (278-254 cm) and the second high-resolution sequence (HR2) has a total of 45 samples (230-186 cm). In the laboratory, the pollen samples were treated with HCl, KOH, HF and acetolysis, following standard preparation methods (e.g. Moore *et al.* 1991). *Lycopodium* tablets were added to the samples previous the chemical treatment, for estimating charcoal, spore and pollen concentrations (Stockmarr 1971). Due to the very low pollen concentrations and the samples volumes of 3 to 8 cm^3 for the four samples of the lowest part of the core, the standard procedure had to be adapted. Here, the samples had to be distributed among several centrifuge tubes and the chemical treatment with HF had to be repeated for better removal of clay particles. The different pollen and spore types were identified using palynological keys and photo atlases (Moore *et al.* 1991; Reille 1992; Beug 2004). Stomata were identified using the stomata key of Trautmann (1953). Microscopic charcoal particles < 10 µm were counted following Tinner & Hu (2003) and Finsinger & Tinner (2005). Charcoal influx (fragments $cm^{-2}yr^{-1}$) were calculated using the accumulation rates (cm yr^{-1}) inferred from the age-depth model and the charcoal concentrations (fragments cm^{-3}).

The pollen diagrams were separated into local pollen assemblage zones (LPAZ) which were identified by the use of optimal sum of squares partitioning (Birks & Gordon 1985). The statistically significant zones were identified following Bennett (1996).

Samples for loss on ignition originate from the same depths as the pollen samples. These 126 samples were treated following Heiri *et al.* (2001).

Macrofossil analysis

The focus of the macrofossil analysis was on the timing of reforestation and on the two high-resolution sequences HR1 and HR2. Totally, 68 samples were analysed. In the two high-resolution sequences, 34 samples (11 and 23 respectively) were taken continuously using 2 cm sections. For the separation of macrofossils and fine-grained sediment, a sieve with a 200 µm mesh width was used. The macrofossils were identified using the reference collection at the Institute of Plant Sciences of the University of Bern and macrofossil keys (e.g. Schoch *et al.* 1988). The macrofossil concentrations are based on an average volume of 15.5 cm^3. Since the resolution of the macrofossil analysis was not constant and the concentration of macrofossils was rather low, the same zonation as for the pollen diagram (LPAZ) was used for the macrofossil diagram.

Quantitative analysis

The program MYSTAT 12 (student version of SYSTAT 12) was used to calculate cross correlations for both high-resolution sequences HR1 (Neolithic) and HR2 (Bronze Age). Pollen percentages and charcoal influx were used to calculate cross correlations (Bahrenberg *et al.* 1992). The pollen percentages were linearly de-trended before the cross-correlation analysis to achieve stationarity of the data set. Each lag comprises 30±0.8 years for the Neolithic sequence (5700-5200 cal. BP) and 28±8.3 years for the Bronze Age sequence (4100-2900 cal. BP).

Pollen richness as a proxy for evenness and species richness in the landscape (Odgaard 2007) was calculated with rarefaction using the program PAST 2.14 (Hammer *et al.* 2001). The analysis is based on the lowest terrestrial pollen count which was 184 at 1376 cm depth.

Results

Lithology, chronology and loss on ignition

The lowest part of the sediment core from 1382 to 606 cm consists of clay and silt. From 1382 to 1265 cm, some gravel layers are incorporated. There is a change in the sediment composition from 606 cm upwards. There, the sediment consists of silty calcareous gyttja with a high number of mollusks.

The age-depth model (Fig. 3), which was compiled with 11 radiocarbon dates, shows an important change at 838 cm depth (13950 cal. BP). Above this depth the sedimentation rate was rather low, whereas in the lower part, the sedimentation rate was extremely high. Linear interpolation of the oldest date at 1146 cm (14025 cal. BP) leads to a basal age estimation of 14200 cal. BP at 1382 cm.

Loss on ignition at 550 °C shows a moderate organic content (< 15 %) throughout the whole sediment core (Fig. 4). However, there is a first increase of the organic content at 542 cm depth (10470 cal. BP) and second more pronounced increase at 382 cm depth (7145 cal. BP), followed by a long period with elevated values.

Pollen, macrofossil and charcoal analysis

Six local pollen assemblage zones (LPAZ) are statistically significant. One additional zone boundary was not statistically significant (LAU-6a/6b) and is marked as dashed line to delimit two subzones (Figs. 5-8).

LAU-1 (14200-13960 cal. BP), *Artemisia–Betula* LPAZ

In this oldest zone, herb and shrub pollen is dominating. The most important tree pollen is *Betula* with values up to 25 %. The dominant shrub pollen is *Juniperus* and the most common herbaceous taxa are *Artemisia* and Poaceae. The upper limit of this zone is given by the strong increase of *Pinus sylvestris*-type pollen. Local occurrence of shrubs is confirmed by *Juniperus nana* needles, *Salix* twigs and *Dryas octopetala* leaves. Microscopic charcoal influx is very low.

LAU-2 (13960-10930 cal. BP), *Pinus* LPAZ

Pinus sylvestris-type pollen becomes dominant in this zone. *Pinus cembra* pollen occurs for the first time at about 13230 cal. BP. Tree pollen reaches values up to 75 % at the beginning of the zone, before it declines again between 13000 and 12400 cal. BP. *Juniperus* pollen declines first and then increases again, while tree *Betula* pollen declines and remains low. At the same time, Poaceae, *Artemisia*, Cyperaceae and Chenopodiaceae pollen percentages increase. The end of this zone is marked by an increase of *Betula* and *Pinus cembra* pollen. *Juniperus* pollen and herbaceous taxa decrease. *Corylus* *avellana*, *Ulmus* and *Alnus glutinosa*-type pollen appears for the first time at about 11155 cal. BP. Terrestrial macrofossils are rare in this zone. Only in the upper part, tree *Betula* fruits and fruit scales as well as *Pinus* needles were found. The microscopic charcoal influx shows a massive peak at 13800 cal. BP.

LAU-3 (10930-7030 cal. BP), *Pinus*-*Corylus* LPAZ

Pinus sylvestris-type is co-dominant with other taxa such as *Corylus avellana*, *Ulmus* and tree *Betula* in the pollen assemblage. *Pinus cembra* pollen is decreasing. The values of herbaceous taxa are low and always remain below 10 %. At the upper border of the zone, *Corylus avellana* and *Pinus sylvestris*-type pollen percentages collapse. *Larix decidua* and *Abies alba* pollen appears for the first time at around 9500 cal. BP and 10000 cal. BP respectively. Finds of macrofossils are comparable to those of LAU-2. Microscopic charcoal influx show an increase with a peak at 7300 cal. BP.

LAU-4 (7300-5500 cal. BP), *Abies alba* LPAZ

Abies alba becomes the dominant pollen type. Other important taxa in the pollen assemblage are *Ulmus* and *Betula alba*. *Fagus sylvatica* pollen appears for the first time at 7000 cal. BP. In the upper part of the zone, *Picea abies* pollen appears at 5800 cal. BP, whereas the pollen percentages of *Abies alba* and *Ulmus* strongly decrease. The increase of *Picea abies* pollen is accompanied with the first occurrence of human indicators, such as Cerealia-type pollen, *Plantago lanceolata* pollen and *Sporormiella* fungal spores. *Abies alba* needles are the dominant macrofossils in this zone. Comparable to the pollen record, there is also a rapid decline of *Abies alba* macrofossils after 5600 cal. BP. Microscopic charcoal influx shows low values followed by a peak at 5600 cal. BP.

LAU-5 (5500-3730 cal. BP), *Picea abies* LPAZ

Picea abies is the dominant tree pollen in this zone with values up to 50 %. *Abies alba* values remain constant at 10 %. The upper limit of the zone is marked by an increase of *Alnus viridis* pollen and human indicators. There, *Picea abies* pollen starts to decrease. *Picea abies* needles are the most common macrofossil. Microscopic charcoal influx is generally higher than in LAU-4 and is fluctuating around 3300 cal. BP.

LAU-6a (3730-1170 cal. BP), *Picea abies-Alnus viridis* LPAZ

Picea abies is less dominant in the pollen record. Other taxa such as *Alnus viridis*, *Fagus sylvatica*, *Alnus glutinosa*-type and *Betula alba* are co-dominant. *Abies alba* and *Ulmus* pollen percentages show a further decrease. Around 1900 cal. BP *Castanea sativa* pollen appears for the first time. Grazing indicators such as *Ranunculus acris*-type, *Rumex acetosa*-type, *Plantago lanceolata* and *Sporormiella* are constantly present. Microscopic charcoal influx peaks around 3300 cal. BP. *Picea abies* stomata and needles decline at the same time.

LAU-6b (1170-0 cal. BP), *Picea abies*-Poaceae LPAZ

This subzone represents the increasing human activity after 1170 cal. BP. The percentage of herbaceous pollen increases up to 50 %. Human indicators show a maximum (e.g. *Cannabis*-type, *Plantago lanceolata* and Cerealia-type). Values of *Picea abies* pollen remain constant around 20-30 %.

Quantitative analysis

The cross-correlation analysis for the Neolithic sequence (HR1: 5700-5200 cal. BP) and the Bronze Age high-resolution sequence (HR2: 4100-2900 cal. BP) reveal that tree species such as *Abies alba* and *Picea abies* generally show significant negative correlations after or sometimes even before a charcoal increase (Figs. 9-10). Herbaceous pollen and grazing indicators are positively correlated with charcoal (*Plantago lanceolata* and *Sporormiella*). Shrub pollen such as *Alnus viridis* also correlate positively. However, this reaction is mostly delayed. The same holds true for pollen richness which has significant positive correlation with charcoal at lag +1 (HR1) and +3 (HR2).

Interpretation and discussion

Early vegetation history from 14200 to 6000 cal. BP under quasi-natural conditions

14200 cal. years is the likely age of the oldest sediments of Lauenensee according to the age-depth model. This basal age is confirmed biostratigraphically by the low *Pinus sylvestris*-type pollen percentages, which are in agreement with other well dated studies in the area (Lotter *et al.* 1992; Lotter 1999; Wegmüller & Lotter 1990). The sediment record cannot be older than 14700 cal. years, i.e. the onset of the

Bølling (no *Juniperus* pollen peak >40%; Lotter 1999; Wegmüller & Lotter 1990). The macrofossil assemblages suggest a treeless, heliophilous open shrub tundra with *Juniperus nana*, *Salix* and *Dryas octopetala* during the Bølling-Allerød interstadial (14200-13000 cal. BP). Thus, the high values of tree pollen in Fig. 5 primarily reflect afforestation below the site and are explainable by long-distance transport. The macrofossil assemblage suggests that Lauenensee was above tree line during the Bølling-Allerød interstadial. By comparing these results with other sediment records, it is now possible to set a limit to the tree line during the Bølling-Allerød in the area. Welten (1982b) found *Pinus* stomata in a sediment record 25 km away at Chutti (Boltigen) at 925 m a.s.l. below a Laacher See tephra (LST) layer. This tephra layer is dated to 12920 cal. BP (Baales *et al.* 2002). Thus, the tree line must have been above 925 m already during the Allerød, since the *Pinus* stomata found at Chutti were frequent. The Regenmoos (1260 m a.s.l.) *Pinus* stomata record (Welten 1952) suggests that during the Allerød pine trees reached at least 1260 m a.s.l., placing the tree line between 1260 and 1380 m. This is somewhat striking because the current (natural) tree line is located 800 m higher at 2100 m (Landolt 1992). Since tree line is limited by temperature (Körner 1999; Ellenberg 2010) we can estimate past temperatures relative to the present using lapse rates of 0.6 °C/100 m, which results in (summer) temperatures ca. 4-5 °C lower than today for the Bølling-Allerød interstadial. This is in contrast to chironomid-inferred temperatures from the Jura Mountains (Heiri & Millet, 2005) as well as the oxygen isotope series from Southern Germany (von Grafenstein *et al.* 1999), which indicate similar or slightly higher temperatures for the Bølling-Allerød interstadial, but in agreement with temperatures reconstructed with pollen- and cladoceran-assemblages from the Swiss Plateau (Lotter *et al.*, 2000). In the Western Central Alps tree line reached an altitude of 1700 to 1800 m during the same time (Welten 1982b; Tobolski & Ammann, 2000). Higher tree lines at 1700 to 1900 m are also given for the Southern Alps (Vescovi *et al.* 2007). This could point to colder summer temperatures in the Northern Alps during the Late Glacial period (Samartin *et al.* 2012).

The charcoal influx peak at 13800 cal. BP (Fig. 5) is possibly an artifact of the age-depth model due to drastic changes in the accumulation rates and may not reflect high fire activity.

During the Younger Dryas cooling (12800 to 11700 cal. BP), the catchment was never reached by re-advancing glaciers. The end moraines of the glacier advances are located just above the lake at Kühtungel at 1823 m a.s.l. (Geologischer Atlas der Schweiz 1962) at 1.5 km distance. The increasing values of herbaceous and *Juniperus* pollen as well as the decrease of *Pinus sylvestris*-type pollen by 20 % point to a lowering of the tree line in the region. Existing forests, even in the lowlands of the Swiss plateau or Northern Italy, became rather open again during this cold event (Ammann *et al.* 2007; Vescovi *et al.* 2007). The tree line in the Central Alps was lowered by 200-300 m and was located at ca. 1500 m (Lang & Tobolski 1985; Zoller *et al.* 1996; Wick 2000; Tobolski & Ammann 2000; Gobet *et al.* 2005).

Afforestation at Lauenensee started right after the end of the Younger Dryas at 11600 cal. BP with *Betula*, followed by *Pinus sylvestris*-type around 11155 cal. BP. The rapid expansion of forest at the onset of the Holocene is explainable by the proximity of tree line during the Younger Dryas, which was located at ca. 1000 m in the Bernese Alps (above Chutti but below Regenmoos: Welten 1952; 1982b). Several studies in the Alps show indeed that the vegetation can track rapid warming with decadal to centennial lags (Ammann *et al.* 2000; Tinner & Kaltenrieder 2005). The afforestation in the catchment is also clearly visible in the lithology of the lake, as the sediment changes from silt to silty calcerous gyttja.

High values of microscopic charcoal influx during the early Holocene (LPAZ LAU-3) suggest high regional fire activity in the area (20-50 km; Tinner *et al.* 1998), probably as a result of warm and dry conditions in response to higher insolation in the northern hemisphere (Kutzbach & Webb 1993; Wanner *et al.* 2008). The increased values for loss on ignition at 550 °C at the same time probably reflect increased productivity in and around the lake.

At Hinterburgsee (1515 m a.s.l.), the afforestation occurred 600 years later around 11000 cal. BP (Heiri *et al.* 2003a). This response discrepancy may reflect more favorable conditions in the more central Alpine region of Lauenensee or dating uncertainties. At comparable altitudes, sites in the Central Alps (Valais, Lower Engadine) and in the Southern Alps, were mostly forested during the Younger Dryas cooling (Zoller 1960; Müller 1971; Welten 1982b; Zoller *et al.* 1996; Gehrig 1997; Tobolski & Ammann 2000), pointing again to a different climate regime in the Northern Alps (Samartin *et al.* 2012).

Major changes in the vegetation occurred after 11100 cal. BP when *Corylus avellana*, *Ulmus* and *Alnus* probably expanded into the catchment forming a mixed deciduous forest. This vegetational change is typical for other sites at comparable altitudes (Welten, 1982b; Heiri *et al.* 2003a). Unfortunately, no macrofossils were found from these taxa and the evidence for their local presence remains somewhat ambiguous. However, since *Alnus incana* grows around the lake today, it is reasonable to assume, that it has been present in the Early Holocene, when summer temperatures were higher than at present. The same can be assumed for *Ulmus* and *Corylus avellana*, since they have about the same altitudinal limit (today ca. 1400 m a.s.l.) as *Alnus incana* (Welten 1952; Lauber & Wagner 2006).

After 7500 cal. BP *Abies alba* populations expanded around the lake, stabilizing soils and reducing erosion in the catchment (decreasing sedimentation rates). The trend to more humid conditions at around the same time, which is documented at several sites in the Alps (e.g. Heiri *et al.* 2003a; Wick *et al.* 2003), may have favored the expansion of *Abies alba*. The timing of the expansion of *Abies alba* in the catchment of Lauenensee agrees well with the macrofossil record at Hinterburgsee (1515 m a.s.l.), where the first *Abies alba* needles appear at 7400 cal. BP. In the Southern Swiss Alps and Prealps the presence of *Abies alba* reaches back to the Late Glacial (e.g. Zoller 1960; Schneider & Tobolski 1985; Hofstetter *et al.* 2006) and to the early Holocene in the Swiss Plateau (Tinner & Lotter 2006). In agreement, *Abies alba* pollen is recorded since ca. 10000 cal. BP at Lauenensee, suggesting that the species was present in the area during the early Holocene. Taken together, our data suggest that dense *Abies alba* forests with some deciduous trees such as *Ulmus, Acer* and *Alnus* were growing between 7000 to 6000 cal. BP in the catchment of Lauenensee.

Expansion of Picea abies *and* Alnus viridis *after 6000 cal. BP: the role of human activities*

The massive expansion of *Picea abies* after 6000 to 5500 cal. BP coincided with the appearance of cultural indicators around Lauenensee and the initial decline of *Abies alba*. Charcoal analysis identified several distinct fire events after 6000 cal. BP. This favored disturbance-adapted plants such as *Alnus viridis*. Several studies in the Alpine region suggested that this species expanded markedly in response to anthropogenic disturbances such as fire and grazing (e.g. Welten 1982b; Tinner *et al.* 1996; Gobet *et al.* 2003; David 2010). The charcoal-inferred increase of fire activity and the onset of alpine farming as evidenced by the occurrence of taxa promoted by grazing (e.g. *Plantago lanceolata* and *Sporormiella*) at 5600 cal. BP coincided with a climatically warm phase (Grosjean *et al.* 2007; Joerin *et al.* 2006). Archaeological evidence unambiguously documents that Neolithic people used high mountain passes in the region to travel across the Alps since at least 6300 cal. BP (Grosjean *et al.* 2007; Hafner 2009).

Our Neolithic high-resolution time-series and cross-correlation analyses (HR1) unambiguously show that *Abies alba* was strongly affected by fire and grazing (Fig. 9). This finding is in agreement with previous studies from the Southern Alps (Tinner *et al.* 1999; Wick & Möhl 2006). *Picea abies* stomata and needles occurred for the first time 100 to 150 years after the largest fire event in the Neolithic at 5600 cal. BP. This strongly suggests that human activity supported the expansion of *Picea abies* in the region. Similar conclusions were presented by Markgraf (1970), while other studies suggest that the expansion of *Picea abies* was favoured by a shift to cooler and more oceanic climatic conditions (Lotter *et al.* 2006). Indeed, at other sites in the Northern Swiss Alps, *Picea abies* expanded 600 years earlier, without any unambiguous evidence of human impact in the area (Heiri *et al.*, 2003a). These different lines of evidence suggest that the establishment of local *Picea abies* stands and the decline of *Abies alba* were most likely triggered by a combination of anthropogenic disturbance and climatic change during the Neolithic (5700 to 5300 cal. BP). After 5500 cal. BP, cultural activities slightly decreased perhaps in response to less favorable climatic conditions. Quantitative temperature reconstructions and glacier advances in the Alps indicate that the late Holocene was cooler than the mid Holocene (Heiri *et al.* 2003a; 2003b; Grosjean *et al.* 2007; Joerin *et al.* 2006), mainly as a result of obliquity change, which reduced the amount of summer solar radiation on the Northern Hemisphere (Wanner *et al.*, 2008). This climatic evolution may explain the further expansion of *Picea abies* and the stabilization of the *Abies alba* stands, since both species are able to cope with oceanic and cool conditions.

After 4100 cal. BP (at the onset of the Bronze Age) favorable climate and technological innovations led to an intensified land use in the region (Tinner *et al.* 2003). The Schnidejoch pass (Grosjean *et al.* 2007) became ice free and was again crossed. At the onset of the Bronze Age fire frequency was higher than during the

Neolithic. Grazing indicators such as *Plantago lanceolata* and *Sporormiella* show exceptionally high values, indicating extensive local animal husbandry which was also practiced at other sites in the region (Heiri *et al.* 2003a; Wick *et al.* 2003) and elsewhere in the Alps (Tinner *et al.* 1996; Gobet *et al.* 2003; Carcaillet *et al.* 2009; Vescovi *et al.* 2010). *Alnus viridis* thickets formed with increasing fire frequencies, while dominant tree species such as *Picea abies* and *Abies alba* decreased. *Abies alba*, which is very sensitive to browsing and fire, almost completely vanished from the catchment. However, single *Abies alba* needles indicate that individual trees may have survived locally. Tinner *et al.* (2005) showed a similar intensification of land use at two sites on the Swiss plateau (Lobsigensee and Soppensee) and at two sites in Ticino (Lago di Muzzano and Lago di Origlio). In the Central Alps, intensive human land use in the Bronze Age led to a lowering of the timberline by about 300 m (Tinner & Theurillat 2003; Heiri *et al.* 2006).

During the Bronze Age (4200-2900 cal. BP), human impact was more or less continuously present. Our second high-resolution time series suggests that the collapse of *Abies alba* was triggered by increasing fire disturbance (significant negative correlations, Fig. 10) which was closely related to land use (significant positive correlation with *Sporormiella*). Increased fire incidence again strongly promoted disturbance-adapted *Alnus viridis*, which is in very good agreement with results from the Central Alps (Gobet *et al.* 2003). *Picea abies* was also disadvantaged by fire, but in contrast to *Abies alba* it was always able to hold its ground. This might be explained by the high browsing tolerance of the species. The same picture emerges from the contiguous macrofossil analyses. The last *Abies alba* needles were found around 3000 cal. BP documenting the extinction of the formerly important mixed silver fir forests. The last *Abies alba* stands had thus already vanished before the large-scale opening of the forests during the Middle Ages. During the Roman period land use became even more intense. However, the most prominent and wide-spread opening of the forests happened only after 800 cal. BP. This last phase of intense clearing of mountain forests to make space for pastures was found in many other studies throughout the whole Alpine region (e.g. Tinner *et al.* 1996; Gobet *et al.* 2003; David 2010).

Conclusions

Lauenensee has one of the oldest sediment records in the Bernese Alps and gives new insights into the vegetation history of the last 14200 cal. years. Our data show that shrub tundra with *Juniperus nana*, *Salix* and *Dryas octopetala* dominated around the study site until 11600 cal. BP when afforestation started with *Betula* and *Pinus sylvestris*. The low tree line during the Late-Glacial and early Holocene in the Northern Alps points to colder summer temperatures compared with the Southern and Central Alps, where tree line was 400 – 500 m higher. Tree species reacted extremely fast to the rapid warming at the beginning of the Holocene and were able to adjust their distribution limit in a matter of decades. This is further evidence that under natural conditions the vegetation at tree line is in dynamic equilibrium with climate. After 7000 cal. BP, under moderately oceanic climates, *Abies alba* replaced the former *Betula-Pinus sylvestris* forests. Human impact started at 5700 cal. BP, providing unambiguous evidence that humans actively used the rather remote northern-alpine mountain landscape already in the Neolithic. As a consequence of increased fire activity and cattle grazing, mixed *Abies alba* forests were replaced by *Picea abies* and *Alnus viridis* started to expand. With increasing anthropogenic activity during the Bronze Age (4100-2900 cal. BP), *Abies alba* finally completely collapsed in response to excessive fire disturbance and land use. Our high-resolution time series analyses provide the first quantitative evidence that the today's almost monospecific *Picea abies* forests of the upper mountain and subalpine belt are of anthropogenic origin, as hypothesized by early authors (Markgraf 1970). Taken together, our results demonstrate that forests in the Alps reacted very rapidly to climatic change and were formed by millennial human impact. We anticipate that rising temperatures as well as changes in human land use will therefore lead to an unprecedented shift in the species distribution and composition of montane forests. However, to confirm our results, more multi-proxy high-resolution studies in the Northern Alps have to be carried out. Another open question is the precise reconstruction of the tree line in the Bernese Alps during the Bølling-Allerød and especially during the Younger Dryas interstadial. A thorough investigation of this open question would allow a better understanding of the response rates and directions of tree line vegetation to rapid climatic changes.

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Figures

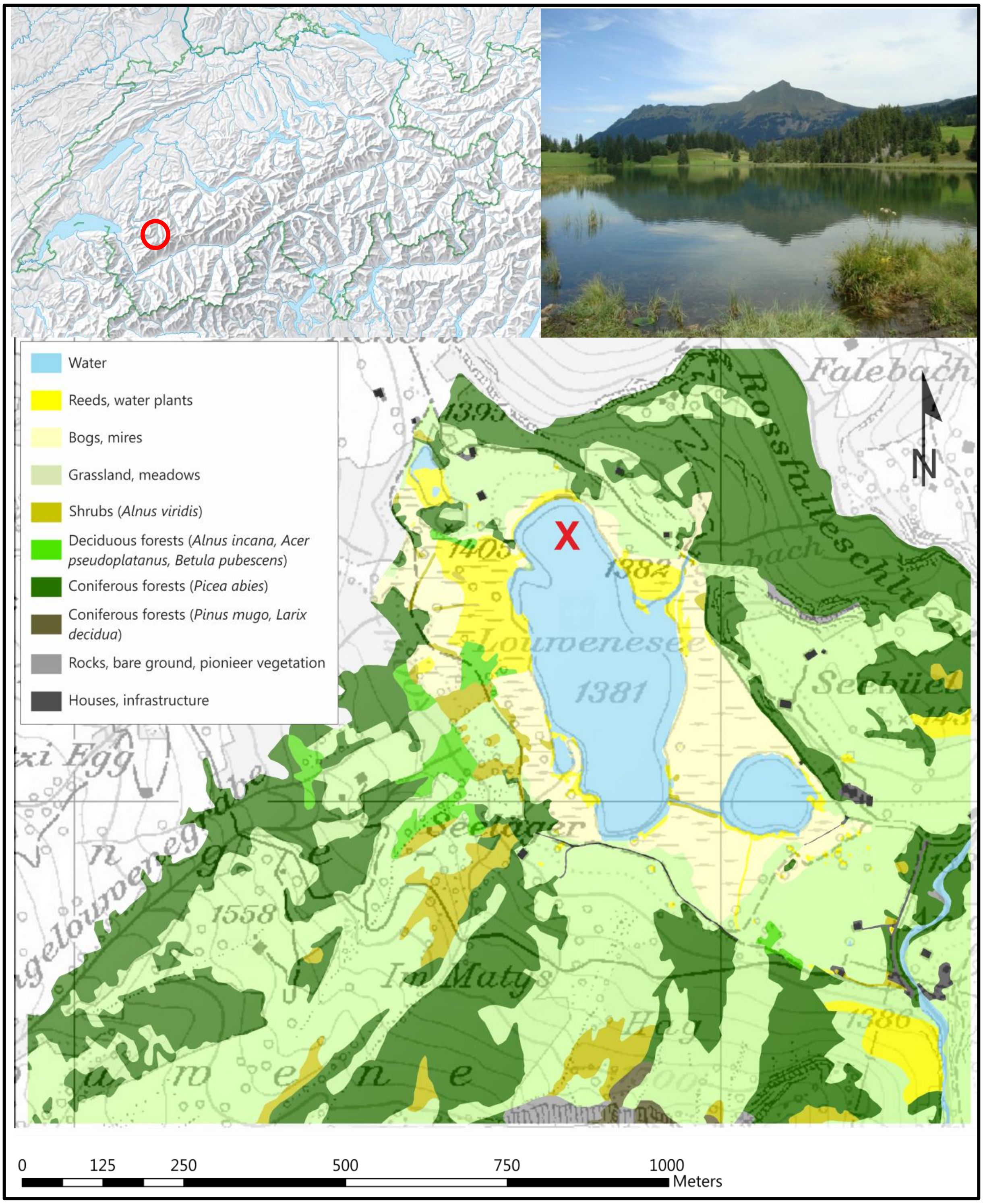

Fig. 1 Map overview (**O** = study site) (© 2007 swisstopo), photograph of Lauenensee (Rey F. 2011) and a section of the vegetation map of the nature reserve Gelten-Iffigen (**X** = coring site) (© 2012 swisstopo; Amt für Naturschutz Bern, modified).

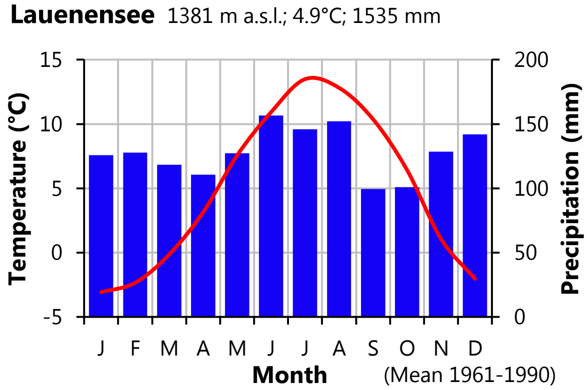

Fig. 2 Climate diagram of Lauenensee (data source: DAYMET model, WSL).

Tab. 1 Radiocarbon dates

Lab code	Depth (cm)	Material	^{14}C age (yr BP conv.)	Age (cal. yr BP)	Age (cal. yr BP, 2σ range)	Age (*clam*)	Age (*clam*, 2σ range)
Poz-45466	61	*Picea abies* seed	385±30	413	507-319	430	517-314
Poz-45465	151-154	*Picea abies* seed	2110±30	2125	2203-2046	2086	2160-1994
Poz-45464	221-223	*Picea abies* needles	3490±35	3801	3906-3695	3765	3864-3650
Poz-45463	252	Bark	4450±50	5134	5339-4929	5103	5301-4890
Poz-45462	274-277	*Abies alba* needles	5060±60	5839	5966-5712	5778	5893-5643
Poz-45460	306	*Abies alba* cone scale	5960±40	6835	6942-6728	6792	6892-6681
Poz-46304	417	Bark	6365±50	7299	7421-7176	7307	7426-7177
Poz-45459	449	Twig	9610±50	11018	11218-10817	Rejected	Rejected
Poz-45458	541	Twig	9280±50	10537	10617-10417	10459	10598-10275
Poz-5456	624.5	Twig	10080±50	11716	12015-11417	11644	11964-11365
Poz-45476	836-840	*Salix* twigs	11940±60	13848	14021-13675	13793	13950-13629
Poz-45475	1144-1148	*Juniperus nana* needles	12160±60	14055	14240-13870	14025	14192-13828

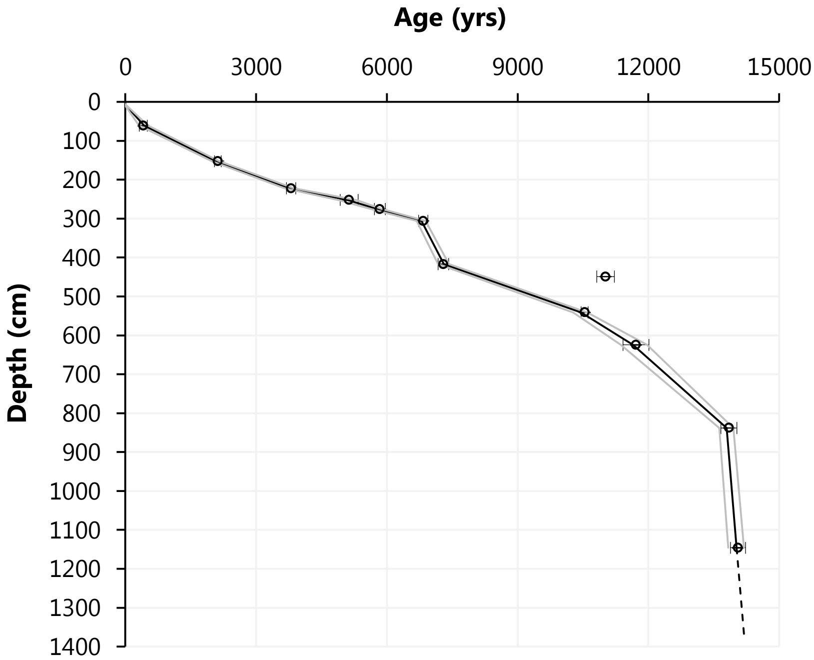

Fig. 3 Age-depth model of Lauenensee. Circles show the calibrated ages of terrestrial macrofossils. The black line is the calculated model with a 2σ envelope (grey lines) (*clam*, Blaauw 2010).

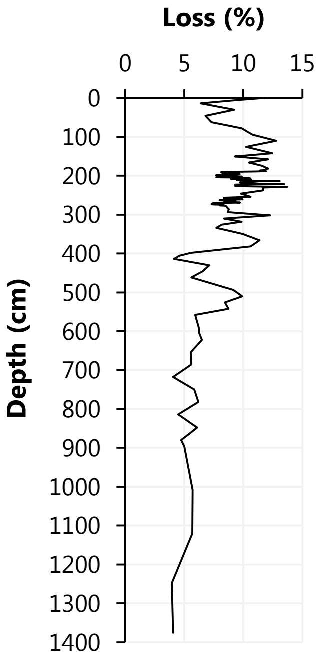

Fig. 4 Loss on ignition at 550 °C.

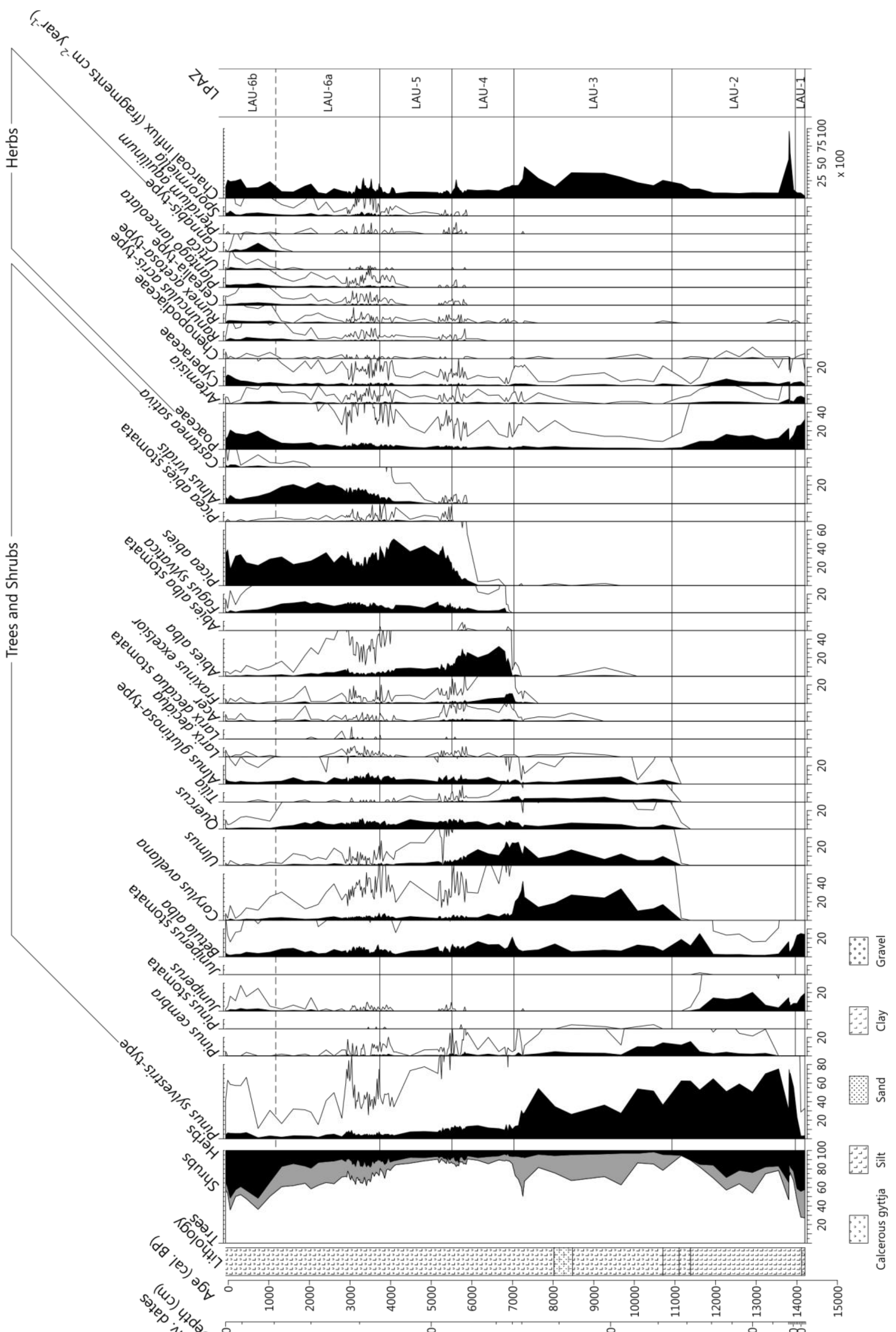

Fig. 5 Pollen and stomata percentage diagram of Lauenensee (selected taxa). The empty curves show the 10x exaggerations (Analysis: Fabian Rey).

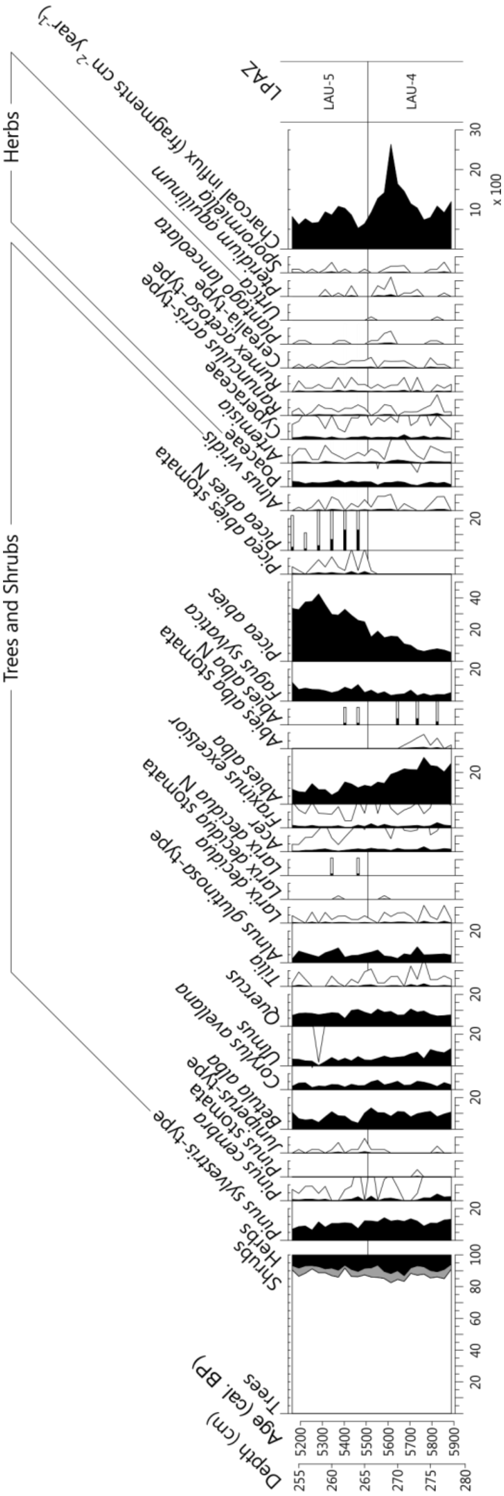

Fig. 6 Pollen and stomata percentage diagram with macrofossil concentrations (Neolithic sequence). The empty curves are the 10x exaggerations. N = needles (Analysis: Fabian Rey).

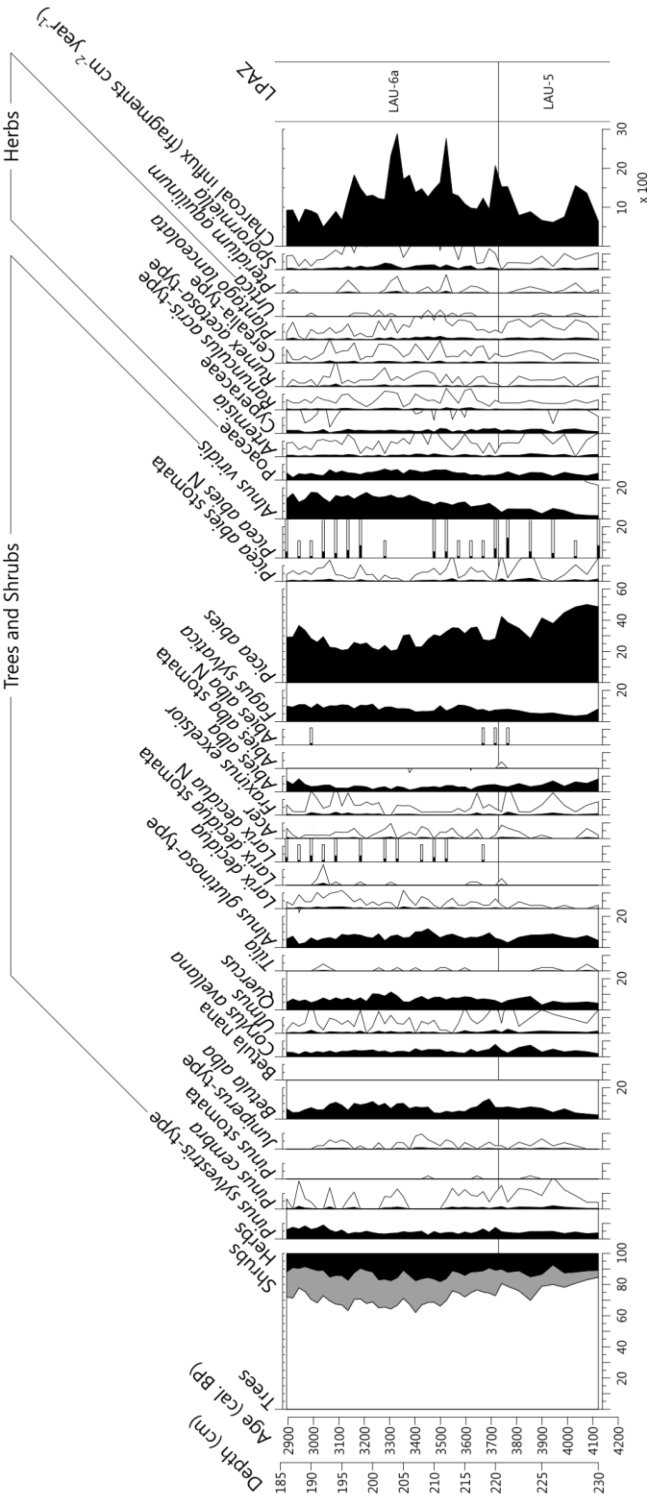

Fig. 7 Pollen and stomata percentage diagram with macrofossil concentrations (Bronze Age sequence). The empty curves are the 10x exaggerations. N = needles (Analysis: Fabian Rey).

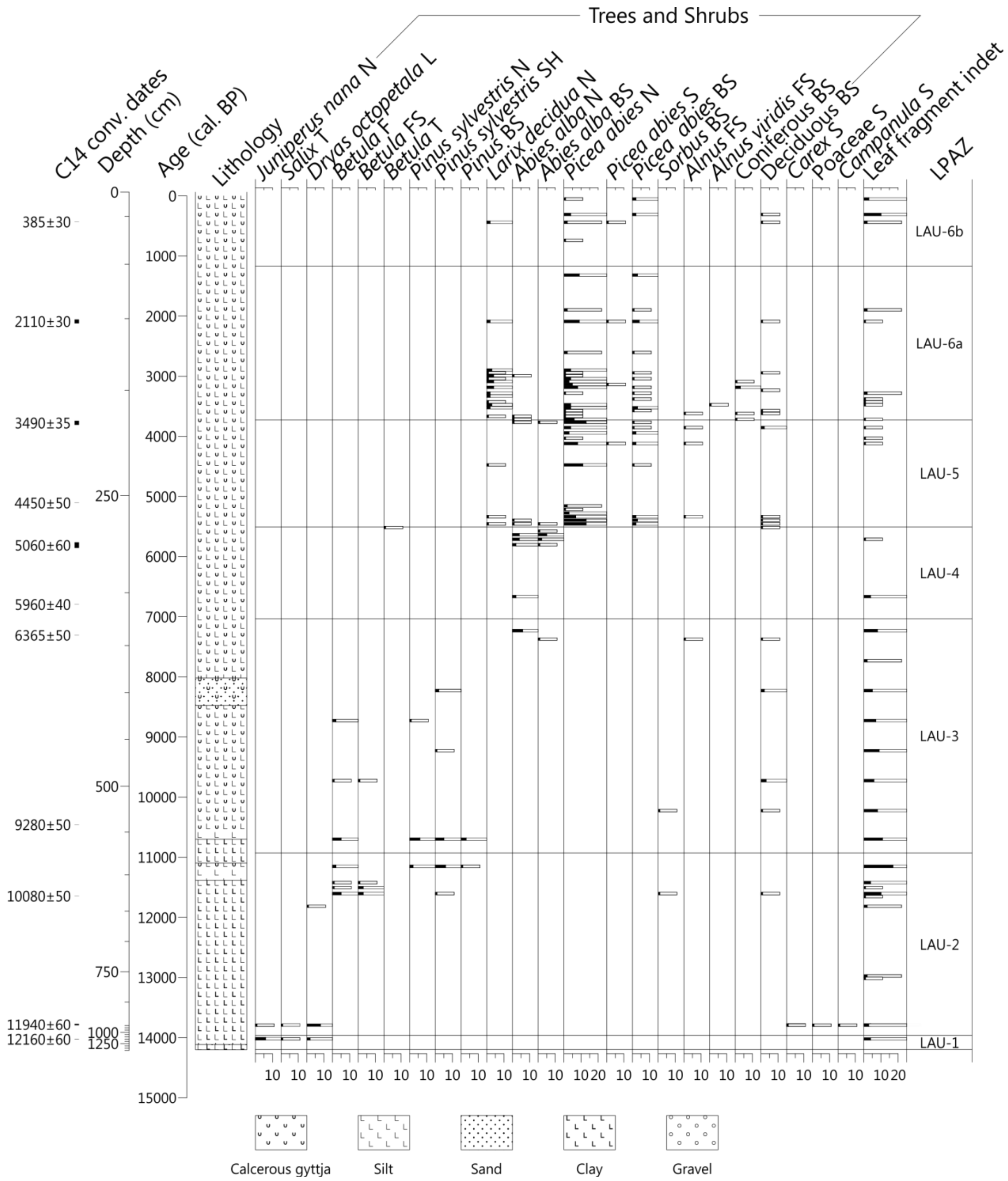

Fig. 8 Macrofossil concentrations diagram Lauenensee (per 15.5 cm^3). The empty curves are the 10x exaggerations. BS = bud scales, F = fruits, FS = fruit scales, L = leaves, N = needles, SH = short shoots, T = twigs (Analysis: Fabian Rey & Silke Schleiss).

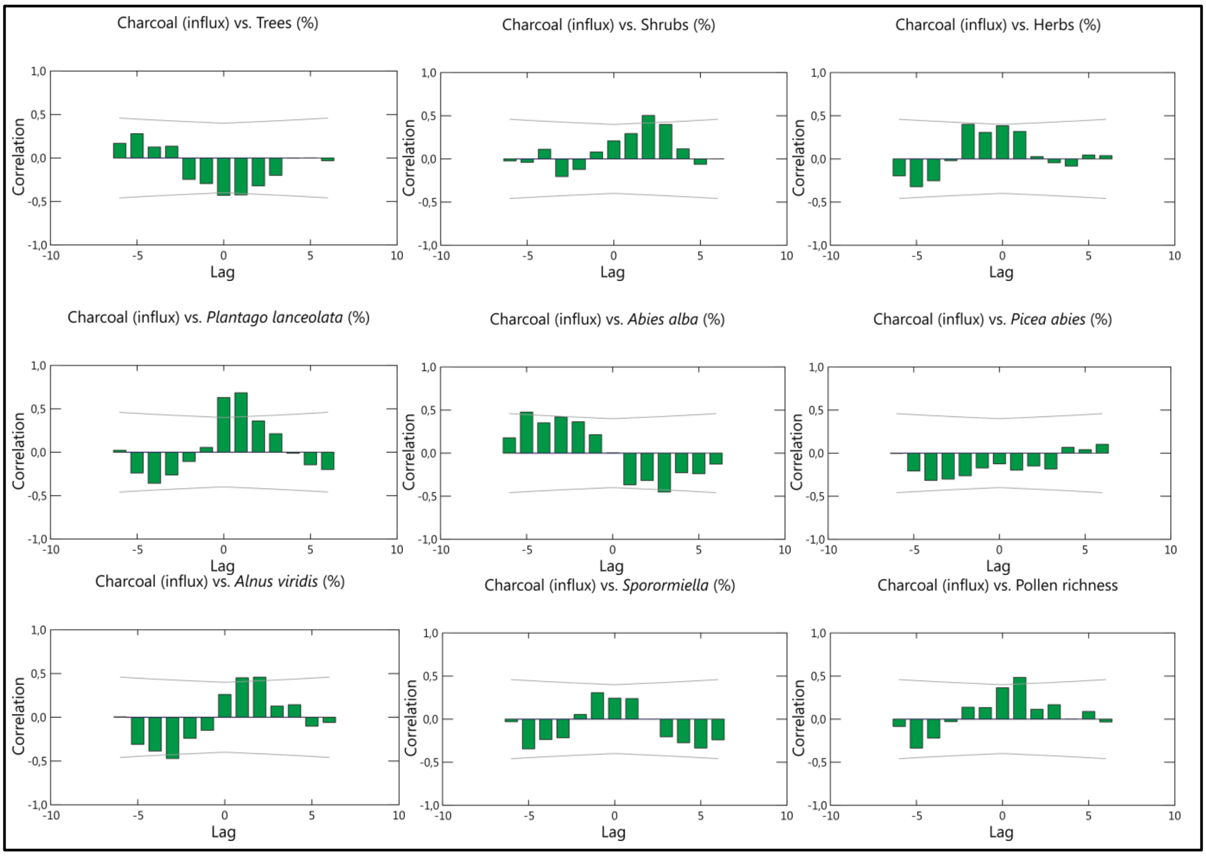

Fig. 9 Selected cross-correlation plots (Neolithic sequence). The grey lines mark the significance level. The horizontal axis shows the lag in years (1 lag =30 years).

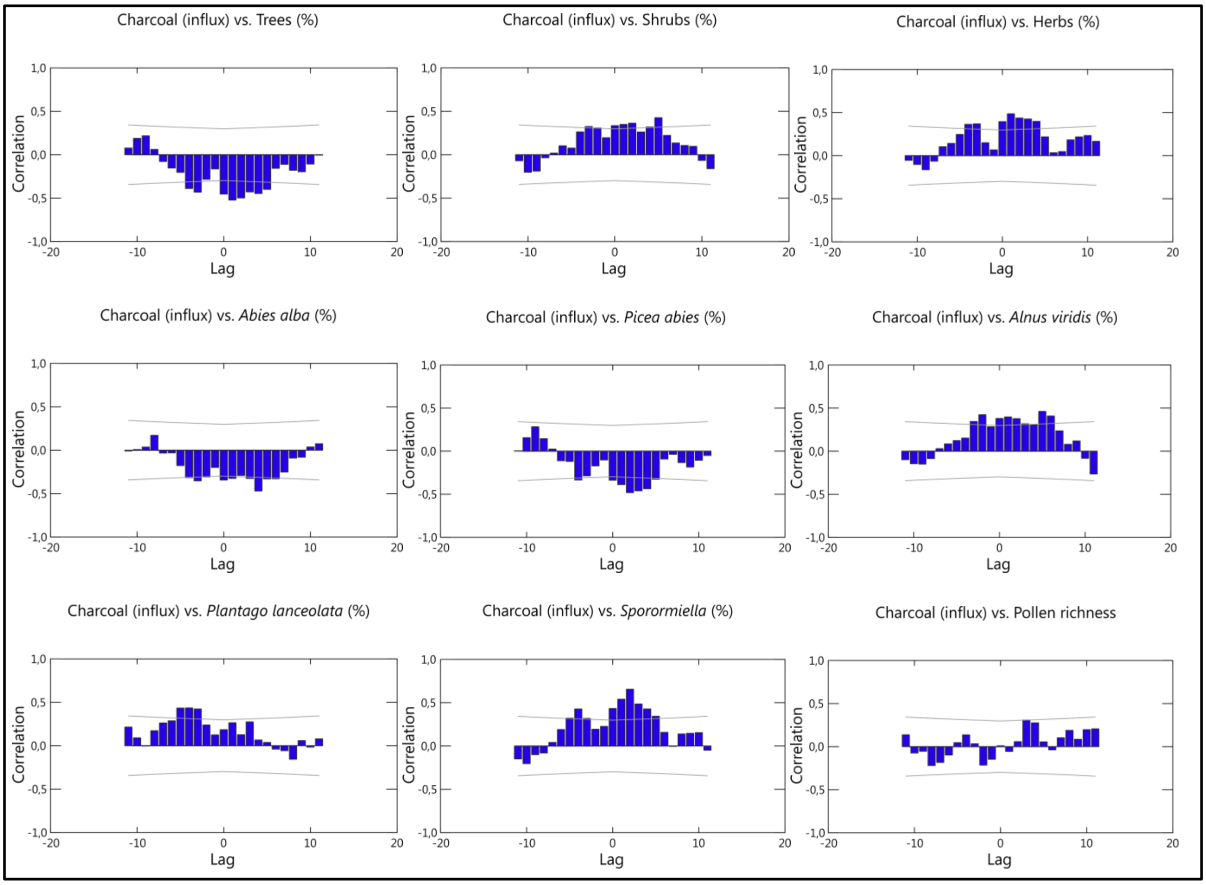

Fig. 10 Selected cross-correlation plots (Bronze Age sequence). The grey lines mark the significance level. The horizontal axis shows the lag in years (1 lag =28 years).

Summary of the manuscript

Lake sediments from Lauenensee were analyzed to reconstruct the vegetation dynamics of the past 14200 cal. years. The study site is located in the Bernese Alps at 1381 m a.s.l. (montane to subalpine vegetation belts). Today, the forests typically consist of *Picea abies* with some scattered stands of deciduous trees (*Betula pubescens*, *Alnus incana* and *Acer pseudoplatanus*). The landscape is fairly open with meadows used for alpine farming.

The first part of the study focuses on the reconstruction of the tree line during the Late Glacial. The macrofossil analysis shows that tundra vegetation with *Juniperus nana*, *Salix* and *Dryas octopetala* were dominant around the study site until 11600 cal. years. Thus, the tree line never reached the lake during the Bølling-Allerød interstadial. Afforestation started after 11600 cal. BP with *Betula*, followed by *Pinus sylvestris*. Those two taxa formed the first forest around the lake. More oceanic climate started the replacement of the former *Pinus sylvestris* stands by *Abies alba* after 7000 cal. BP. A mixed *Abies alba*, *Ulmus* and *Acer* forest persisted for the following 1000 cal. years. Under natural conditions, *Abies alba* would probably still dominating the landscape around Lauenensee today.

Human impact started to disturb the natural vegetation during the Neolithic after 5700 cal. BP. The analysis of the anthropogenic disturbances was the main issue of the second part of the thesis. Two high-resolution sequences of pollen and macrofossils were analyzed. During the Neolithic sequence (5700-5200 cal. BP),

grazing indicators such as fungal spores (*Sporormiella*) and *Plantago lanceolata* appeared for the first time. In the second sequence, covering the Bronze Age (4100-2900 cal. BP), those grazing indicators were found more frequently. Charcoal peaks showed an increasing fire activity. The cross-correlation analysis shows that *Abies alba* declined during both periods, whereas *Picea abies* only suffered during Bronze Age. This might be the reason why *Picea abies* could replace *Abies alba* after the Neolithic. The massive expansion of *Alnus viridis* can only be explained by the increasing human impact. On the other hand, *Abies alba* almost completely vanished from the catchment during the same time.

This Master's thesis concludes that the area around Lauenensee was never forested during the Late Glacial and that the monospecific *Picea abies* forests today can only be a sign of millennial human impact in the region.

Acknowledgements

I would like to thank the following persons:

- Willy Tinner for being my supervisor and for his two favorite words ("witer so")
- Christoph Schwörer for his assistance and for bearing me
- Noëmi Zweifel for sharing the burden
- Erika Gobet for her help with the sediment cores and the good advices
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- Silke Schleiss for her help with the macrofossil analysis
- The whole paleoecology group for always being there for me (I am sorry for my never ending talking...)
- My parents and my friends for listening to me and supporting me although they mostly did not understand what I was working with

Appendix

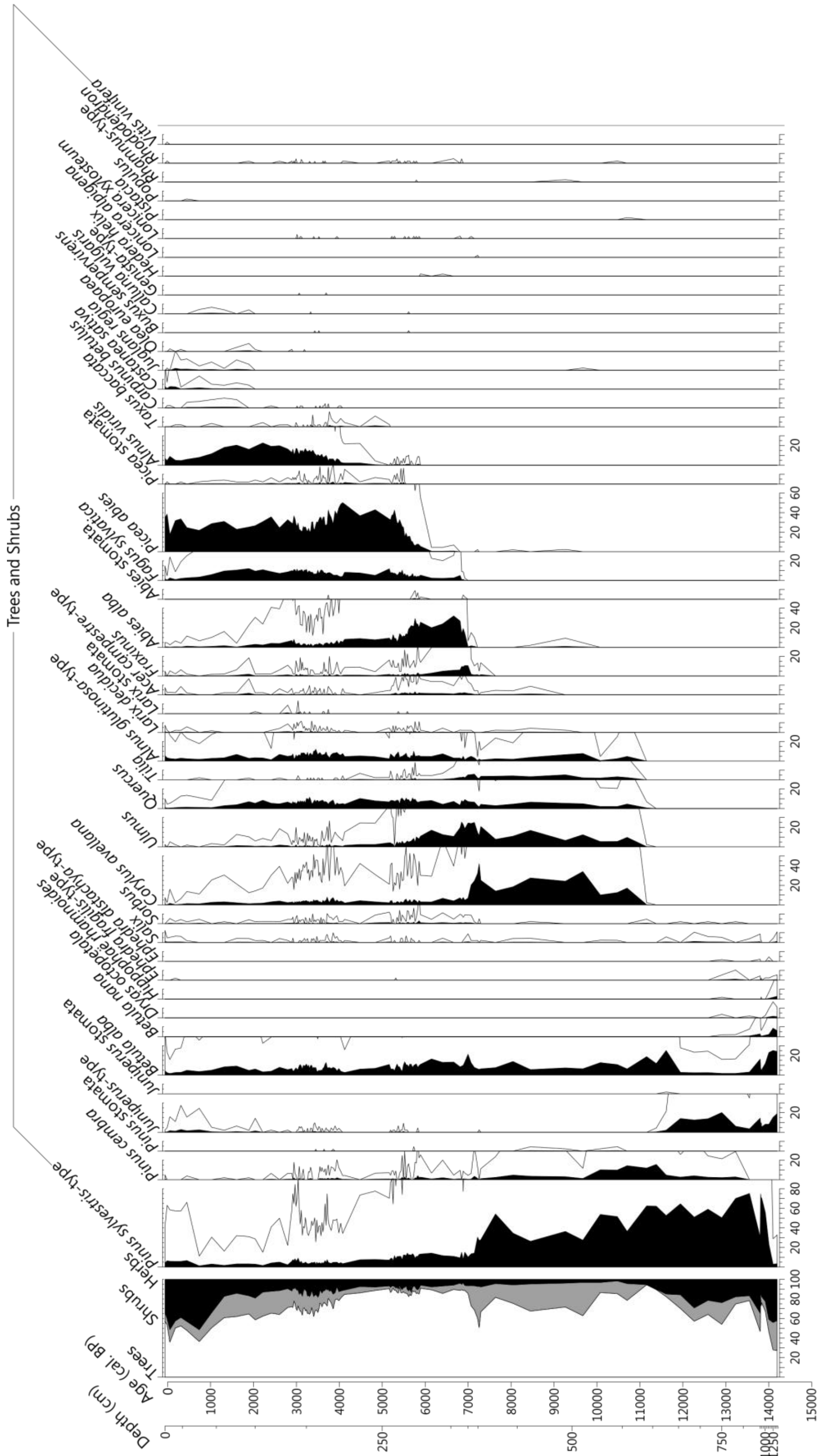

Fig. 11a Pollen percentage diagram (trees and shrubs). The empty curves show the 10x exaggerations (Analysis: Fabian Rey).

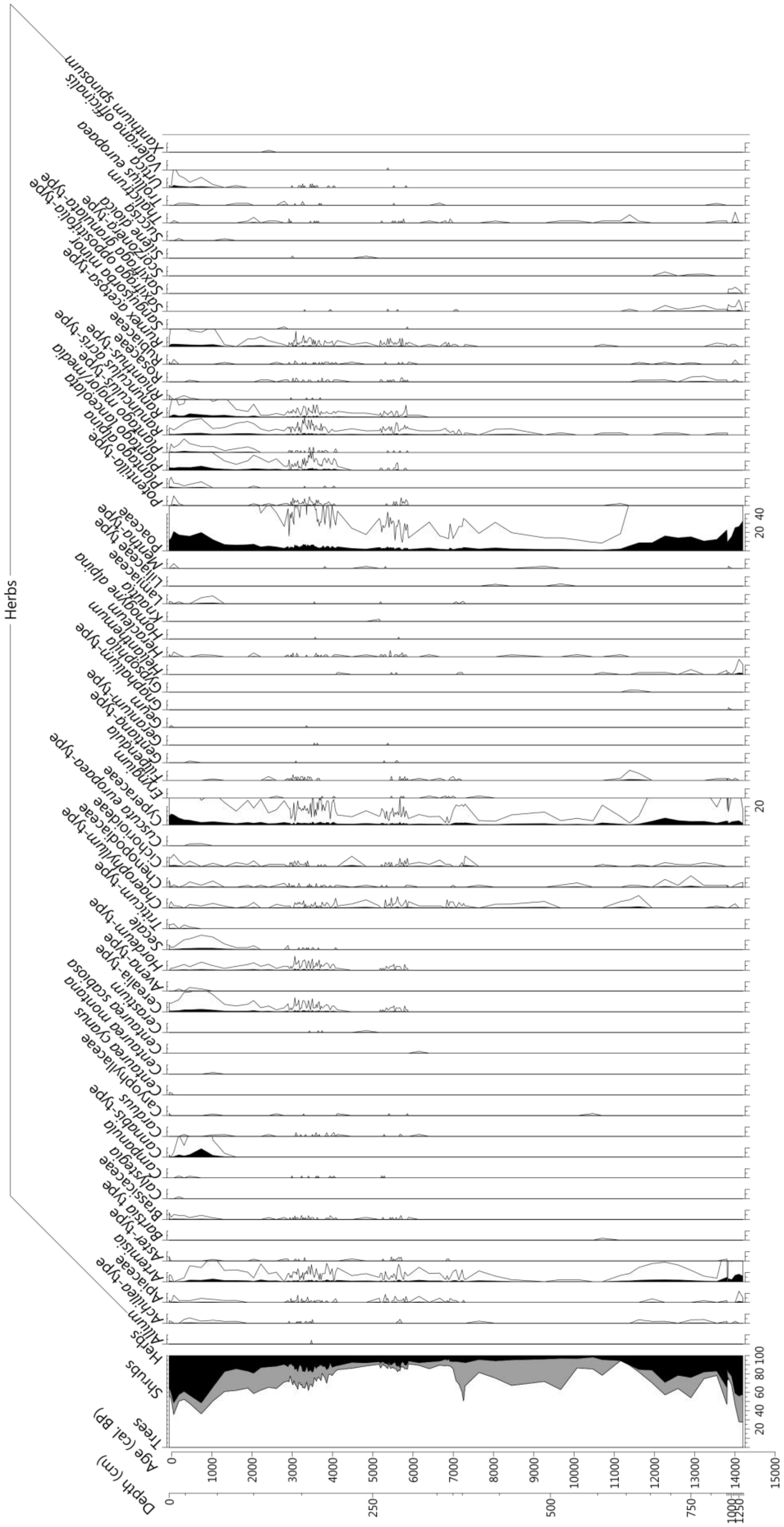

Fig. 11b Pollen percentage diagram (herbs). The empty curves show the 10x exaggerations (Analysis: Fabian Rey).

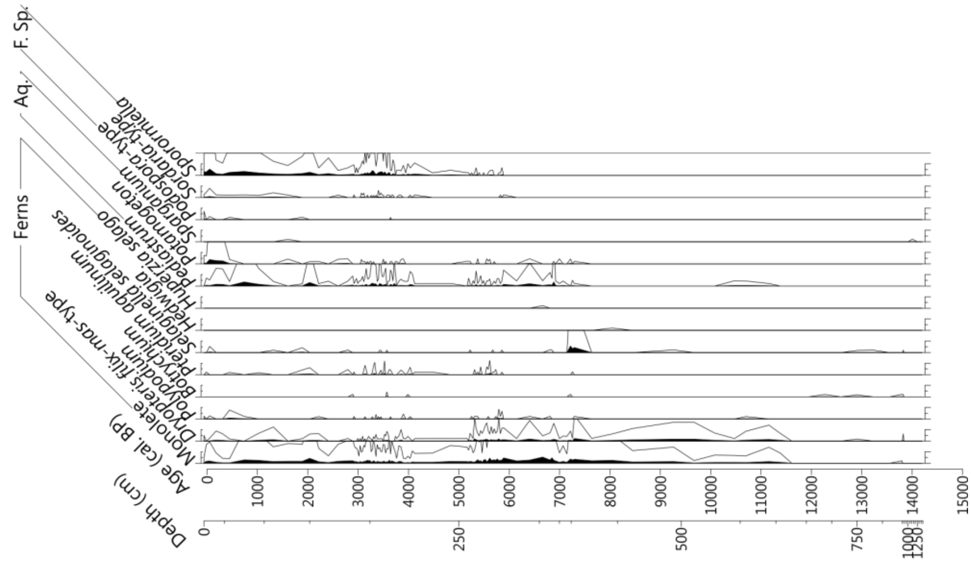

Fig. 11c Pollen percentage diagram (ferns, aquatics and fungal spores). The empty curves show the 10x exaggerations (Analysis: Fabian Rey).

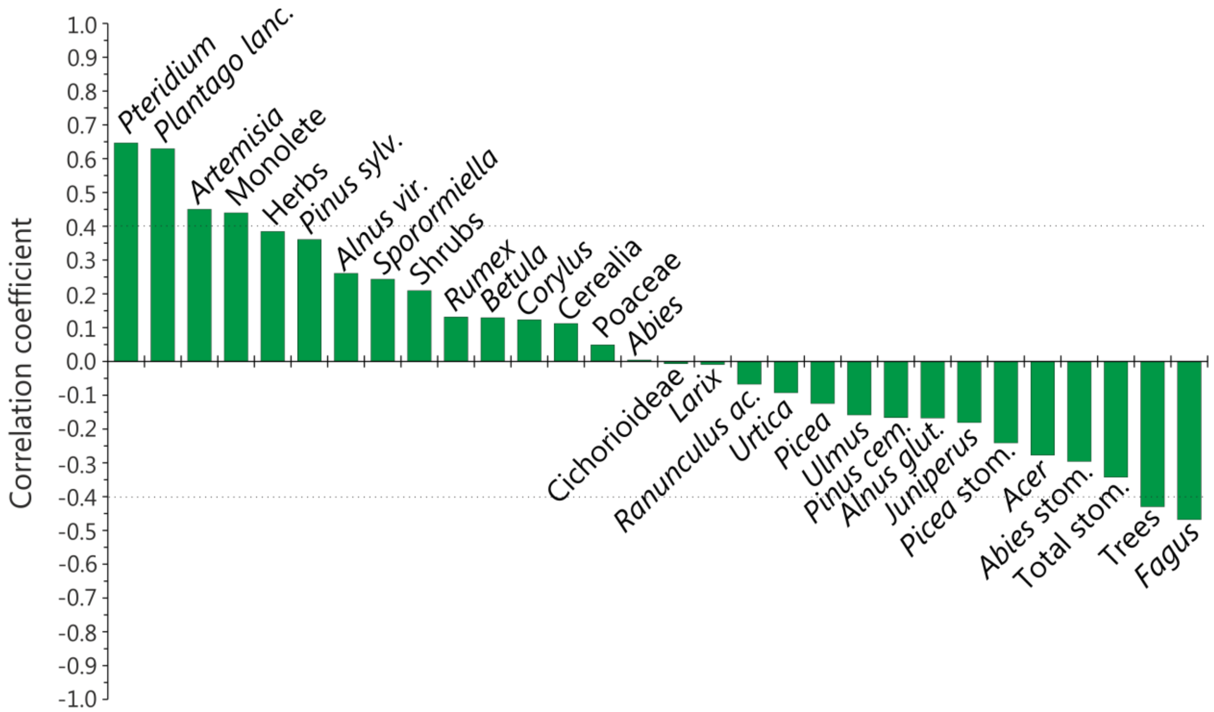

Fig. 12 Correlogram for the Neolithic sequence at lag 0. The dotted lines mark the significance level.

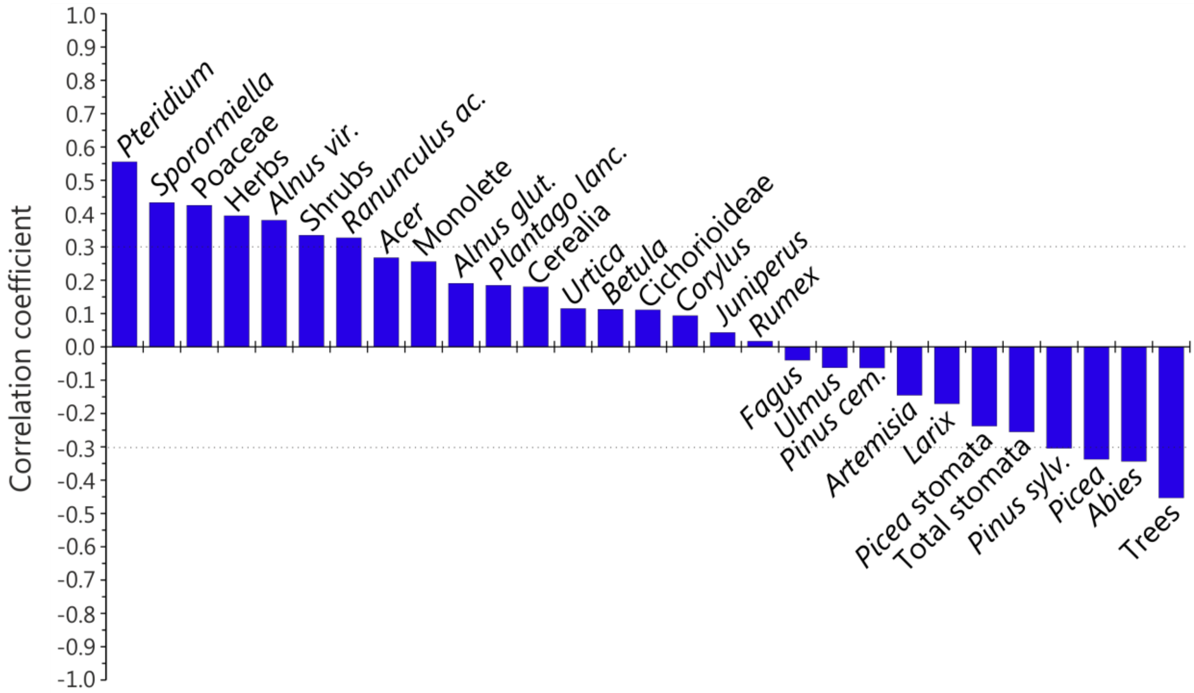

Fig. 13 Correlogram for the Bronze Age sequence at lag 0. The dotted lines mark the significance level.

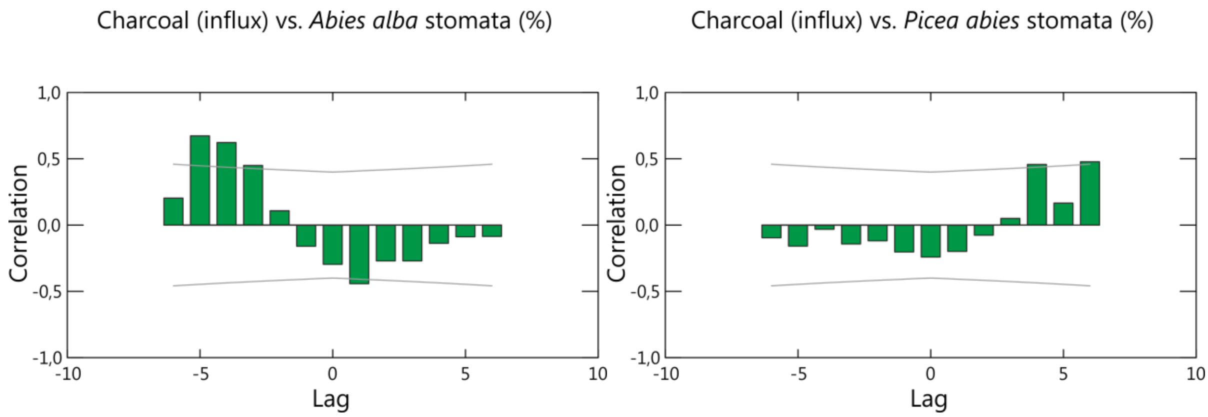

Fig. 14 Additional cross correlation plots (Neolithic sequence). The grey lines mark the significance level. The horizontal axis shows the lag in years (1 lag =30 years).

Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Rey, Fabian

Matriculation number: 07-054-893

Programme: Climate Sciences

Bachelor ☐ Master ☒ Dissertation ☐

Thesis title: Climatic and human impacts on mountain vegetation at Lauenensee (Bernese Alps, Switzerland) during the last 14000 years

Thesis supervisor: Prof. Dr. Willy Tinner

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise.

Bern, 1.7.2012
Place, date

....
Signature