Palaeoecological investigations of pasture woodland in Combe des Amburnex, Swiss Jura Mountains

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

Vorgelegt von

Per J.E. Sjögren

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Leiterin der Arbeit:

Prof. Dr. Brigitta Ammann

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Summary

The Jura Mountains are situated along the border between Switzerland and France. In the high western part of the mountain chain the vegetation consists of a patchwork of forests, open pastures and wooded pastures, a mosaic that in all makes up a pasture woodland. The trees are dominated by spruce (*Picea*), with fir (*Abies*), beech (*Fagus*) and a few scattered maples (*Acer*) growing in less grazed areas. This special landscape has been created by centuries of summer grazing and forestry practices. It is thus a cultural landscape, to a large degree dependent on human activities and management decisions.

The mix of pastures and forests gives the landscape special values apart from the purely economic. Historically the landscape can be seen as a reminiscence of an earlier much more widespread occurrence, thus giving it a cultural-heritage value not only for the region but for large parts of Europe. The variation and moderate disturbance of the vegetation favours biodiversity and may create a special habitat for some rare species (e.g. *Lobaria pulmonaria* and *Saxifraga hirculus*). The open pastures with scattered spruce trees trimmed by grazing cattle also creates a park-like appearance beloved by hikers, cross-country skiers and Sunday picnickers.

Within the framework of *NCCR Plant Survival* sub-project 6 (*Pattern and long-term changes in pasture-woodlands: Complex plant-herbivore interactions in a traditional type of agro-forestry)* the thesis project was launched as part of an effort to gain a better understanding of the processes that create and maintain pasture woodlands, with the practical goal of improving future management plans in a changing economic and natural environment. The specific goal for the thesis project was the long-time development and the vegetation history of pasture woodland as recorded in natural archives like peat deposits. The results are of independent value but are primarily planned for the larger project.

The small mountain valley Combe des Amburnex (1300 m a.s.l.), 12 km NW of Lake Geneva, was chosen as the investigation area. Three peat profiles 1 km apart were extracted in 2002, two from a large mire in the valley bottom (Sèche de Gimel) and one from a small mire up the valley side (Les Amburnex, 1370 m a.s.l.). The pollen content and other properties of the peat were stratigraphically analysed, allowing an estimation of past vegetation cover and its changes. The short distance between the peat profiles allowed better spatial resolution than would otherwise be possible. The lowland pollen transported from a long distance were similar for all three peat profiles and could be used for internal correlation. Other sites from the Alps have been included for comparison and establishment of general trends.

Several pasture expansion and forest regeneration phases have occurred in Combe des Amburnex during the past 2000 years. The central part of the valley gained its modern open appearance c. AD 1200, while the pasture woodland in the landscape as a whole came into being c. AD 1700. The creation of pasture woodland is clearly associated with fire activities, and charcoal production or similar activities may have played a major role in the opening of the landscape. The forest in the first millennium AD was made up of equal parts spruce, fir and beech. From the end of the same millennium spruce started to become more dominant, possibly an effect of long-time forest grazing and creation of wooded pastures. The large deforestations around AD 1700 increased the groundwater table and re-initiated peat growth in some of the mires. The mires have also been severely affected by grazing, a phenomenon that can be seen across the Alps.

The landscape structure has thus been rather stable during the past 300 years and remains so under the current land-use regime, but changes in nutrients, grazing–pressure and climate during the 20th century have had an increasing effect on the species composition.

Contents

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Introduction

The high part of the Jura Mountains extends in an arc along the border between Switzerland and France. The vegetation is a patchwork of pastures, wooded pastures and forests. This type of vegetation pattern is referred to as pasture woodland, i.e. a mix of pastures and forests. There are many interesting aspects of the landscape, most importantly historical, biological, economic and esthetic. The landscape is a product of old traditions and land-use practices, and in former days it was much more widespread across Europe. From an ecological point of view the land-use and landscape pattern have created high biodiversity and special dynamics. Economically the area is important for summer grazing and to some degree for forestry. Best known to the public are probably the esthetic values, especially the park-like appearance with wooded pastures and spruce-trees trimmed by cattle. It has thus become a popular area for hiking, picnicking and cross-country skiing.

To study the long term history and development of pasture woodland three peat profiles were extracted from the small high-altitude (1300 m a.s.l.) valley Combe des Amburnex, and the fossil pollen content in the peat was systematically analysed in order to assess changes in the past vegetation. The development of the landscape during the past 2000 years as determined from fossil pollen assemblages is described and discussed in paper I, a short description of the major changes is also found below. For the Late-glacial and Holocene development and vegetation history in general see Wegmüller (1966). The effect and implication of past land-use on mires and peat deposits in this type of land-scape is discussed in papers II and IV. The effect of climate on pollen productivity and possible implications for interpretation of pollen assemblages is discussed in paper III.

NCCR Plant Survival

This PhD-project is part of NCCR *Plant Survival,* a project funded by the *Swiss National Science Foundation* (SNF). The project was launched in 2001 under the full name NCCR *Plant Survival in Natural and Agricultural Ecosystem* administrated by the University of Neuchâtel and planned to run for at least two four-year periods. The project is made up of several related sub-projects. This thesis is part of sub-project 6: *Pattern and long-term changes in pasture-woodlands: Complex plant–herbivore interactions in a traditional type of agro-forestry,* headed by PD Dr.

Christoph Scheidegger and co-ordinated by Dr. Helene Wagner at WSL Birmensdorf. The applied goal of the sub-project is to establish bounds for the range of management options that have a high probability of maintaining the typical structure and dynamics of wooded pastures and viable and genetically diverse metapopulations of epiphytic lichens. The sub-project has two main hypotheses of how the modern vegetation patterns of pasture woodland have been established and are maintained: 1) Facilitation hypothesis: complex interactions significantly affect the spatial structure and equilibrium conditions of the wooded-pasture ecosystem; and 2) Historicality hypothesis: Past pasture-woodland landscape dynamics have a lasting effect on biodiversity.

The specific contribution of this PhD-project is to use natural archives to "reconstruct the disturbance regime and its historical variability for the study area in general and, in more detail, for specific areas where lichen data have been collected". Lack of suitable natural archives have made it problematic to use sites where lichen data have been collected, thus leaving the general development of the study area as the primary contribution to sub-project 6. The development of the landscape and different disturbance regimes are assessed in paper I, with additional details in paper IV.

Palaeoecological investigations

The palaeoecological investigations in the valley Combe des Amburnex are based on pollen analysis of three peat profiles less than 1 km apart (paper I). The main peat profile is extracted from a large central mire (1300 m a.s.l.) and provides a more regional pollen signal than the secondary peat profiles from the edge of the mire and from a smaller mire up the hill slope (1370 m a.s.l.). Wetlands are not uncommon in the area, but the limestone bedrock drains most hollows in higher forested areas, prohibiting peat accumulation, while peat deposits in low open areas are heavily damaged by grazing and trampling (paper II and IV). One of the main study objects, past grazing regimes, thus has a damaging impact on the archives themselves. The partially low and uneven peat-accumulation rate made independent depth-age models unreliable for comparison, and a chronostratigraphy based on extra-regional (here lowland) pollen was developed (paper I). This approach requires more assumptions than single-site depth-age models (i.e. the correctness and resolution of the correlation) but allows direct comparison and increases the effective use of the available ^{14}C-dates (here from c. 10 per profile for a total of 30 for the chronozones). Such chronozones are theoretically not the best units to describe local changes in the vegetation, but in this case they are satisfactory, as they largely coincide with qualitative changes in the local pollen assemblages. The use of three adjacent peat profiles with different pollen-source areas allowed a higher spatial resolution of landscape development than a single site would permit (paper I). For the small mire up the valley slope the pollen analysis was supplemented with testate amoebae and macrofossil analysis, which allowed more detailed information on the effects of land-use and climate on the local mire development (paper IV). The effect of climate on pollen productivity, especially important in high resolution studies, was assessed with a *Sphagnum* hummock from the same mire (paper III). High spatial resolution for the latter half of the 20th century was achieved through use of variation in atmospheric ^{14}C caused by testing of nuclear weapons in the 1960's. Effects of land-use and climate on mire development and pollen accumulation were also compared with sites in the Alps to establish regional patterns (paper II and III).

Current and future palynological investigations

Five pollen traps were place in a transect along the side on the valley in early 2002. These are now part of the Alpine pollen-trapping effort (see van der Knaap *et al.*, 2001) and are estimated to run until 2006, resulting in 5 years of pollen influx data supplemented with surface samples. The investigation has already yielded interesting results for interpreting pollen assemblages in this type of landscape, but scientific publication must await a more robust data set in 2006. Investigations of modern pollen spectra and vegetation by Florence Mazier, Université de Franche-Comté, Besançon, will result in estimations of local relative pollen productivity (PPE) and relevant source area of pollen (RSAP). Together with the fossil pollen data and landscape-development models (Helene Wagner, WSL, Birmensdorf) it will be possible to produce quantitative hypotheses for landscape reconstructions and development, linking the palaeoecological data with other aspects of NCCR Plant Survival.

Vegetation history of Combe des Amburnex

Humans have been present in the Jura Mountains since more or less the end of the last glaciation 10 000 BC (Kaenel and Crotti, 1991). The first remains of animal husbandry in the region (cattle, sheep, pig) are dated to 5000-4000 BC, found near Col du Mollendruz c. 15 km NW of the investigation site. This date fits well with increased human impact in Combe des Amburnex (Wegmüller, 1966), after which the forest closed again. A fortification at the summit of Châtel d'Arrufens (1390 m a.s.l.) north of the investigation area is dated to 1500 BC (Pousaz, 1984), and weak signs of human impact can be seen in Combe des Amburnex at approximately the same time (Wegmüller, 1966). The landscape is then opened up and reached a maximum in openness in the late La Tène culture during the first centuries BC. After the failed migration of the Helvetii 58 BC (Ceasar, -51) Combe des Amburnex was again reforested, and, except for a short amelioration in the late Roman Age, remained so until the Middle Ages. Despite the fluctuations in the amount of surrounding pastureland, grazing on the mires seemed to occur throughout the time (see Wegmüller 1966), at least after AD 1. During the Middle Ages openness increased from the 6th century and reached a maximum in the 13th century (paper I).

Possibly the work of monks from the nearby monastery of Oujon (near Azier, c. 10 km south), founded in AD 1146, who owned pastures in Combe des Amburnex (Mottaz, 1982). Other written records mention pastures in Combe des Amburnex from AD 1301 (Rochat, 1995). At this time the central part of the valley gained a vegetation structure similar to today’s. Forest composition started to change already in the 9th century. From a forest approximately composed of equal parts *Abies*, *Fagus* and *Picea* the forest became increasingly dominated by *Picea*. This change might partly have been caused by development of wooded pastures (paper I).

The use of the forest seems to increase from the 16th century, with charcoal production and extensive felling (Rochat, 1995) and in AD 1698–1708 even a small glass industry was at work in the area (Piguet, 1998). Around AD 1700 the landscape changed drastically, and pasture woodland can now be said to exist around Combe des Amburnex. Most likely it was created by extensive felling and burning of wood (e.g. for charcoal or glass production). The clearance was followed by an increase in the number of husbandry animals, especially cattle. As a result of changing ground-water level caused by the deforestation and the new grazing regime the mire vegetation changed (paper I and IV). After the openness maximum from the 18th to early 20th century a minor reforestation started, primarily caused by reduced forest grazing. Also the herb layer changed during the 20th century. *Poaceae* and nutrient-demanding herbs as *Urtica* increased in relation to other herbs, most likely a result of manuring and more effectively used pastureland through rotation systems of the cattle (paper I). Parts of the mires also show increased peat accumulation and acidification during the 20th century as an effect of decreased trampling and grazing of the mire surface caused by protective fences (paper IV).

Future development of Combe des Amburnex

The structure of the vegetation in Combe des Amburnex has been relatively stable for the past 300 years, suggesting that the current land-use management is effective in sustaining the traditional landscape structure. Structural changes during the last century are better traced with maps and aerial photographs. Here a closing of the forest and increasingly sharp division between open pastures and forest can be seen (Kalwij *et al.*, 2005). Forest grazing has occurred over the past 6000 years, continuously in some areas for at least 1000 years, a traditional land-use that now risks disruption. The open pastures show minor but clear changes in herb composition in favour of grasses and more nutrient-demanding herbs. Changes in the mires are more profound, and fenced areas show an increase in vegetation associated with bogs, while new species start to appear in the large central mire (Sèche de Gimel).

From the point of view of historical continuation the landscape is well managed, even though some changes occur. Still, the landscape should not be a museum of past land-use but a living and economically viable feature, so some degree of change must be accepted. But it is important to take these changes into account in planning future land-use strategies, so that the right consideration among cultural, biological, economic, and recreational values can be taken, especially to avoid overlooking and unnecesarily losing such values. Here the following considerations are raised:

1) Grazed forests have long historical continuation but are likely to disappear in the near future. It should be assessed if this development is preferable or not, i.e. if some important habitats or other values worth preservation are threatened by this development.

2) Open pastures seem to show changes in herb composition during the 20th century, most likely an effect of manuring and rotation systems for cattle. As the landscape has a variable topography, manuring and grazing pressure will still be uneven and nutrient-poor areas of variable grazing pressure will most likely still be present, but it should be assessed if these areas are large enough to maintain the preferred biological diversity.

3) The mires are in state of change that should be considered in land-use planning. The fenced parts seem to develop toward raised bog types. This may well be the mires' "original" form, but they have not to been present in the Combe des Amburnex for the past 3000 years. The vegetation composition of the large mire Sèche de Gimel is also changing, with new taxa arriving or expanding. Here some care should be considered, as it is the only growing place for *Saxifraga hirculus* in Switzerland.

4) No clear effects of global warming can be detected, but this may be because the major changes in land-use during the 20th century blur or coincide with any climatic signal. Still, parts of the observed changes, especially in the mires, are likely to be partially affected by the changing climate. Continued climatic change will most likely have an effect on the landscape and species composition, so the future long-term development should be monitored so that land-use practises can be adjusted accordingly.

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The development of pasture woodland in the SW Swiss Jura Mountains over 2000 years, based on three adjacent peat profiles

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Abstract: The pollen content from three adjacent peat profiles has been analysed in order to study the development of pasture woodland in the small valley Combe des Amburnex (1300 m a.s.l.). Chronostratigraphy based on extra-regional pollen assemblages was used to correlate the profiles. Forest and mire grazing occurred throughout the last two millennia. Before the 9th century the forest consisted of about equal parts of *Abies*, *Fagus* and *Picea*. Thereafter *Picea* increased and today it strongly dominates the forest composition around the sites, likely an effect of selective grazing pressure. The central part of the valley gained its modern structure in the 12th century, and the pasture woodland in general came into existence during the 17th century as an effect of extensive fire activity, possibly charcoal production. In the 20th century grass and nutrient demanding species increased in relation to other herbs.

Key words: cultural landscape, Jura Mountains, palaeoecology, pasture, pollen, Switzerland

1. Introduction

Pasture woodland is a typical landscape for the Jura Mountains at middle elevation (c. 900-1400 m a.s.l.). It consists of a mosaic of open pastures, wooded pastures and forests, kept in this state by summer grazing and forest management (Gillet and Gallandat, 1996). This traditional type of cultural landscape has probably once been widespread across Europe, but today it is only present in limited areas because of the activities of modern agriculture and forestry.

The parklike landscape with its free-standing spruces, well trimmed by cattle, has a high esthetical value and is important in biological and economical aspects. The mosaic landscape in general and the wooded pastures with its mixed vegetation in particular show a high biodiversity (Gallandat *et al.* 1995). Traditional types of land-uses, now in modern forms, have in the recent decennia been complemented with tourism. Especially hiking, cross-country skiing and picnicking in the picturesque landscape are popular recreation activities.

The general vegetation history of the SW Jura Mountains is well established (Wegmüller, 1966), as is the general development of the cultural landscape (Gauthier, 2004). Several other palaeoecological investigations along the SE edge of the mountain chain have been published (e.g. Ruffaldi, 1993; Schoellammer, 1997; van der Knaap *et al.*, 2000; Mitchell *et al.*, 2001; Roos-Barraclough *et al.*, 2004), but they have little focus on the cultural landscape. In the present investigation the period of concern is the past 2000 years, which is considered to be the most relevant period for the development of todays pasture woodland landscape.

The study is based on the analysis of pollen in three peat profiles from the small valley Combe des Amburnex. All three sites are within 1 km of each other, which enables assessment of local changes in the landscape structure. Different basin sizes have been used to improve the spatial resolution (e.g. Björkman and Sjögren, 2003; Koff and Kangur, 2003). The study is part of the Swiss national project NCCR Plant Survival. Here modern and historical ecology of pasture woodland are studied in order to improve scientific understanding and management strategies. The specific contribution of this paper is the assessment of the vegetation history and long-term development of pasture woodland within the investigation area.

2. Study sites and regional settings

2.1 Geographical setting

The valley Combe des Amburnex at 1300 m altitude is separated from the Swiss lowland by one main ridge (Figure 1). The nearest larger agricultural areas are situated c. 5 km to the east. The dominating humid wind direction is from the SSW, with weak winds from NNE. Mean yearly temperature is c. 3°C, with a mean July temperature of c. 11°C and a mean February temperature of c. -4°C. Single days may be extremely cold, and frost may occur even in summer.

Precipitation is high, c. 1600 mm/year, but the water is quickly drained away in the permeable limestone bedrock, and summer droughts do occur. Wetlands are common in the lower parts of the valley where depressions may be sealed off with clay and/or fed by springs. Nearly half the area is tree covered. The tree composition is dominated by *Picea*, while *Abies, Fagus* and a few *Acer* trees occur in more protected areas, e.g. on stony ridges and in denser forests. The pastures are species-rich, and 550 plant species have been listed in the surrounding area (Vittoz, 1998).

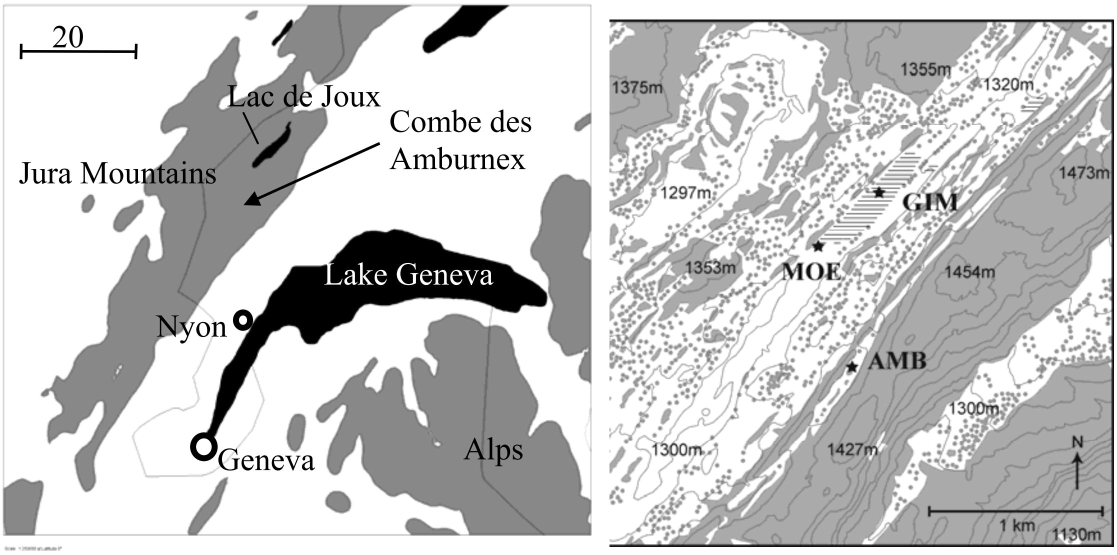

Figure 1 Overview map (a, left) and site map (b, rigth). Figure 1a: Grey represents areas above 1000 m a.s.l. The thin line marks the border between France and Switzerland. Figure 1b: Gray represents forest, small dots are single or small groups of trees, mainly Picea. Wetlands are marked with stripes, site locations are marked with stars. The map covers the northern part of Combe des Amburnex.

2.2 Historical setting

In 58 BC the Helvetii, who occupied all the land between the Jura Mountains and the river Rhine, burnt their own cities and villages, and set out to conquer Gaul (France). But they were defeated by the famous Roman commander Julius Ceasar in the same year, and, heavily decimated, they were forced to return to their old lands (Ceasar, -51). The Romans founded Nyon (Colonia Iulia Equestris) in 45/44 BC as a colony for retired soldiers. It lies at the shore of Lake Geneva 20 km south of the investigation area, but it is unclear whether or not the colony included the slopes of the Jura Mountains (Tarpin *et al.*, 2002). Monks were active in the Jura Mountains already in the 5th century, but in the region of investigation they had no major impact until the 12th and 13th centuries. The Abbey du Lac de Joux was founded in AD 1126 and became important for the opening up of the Joux valley, less than 5 km NW of the investigation area. Pastures in Combe des Amburnex were mentioned in connection with the opening of the Carthusian monastery of Oujon (near Azier, 8 km S), in AD 1146 (Mottaz, 1982). Later written sources mention pastures in Combe des Amburnex in AD 1301, then own by the village St. Oyens, 8 km SE (Rochat 1995). In AD 1348 the plague (Black Death) severely reduced the population in this part of Europe.

Major glass and iron production was established in the Jura Mountains in the Middle Ages (Rieben, 1957). Charcoal was produced in the area around Combe des Amburnex from at least the 16th century (Rochat 1995). As glass and charcoal production increased in the 18th and 19th centuries the forests became increasingly overexploited. Charcoal production stopped first when the railroad allowed importation of cheap stone coal in the second half of the 19th century. Map material shows that the treeless areas in Combe des Amburnex (*Die Siegfried Karten*, Marchairuz, section XVI, 2b) were about 10% larger in 1892-93 than today, but the structure of the landscape was more or less the same. In 1902 different cantonal and federal laws finally allowed an organised forestry, and in the 1950's to 1970's the separation promoted of forest and pastures was promoted. The landscape is today kept open by a combination of summer grazing and selective forestry (Gillet and Gallandat, 1996), and since 1973 the area is under protection as part of the 50 km^2 large Parc Jurassien Vaudois.

2.3 Site descriptions

The main pollen profile, GIM, is based on a core from the middle part of the large mire Sèche de Gimel (c. 12 ha) at 1300 m altitude (Figure 1b). The same site was used for palaeoecological investigations by S. Wegmüller (1966, "Le Marais des Amburnex"). A second profile, MOE, is based on a core from the SW edge of the same mire. The mire is famous among botanists for the occurrence of *Saxifraga hirculus*, the only locality in Switzerland. A third core, AMB, came from a small raised mire (c. 0.1 ha) on the valley side at 1370 m altitude. This bog is largely overgrown by *Picea,* and a colony of badgers has settled in the southern part. Both MOE and AMB are used for water extraction and are today also fenced and protected from grazing. The short names derive from geographical places, i.e. GIM for Sèche de Gimel, MOE for Le Moé, and AMB for Les Amburnex.

3. Material and methods

3.1 Pollen source area

The pollen load (the pollen deposited at a place) can theoretically be divided into different categories depending on mode of transport and area of origin, often expressed as the distances from the site (Tauber, 1965; Janssen, 1966). Prentice (1985) suggested the following categories (distance from edge of basin): local = 0-20 m, extra-local = 20 m-2 km, regional = 2-200 km and extra-regional > 200 km. This terminology works fairly well for the present investigation, but some clarifications are needed. Local includes fen, bog and wetland plants that grow on or in direct connection with the mires. Most of these pollen types can be identified by the preferred habitat of the plant and/or its spiky appearance in the pollen diagram. This category is, as usual, excluded from the pollen sum. The extra-local pollen load is here considered the component that derives from the RSAP (relevant source area of pollen), which is defined as the limit beyond which pollen does not sense the spatial patterns of vegetation (Sugita, 1994). Simulated RSAP for moss polsters (r = 0 m) in the area is 800-1000 m (Florence Mazier, pers. com.), so the RSAP for the sites should be similar or somewhat larger depending on the basin sizes.

The regional component is here considered to be from the Jura Mountains above c. 1000 m, and the extra-regional component is thus the pollen that arrives from outside that area. Most of the trees that are common above 1000 m also occur at lower altitude, but it can be assumed that the strongest pollen signal arrives from within the region. As an example, Tauber (1965) estimated that in a forest composed of species with light pollen grains c. 75% of all pollen would come from within 5 km, and for species with heavier pollen grains the percentage would be even higher. In the pollen diagrams the taxa are grouped according to their modern distribution: highland taxa = regional taxa (excluding *Pinus*), lowland taxa = extra-regional taxa (excluding highland taxa), and wetland taxa = taxa growing on or in close association with the wetlands. *Pinus* is excluded from the highland taxa because it does not occur extra-locally and only in scattered populations in the region as a whole.

Alnus, *Corylus*, *Betula,* and *Fraxinus* do not grow in the area today and are thus treated as lowland species, but according to the climate they might well have grown locally in earlier times. Complicating factors for interpreting pasture woodland is that grazing may reduce the pollen productivity for herbs (Hjelle, 1998), while free standing and well exposed trees may have an increased pollen production (Aaby, 1988). As GIM comes from the middle part of the largest mire area it can be assumed that it has a more regional pollen signal than MOE and AMB (e.g. Janssen, 1966; Jacobson and Bradshaw, 1981).

3.2 Field coring

The GIM core was obtained with a gauge corer of 6 cm diameter in the end of July 2003. The first half meter of the top drive (in profile 0-96 cm) was dug free from surrounding peat before extraction to allow an undisturbed peat recovery. For the lower part of the profile a parallel core 1.2 m away was used, as this had a longer and undisturbed recovery for the lower drives. Total coring depth was 3.4 m. The MOE and AMB profiles were based on c. 50 cm deep monoliths. MOE was collected in April 2002 and AMB in June 2002.

3.3 Peat stratigraphy

GIM has a decomposed top layer of c. 40 cm, below which the peat is well preserved. MOE has a c. 30 cm thick top layer of well-preserved *Sphagnum*, but below that the peat is strongly decomposed. AMB has a c. 10 cm thick layer of well-preserved *Sphagnum* overlying decomposed peat.

3.4 Pollen analysis

The pollen samples were prepared by the acetolysis method (Faegri and Iversen, 1989): hot KOH 8 min, addition of *Lycopodium*–tablets dissolved in HCL, sieving at 0.2 mm, acetolysis 2 min, hot KOH 5 min, glycerine, mounting in glycerine, and staining with fuchsin. The dissolved *Lycopodium*-tablets were added first directly prior to sieving because some plant material did not settle well in HCl. Analysis was carried out at 400 times magnification. Reference material used for identification of pollen types included literature (Punt and Clarke, 1984; Moore *et al.*, 1991; Reille, 1992, 1995, 1998; Punt *et al.*, 1995; van Geel *et al.*, 2003; Beug, 2004) and the reference collection at the Institute of Plant Sciences in Bern. Nomenclature follows ALPADABA (Alpine Palynological Data-Base, housed in Bern). Approximately 500 upland pollen grains have been counted in each sample (mean pollen sum for the main diagrams is 570).

3.5 Chronostratigraphy

The chrono-correlations (Figure 2) between the sites are based on the pollen assemblages from taxa not growing in the area, and believed to never have grown there in the past, i.e. the extra-regional component. The maximum distance between the sites is 1 km, and at least 5 km exists to any substantial population of the taxa used for correlation, so the extra-regional pollen assemblages should theoretically be the same in all three sites (e.g. Janssen, 1966, 1981; Jacobson and Bradshaw, 1981; Prentice, 1985). Minor differences in the extra-regional pollen assemblages among the sites are attributed to differences in local air currents, sedimentation surfaces, decomposition, sampling resolution, and statistical errors due to low extra-regional pollen sums (mean 110). The chronozones are based on distinctive features within zones and at zone transitions (increases, decreases, and amplitude). In addition pollen assemblage zones (PAZ) have been determined statistically by optimal sum-of-squares partitioning (Birks and Gordon, 1985; Birks, 1986) and their significance has been tested with the broken-stick method (MacArthur, 1957; Bennett, 1996). Considering the different resolutions of the cores the PAZ correlate well, and are in accordance with the chronozones.

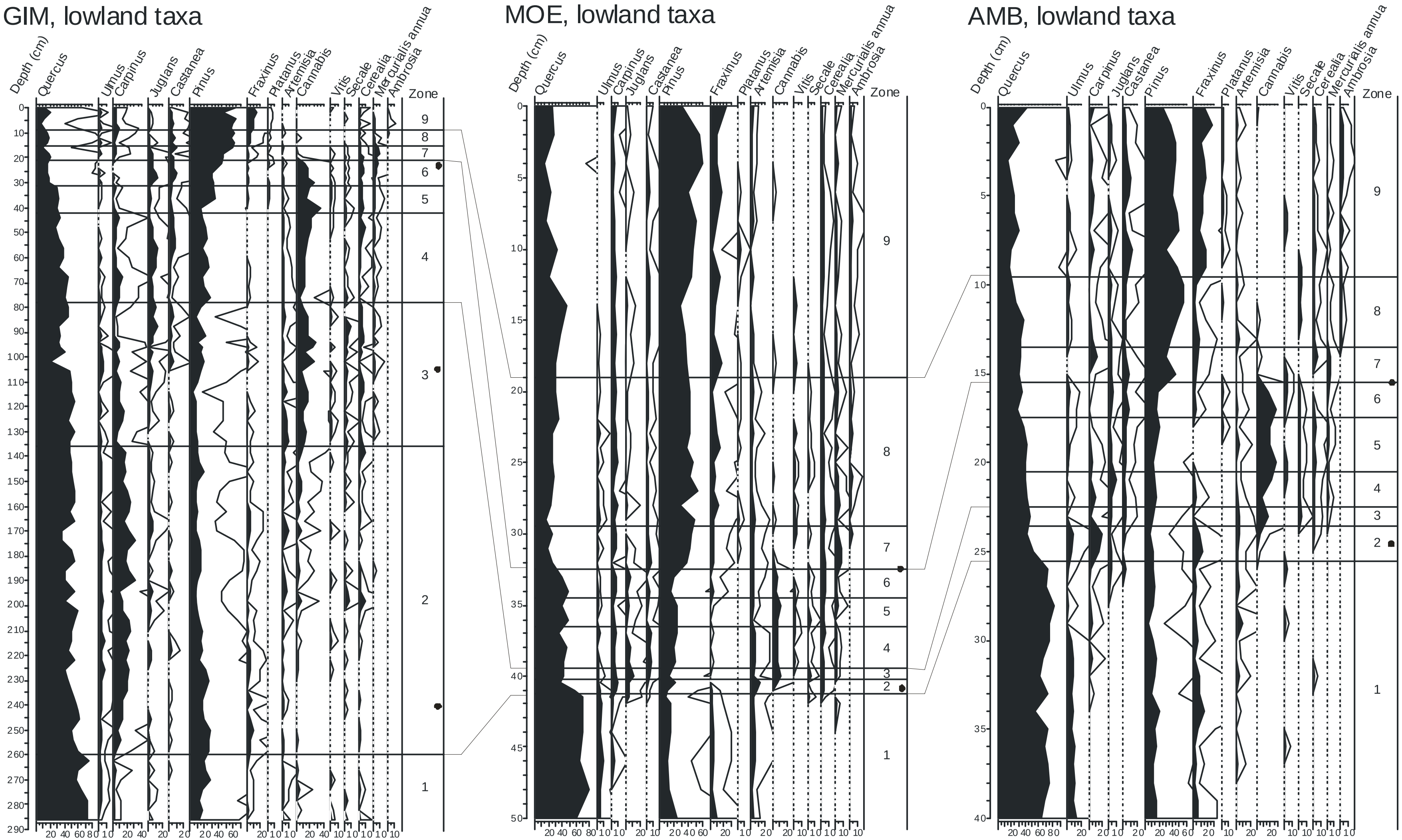

Figure 2 Pollen percentage diagrams from GIM, MOE and AMB for correlation based on the extra-regional (i.e. non extra-local) pollen sum. Chronozone boundaries are marked with full lines and statistically determined PAZ boundaries are marked with black dots. The chronozone boundaries drawn between the diagrams are for clarification purpose only.

Characteristics for the chronozones are as follows:

Zone 1 - High values for *Quercus*, moderate values for *Ulmus*, *Pinus,* and *Fraxinus*. Appearing towards the top of the zone are *Carpinus*, *Juglans,* and *Castania. Artemisia* increases.

Zone 2 – *Quercus* and *Pinus* decrease. *Carpinus* increases and reaches a maximum in the upper half of the zone. *Fraxinus* reaches a maximum early in the zone. *Artemisia*, *Cannabis*, and *Cerealia* increase.

Zone 3 – *Ulmus*, *Carpinus,* and *Fraxinus* decrease. *Juglans*, *Castania*, *Pinus*, *Cannabis*, *Secale* and *Mercurialis annua* increase.

Zone 4 – *Pinus* and *Secale* decrease. *Cannabis* makes a dip in the lower part of the zone but recovers.

Zone 5 – *Carpinus*, *Juglans* and *Castania* decrease.

Zone 6 – *Carpinus* and *Pinus* make a dip. *Juglans* and *Castania* peak. *Fraxinus* reappears.

Zone 7 – *Carpinus*, *Pinus*, *Fraxinus*, *Platanu,* and *Mercurialis annua* increase. *Cannabis* and *Secale* decrease.

Zone 8 – *Juglans* and *Mercurialis annua* decrease. *Ambrosia* appears.

Zone 9 – *Fraxinus* increases.

3.6 ^{14}C-dating

In total 30 ^{14}C-samples have been dated (Table 1). Calibration of pre-bomb samples (<AD 1950) was done by OxCal (Bronk Ramsey, 1995; Bronk Ramsey, 2001) with the IntCal98 calibration set (Stuiver *et al.*, 1998). Post-bomb dates (>AD 1950) are based on the peak and subsequently decline in atmospheric ^{14}C following nuclear weapon tests in the early 1960s (Nydal and Lövseth, 1983). For age determinations the measurements from Vermunt (Levin *et al.*, 1994) and Schauinsland (Levin and Kromer, 1997) are used. Post-bomb dates have an accuracy of 2-3 years (Goslar *et al.*, 2005). For site-specific depth-age models (Figure 3) the midpoint of one standard deviation normally has been used for linear interpolation and extrapolation. When the midpoint seemed unreasonable in relation to peat accumulation, the midpoint of the best fitting probability interval within one standard deviation was used, or the sample was omitted from the depth-age calculation.

Some dates are problematic. MOE-33cm gives a too young age, probably due to contamination with post-bomb material. Too high a ^{14}C-activity is often found in peat samples between AD 1930 and AD 1955, this is probably an effect of integration of younger material (Goslar *et al.*, 2005). Some samples are based on the peat fraction <0.2 mm. Even though most modern and younger material are sieved away, as shown in the test sample Amb-32cmB, the peat fraction <0.2 mm seems to give age determinations that are between 0 and 1000 years too young.

Table 1 Radiocarbon dates. Underlined age-intervals are considered most reasonable and are used for the depth-age models. "Date used" are for the site-specific depth-age model. Comments: *determination based primarily on within profile stratigraphy; **determination based primarily on correlation between profiles; ***possibly too young

Site	**Depth**	**^{14}C-age (1σ)**	**Calibrated ^{14}C-age (1σ)**	**Cal. age range**	**Date used**	**Lab. No**	**Material**
GIM	5 cm	-840 ± 30 BP	AD 1995	AD 1995	AD 1995	Poz-5968	Moss stems
GIM	10 cm	-4120 ± 25 BP	AD 1963, 1967	AD 1963, 1967	AD 1967**	Poz-3768	Mosses, primarily stems
GIM	15 cm	150 ± 30 BP	AD 1670-1700 (11.2%), 1720-1780 (29.4%), 1800-1820 (6.7%), 1840-1880 (7.4%), 1910-1950 (13.5%)	AD 1810 ± 140	AD 1930**	Poz-3769	Mosses, primarily stems
GIM	30 cm	515 ± 30 BP	AD 1407-1433	AD 1420 ± 15	Not used*	Poz-5969	Moss stems
GIM	45 cm	315 ± 30 BP	AD 1520-1600 (56.1%), 1620-1640 (12.1%)	AD 1580 ± 60	AD 1580	Poz-3770	Moss parts, primarily stems
GIM	66 cm	675 ± 35 BP	AD 1280-1310 (33.4%), 1350-1390 (34.8%)	AD 1335 ± 55	AD 1335	Poz-5970	Moss stems
GIM	90 cm	790 ± 30 BP	AD 1223-1232 (15.6%), 1240-1272 (52.6%)	AD 1250 ± 25	AD 1250	Poz-3771	Moss stems, 4 Cyperaceae seeds
GIM	112 cm	875 ± 35 BP	AD 1060-1090 (11%), 1120-1140 (8.6%), 1150-1220 (48.6%)	AD 1140 ± 80	AD 1140	Poz-5971	15 Cyperaceae seeds
GIM	148 cm	1375 ± 40 BP	AD 620-630 (2.6%), 635-690 (65.6%)	AD 655 ± 35	AD 655	Poz-3772	Moss stems, 2 Cyperaceae seeds
GIM	200 cm	1780 ± 40 BP	AD 130-150 (3.4%), 170-200 (5.1%), 210-340 (59.7%)	AD 235 ± 95	AD 235	Poz-5972	Moss parts
GIM	250 cm	1870 ± 40 BP	AD 80-220 (68.2%)	AD 150 ± 70	Not used*	Poz-5974	Moss stems
GIM	270 cm	2065 ± 30 BP	150-130 (5.0%), 120-40 (58.7%), 10-0 (4.5%) BC	75 ± 75 BC	75 BC	Poz-8710	Moss stems, 5 Cyperaceae seeds
MOE	10 cm	-1080 ± 35 BP	AD 1991	AD 1991	AD 1991	Poz-5981	*Sphagnum* and *Polytrichum* stems
MOE	21 cm	-2695 ± 25 BP	AD 1963, 1974	AD 1963, 1974	AD 1974	Poz-1713	*Sphagnum*
MOE	26 cm	-3530 ± 45 BP	AD 1963, 1969	AD 1963, 1969	AD 1963*	Poz-1714	*Sphagnum*
MOE	31 cm	-10 ± 35 BP	c. AD 1950	c. AD 1950	AD 1950	Poz-1704	*Sphagnum*
MOE	33 cm	-15 ± 25 BP	c. AD 1950	c. AD 1950	Not used*	Poz-3778	*Sphagnum*, 2 Cyperaceae seeds
MOE	40 cm	155 ± 30 BP	AD 1670-1700 (11.8%), 1720-1780 (32.0%), 1790-1820 (7.4%), 1850-1860 (2.6%), 1910-1950 (14.4%)	AD 1810 ± 140	AD 1685**	Poz-3779	*Sphagnum*, 4 *Potentilla* seeds
MOE	42 cm	2090 ± 40 BP	170-50 (68.2%) BC	110 ± 55 BC	110 BC***	Poz-1706	Peat fraction <0.2mm
MOE	50 cm	3000 ± 40 BP	1370-1360 (1.5%), 1320-1190 (55.1%), 1180-1160 (6.2%), 1150-1130 (5.3%) BC	1250 ± 120 BC	1250 BC	Poz-5982	Moss stems
AMB	5 cm	-975 ± 30 BP	AD 1993	AD 1993	AD 1993	Poz-5983	Moss stems
AMB	11 cm	-1660 ± 40 BP	AD 1959, 1960, 1962, 1983	c. AD 1960, 1983	AD 1960	Poz-1715	*Sphagnum* stems
AMB	15 cm	45 ± 35 BP	AD 1700-1730 (12.4%), 1810-1830 (8.9%), 1880-1920 (35.3%), 1940-1950+ (11.5%)	AD 1825 ± 125	AD 1900*	Poz-1702	*Sphagnum*, 14 *Potentilla* seeds, 1 *Viola* seed, ¼ *Picia* needle
AMB	20 cm	155 ± 35 BP	AD 1670-1700 (11.4%), 1720-1820 (36.0%), 1840-1880 (7.2%), 1910-1950 (13.7%)	AD 1810 ± 140	AD 1770*	Poz-3759	Conifer bark, small carbonised *Picea* needle fragment; small (0.36 mg C)
AMB	22 cm	455 ± 35 BP	AD 1422-1467 (68.2%)	AD 1445 ± 25	AD 1445	Poz-1701	Carbonised *Picea* needle fragment
AMB	25 cm	1550 ± 50 BP	AD 430-560 (68.2%)	AD 495 ± 65	AD 495	Poz-3760	Bark; very small (0.16 mg C)
AMB	32 cm A	2110 ± 40 BP	200-190 (2.5%), 180-50 (65.7%) BC	125 ± 75 BC	Not used*	Poz-1703	Peat fraction <0.2mm
AMB	32 cm B	-100 ± 40 BP	c. AD 1950	c. AD 1950	Test sample	Poz-1716	Peat fraction >0.2mm
AMB	40 cm	3300 ± 40 BP	1620-1520 BC	1570 ± 50 BC	1570 BC	Poz-5873	10 Cyperaceae seeds, ½ seed indet.; small (0.38 mg C)
AMB	53 cm	3400 ± 35 BP	1750-1680 (50.4%), 1670-1630 (17.8%) BC	1690 ± 60 BC	Not used*	Poz-1717	Peat fraction <0.2mm

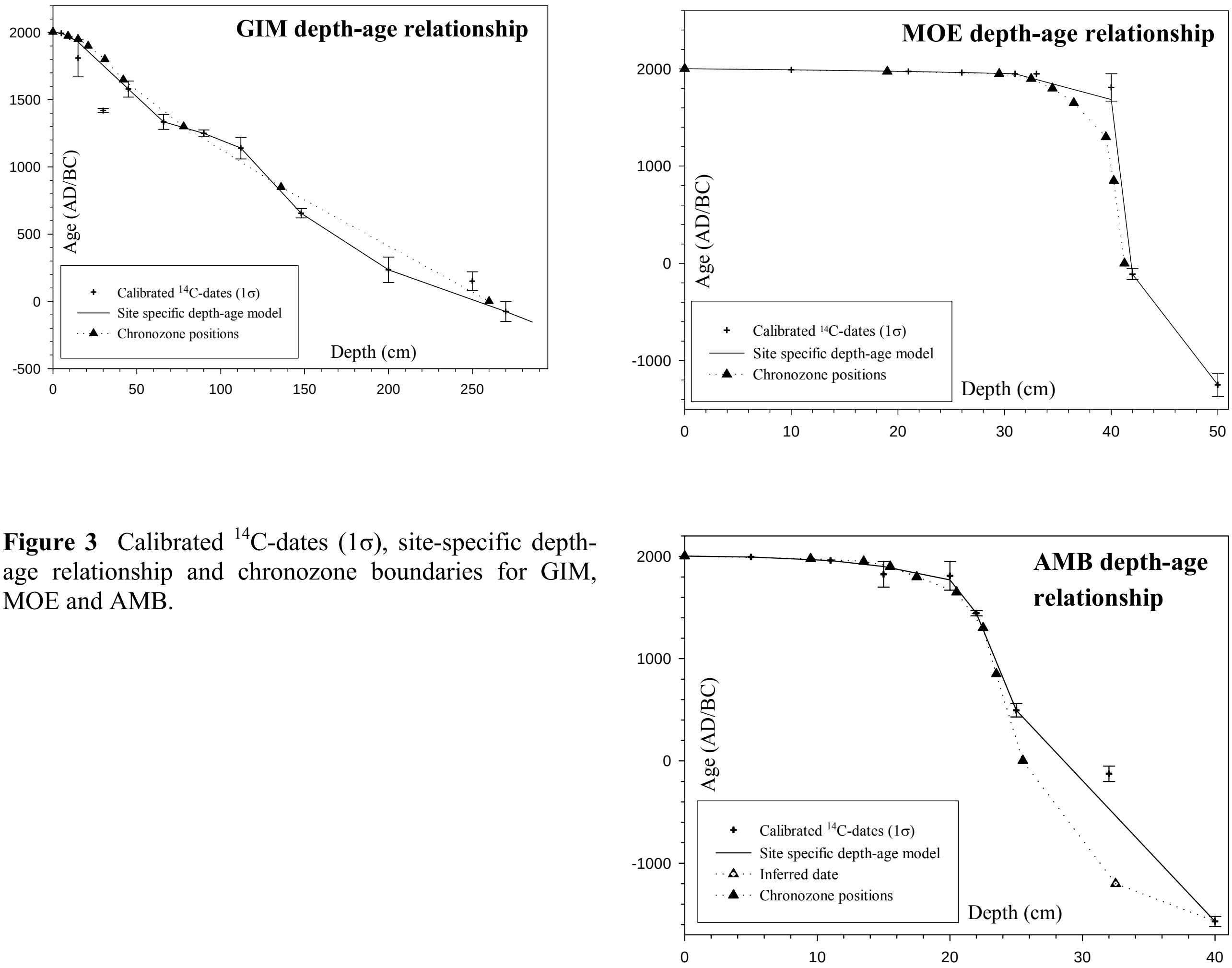

Figure 3 Calibrated ^{14}C-dates (1σ), site-specific depth-age relationship and chronozone boundaries for GIM, MOE and AMB.

The age of an important transition in AMB at 32.5 cm is calculated on peat accumulation rates. For the lowest part of AMB (35-40 cm) a peat accumulation rate of 20 years/cm is estimated. This gives an age of 1470 BC at 35 cm depth. Linear interpolation to the AMB-25cm date gives a peat-accumulation rate for 35-25 cm of c. 200 years/cm, which puts the 32.5 cm boundary at an age of c. 1000 BC. But the pollen concentration does not indicate this abrupt change exactly at 35 cm, but it reaches its high values first at 32.5 cm, making a rate of 100 years/cm more reasonable. The most likely boundary age would then be c. 1200 BC, with a ± 200 years range.

3.7 Zone-age determination and representativity of periods

The ages of the chronozones have been determined by comparison of the linear intercept dates from the three sites (Table 2). The intercept dates are given different weight according to the resolution and reliability of the site-specific depth-age models. GIM is considered the most reliable in the Roman-period and the Middle Ages (AD 1-1650), AMB in Modern Times (AD 1650-1900), and MOE in the late

20th century (AD 1950-2000). The accuracy of the zone-ages is approximately ± 50 years, except for the 20th century when it is c. ± 10 years.

In MOE the site-specific depth-age model deviates in some parts a lot from the chronozone-inferred age. This might be due to partial mixing of the peat, which brought down younger material. The stratigraphy might thus be disturbed and some caution should be taken with the interpretation. The age determination of the chronozones is considered more reliable than the site-specific depth-age models. Also the site-specific depth-age model AMB show some major deviation from the chronozone-inferred ages in the lower part. This is likely caused by the low and uneven peat accumulation that results in very low resolution. There are no signs that peat material is missing, but it cannot be ruled out considering the high decomposition and compaction. Ages throughout the paper are based on the chronozones unless otherwise stated.

Periods are inferred from the chronozones. Calibrated radiocarbon dates, site-specific depth-age models (Age AD/BC), and chronozone dates (presented under Periods) are presented in the pollen diagrams (Figure 4-6) to allow direct comparison and alternative use of dates. All ages used in the text is inferred from the chronozones ages unless otherwise stated. An additional line has been added to the AMB diagram at 32.5 cm (see Figure 6) to mark an important transition. The age is inferred from the site-specific depth-age model of AMB (see ^{14}C-dating above). Parts of MOE and AMB are very compacted. A single pollen sample might represent an entire period or more than 400 years. Such a samples should not be considered representative for the entire time-span as shorter variations in vegetation will be missed or some material might be underrepresented or absent. Spatial resolution follows the sample resolution. In MOE partial mixing of the peat might have occurred in period M2-M6 and all interpretation concerning this interval might be biased.

Table 2 Intercept dates for site-specific depth-age models and chronozones. Bold face refers to the more reliable dates used for age determination of the chronozones. Time interval refers to the range within which it is highly probable that the real age occurs.

Chrono-zone	**Lower boundary depth**			**Lower boundary intercept age**			**Lower boundary age**	
	GIM	**MOE**	**AMB**	**GIM**	**MOE**	**AMB**	**Date**	**Interval**
ZONE 9	9 cm	19 cm	9,5 cm	AD 1973	**AD 1977**	AD 1968	**AD 1975**	AD 1970-1980
ZONE 8	15 cm	29,5 cm	13,5 cm	AD 1930	**AD 1954**	AD 1923	**AD 1950**	AD 1930-1955
ZONE 7	21 cm	32,5 cm	15,5 cm	AD 1880	AD 1905	**AD 1887**	**AD 1900**	AD 1880-1910
ZONE 6	31 cm	34,5 cm	17,5 cm	AD 1745	AD 1847	**AD 1835**	**AD 1800**	AD 1750-1850
ZONE 5	42 cm	36,5 cm	20,5 cm	**AD 1615**	AD 1788	**AD 1689**	**AD 1650**	AD 1600-1700
ZONE 4	78 cm	39,5 cm	22,5 cm	**AD 1293**	AD 1729	**AD 1287**	**AD 1300**	AD 1250-1350
ZONE 3	136 cm	40,25 cm	23,5 cm	**AD 817**	AD 1461	AD 970	**AD 850**	AD 800-1000
ZONE 2	260 cm	41,25 cm	25,5 cm	**25 BC**	AD 563	AD 426	**AD 1**	AD 50-50 BC

3.8 Biostratigraphy

The trends of some pollen-types in Switzerland during the last millennium are rather well established (van der Knaap *et al.*, 2000). The same trends can be identified in the correlation diagrams, and the zone-ages are used to date them. Comparison (Table 3) shows that the consistency is good and confirms that the zone-ages are fairly correct for the comparable time-period.

Table 3 Comparison of biostratigraphic dates based on the chronozones and the relevant biostratigraphy of Switzerland (van der Knaap *et al.,* 1999).

Taxa	**Trend**	**Combe des Amburnex**	**Switzerland**
Ambrosia	1st grain	AD 1950	AD 1950
Mercurialis annua	Last maximum	AD 1925	AD 1950
Mercurialis annua	3rd increase	AD 1900	AD 1920
Mercurialis annua	2nd increase	AD 1850	AD 1820-1880
Mercurialis annua	1st increase	(AD 850)	AD 1770-1990
Cannabis sativa	Last decline	AD 1900	AD 1900
Cannabis sativa	Last maximum	AD 1825	AD 1850
Cannabis sativa	3rd increase	AD 1650	AD 1700
Cannabis sativa	2nd increase	AD 1550	AD 1500
Cannabis sativa	1st increase	AD 850	AD 1000

4 Results and interpretation

4.1 Interpretation and period description

The pollen data are presented in diagrams (Figure 4-6), and the main trends are described in text below. Changes in the pollen values of *Abies*, *Fagus*, *Picea* and *Acer* are assumed to be mainly of extra-local origin. But *Fagus* thrives on the lower slopes and in the lowland, and some caution should be taken with the interpretation of this taxon. High values of *Alnus*, *Corylus* and *Betula* in the lower part of the diagrams might partly be of local and extra-local origin, although strong fluctuations of these taxa in the Swiss lowland make any interpretation uncertain (Ammann *et al*., 1996; van der Knaap and Ammann, 1997). AMB correlates in fact rather well with the lowland locality Lobsigensee, c.100 km NE (Ammann 1989), which means that the extra-regional influx may be considerable. In the interpretation and discussion *Alnus*, *Corylus* and *Betula* will be treated as locally present in the lower parts of the profiles, but it should be noted that any assumed presence might be a lowland artefact. In the descriptions correction factors are used to estimate forest composition. Correction factors are: *Pinus*, *Betula*, *Quercus*, *Alnus* 1:4; *Carpinus* 1:3, *Ulmus*, *Picea* 1:2; *Fagus*, *Abies* 1:1; *Tilia*, *Fraxinus*, (*Acer*) 1x2 (Andersen, 1970). The most characteristics features of the periods are described and commented below. After a general assessment of each period are site-specific characteristics presented. All ages are inferred from the chronozones.

Period 1, 1600 - 1 BC, Closed forest with increasing human impact

The forest is composed of approximately equal parts of *Abies*, *Fagus* and *Picea*, including some *Acer*. In addition, *Alnus*, *Betula,* and *Corylus* might occur locally at the mire edge or scattered in the forest. In the early part of the period (1600-1200 BC) there are no indications of local human impact. The few pollen grains from *Plantago lanceolata* and other apophytes might derive from the lowland or be part of the natural vegetation. During the first centuries BC the presence of indicators for heavy grazing as *Plantago media* and *Plantago montana* at all three sites also suggests that patches of open pastures where spread out in the landscape. AMB: Around 1200 BC the previous local pollen assemblage dominated by Cyperaceae pollen is succeeded by one dominated by fern spores. In the latter part of the period (1200-1 BC) there is an increase in herb and grass pollen that a peaks in the first centuries BC. MOE: An increase in herb and grass pollen as in AMB also occurs here, but only in the last sample, probably because of the very low peat accumulation rate and low resolution in this part of the profile. The early increase of herb and grass pollen that occurs in AMB is not detectible in MOE, suggesting that this change is restricted to AMB.

Period 2, AD 1-850, Closed forest with mire and forest grazing

The forest closes in the first centuries AD (AD 1-250). An initial increase in pollen from *Alnus*, *Corylus* and *Betula* is countered by a subsequent increase in *Abies*, *Fagus* and *Picea* pollen. This indicates a succession from pioneers to a more mature forest type. A short open phase AD 250-350 is followed by a new forest-regeneration phase AD 350-550, which shows a similar pattern of succession as the previous regeneration phase, except that now only *Picea* eventually re-establishes. After this second regeneration phase the landscape begins to open up again (550-850). GIM: Higher amounts of microscopic charcoal and an increase in openness appear c. AD 700. Peaks in local pollen types such as *Rubiaceae*, *Rumex acetosa*-type and *Cruciferae*, together with the presence of a wide array of NAP suggest local grazing and nearby pastures throughout period 2. MOE: Period 2 is very compressed. Many indicators of heavy grazing, such as *Plantago media* and *Plantago montana* pollen, together with very high NAP values and the occurrence of *Podospora* spores (a dung fungus on cow pats), suggest that this part of the mire and the immediate surroundings were grazed. At the start of the period a high peak in *Urtica* pollen suggests a local disturbance and/or nutrient enrichment, e.g. a nearby pathway, waterhole, or cottage. AMB: In opposition to MOE there are no clear signs of human impact during this period.

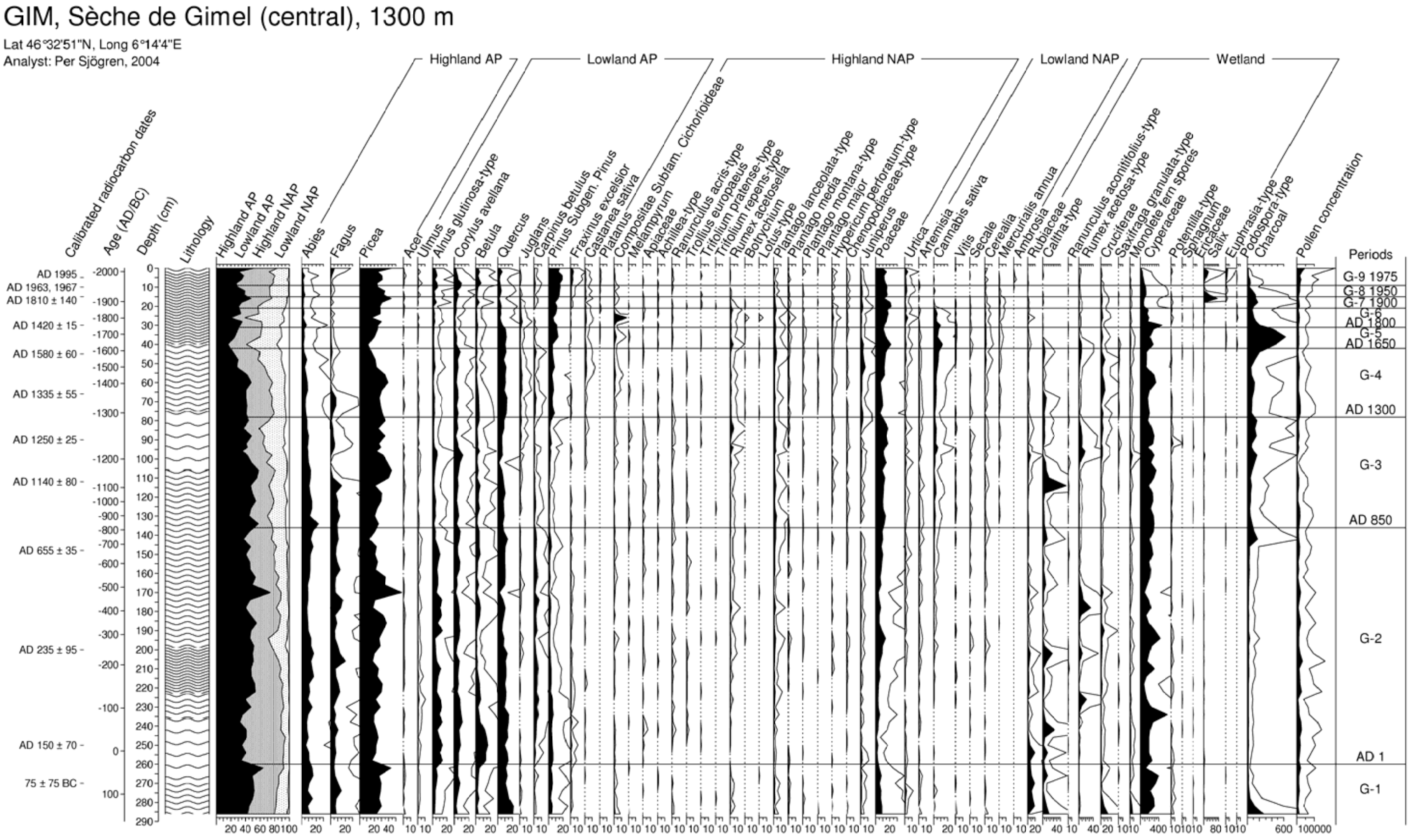

Figure 4 Pollen diagram for GIM in the middle part of Le Marais de Sèche de Gimel. The non-local (non-wetland) sum of pollen and spores has been used for percentage calculation. Some wetland (local) taxa in GIM are in MOE and AMB classified as highland taxa. Unfilled curves show x5 exaggeration. Note that wetland and some non-pollen curves differ in scale. Periods are based on the chronozones (Figure 2). The lithology shows the degree of decomposition by increasingly close line spacing: 1) Undecomposed peat; 2) Peat; 3) Decomposed peat; 4) Strongly decomposed peat.

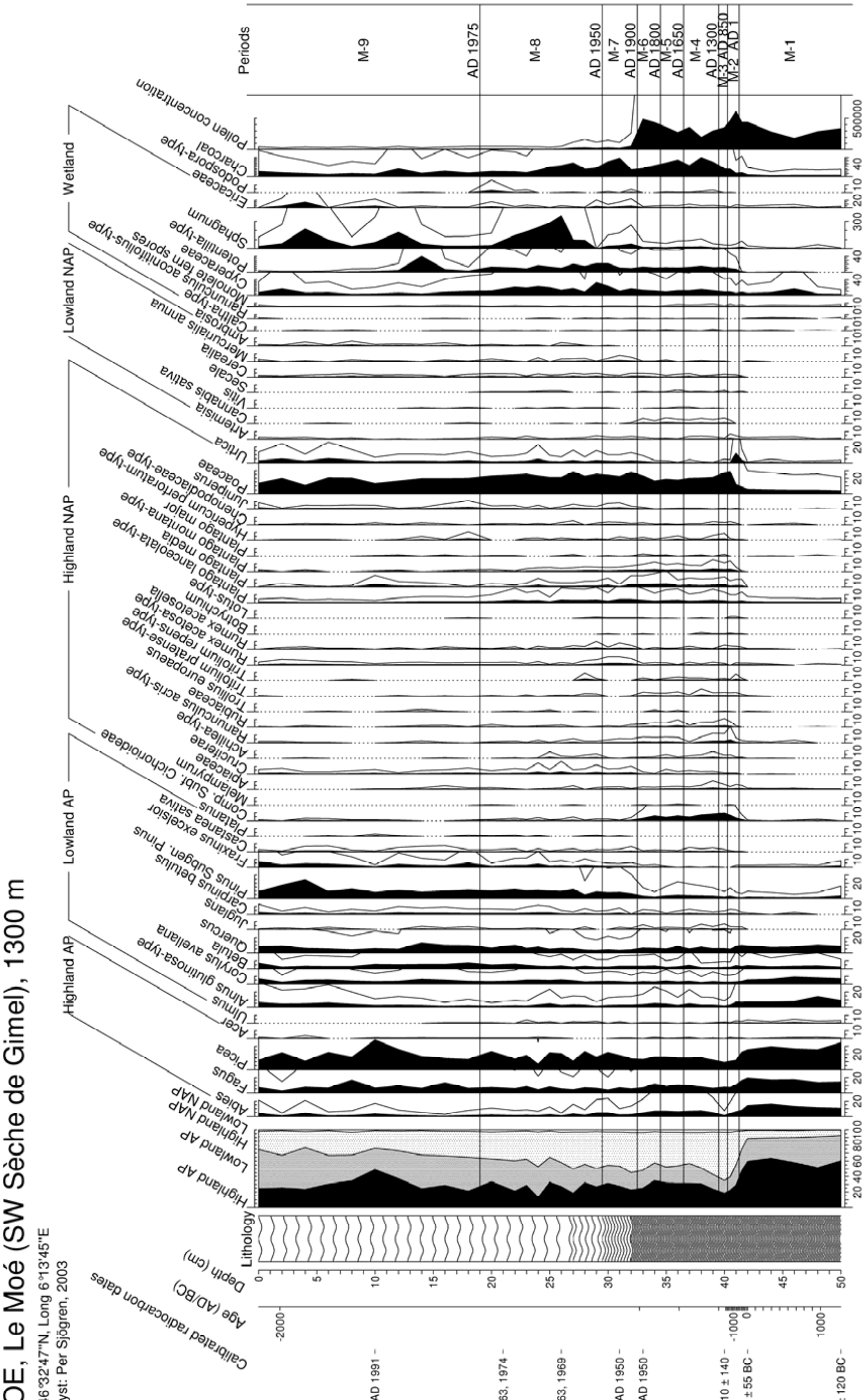

Figure 5 Pollen diagram for MOE in the southwestern part of Le Marais de Sèche de Gimel. See Figure 4 caption for explanation.

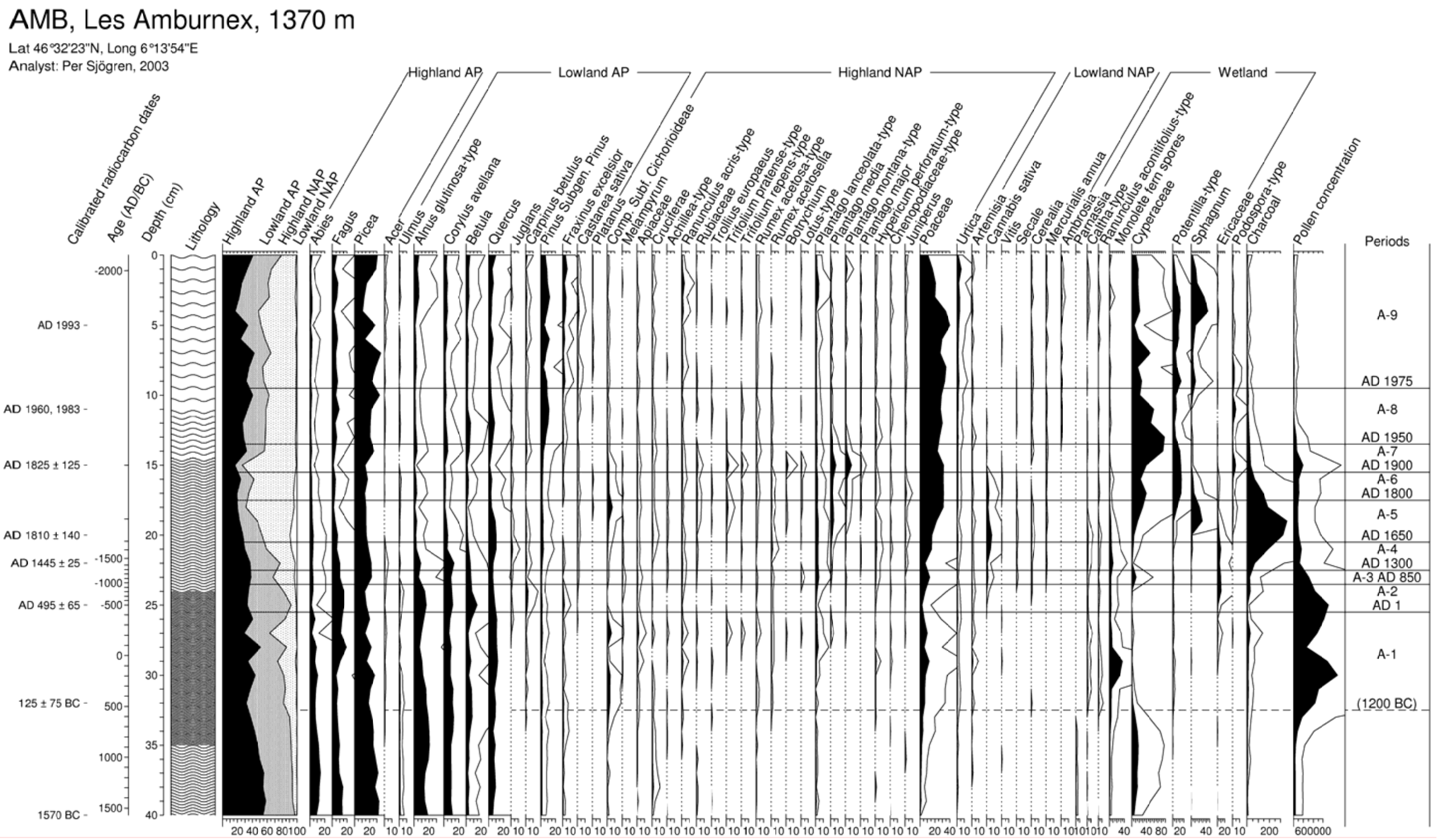

Figure 6 Pollen diagram for AMB, Les Amburnex mire. See Figure 4 caption for explanation.

Period 3, AD 850-1300, Grazed forest and open pastures

A decrease of *Abies* and *Fagus* pollen and an increase in *Picea* pollen indicate that the forest becomes more dominated by *Picea*, which now probably constitutes more than 50% of the forest cover. Lower pollen values for *Alnus*, *Corylus* and *Betula* suggest a reduction in these taxa. The amount of open pastureland, as reflected in the NAP, *Plantago lanceolata* and Poaceae pollen, seems to be rather constant during the first half of the period (AD 850-1150) but expands in the latter half (AD 1150-1300), and the central parts of the valley seems to become as open as today.

Period 4, AD 1300-1650, Grazed forest and open pastures

The earlier part of the period (AD 1300-1450) is marked by an increase of tree pollen. In the younger part of the period (AD 1450-1650) there is a clear decline in *Fagus* and *Picea* pollen, with a corresponding increase in NAP. GIM: The early increase in tree pollen mainly comes from *Quercus* and *Pinus*, which do not grow in the vicinity. The decrease in NAP is primarily caused by well dispersed pollen types as *Plantago lanceolata*, Poaceae and *Juniperus*, while other NAP types seem to be little or not at all affected. It thus seems that the central part of the valley was little affected by this regeneration phase. AMB: In contrast to GIM comes the increase in tree pollen primarily from *Alnus* and *Corylus*, species that may be local. In the younger part of the period (AD 1450-1650) there is a decline in *Alnus*, *Corylusand Betula* pollen, suggesting a local reopening of the area around the site.

Period 5, AD 1650-1800, Pasture woodland

GIM: The period starts with a peak in Poaceae and a dip in the *Picea* pollen frequencies. This may be the result of forest clearings that could not be kept open by the existing animals, leaving tall grasses to flower and eventually allow the recolonisation of *Picea*. Otherwise the Poaceae and herb pollen content suggests that the grazing pressure and the extent of the surrounding pastures are similar to that of the end of period 4. Locally the pollen values indicate that *Caltha* more or less disappears while Cyperaceae increases. AMB: The Poaceae value doubles during the period, and there is an increase in many herb pollen, including indicators for heavy grazing. The values for *Fagus* decline, and the pollen assemblages suggest that any remaining stands of *Alnus*, *Corylus* and *Betula* finally are cleared away. Locally *Sphagnum* suddenly appears c. AD 1700 and peaks, followed by an increase in Cyperaceae and *Potentilla* pollen. The presence of *Podospora* spores suggests local cattle grazing.

Both AMB and GIM have very clear and strong peaks in microscopic charcoal particles that indicate major fire activity in the area, and a general openness comparable with todays is reached during the 18th century. The largest lasting expansion of pastureland during this period seems to be in the periphery areas, possibly because most useful land in the central part already had been turned into pastures. The more frequent occurrence of Podospora spore suggests an increased number of cattle.

Period 6, AD 1800-1900, Pasture woodland, open

The pollen assemblages reflect an open landscape very similar to that at the end of period 5. GIM: pollen peaks from Cyperaceae and Compositae subf. Cichorioideae which suggest some changes in the local mire vegetation. The very low values for *Fagus* in GIM are unexplained, especially as *Fagus* is much more strongly represented in MOE.

Period 7, AD 1900-1950, Pasture woodland, manuring and forest-regeneration

The maximum openness and grazing pressure seems to occur around AD 1900. AMB: Very high grazing pressure is indicated with peaks in *Trifolium repens*, *Plantago media*, *Plantago montana*, *Plantago major*, *Botrychium* and *Lotus*. There is also a peak in *Podospora* spores, which suggests local grazing. MOE: Compositae subf. Cichorioideae decrease. Increase of Poaceae and *Urtica* suggests an increase in nutrients. It should be noted that from here on an increase in lowland pollen from *Alnus*, *Corylus*, *Betula*, *Pinus* and *Fraxinus* occur at all sites, which suppress the local and extra-local pollen signals.

Period 8, AD 1950-1975, Pasture woodland, nutrient-rich

Pollen values decline for most herbs except *Urtica*. Poaceae pollen values remain high.

Period 9, AD 1975-2000, Improved pasture woodland, nutrient-rich

Here the trend from period 8 becomes clearer, with even lower pollen frequencies for most herbs, and stable or increasing frequencies for Poaceae and *Urtica* pollen. GIM: Pollen values of Cruciferae, ferns and Cyperaceae decreases, while *Salix* and *Euphrasia*-type pollen increases. MOE: Here it seems to be a shift in local land use, with a decrease in Cyperaceae, *Potentilla* and *Podospora*.

5 Discussion

5.1 Major trends and developments during the past 2000 years

An estimation of the natural forest composition in the first millennium BC would be approximately 30% each of *Abies*, *Fagusand Picea*, 5% scattered *Acer*, and 5% of *Alnus*, *Corylus* and *Betula*. The last three taxa are assumed to be most common around the wetlands and in forest gaps. The low pollen productivity of *Acer* makes it hard to estimate its cover, but it has at least been present during the time period studied here. A distribution similar to the modern can be assumed as no changes no major changes in the pollen spectra was detected. For *Alnus*, *Corylus* and *Betula* some variations between the sites suggest local differences, and thereby local presence. Still, the variations are not big enough to assume any larger populations. *Picea* started to increase at the expense of *Abies* and *Fagus* in the 9th century, and in the 13th century it constituted around 50% of the forest composition. Increased grazing pressure in the surrounding forests likely favoured *Picea* in relation to other trees. Grazed forests started to occur across Europe at approximately the same time (Behre, 1988). The wooded pastures of today consist nearly entirely of *Picea*, and this vegetation type might have emerged during this time. *Alnus*, *Corylus and Betula* decreased from the 9th century and seem to have disappeared completely from the area in the 17th century. In the 20th century *Picea* and *Fagus* expanded, giving a suggested modern tree cover of approximately 60% *Picea*, 20% *Fagus*, 15% *Abies,* and 5% *Acer*, which is not a bad approximation for the vegetation a few kilometres around the sites.

After the open phase in the first centuries BC the following forest-regeneration phases can be detected: AD 1-250, AD 350-550, AD 1300-1450 and AD 1925-2000. Pasture-expansion phases are: AD 250-350, AD 550-1300 and AD 1650-1800. Phases with maximum openness are: AD 1200-1300 and AD 1700-1925. The opening of the landscape is a rather slow process, while the regrowth is quick. This is to be expected considering the labour needed to clear a forest and the suitable increase in livestock that must follow to keep the area open, while reforestation can occur over large areas simply through neglect. Reforestation typically starts with an increase in *Alnus*, *Corylus* and *Betula*, followed 100-200 years later by an increase in *Abies*, *Fagus* and *Picea*. But regardless of the regeneration it seems as the central mire, Sèche de Gimel, and the immediately surrounding area was continuously used for grazing with no or little change in intensity.

During the early Middle Ages increasingly large areas in the central part of the valley were cleared, and in the 13th century the central part was probably as open as today. The general opening of the landscape occurred first in the 17th and 18th centuries, and now a pasture woodland landscape similar to todays can be said to have come into existence. This opening is closely related to fire activity, and the most reasonable explanation for the landscape development is that the forest was cut down and burnt to charcoal. Subsequent increase in husbandry animals, most likely cattle, hampered the forest regeneration. From 1925 a minor regeneration of the forests correlates well with the approximately 10% reduction of open land since the end of the 19th century shown by the Siegfried-map (*Die Siegfried Karten*, Marchairuz, section XVI, 2b, 1892-93). It is primarily wooded pastures and grazed forests that become denser.

The pastures in the last two millennia were generally nutrient poor and well grazed (indicated by *Plantago media*, *Plantago montana*, *Botrychium* and *Lotus*), but areas with weaker grazing pressure, more nutrient-rich and/or in a state of regeneration were also present (indicated by Apiaceae, *Trollius*, *Rumex obtusifolius* and *Urtica*). The surrounding forest was grazed and rather open (indicated by *Melampyrum*). Poaceae was common all the time and became even more dominating after AD 1900. During the 20th century Poaceae pollen it increased its portion of NAP from c. 1/2 to 2/3. Together with the increase in Poaceae an increase in *Urtica* suggests a nutrient enrichment of the area, probably as an effect of 20th century manuring.

5. 2 Major trends in the lowland vegetation

The amount of *Quercus* pollen decreased the first centuries AD and then rised again in the 19th century. *Carpinus* pollen frequencies reached their highest values AD 1-850. The *Carpinus* curve seems to be consistent with that in the lowland (Rachoud-Schneider, 1998), but the first major increase is a few hundered years earlier than in many other parts of the Jura Mountains (e.g. Wegmüller, 1966; van der Knaap *et al.*, 2000; Mitchell *et al.*, 2001; Gauthier, 2002). This may either be due to differences in pollen source areas or to dating problems. Around AD 850 a clear increase in *Cannabis sativa* pollen occured. The highest values was reached AD 1650-1900, after which it sharply declined. Around AD 1300 the amount of *Pinus* pollen increased. This seems to be in connection with the forest-regeneration phase that started at the same time. The amount of *Pinus* pollen is not reduced when the landscape is opened up again, implying that either different parts of the landscape were opened up or that *Pinus*, after its initial establishment, was able to compete with existing trees or establish in earlier uncolonised areas. Climatic deterioration is an alternative explanation.

In the 20th century an increase in *Alnus*, *Corylus*, *Betula*, *Pinus*, *Fraxinus* and *Castanea* pollen occurred. This is probably caused by the general reforestation after abandonment in the 20th century. In some cases, especially for *Fraxinus* and *Castanea*, it may be because pollarding stopped, which would increase pollen production from existing trees.

5.3 Grazing, climate, and water-table changes

Around 1200 BC (1400-1000 BC) the local vegetation at AMB changed from Cyperaceae fen, including *Parnassia*, to one dominated by ferns. The change coincides with a strong increase in pollen concentration (indicating increased decomposition) that perhaps reflects a decrease in the water table. The period 1550-1150 BC is characterised by high lake levels in the Jura Mountains (Magny, 2004), and the end of this period fits well with the estimated date for the local vegetation change in AMB. On the other hand, a new phase of high lake-levels started at 800 BC, without any reversal of vegetation and decomposition in AMB. The pollen shows no clear indications of grazing, but a slight increase is apparent in Poaceae and several herbs, including Compositae subfam. Cichorioideae, *Rumex acetosa, Rumex acetosella, Caltha* and *Ranunculus aconitifolius*, suggesting a wet meadow or pasture (Behre, 1981). It thus seems that the local changes in mire vegetation coincide with a local opening of the forest, but it is unclear whether climate or humans caused the transition.

In MOE a large increase in Cyperaceae, *Potentilla* and *Sphagnum* occured in the centuries around the birth of Christ (uncertain age), and a similar change occured in AMB in the beginning of the 18th century. These changes are associated with increased openness and grazing pressure, including the presence of *Podospora* spores (a dung fungus on cow pats). There may be several reasons for the change in local vegetation: 1) Use of the wetlands as hay-mires, wich would increase the Cyperaceae pollen as the mires were cut after flowering (Segerström and Emanuelsson, 2002); 2) Change of husbandry composition from pig/sheep/goat/horse to cattle, which graze on wetland and avoid some Cyperaceae (Alm *et al.*, 1999); 3) Protection (fencing) of the mire for clean-water isolation; 4) Change in grazing pressure; 5) Deforestation that leads to an increase in the water-table through reduced evapotranspiration; 6) Climatic change, e.g. the onset of the second phase of the Little Ice-Age in the 17th century (Wanner *et al.,* 2000). According to the data at hand a rise in the water table caused by deforestation must be seen as the most plausible explanation, although grazing intensity and a change in husbandry animals composition towards cattle most likely had an influence.

It seems likely that the strong shifts in pollen concentration and rate of peat accumulation in MOE and AMB have been caused at least in part by changes in the water table. Another possibility would be compaction and surface damage caused by grazing animals. The associated Monolete fern-spore – Cyperaceae – *Sphagnum* sequence from high to low pollen concentration makes changes in the likely. Increased grazing pressure is normally associated with deforestation, which may lead to an increase in the water table and thus obscure the negative impact of trampling. But very high grazing pressure, e.g. MOE in period 2 and 3, obviously damaged the mire. The local vegetation in GIM changed around AD 1700. *Caltha* and possible also *Rumex acetosa* and *Cruciferae* decreased while Cyperaceae increased. As in AMB at the same time the local changes in vegetation are associated with a more frequent occurrence of *Podospora* spores together with increased fire activity, suggesting increased number of cattle and deforestation. Above this change the peat are much more decomposed, which interestingly is the opposite of the development in AMB at the same time. The discrepancy can be explained with that the central part of the valley was largely deforested already in the 12th century, and the major increase in water table and related peat accumulation rate thus occurred in GIM already in the late Middle Ages (AD 1150-1300). The damaging effect of increased grazing and trampling of cattle could thus not be offset by an increased water table, and the result would be increased compaction and decomposition of the peat. A complementary explanation is that the mire was ditched and drained, possible to improve grazing conditions. The ditches are not tended anymore and todays drainage capacity is limited. Some major changes in GIM also occur around AD 1975. Cruciferae and Cyperaceae decreased while *Euphrasia* and *Salix* increased. The reason for this is unknown, but the absence of earlier high values for *Euprasia* and *Salix* suggest that they are invading the mire.

5.4 Regional and historical context

Wegmüller (1966) studied another 4 sites along the eastern edge of the Jura Mountains (Le Couchant 1400 m, Creux du Croue 1360 m, La Pile 1220 m, La Maréchaude 1590 m). All sites record an opening in the first centuries BC, while the peat from the past 2000 years is missing or very compressed. This suggests that the peat development at these sites was similar to that at MOE and AMB. A sediment profile from the large lake Lac du Joux c. 10 km to the north shows the same general development in expansion and regeneration phases (Wegmüller, 1966). A peat profile from the Praz-Rodet bog (Mitchell *et al.*, 2001), 5 km to the NW, does show some differences, but the main features can be still be recognised. For the Jura Mountains as a whole the two general forest-regeneration phases in the time period of concern are c. AD 250-600 and c. AD 1350-1500 (Gauthier, 2004). These correlate well with the locally recorded forest-regeneration phases at AD 350-550 and AD 1300-1450.

The late-Holocene vegetation history in the lowland north of Lake Geneva is not well recorded, as the top part of most peat deposits has been damaged (Gaillard, 1984). But the vegetation history recorded in Lake Geneva itself (Rachoud-Schneider, 1998) shows that the main trends are similar.

The forest-regeneration phase AD 1-250 seems to have been less pronounced in the Joux valley (Wegmüller, 1966; Mitchell *et al.*, 2001) and very minor in the lowland (Rachoud-Schneider, 1998), which suggests an abandonment of more peripheral areas in the early Roman Period. This forest-regeneration phase started at more or less the same time as the migration of the Helvetii. For the rest of the history the general development in Combe des Amburnex is similar to that of the surrounding areas, suggesting that the valley was well integrated in the economic system. A transhumance system similar to that of today probably developed towards the end of the first millennium AD. The major difference from the lowland seems to be the much larger impact of modern forestry in the high Jura Mountains, which together with summer grazing finally created the pasture woodland we see today.

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Resumed peat growth in high-altitude mires across the Alps and the Jura Mountains during the 19th and 20th centuries

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Summary

1. Wetlands have been severely reduced or changed by human activities (drainage, ploughing, peat-cutting) and very few natural mires remains in central Europe today. Relatively remote high-altitude mires are thus of great ecological value, but findings suggest that also these have been or are severely affected by human activities.
2. The upper peat layers of nine small mires across the Alps and the Jura Mountains have been analysed, dated and compared in order to find common trends and effects in the recent development (c. 200 years) of the mires.
3. Ash content and dry bulk density measurements consistently show a peak in decomposition and minerogenic concentration close to the mire surface. Pollen and spore content suggest that high grazing pressure and trampling are the most probable cause of the observed pattern.
4. Two phases of re-initiated peat growth can be observed, one in the Jura Mountains and central parts of the Alps around the mid 20th century (AD 1940-60), and one in the eastern Alps in the early and mid 19th century (AD 1820-70).
5. As a result of grazing slow and uneven peat accumulation is common in deposits that cover the past 2000 years. This should be taken into consideration in planning the sampling strategy for palaeoecological or palaeoclimatological investigations.
6. Many high-altitude mires are or have been heavily damaged by grazing. Fast peat growth is initiated locally soon after the grazing regime falls below a critical level, and the mires will return into a natural state with time, unless invaded by wooded species. Most high-altitude mires are not in a stable state, which must be taken into consideration when evaluating ecological functions, values and future development.

Key words: Alps, Jura Mountains, grazing, mires, peat growth

1. Introduction

In many investigations of European peatlands a layer with increased decomposition is observed near the surface of the peat profiles (e.g. Aaby and Tauber 1975; van der Knaap et al. 2000; Mauquoy et al. 2002; Shotyk 2002; Roos-Barraclough et al. 2004). The cause and occurrence may differ between regions, and we will here concentrate on the central European mountain region, i.e. the Alps and the Jura Mountains.

Decomposition of peat primarily occurs in the acrotelm (the periodically water-saturated surface layer) and is dependent on the rate the material is passed into the underlying catotelm (permanently water-saturated) (Clymo 1965). Below this level the decomposition rate is very low. It is thus normal that the degree of decomposition increases sharply in the first 10-50 cm below the mire surface, and then keeps relatively constant. It has been suggested that autocompaction in the catotelm may affect the peat accumulation rate (Aaby and Tauber 1975), but the evidences are inconclusive.

Changes in peat-accumulation rate and decomposition have in many studies been contributed to climatic shifts (Mauquoy et al. 2002; Barber and Charman 2003; Roos-Barraclough et al. 2004). The underlying assumption is that climatic shifts affect the growth rate of the mire vegetation (primarily affected by temperature) and/or the decomposition rate in the acrotelm (primarily affected by precipitation).

Human activity has also had a major and often harmful effect on mires and peat accumulation. As an example have 80-90% of the raised bogs of Switzerland disappeared because of human activity, mostly during the 19th and 20th century (Grünig, Vetterli & Wildi 1986). While drainage for agricultural purposes and peat extraction have been common in the lowland and major valleys, few signs of such activity are found at higher altitude. The traditional high-altitude land-use in the region of investigation is summer grazing. Considering the high number of grazing animals in the region, especially during the early part of the 20th century. Impact of such activities on mires is more likely than direct human disturbance such as ploughing or peat cutting, although some drainage may occur.

Major change of peat-deposition environment in the near past is of importance for the ecological understanding and management of mires. If a mire is in a state of change or has special characteristics caused by past disturbances it will effect the interpretation of modern data and the assessment of future changes caused by land-use, global warming or natural succession. For palaeoecological and palaeoclimatic studies that use peatlands as environmental archives an understanding of the general development will improve site selection and sampling strategies.

In this study 9 small high-altitude mires across the Alps and the Jura Mountains have been sampled and used to assess the general trends in the uppermost peat development. Sites from different regions and countries have been used to avoid bias by specific local conditions, e.g. climate, soil, land-use practises etc.

The proxies used are ash content, dry bulk density, pollen and spore content, and ^{14}C-dating. Possible causes of the observed patterns will be discussed and exemplified by two localities from Switzerland and Austria.

1.1. Sites

The sites of investigation are spread in an west-east transect, from the Jura Mountains in the west to the Austrian and Slovenian Alps in the east, see Table 1 and Fig. 1. Altitude of the sites varies from 1200 to 2100 m and they are all more than 500 m higher than major settlement areas. MOE and AMB in the Jura Mountains are situated in pasture woodland, a mosaic of open pastures, wooded pastures and forest.

Table 1. Site descriptions

Site	Locality	Region	Altitude	Lat. N	Long E	Surface	Size	Edge
MOE	Le Moé	Vaud, Switzerland	1300 m	46°32'47"	6°13'45"	*Sphagnum* lawn	12 ha	20 m
AMB	Les Amburnex	Vaud, Switzerland	1370 m	46°32'23"	6°13'54"	*Sphagnum* lawn	0.1 ha	15 m
WE1	Weissbrunnalm 1	Ultental, South Tyrol	2070 m	46°28'39	10°49'27"	*Sphagnum* hummock	1.5 ha	10 m
WE2	Weissbrunnalm 2	Ultental, South Tyrol	2070 m	46°28'39	10°49'27"	*Sphagnum* lawn	1.5 ha	6 m
FIS	Fishersee	Ultental, South Tyrol	2060 m	46°28'46"	10°49'40"	*Sphagnum* hummock	0.5 ha	12 m
ROA	Rosaninalm	Lungau, Austria	1830 m	46°57'40"	13°47'20"	*Sphagnum* hummock	0.5 ha	17 m
WEN	Wengerkopf	Lungau, Austria	1790 m	47°10'40"	13°52'40"	*Sphagnum* hummock	12 ha	100 m
GUS	Gr. Überling Schattseit-Moor	Lungau, Austria	1750 m	47°10'20"	13°54'00"	*Sphagnum* hummock	0.25 ha	12 m
SIJ	Šijec	Pokljuka, Slovenia	1200 m	46°20'09"	14°00'00'	*Sphagnum* hummock	16 ha	60 m

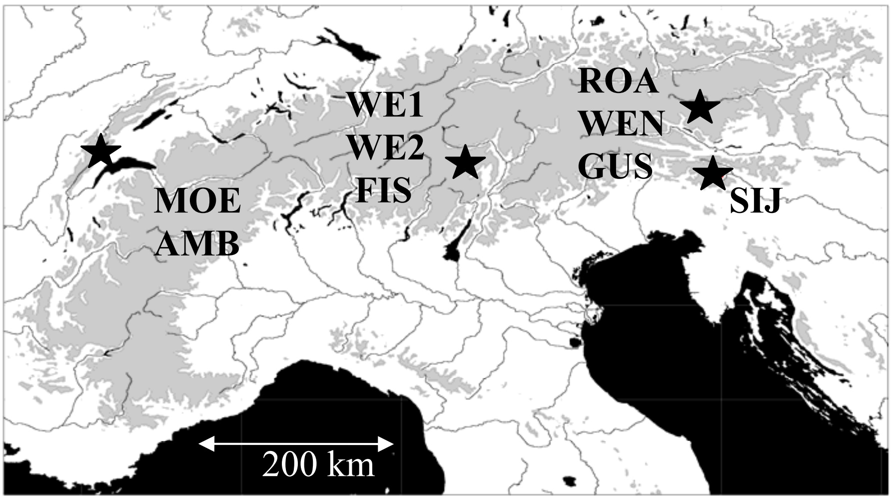

Figure 1. Overview map. Areas with an altitude above 1000 m are marked with grey, outlining the eastern Jura Mountains and the Alps.

The forest is *Picea* dominated with *Abies* and *Fagus* admixed. WE1, WE2 and FIS in the South Tyrol Alps are extracted from pastureland surrounded by grazed forest. The Austrian sites WEN and GUS are surrounded by grazed forest, while ROA is from an open pastureland with patches of forest nearby. The forest at the South Tyrolian and Austrian sites is *Picea* dominated, with admixture of *Larix* and *Pinus cembra*. SIJ in the Slovenian Alps is surrounded by *Picea* forest.

2.1. Field work

All profiles were extracted as peat-monoliths. The aim was to obtain undisturbed peat profiles deposited during the past few centuries for usage as high-resolution environmental archives. Sampling sites were preferred where the surface plant material consisted of healthy growing *Sphagnum* and the peat decomposition could be assumed low. Several test profiles were made (using a 3 cm diameter gouge-corer) to find the least decomposed peat profiles. The profiles used here thus represents the fastest growing and least decomposed parts of the mires.

2.2. Laboratory work

For dry bulk density measurements (dry weight per unit fresh peat volume) was a 1.5-2.5 cm side sub-monolith cut from the peat monolith. It was subsequently divided in 1-3 cm long segments with a sharp knife or when fibrous with scissors. Sample volume was 2 to 12 cm^3 depending on the degree of compaction. The samples were dried in open containers for one week slightly above room temperature before weighting. Larger samples, 10-15 cm^3, have been suggested by Aaby (1986) to reduce sampling errors and disturbing effects of heterogeneous material (e.g. twigs, roots), but as the variations in density relevant here are large the smaller sampling volumes are adequate. Ash-content measurements (ash percentage of dry weight, or loss-on-ignition residue) were carried out on the same samples as used for the determination of the dry bulk density. The samples were dried at 105°C for 16 h, weighted, and then burned at 550°C for 4 hours. For method discussion see Heiri, Lotter & Lemcke (2001). Pollen samples were prepared using the standard acetolysis method (Berglund and Ralska-Jasiewczowa 1986; Faegri and Iversen 1989). Pollen-type classification follows Moore, Webb & Collinson (1991) and dung-related fungal spores are classified according to (van Geel et al. 2003).

2.3. Age determination

The peat profiles have been dated using AMS ^{14}C-dating. Some of the ^{14}C-dates are published elsewhere (MOE and AMB in Sjögren, 2005; WE1, WEN and SIJ in Goslar et al., 2005). ^{14}C dates and depth-age models for WE2, FIS, ROA and GUS are presented in Table 2 and Fig. 3.

Calibration of pre-bomb samples (<AD 1950) was done using OxCal (Bronk Ramsey 1995, 2001) with the IntCal98 calibration set (Stuiver et al. 1998). Post-bomb dates (>AD 1950) are calibrated using changes in atmospheric ^{14}C following nuclear-weapon tests in the early 1960s (Nydal and Lövseth 1983). For calibration the measurements from Vermunt (Levin et al. 1994) and Schauinsland (Levin and Kromer 1997) are used. Post-bomb dates have an accuracy of 2-3 years, except for dates around 1950, which in reality may be from the age interval AD 1930-55 because of peat integration (Goslar et al. 2005).

The depth-age models of WE2, FIS, ROA and GUS are based on the midpoints of the calibrated time-ranges (at 1 σ for pre-bomb dates) and linear interpolation/extrapolation. In MOE and AMB some deviations occur from the midpoints of the calibrated time-ranges as correlation with nearby sites has been taken into consideration (Sjögren 2005). The dates used for the depth-age models for WE1, WEN and SIJ are based on the calibration software PozCal (Goslar et al. 2005).

Table 2. Radiocarbon dates

Radiocarbon dates						
Site	**Depth**	**Lab. No**	**^{14}C-age (1σ)**	**Cal. ^{14}C-age (1σ)**	**Date used**	**Material dated**
WE2	6 cm	Poz-1095	-970 ± 20 BP	AD 1994	AD 1995	*Aulacomnium palustre*
WE2	11 cm	Poz-1096	-3245 ± 20 BP	AD 1963, 1971	AD 1970	Bryophyta
WE2	13 cm	Poz-1102	-125 ± 25 BP	c. AD 1950 (1930-55)	AD 1950	*Sphagnum*
WE2	19 cm	Poz-3739	130 ± 30 BP	AD 1810 ± 140	AD 1810	Bryophyta + seeds
FIS	17.5 cm	Poz-3776	-3055 ± 20 BP	AD 1963, 1973	AD 1970	*Sphagnum*
FIS	20cm	Poz-1188	760 ± 30 BP	AD 1265 ± 20	Not used	Bryophyta + seeds
FIS	28 cm	Poz-1105	150 ± 35 BP	AD 1810 ± 140	AD 1810	Bryophyta
FIS	37.5 cm	Poz-1104	305 ± 25 BP	AD 1585 ± 65	AD 1585	Bryophyta
ROA	34.5 cm	Poz-3774	-3895 ± 20 BP	AD 1963, 1967	AD 1965	*Sphagnum*
ROA	38 cm	Poz-3775	-170 ± 25 BP	c. AD 1950 (1930-55)	AD 1950	Bryophyta
ROA	51 cm	Poz-3765	905 ± 35 BP	AD 1115 ± 75	AD 1115	Bark
GUS	52 cm	Poz-1107	-1755 ± 20 BP	AD 1959, 1961, 1982	AD 1970	*Sphagnum*
GUS	59 cm	Poz-1106	170 ± 30 BP	AD 1805 ± 145	AD 1805	*Pinus mugo* needles
GUS	62 cm	Poz-1094	1020 ± 25 BP	AD 1010 ± 15	AD 1010	*Sphagnum*

3. Results

3.1. Ash content and dry bulk density

The depth scales have been set to zero at the level of the most profound change in peat characteristics, see Fig. 2. The values in all the sites show a similar pattern, although length and amplitude differ between profiles. The general pattern is summarized in Table 3. Dry bulk density is affected by compaction, decomposition and minerogenic influx. Ash content is affected by decomposition but not by compaction, and is especially sensitive to minerogenic influx because of the relatively lower weight of the organic component.

Increased ratio of ash content in relation to dry bulk density thus indicate concentration of minerogenic material. During pollen analysis of MOE, AMB, WEN and SIJ increased concentration of minerogenic material (sand, silt, clay) has been observed in Layer 3, which coincide with the increase in ash content. The minerogenic concentration is affected by minerogenic influx and the peat accumulation rate. If the peat accumulation rate can be assumed constant or increasing, then an increased ash content in relation to dry bulk density would indicate an increased minerogenic influx.

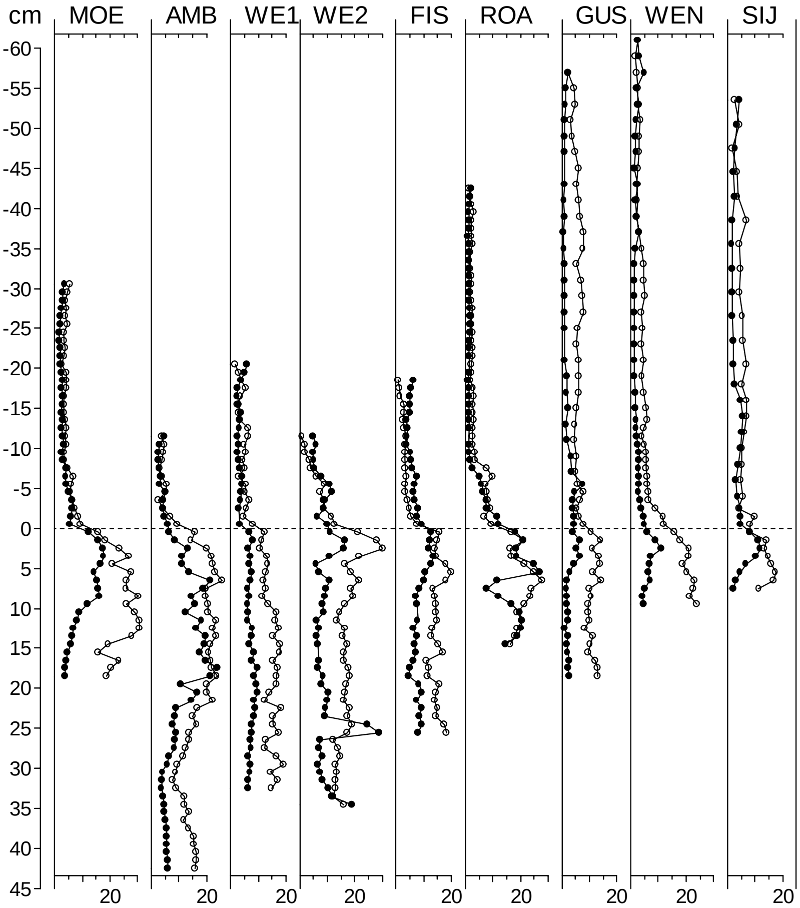

Figure 2. Comparison between sites of ash percentage (dots, ●) and dry bulk density (circles, ○). The transition from decomposed to more well-preserved peat is marked with a dashed line. Depth is relative to this line and the lowest negative depth constitutes the peat surface.

Table 3. General pattern and layers

Lower limit	Upper limit	Ash %	Dry bulk Density	Description	Peat accumulation	Layer
-3 to -8 cm	-12 to -61 cm	Very low	Very low	Loose *Sphagnum*	Fast	5
0	-3 to -8 cm	Low	Low	Sphagnum	Fast	4
3 to 10 cm	0	High	High	Decomposed, dust	Intermediate	3
5 to 20 cm	3 to 10 cm	Low	High	Decomposed, compacted	Slow	2
-	5 to 20 cm	Low	Low	Rather decomposed	(Intermediate)	1

3.2. Depth-age models

In the western sites the 0-cm lines in the depth-age models (Fig. 3), drawn at the most profound change in peat characteristics, also mark an increase in peat-accumulation rate (here regrowth) in the mid 20th century (MOE at AD 1945, AMB 1950, WE1 1960, WE2 1960, FIS 1945). Regrowth in the eastern sites started already in the early and mid 19th century (WEN 1820, GUS 1825, SIJ 1865). The depth-age model for ROA is inconclusive as the ^{14}C-dates are few, and the intercept age of AD 1630 is most likely to old. Probably the transition to faster peat growth in ROA occurs in the same time span as in the other sites (c. AD 1800-1950). The peat accumulation rate is lowest in the deeper part of the profiles, but start to increase a few cm below the 0-cm line. Peat accumulation rate seem to be higher in the first millennia BC, but this time period is only represented in MOE and AMB.

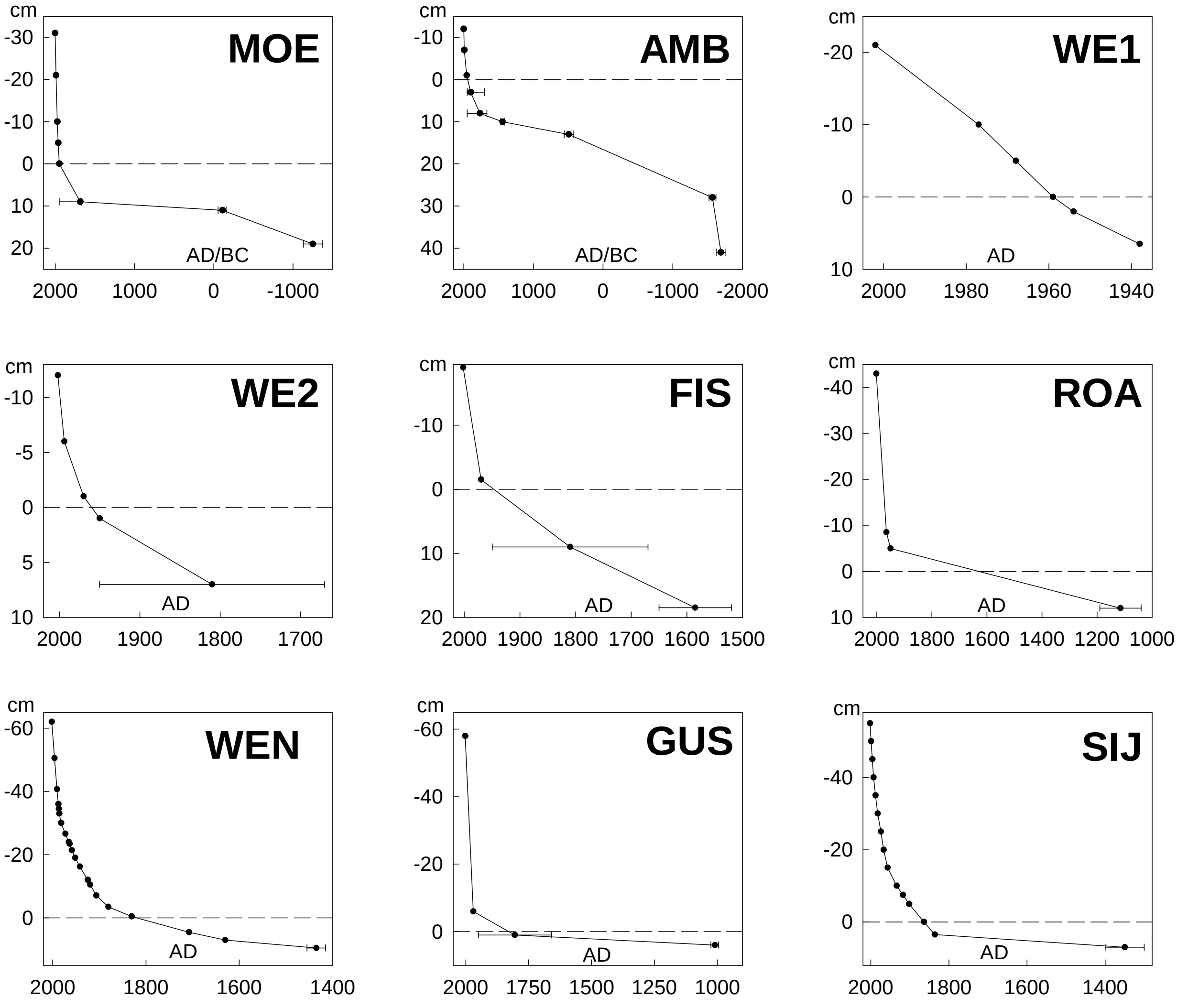

Figure 3. Depth-age relationships. The transition from decomposed to more well-preserved peat is marked with a dashed line; Depth is relative to this transition and the lowest negative depth constitutes the peat surface.

3.3. Pollen analysis

In the pollen diagrams (Fig. 4) the percentages of non-arboreal pollen (NAP; sum of herb, grass and shrub pollen), *Plantago media/montana* (*P. media* + *P. montana*) and dung-fungal spores are calculated on the sum of pollen and spores from upland plants, i.e. mire plants are excluded. The same sum (AP + NAP) is the basis for the pollen concentration. *Plantago media/montana* has not been displayed in the WEN diagram because of low values (peak <1%). Pollen concentration responds to changes in pollen influx, peat compaction and decomposition of the organic matrix (which results in loss of volume). Pollen accumulation (pollen deposition per unit time and surface) is not likely to vary more than with a factor of 2-3 except at very strong changes in the vegetation (see Hicks 1998, 2001; van der Knaap, van Leeuwen & Ammann 2001), and there is also a limit to how much the material can be compacted. It can therefore be assumed that the high pollen concentration primarily is caused by decomposition. The pollen-concentration curve in both MOE and WEN correlates well with the dry bulk density curve.

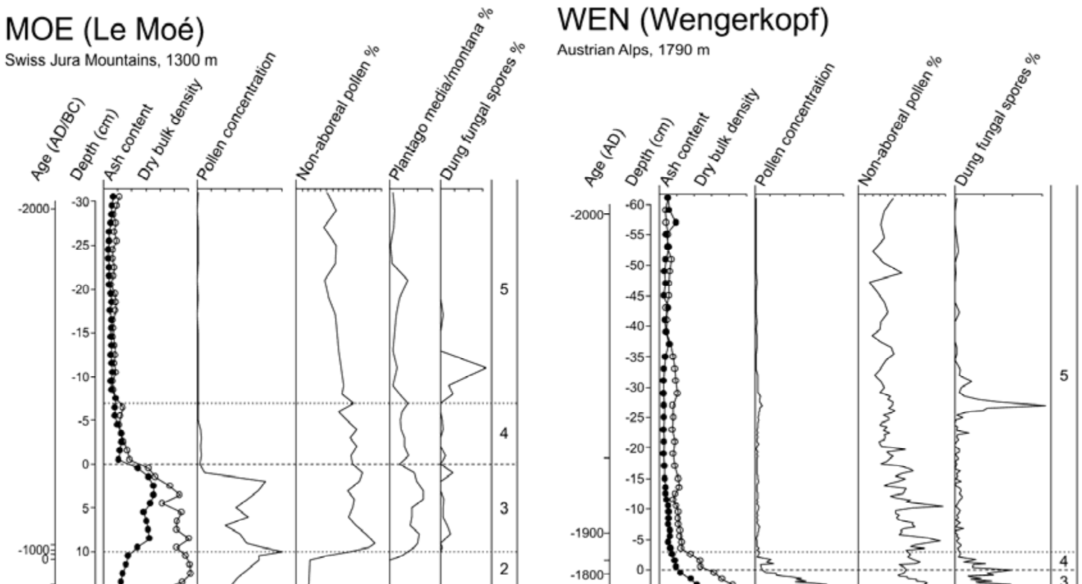

Figure 4. Selected biological data from a western (MOE) and eastern site (WEN). Ash percentage is shown with dots (●) and dry bulk density with circles (○). Pollen and spore values are express as percentage of the total upland pollen and spore content. Pollen concentrations are expressed as 1000s of upland pollen grains per cm^3. Depth is relative to the transition from decomposed to more well-preserved peat. Zonation follow Table 3. Lowest negative depth constitutes the peat surface.

The sum of non-arboreal pollen is used to assess changes in the general openness of the landscape. A clear increase can be seen at the beginning of Layer 3, which coincides with an increase of minerogenic influx and dung-fungal spores. After this peak a slow and shaky decrease occurs until the late 20th century when the NAP values level out. The dung-fungal spore group includes *Cercophora*-type, *Podospora*-type and *Sporormiella*. Dung-fungal spores primarily occur on cowpats and indicate cattle activity. In MOE the first appearance occurs at the transition from Layer 2 to 3, and WEN shows a clear increase in dung-fungal spores at the same transition. Low frequencies of dung-fungal spores also occur in the uppermost part of the peat and reflects continued cattle activity. The single peak values that occur in upper fast-growing part of both profiles (*Podospora*-type in MOE, *Sporormiella*-type in WEN) are ascribed to a single dispersal event from a cowpat close to the sampling spot. The same phenomenom has been observed elsewhere (van der Knaap et al. 2000; van der Knaap and van Leeuwen 2003).

4. Discussion

4.1. Patterns

The clearest pattern noted in the peat stratigraphy of small high-altitude mires across the Jura Mountains and the Alps is the occurrence of decomposed peat close to the mire surface (Layer 2 and 3; high dry bulk density, low peat accumulation rate, high pollen concentration). In the upper part of the decomposed peat an increased minerogenic influx is observed (Layer 3; high ash content). Below the decomposed peat "normal" moderately decomposed peat occur (Layer 1), and above it well-preserved fast-growing *Sphagnum* peat (Layer 4 and 5).

There seem to be two phases of re-initiated peat growth, one in the early and middle 19th century (c. AD 1820-1870), and another in the middle 20th century (c. AD 1940-1960). Historically the strongest grazing pressure in the region occurred around the end of the 19th century (Bätzing 2003), a time period where no initiation of peat growth is recorded. Large hummocks that were established before the period of grazing maxima may have been protected from trampling by its own size and by *Juniperus* and other shrubs growing in the hummock.

4.2. Cause

The pollen and spore data show that grazing and human activity occur together with increased minerogenic influx. Peaks in ash content or dust particles have been shown to be an effect of windblown dust input from agricultural or pastoral activity (Bahnson 1973, Kramm 1978, Vuorela 1983). The high-altitude locations of the mires studied here, the observed sand-sized particles, and the appearance of fungal dung-spores makes it probable that the minerogenic material derive from the local surrounding and not from agricultural activities in the lowland. Dust has been blown in from areas where the vegetation cover has been damaged by trampling, e.g. clearances, pastures, pathways, slopes and waterholes, or transported directly on the mires on the hooves of husbandry animals. The observed slowness of decrease in NAP after the maximum grazing phase of the mires (and presumably the surrounding areas) is understandable as regrowth take time, and NAP pollen production may temporary increase with lower grazing intensity (Groenman-van Waateringe 1993).

The presence of high densities of husbandry animals will affect the peat growth and accumulation rate in different ways. Trampling by animals on the mire surface can destroy the vegetation cover (especially *Sphagnum*) and expose the peat to aeration. Such trampling damage would be extra high where animal density goes up, e.g. close to water holes. Examples of such extensive surface damage done on mires by animals can be found in the Aletschwald nature reserve, central Swiss Alps, where high numbers of game seek refuge from hunting (Bodenmann and Eiberle 1967; Müller 1972; van der Knaap and van Leeuwen 2003). Another important effect of trampling is the mechanical compaction of the peat, which has a direct effect on dry bulk density. Decomposition will also increase, as the mass of peat in the acrotelm will increase, with more material exposed to aeration. It may be noted that the mire surface might actually become wetter in parts (in the holes/depressions) as the surface is pressed down, but the mass of plant material between depressions and during dry periods exposed to decomposition will increase. The point pressure of a hoof is also different from the general pressure of autocompaction as there is no counter-pressure of water.

Compaction and decomposition reduce the permeability of the peat and downward losses of rainwater will decrease (Buttler, Dinel & Lévesque 1994). Damage of the vegetation layer will on the other hand increase surface runoff, especially in combination with animal pathways. The effect on the hydrology of the mire thus depends on the surface topography and groundwater regime, and must likely be determined from case to case.

The most probable explanation of the pattern detected in all the peat profiles is therefore a high grazing activity during the time when Layer 3 accumulated. The underlying Layer 2 was affected by compaction and decomposition caused by surface damage and lowering of the effective water table. Deeper down, in Layer 1, the peat was less affected by the subsequent trampling, but the short depth covered in the peat profiles used here as well an unstable environment (earlier periods of human activity, climatic change and natural heterogeneity) makes it hard to estimate any “natural” state. Layer 4 could be classified as a regrowth layer where the *Sphagnum* was influenced by the nutrient and groundwater conditions of Layer 3, although autocompaction cannot be disregarded. The top part, Layer 5, is constituted of relatively unaffected, or natural, well preserved *Sphagnum* peat.

4.3. Consequences

For palaeoecological studies the damaging effect of grazing on peat development has major implications for the temporal resolution, dating and the interpretation of some proxies. Fine sub-sampling can still provide data with good time-resolution (e.g. WEN), but the risk for contamination increases. The uneven and slow peat accumulation rate also makes accurate depth-age models for the past 500-2000 years problematic. The Little Ice Age ^{14}C-plateau accentuates the problem of dating as calibrated ^{14}C-dates get wide and multimodal probability distributions. The age control can be improved by combining the probability functions of a high number of dates (e.g. PozCal, see Goslar et al. 2005), or if the ^{14}C-dates are used in combination with correlation of pollen assemblage characteristics with less affected peat/sediment profiles (e.g. Sjögren 2005). It would also be problematic to use peat characteristics to interpret climatic fluctuations as any such signals are blurred or hidden by the strong human impact. The only solution for this is careful site selection in remote areas, or to rely on less affected proxies, e.g. pollen percentage data.

An important ecological observation is that most mires at high elevation in the Jura Mountains and the Alps either are severely damaged by grazing, or were severely damaged during the 19th or 20th century. The compaction and decomposition of the peat have changed the water and nutrient conditions of the mires, and increased influx of minerogenic material have further altered the soil conditions. During the latter half of the 20th century the number of husbandry animals has decreased considerably in the Alps and this has allowed regeneration of *Sphagnum* peat formation in some mires. A similar effect has been achieved in the Jura Mountains by fencing. The climatic warming that occurred during the 20th century (Auer, Böhm & Schöner 2001) might have helped the process by increasing the growth rate of *Sphagnum*. The crucial point in mire restoration is the creation of stable *Sphagnum* growth. A dry and nutrient-rich mire surface is prone to invasion of woody species (below the tree-limit). This will increase the evotranspiration and further damage the mire. But generally, peat growth seems to be initiated naturally as soon as grazing pressure decrease below a critical level.

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The effect of climate on pollen productivity AD 1975-2000 recorded in a *Sphagnum* peat hummock

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Abstract

A fast growing *Sphagnum* peat hummock in the Jura Mountains was used as a high-resolution archive for past pollen deposition. Post-bomb calibrated radiocarbon dates gave a dating accuracy of ±1 year, which allowed estimations of annual variability in pollen productivity AD 1975-2000. The pollen percentage value of abundant taxa was down-weighted to reduce the influence of plant cover, mean pollen productivity and inter-dependence of the variables. Comparison with other sites showed correlation between the Jura Mountains, the Western- and the Eastern Alps. Significant correlation between pollen production and seasonal climatic parameters were found for several taxa. Winter temperature is the single most important factor for pollen productivity by trees (simple linear regression). The climatic effect on the pollen assemblage is best explained by a wet/warm to cold/dry gradient, but seasonal influence is considerable (ordination by PCA, RDA).

Key words: Annual resolution, climate, pollen productivity, *Sphagnum* hummock.

1. Introduction

It is commonly assumed that changes in fossil pollen records are caused by changes in the surrounding vegetation (von Post, 1916). But if this change in vegetation is caused by climatic fluctuations a problem may arise. Pollen productivity will change together with the climate, making it hard to estimate the response in the vegetation pattern. Many investigations have given results that are problematic to explain entirely with shifts in the vegetation, e.g. when there is no detectable time-lag between shift in climate and pollen values (Ammann *et al.*, 2000), a very rapid increase of pollen values of a taxon over a large area (Tallantire, 2002), or the absence of pollen while mega-fossils are present (Kullman, 1998). Recent measurements of relative pollen productivity have resulted in rather different values (Broström *et al.*, 2004; Hjelle, 1998). The methodology has not been the same in all investigations, but the most likely explanation is that there are regional differences in pollen productivity.

It may be assumed that pollen production follows a species general performance. A decline of pollen frequencies from warmth-demanding taxa can be interpreted as a response to colder climate, regardless whether the decline is caused by reduced pollen productivity or decreased plant cover. When a pollen record is used directly to reconstruct climatic change this is thus not so problematic, but it may be so if pollen production and plant cover should be separated.

The needs to better understand the influence of climate on pollen productivity has increased in the past decennia as more subtle and short-lived climatic shifts come under study (e.g. Hausmann *et al.*, 2002; Tinner and Lotter, 2001). Under such circumstances increases the relative importance of pollen productivity over migrations, die-backs and colonization. New methods for quantitative landscape reconstruction are also developing (Gaillard *et al.*, 2005; Prentice, 1985; Sugita, 1994) in which correct estimation of pollen productivity is here crucial.

One reason that this subject has earned relatively little attention is that it is problematic to study. To directly compare pollen productivity with climatic change, a site with stable and well documented past vegetation is needed, and few, if any, such data sets exist, mainly because of large changes in land-use during the past few centuries (Nielsen and Odgaard, 2004). And even if our current climate is changing fast it is not fast enough for the time frame of modern research projects. The aim of many investigations is to predict climatic change and/or possible effects of such a change, and in that perspective it is not an option to wait until the change has occurred. An alternative is to study modern pollen productivity in different climatic regions. Different estimations of relative pollen productivity might be compared (Broström *et al.*, 2004), but currently these investigations are too few. In regions with similar vegetation but with climatic differences, pollen traps can be used to measure actual differences in pollen influx (Hicks *et al.*, 2001), but such investigations are time consuming and measurements can only be achieved for a few taxa.

The alternative pursued here is to study annual variability in pollen production. A climatic change can be described as changed frequencies of years with certain characteristics, e.g. a mean warmer climate is equivalent to an increased number of years with warmer summers, mild winter etc. It may thus be possible to use the annual variability to assess the effect of climatic change. An assumption is that the reaction of a taxon to specific weather conditions for a single year is similar to that of the same condition sustained over a period of time. This is probably not entirely correct, but it seems unlikely that a taxon with a negative response for a single annual events would have a positive response if the frequencies would increase for the same type of event.

The most exact results are achieved by studying the direct flowering of the plants (Litschauer, 2000) or by yearly measurements of pollen influx with pollen traps (Hicks, 2001; van der Knaap *et al.*, 2001). To get even reasonably long time series with these methods a considerable amount of work and planning is needed. An alternative is to use existing lake or peat deposits as natural archives of fluctuations in the pollen production (van der Knaap and van Leeuwen, 2003).

In this investigation a *Sphagnum* peat hummock from the Jura Mountains is used as an environmental archive. The relative variance in the pollen record will be compared with measured climate and correlated with two other sites in the Swiss and the Austrian Alps. Annually constrained pollen samples and modified pollen percentages will be used to achieve statistical relationships with measured climatic data (van der Knaap and van Leeuwen, 2003).

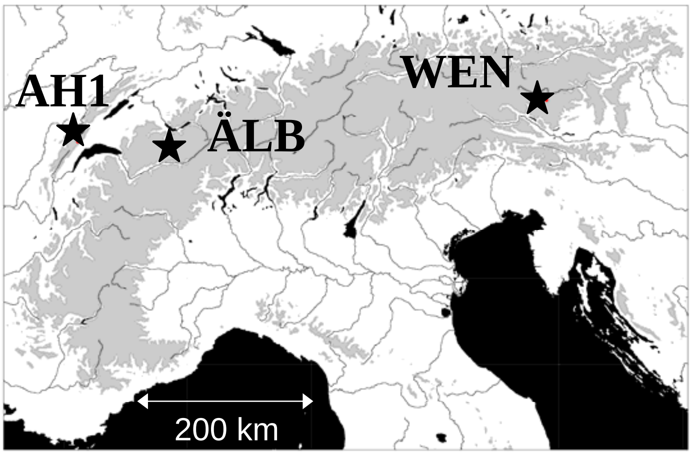

Figure 1 Overview map of localities: AH1 = Les Amburnex Hummock 1, SW Swiss Jura Mountains; ÄLB = Älbi Flue mire, NW Swiss Alps; WEN = Wengerkopf mire, Austrian Alps. Grey indicates areas above 1000 m altitude.

2. Methods

2.1. Site description and fieldwork

The peat section AH1 was cut out from a *Sphagnum* hummock in a small mire in the Combe des Amburnex (Les Amburnex mire, 46°32’23’’ N, 6°13’54’’ E, 1370 m a.s.l.) in the Swiss Jura Mountains (Figure 1). The mire is partly covered by *Picea* and the hummock grows at the edge of the forested part. The hummock was growing below *Picea* branches, which seems to be the case for all *Sphagnum* hummocks in the area. The vegetation around the mire is a mosaic of pasture and forest. *Picea* is the most abundant tree followed by *Abies*, *Fagus* and some *Acer*.

2.2. Laboratory work

Sub-sampling was done with scissors and the existing layers were followed as far as possible. Pollen samples were prepared using the standard acetolysis method (Berglund and Ralska-Jasiewiczowa, 1986). For identification of pollen, literature (Moore *et al.*, 1991; Punt and Blackmore, 1991) and the reference collection at the University of Bern were used. Nomenclature follows ALPADABA (Alpine Palynological Data-base, housed in Bern, Switzerland).

2.3. Radiocarbon dating and depth-age relationship

Five *Sphagnum* samples were used for radiocarbon analysis with the AMS facility of Utrecht University. The results of the ^{14}C analysis showed increased activities, expressed as fractions modern, and were accounted for by the effects from the atomic bomb activity in the atmosphere (Nydal and Lövseth, 1983). Using the computer program CALIBomb (Reimer *et al.* 2004; data set: Levin and Kromer, 2004) we retrieved 1σ- calendar ages. From the calendar ages we derive the depth-age relationship of core AH1 (figure 2). Age determination of the pollen samples is based on linear interpolation between the ^{14}C-dates, and the time of the hummock was collected (AD 2001.8). For AH1-6 AD 1997 was used, i.e. the first full year after the youngest possibility within the confidence (AD 1996.2). A younger age would infer that there was a decrease in peat accumulation between 10 and 17 cm depth, which is highly unlikely considering the upward decrease in compaction and decomposition.

Table 1 Radiocarbon analysis.

Sample	Depth	Lab code	δ13C ‰	Fraction modern	1σ-calendar age	Mean
AH1 6	9.5	UtC-12572	-29.5	1.091 +/- 0.006	1996.2-2002.0	1999.1 ± 2.0
AH1 16	17.7	UtC-11407	-28.7	1.173 +/- 0.005	1986.1-1990.2	1988.2 ± 2.0
AH1 24	23.9	UtC-11408	-29.1	1.249 +/- 0.005	1980.7-1983.7	1982.2 ± 1.0
AH1 30	28.4	UtC-11722	-29.4	1.462 +/- 0.006	1972.3-1972.8	1972.6 ± 1.0
AH1 32	29.5	UtC-11409	-30.6	1.562 +/- 0.006	1968.2-1969.9	1969.1 ± 1.0

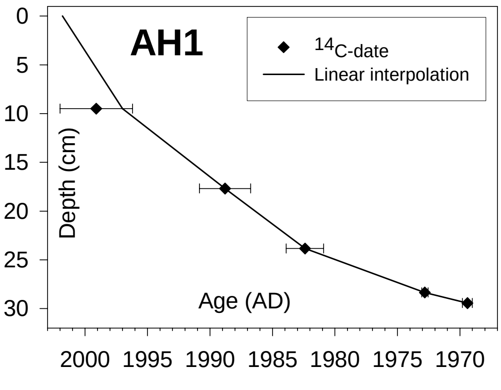

Figure 2 Depth-age relationship for AH1. Error bars show 1σ confidence interval. Linear interpolation used to infer the age of pollen samples is showed with a line. Upper end of line is the surface (0 cm at AD 2001.8).

2.4. Modification of pollen values

The six most abundant taxa in the pollen diagram have been down-weighted (*Fagus, Picea, Pinus, Quercus,* Gramineae and *Urtica*) as the high original percentage values disturb the annual climatic signal. The adjustment factors have been calculated by dividing the mean pollen percentage value (AD 1976-2001) of *Betula* (the 7th most abundant pollen-type) with the mean pollen percentage value of the specific taxa. The reduction factors have then been applied in the same way as correction factors (Andersen, 1970), i.e. the original pollen percentage values of a taxon have been multiplied with a reduction factor (Table 2) and subsequently new percentages have been calculated. With the modification the mean effective pollen sum decreases from 592 to 303. The mean pollen percentage value for the down-weighted taxa after percentage recalculation is 6.1%. In the ideal case all taxa are down-weighted to the same value, because this completely removes the differences between taxa in pollen productivity and plant cover. But the disadvantage is that this would enhance the statistical error from taxa with a low pollen count. The removal of taxa with low pollen counts (e.g. <1% of the pollen sum) also has disadvantages, since this reduces the effective pollen sum and increases inter-dependence between the remaining taxa, and moreover it would be relative to the taxonomic resolution of the investigation. The modification of the pollen sum done here should thus be seen as a reduction of inter-taxa differences in pollen productivity and vegetation cover, thus increasing the ratio signal to noise.

Table 2 Reduction factors. Abundant taxa have been multiplied by a reduction factor to get a value similar to the 7th most abundant taxa. Average percentage refers to the average percentage value of the taxa AD 1976-2001 prior to modification

Sites and taxa	**Reduction factor**	**Average percentage**
Les Amburnex (AH1)		
Betula	1	3.1
Fagus	0.73	4.3
Gramineae	0.13	23.9
Picea	0.12	25.3
Pinus non-*cembra*	0.52	6.1
Quercus	0.81	3.9
Urtica	0.83	3.8
Älbi Flue (ÄLB)		
Alnus viriridis	0.45	4.7
Betula	0.98	2.1
Gramineae	0.13	16.6
Picea	0.046	45.2
Pinus cembra.	0.21	10.8
Pinus non-*cembra*	0.79	2.6
Urtica	1	2.1
Wengerkopf (WEN)		
Alnus glutinosa	1	3.1
Betula	0.61	5.1
Gramineae	0.42	7.5
Larix	0.35	8.8
Picea	0.097	32.2
Pinus cembra	0.28	11.0
Pinus non-*cembra*	0.30	10.5

2.5. Sample-age constraints and annual resolution

In order to compare pollen data with climatic data, each pollen sample has been constrained to a full year. In the pollen data set covering the period 1976 to 2001 there were 28 samples. Samples assigned to the same year were averaged. The pollen years are not exactly equivalent to calendar years, as the sampling precision is too low and natural conditions make this impossible. The signal is smoothed 2-3 years compared to annually separated pollen deposition. The growth pattern of *Sphagnum* also affects the pollen signal. Field and laboratory observations suggest that *Sphagnum* (in central European mountain regions) grows rapidly in height early in the growing season primarily by expansion of biomass accumulated the previous year. Later in the season *Sphagnum* does not grow so much in height but forms a dense surface layer that can expand next year. The surface of a *Sphagnum* hummock thus remains more or less the same from the summer until the following spring. Thus late-flowering taxa deposit their pollen on the same surface as early flowering taxa of the following year, so the "pollen deposition year" runs from summer to summer. Additional time-lag must therefore be allowed for late-flowering taxa. The uppermost sample (collected in the autumn 2001) will thus theoretically contain pollen from the late flower season AD 2000 and AD 2001 together with the early flowering season 2001. High pollen values of summer flowering plants (Gramineae, *Rumex acetosa, Urtica*) in the uppermost samples supports this assumption. Together with uncertainties in the determination of the depth-age relationship this sums up to a possible deviation of one year of a taxon-specific pollen signal, which must be accounted for in the analysis of the data.

2.6. Comparison between sites

Two other sites have been used for comparison with AH1 (see Figure 1). ÄLB (Älbi Flue mire, 46°35’55’’ N, 7°58’35’’ E, 1850 m a.s.l.) is situated in the northern Alps of central Switzerland just below the forest limit (van der Knaap and van Leeuwen, 2003). The nearest trees (12 m) are *Pinus cembra* but the general vegetation in the area is dominated by *Picea*. WEN (Wengerkopf, 47°10’40’’ N, 13°52’40’’, 1790 m a.s.l.) is situated in the Austrian Alps (Goslar *et al.*, 2005). *Pinus mugo* grows on the mire itself while the surrounding forest is dominated by *Picea* with an admix of *Larix* and *Pinus cembra*. The pollen records from the sites have been prepared in the same way as for AH1 with reduction of the 6 most common taxa to the mean value of the 7th most common taxon (Table 2). In ÄLB the pollen sum decreased from 1226 to 383 and the mean modified pollen percentage of the down-weighted taxa is 6.7%. In WEN the numbers are 703 to 306, and the mean modified pollen percentage of down-weighted taxa is 7.2%. Taxa with a mean modified pollen percentage > 1% at all the sites have been used for comparison, and those with visible correlation have been graphically displayed (Figure 4). Cyperaceae, *Potentilla* and *Vaccinium* are considered local plants and are not included in the pollen sum or subject of down-weighting.

2.7. Climatic parameters and pollen-climate relationships

The climatic data are derived from the Geneva measurement station (MeteoSchweiz; see also Begert et al. (2005)) c. 35 km south of the sampling site. Seasonal and annual temperature and precipitation were used as climatic parameters. Seasons are January/March (Winter), April/June (Spring), July/September (Summer) and October/December (Autumn). Results from pollen traps in the Alps show that the pollen deposition of trees is affected by the climate the previous year (Hicks, 2001; van der Knaap *et al.*, 2001). Considering the uncertainties in the determination of the depth-age relationship and the characteristics of *Sphagnum* peat growth we test both a 1- and 2-year time lag. One might infer that herbs responds faster to climate, but statistical tests with a 0-year time lag did not confirm this. A statistical effect of using different time lags and of the smoothed character of the pollen data is autocorrelation. Plants might on the other hand show a longer response than 1-year to climate as their general condition and reserves from the previous years are of importance.

2.8. Statistics

The type of relationships within the modified pollen assemblage was tested with a detrended correspondence analysis (DCA), which gave short gradient length (0.95 SD), suggesting that a linear response model is appropriate (ter Braak and Prentice, 1988). Linear regression was used to test the correlation of single taxa between sites and with climatic parameters. Principal component analysis (PCA) and redundancy analysis (RDA) (ter Braak, 1987; ter Braak and Prentice, 1988) were applied to assess the internal relationships of the modified pollen assemblages and the relation between the modified pollen assemblages and climatic parameters. In PCA the grouping is done on the species composition, so the environmental variables do not affect the analysis. In RDA the ordination axes are linearly related to the climatic variables and thus show the impact of climate, but the choice of climatic variables affects the outcome. Both methods thus complement each other. *Sorbus*-type was removed from both PCA and RDA as the single strong peak would distort the analyses. The annual parameters of precipitation and temperatures were removed from the RDA to reduce autocorrelation between the climatic parameters. The statistical analyses were made with SYSTAT (Wilkinson, 1990) and CANOCO.

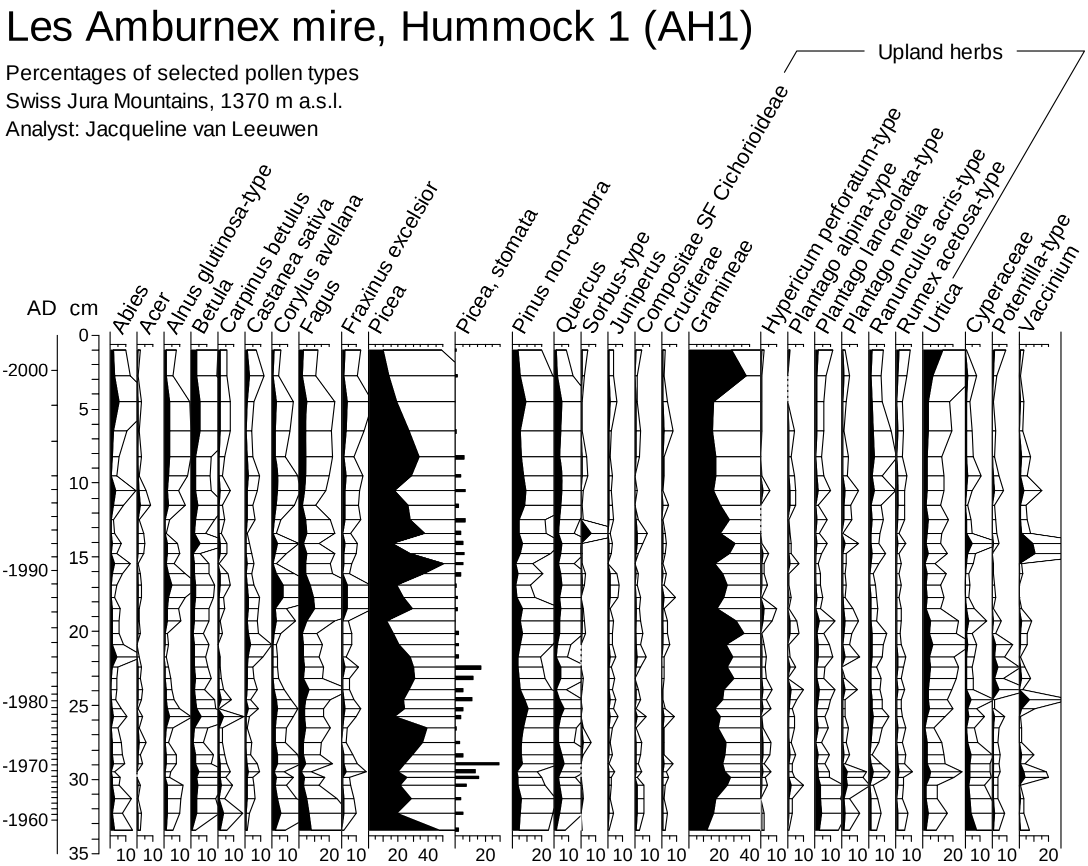

Figure 3 Pollen diagram from the Les Amburnex Hummock (AH1). Percentage is based on the upland pollen sum.

3. Results

3.1 Pollen diagrams

Both a non-modified pollen diagram (Figure 3) and a modified pollen diagram (Figure 4) are presented. Cyperaceae, *Potentilla*-type and *Vaccinium* are not included in the pollen sum and have not been subjected to down-weighting. These taxa occur on the mire itself and their pollen values are largely dependent on the plant distribution within the nearest few meters. *Picea* also occurs in the direct vicinity, but trees show less local influence on small distances (van der Knaap *et al.*, 2001), and it is included. In general an as many species as feasible are included in the pollen sum (Wright and Harvey, 1963).

The position of the hummock below Picea branches allows a ready supply of *Picea* needles. Undecomposed needles are sieved away during pollen preparation, so the frequencies of *Picea* stomata are thus probably more reflective of the decomposition rate than the deposition-rate. Interestingly, increased values of *Picea* stomata correspond to increased pollen values of *Vaccinium* (Figure 3), suggesting a mutual cause.

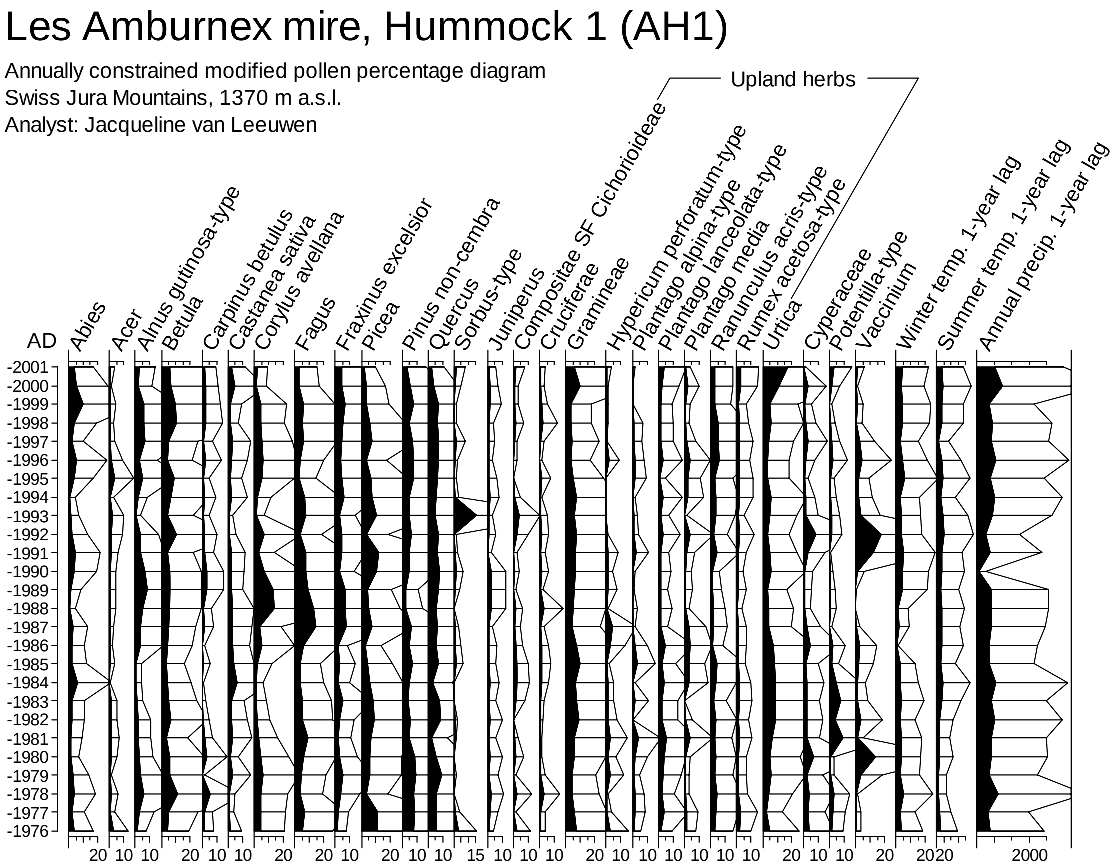

Figure 4 Modified and annually constrained pollen percentage diagram. Climatic parameters have been added for direct comparison. The scale for summer temperature starts at 15°C, annual precipitation starts at 500 mm/yr. Taxa >1% have been included.

The modified pollen percentage diagram (Figure 4) shows clear synchronous peaks and dips for some taxa. In 1978 there is a peak in *Alnus*, *Betula* and Cruciferae, while *Fagus*, *Picea* and Gramineae dip. In 1987-1989 there is a peak in *Corylus*, *Fagus* and *Fraxinus*.

3.2. Correlation between sites

Several taxa show visual correlation between the sites (*Betula*, *Corylus*, *Fagus*, *Fraxinus*, *Picea*, *Pinus*, *Quercus*, Cyperaceae and *Vaccinium*). Others show little or no visual correlation (*Alnus glutinosa*, Gramineae, *Plantago lanceolata*-type, *Rumex acetosa*-type, *Urtica* and *Potentilla*-type). Linear regression analysis resulted in statistical significant correlation of *Corylus* for AH1-WEN (P = 0.034), *Fagus* for AH1-ÄLB (P = 0.012), and *Fraxinus* for AH1-ÄLB (P = 0.034) and AH1-WEN (P = 0.016). *Potentilla*-type show negative correlation for AH1-ÄLB (P = -0.03), but this makes no ecological sense and is likely by chance. The strong correlation of *Vaccinium* for ÄLB-WEN (P = 0.001) depends on the single-peak distribution of the *Vaccinium* pollen values.

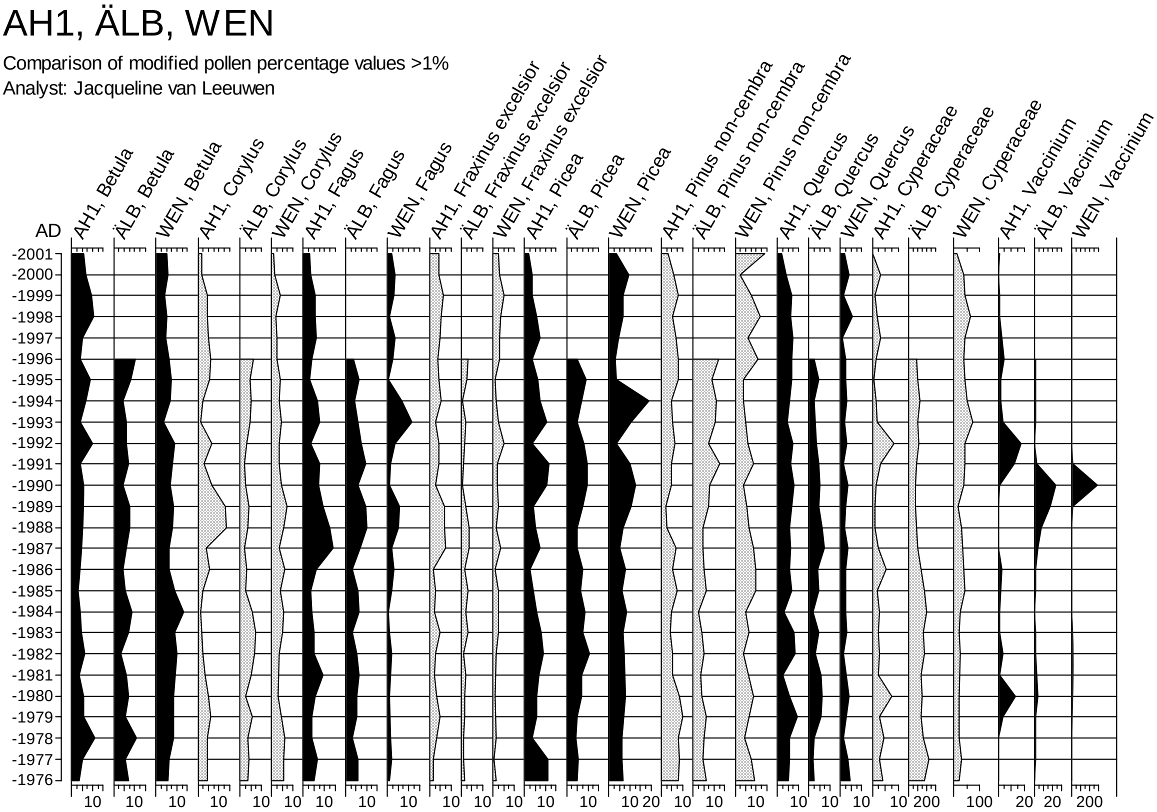

Figure 5 Comparison between modified and annually constrained pollen percentage values from sites in the Jura Mountains and the Alps. Taxa >1% have been included.

The fact that annual fluctuation in pollen deposition can be correlated between sites with different vegetation and over a distance of 600 km suggests that climatic forcing of pollen production occurs on at least a regional scale. Trees seem to correlate better than upland herbs. Gramineae consist of several species, which may blur a climatic signal, while *Plantago lanceolata*, *Rumex acetosa* and *Urtica* are dependent on the local land-use and their habitat may differ more between sites than that for most trees.

3.3. Correlation of single taxa with climatic parameters

All taxa with a mean modified percentage above 1 were tested with simple linear regression against seasonal and annual climatic parameters (Table 3). The high number of tested cases (500) implies that several cases might show significance by coincidence (expected 25 coincidental in a random data set; here 47 significant cases). Single significant cases should thus be considered with caution and statistically or ecologically meaningful patterns should be considered.

Table 3 Statistically significant correlations between single taxa and climatic parameters: + = significant positive correlation (p ≤ 0.05) at 1-year time lag; ++ = highly significant positive correlation (p ≤ 0.01) at 1-year time lag; n = significant negative correlation (p ≤ 0.05) at 1-year time lag; nn = highly significant negative correlation (p ≤ 0.01) at 1-year time lag; (+) (++) (n) (nn) as above but with 2-years time lag. No correlation was found for *Juniperus*, Compositae Subfam. Cichorioideae, *Plantago media* and *Potentilla*, and they are not presented in the table. Win = Winter (January/March); Spr = Spring (April/June); Sum = Summer (July/September); Aut = Autumn (October/December); Ann = Annual

Taxa	**Temperature**					**Precipitation**					**Interpretation**
	Win	**Spr**	**Sum**	**Aut**	**Ann**	**Win**	**Spr**	**Sum**	**Aut**	**Ann**	**Favourable climate**
Trees											
Abies	+ (+)	(+)			+ (+)	(n)					Warm winter and spring
Acer	+										Warm winter
Alnus				(+)							Warm autumn?
Betula	+	(+)									Warm winter and spring
Carpinus	+										Warm winter
Castanea							+				Wet spring?
Corylus				(+)					n		Warm autumn?, dry?
Fagus	(nn)							(nn)	(nn)		Cold winter, dry
Fraxinus	(n)						(++)				Cold winter, wet spring?
Picea				(n)		n				(n)	Dry?
Pinus			n								?
Quercus										n	Dry?
Sorbus			(+)								Warm summer?
Herbs											
Cruciferae							++				Wet spring?
Gramineae				(n)							Cold autumn?
Hypericum		(nn)			nn (n)	+ (+)		(n)	n (n)		Cold spring,
Plantago alpina		nn									Cold spring
P. lanceolata					n						Cold?
Ranunculus acris										+	Wet?
Rumex acetosa		+						++ (+)	++		Warm spring?, wet
Urtica										(+)	Wet?
Wetland											
Cyperaceae		n			n						Cold spring
Vaccinium								n (n)			Dry

Winter temperatures have a strong impact on the pollen productivity of several deciduous tree taxa, positive for *Abies*, *Acer*, *Betula* and *Carpinus*, negative for *Fagus* and *Fraxinus*. Many herbs are negatively correlated with temperature (Gramineae, *Hypericum*, *Plantago alpina*, *Plantago lanceolata*, Cyperaceae), especially with spring temperature (*Hypericum*, *Plantago alpina*, Cyperaceae). Low summer precipitation also seems beneficial for some taxa (negative correlation with *Hypericum* and *Vaccinium*). *Ranunculus acris*-type has the opposite requirements with a warm spring and a wet summer and autumn.

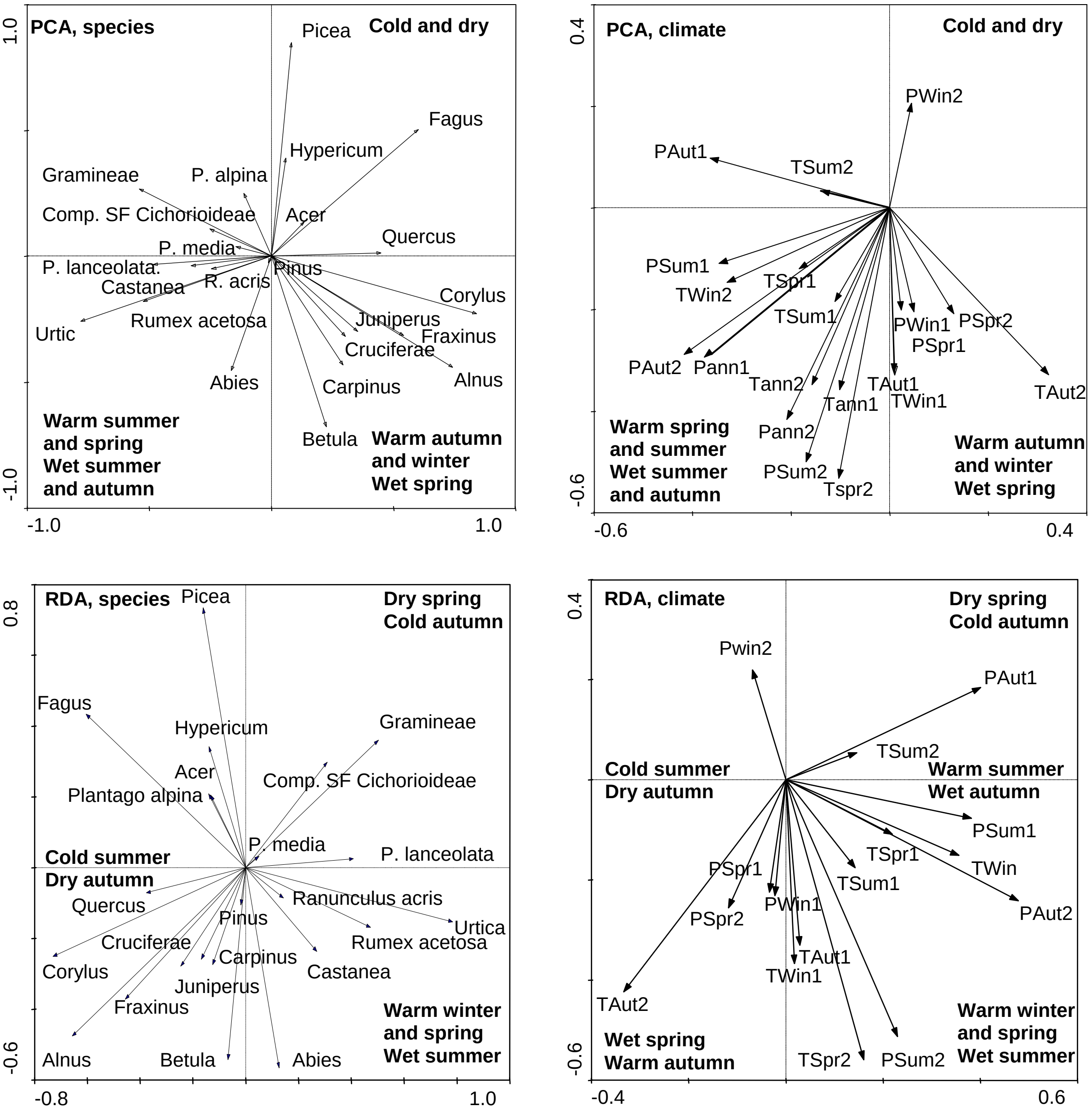

Figure 6 PCA and RDA scatter plots of the modified pollen percentage values (*Sorbus*-type excluded) and annual and seasonal temperature and precipitation with 1- and 2-years time lag. Species and climatic parameters are displayed on separate plots. The first ordination axis of the PCA explains 30% of the variance, the first two 49%. The first ordination axis of the RDA explains 26 % of the variance, the first two 42 %. The general relationships between the climatic parameters and the modified pollen assemblage have been noted in the plots.

3.4. Statistical analyses of the pollen assemblage and its relation to climate

The first two PCA ordination axes explain 49% of the variance, for RDA this is 42%. The two first RDA ordination axes together are significant (P = 0.004). PCA and RDA show essentially the same pattern (Figure 5), suggesting that the applied climatic parameters explain the general pattern in the modified pollen assemblages. The first RDA axis is primarily related to summer temperature and autumn precipitation, the second RDA axis to winter-, spring- and autumn temperature together with summer and autumn precipitation. Some taxa are clearly grouped together: *Abies* and *Betula*; *Alnus*, *Corylus* and *Fraxinus*; Gramineae and Compositae Subfam. Cichorioideae; *Ranunculus acris*-type, *Rumex acetosa*, *Plantago lanceolata* and *Urtica*. It is likely that the pollen production of these taxa react in a similar way to annual climatic variation.

4. Discussion and conclusions

Even a rather short time-series of 25 years is sufficient to capture an annual climatic signal in pollen productivity for many taxa, and the correlation between sites far apart (600 km) suggests that pollen/climate relationship are valid on a regional scale. Still, differences growing conditions are likely to affect the biotic responses to climate.. The results here are thus primarily valid for central European low- and mid-altitude areas. For example precipitation does not seem to affect pollen productivity in the northern boreal forests (Hicks, 2001), and pollen productivity of plants growing near their highest altitudinal limit is primarily affected by summer temperatures (van der Knaap and van Leeuwen, 2003).

The main results are summarized in Table 3 and Figure 6, and the most important conclusions will be listed and shortly discussed below.

1) *Sphagnum* hummocks, or fast growing peat, can be dated with an accuracy of ±1 year from 1960 onwards. This allows environmental parameters to be traced with annual resolution, but a 2-3 year smoothing has to be allowed for.

2) Down-weighting of the most abundant taxa reduces the effects of plant cover, mean pollen productivity and inter-dependence of the pollen values. This increases the direct annual effect on single taxa and allows comparison between sites with different surrounding vegetation,

3) Annual correlation in pollen deposition can be shown between sites up to 600 km apart. Trees show better correlation than herbs, and lowland trees (*Corylus*, *Fagus* and *Franxinus*) give the best correlation.

4) The increased pollen values of *Fagus* and *Fraxinus* AD 1987-1994 that occurred at all three localities can hardly be explained by anything else than climate. One explanation might be the rise in temperature in central Europe during the 80’s (Auer *et al.*, 2001). Several taxa show large variations in their pollen values the past 100 years (van der Knaap *et al.*, 2000), which have normally been contributed to changes in land-use. Considering the large changes in the landscape during the past century this is likely a correct assumption, but the results here suggests that this shall not be done uncritically.

5) Winter temperature is important for the pollen productivity of many tree taxa. *Abies* and *Betula* respond positively to both winter and spring temperature; *Acer* and *Carpinus* respond positively to winter temperature; *Fagus* and *Fraxinus* respond negatively to winter temperature; *Alnus* and *Corylus* respond positively to autumn temperature. The pollen production of many trees thus seems to be affected by climatic conditions outside the main growing season. Possible explanations are frost damage, failed hibernation or premature flowering. Careful studies of the physiology and ecology of specific taxa will be required to better understand the processes involved.

6) Three major climatic factors affect pollen production: summer and spring temperature (April-September) together winter and autumn precipitation (October-March); autumn and winter temperature (October-March) together with winter and spring precipitation (January-June); and temperature together with precipitation in general. The clearest climatic gradient in PCA and RDA is warm/wet to dry/cold, but the seasonal influence is considerable.

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Human and climatic impact on a small mire in the Jura Mountains during the Little Ice Age and the 20th century

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Abstract

Analyses of testate amoebae, macrofossils and pollen have been used to study the development of a small mire in the Jura Mountains. The water table of the mire increased after AD 1300 and reached a maximum AD 1850-1950. The mire vegetation AD 1300-1700 was characterised by ferns, *Caltha* and *Vaccinium*, but around AD 1700 it changed into the modern vegetation characterised by Cyperaceae, *Potentilla* and *Sphagnum*. Causes for these changes in vegetation and water table were deforestation, and changes in husbandry (animal type and density) and in climate. The vegetation microtopography seems to have been important for the mire development (peat regeneration) for the past 50 years. The effects of climatic and land-use changes are interdependent and cannot be clearly separated, but the use of multiproxy data allows a more nuanced understanding of the mire development than is otherwise possible.

Keywords Testate amoebae, Macrofossil, Pollen analysis, Human impact, Switzerland, Jura Mountains

1. Introduction

The last millennium has witnessed large changes in climate and land-use in Europe: from the Medieval Warm Period over the Little Ice Age to human induced global warming. Agriculture first flourished in the 13th century, collapsed in the 14th century in the wake of climatic deterioration and the Black Death, expanded in Modern Times together with increasing exploitation of the forest to fuel the industrial revolution, to finally become ecologically independent with mechanisation and artificial fertilizers during the 20th century. With the ever faster climatic, economical and technological changes together with growing economical strength and popular environmental concerns, aspiration for political control of the environment has arisen. Mires and sedimentary basins are used as natural archives in order to improve our understanding of past, present and future long-term environmental change.

Problems arise as the mires themselves are affected by changes in climate and land-use, and the interpretations become difficult as there might be several potential causes for the response in a single proxy. A multiproxy approach would give a smaller range of possible causes, and thus a more precise interpretation (e.g. Ammann et al. 2000; Birks et al. 2000, Mitchell et al., 2001).

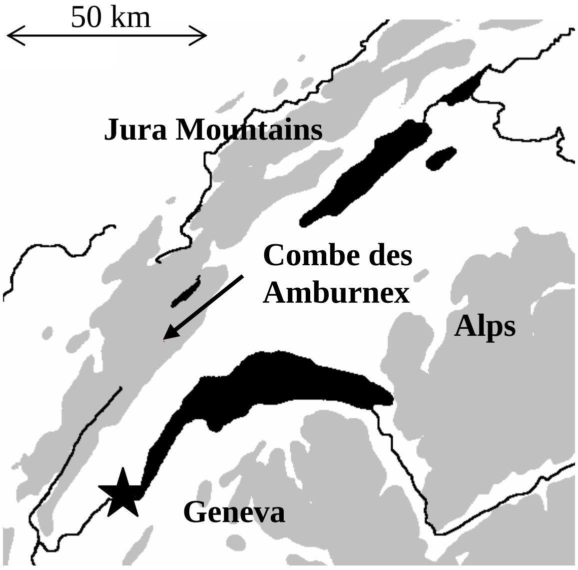
Here several proxies are used to study different environmental parameters on a range of scales. Testate amoebae indicate very local changes in the environment (primarily humidity) on a scale of a few cm (Mitchell et al. 2000); macrofossils primarily determine the local vegetation (Birks & Birks 2003); pollen and spores of wetland plants infer the general mire development (c. 0-20 m; local component (Jacobson & Bradshaw 1981)); Upland pollen records the landscape development (c. 20-2000 m; extra-local component (Prentice 1985), here highland pollen); Charcoal particles and dust allows a reconstruction of past fire intensity at a local and regional scale (Tinner et al. 1998). Independent historic and climatic records give the data a larger framework. The study period is the last 700 years, a time period with both strong human impact and climatic change.

1.1. Site description

The landscape in the high Jura Mountains along the border between France and Switzerland (Fig. 1) is a mosaic of approximately equal parts of conifer forests, open- and wooded pastures. The tree populations are dominated by *Picea*, while *Abies*, *Fagus* and scattered *Acer* are found in more protected areas. Local climate is cold and wet (annual mean c. 3°C and 1600 mm/year), but periodic droughts may occur because the water is quickly drained away in the permeable limestone bedrock. Traditional land-uses are summer grazing and forestry (Gillet & Gallandat 1996). In the last decades the area has become popular for different recreational activities such as hiking, cross-country skiing and picnicking. The area is under protection since 1973 as part of the Parc Jurassien Vaudois.

Written sources reveal that pastures were well established in the Amburnex valley already in AD 1301, and charcoal production in this part of the Jura Mountains is indicated from the 16th century (Rochat 1995). The exploitation of the forest seems to have been very strong in the 18th and 19th centuries until different cantonal laws allowed an organized forestry in AD 1902.

Fig. 1 Overview map. Grey marks areas above 1000 m altitude.



The mire Les Amburnex (Lat 46°32'23" N, Long 6°13'54" E, 1370 m a.s.l.) is situated on the side of Combe des Amburnex, a small valley 1300 m a.s.l. The mire is approximately 0.2 ha and peanut shaped. The markedly raised surface suggests a history as a raised bog, although strong decomposition along the edges may have enhanced the raised appearance. Large parts of the mire are today overgrown by *Picea* and a badger colony is present in the southern driest part. The peat profile is extracted from the northern treeless part. The mire was used for water extraction since the beginning of the last century by the nearby summer farm and is today fenced and protected from cattle. The vegetation of the mire and the valley is described by Vittoz (1997; 1998), and the vegetation history is covered by Wegmüller (1966) and Sjögren (2005).

2. Methods

The peat profile studied was extracted by hand as a 0.5 m monolith. Total peat depth at the sampling place is c. 3 m, and below it lies calcareous clay. Samples for testate amoebae analysis were prepared according to standard procedures (Charman *et al.* 2000; Hendon & Charman 1997; Tolonen 1986; Warner 1990b). Approximately 150 testate amoebae were counted per sample except for the lower samples (at 17 and 18 cm) because of low concentrations. At 19 and 20 cm only the presence of taxa has been noted. Identification follows Charman et al. (2000), Grospietsch (1958), Hoogenraad and de Groot (1940), and Ogden and Hedley (1980).

In addition to standard macrofossil analysis one slide from each sample was prepared for detailed description of peat constituents and examined under the light microscope (100-400 x). A five-degree scale represents the peat constituents (e.g. *Sphagnum*, *Hypnaceae* or sedge rootlets) as follows: 1 = <5%, 2 = 5-25%, 3 = 25-50%, 4 = 50-75%, 5 = 75-100%. Countable fossils such as sedge endocarps are presented as absolute values. Macroscopic charcoals were classified in millimetre size classes. Available descriptions and keys were used for identification (Daniels & Eddy 1985; Grosse-Brauckmann 1975, 1986; Katz *et al.* 1965; Katz *et al.* 1977; Tobolski 2000; Warner 1990a).

Pollen slides were prepared using the acetolysis method (Berglund & Ralska-Jasiewiczowa 1986; Faegri & Iversen 1989). For identification literature (Moore *et al.* 1991; Punt *et al.* 1995; Punt & Clarke 1984; Reille 1992, 1995, 1998; van Geel *et al.* 2003) and the reference collection at the Institute of Plant Sciences in Bern were used. The pollen values are expressed as percentages of all upland taxa; wetland and local pollen are excluded from the pollen sum. At least 500 upland pollen grains were counted per sample (mean 660). For dry bulk density measurements peat samples were dried at 40°C in open containers for one week before weighing (see Aaby 1986). Ash content (LOI residue) was measured on the same samples (drying at 105°C overnight, burning at 550°C for 4 h, see Heiri et al. (2001). The depth-age model is based on six radiocarbon dates and chronostratigraphy, and checked against regional biostratigraphical markers (van der Knaap *et al.* 2000); see Sjögren (2005) for details. The precision of the depth-age model is c. ± 50 years for AD 1300-1900, and c. ± 5 years for AD 1950-2000.

3. Results and interpretation

The results are presented in three diagrams, Fig. 2-4. The diagrams have been divided into periods for descriptive purpose, and the taxa are sorted after type and weighted average (using TRAN by S. Juggins 1992). The most important local changes are described below and summarized in Table 1. Note that *Picea, Abies, Fagus* and *Acer* are the present in the area today. *Vaccinium* pollen might include some *Andromeda* pollen.

Period 1, c. AD 500

High pollen values of *Alnus*, *Corylus* and *Betula* together with high decomposition of the peat suggest forested carr. Still, this must remain speculative as strong fluctuations of these taxa in the Swiss lowland (Ammann 1988; van der Knaap *et al.* 2000) might influence the pollen spectra and make interpretation of local changes in vegetation hazardous.

Period 2, AD 500-1300

Increasing macroscopic charcoal indicates local fires (Tinner *et al.* 1998) in the later half of the first millennium AD (macroscopic charcoal particles are absent in earlier strata). Peat decomposition starts to decrease at the same time. *Vaccinium* pollen frequencies increase at the same time, so the mire surface is probably rather dry.

Period 3, AD 1300-1700

The peat becomes less decomposed after AD 1300, which suggests a higher water table. *Caltha* and *Ranunculus aconitifolius* pollen increases together with Monolete fern spores, indicating forest disturbance in the surroundings and the creation of open wetlands. The reduction of *Fagus*, *Alnus*, *Corylus* and *Betula* pollen suggests that local trees of these taxa were cleared away. A strong increase in charcoal dust together with an increase in NAP indicates a general opening of the landscape in connection with increased fire activity. At the end of the period single shells of *Trigonopyxis arcula*, cf. *Phryganella paradoxa* and *Cyclopyxis arcelloides* were recorded.

Period 4, AD 1700-1800

The high amount of macroscopic charcoals and charcoal dust around the start of this period indicates local fire activity. The peak in charcoal dust can also be clearly identified in a mire 1 km away (Sèche de Gimel; Sjögren 2005), suggesting that fire activity was strong in large parts of the landscape. After c. AD 1700 a lower degree of peat decomposition allowed better preservation of testate amoebae. The recorded taxon cf. *Phryganella paradoxa* is regarded aquatic (Schönborn 1962), and the high values indicate wet conditions. Co-occurrence with *Trigonopyxis arcula* in the 18th and 19th centuries suggests rapid water table changes as the latter indicates dry conditions. (Charman et al. 2000; Mitchell et al. 1999; 2000).

S*phagnum* spores also start to occur at high values around AD 1700 and then slowly decline together with cf. *Phryganella paradoxa* until AD 1900. There are major changes in the mire vegetation: *Caltha*, *Ranunculus aconitifolius* and ferns decrease, while *Cyperaceae* and *Potentilla* increase together with many upland herbs. *Podospora* dung fungal spores also start to appear. These spores are primarily associated with cattle dung pats and do not disperse well (JFN van Leeuwen, pers. comm.).

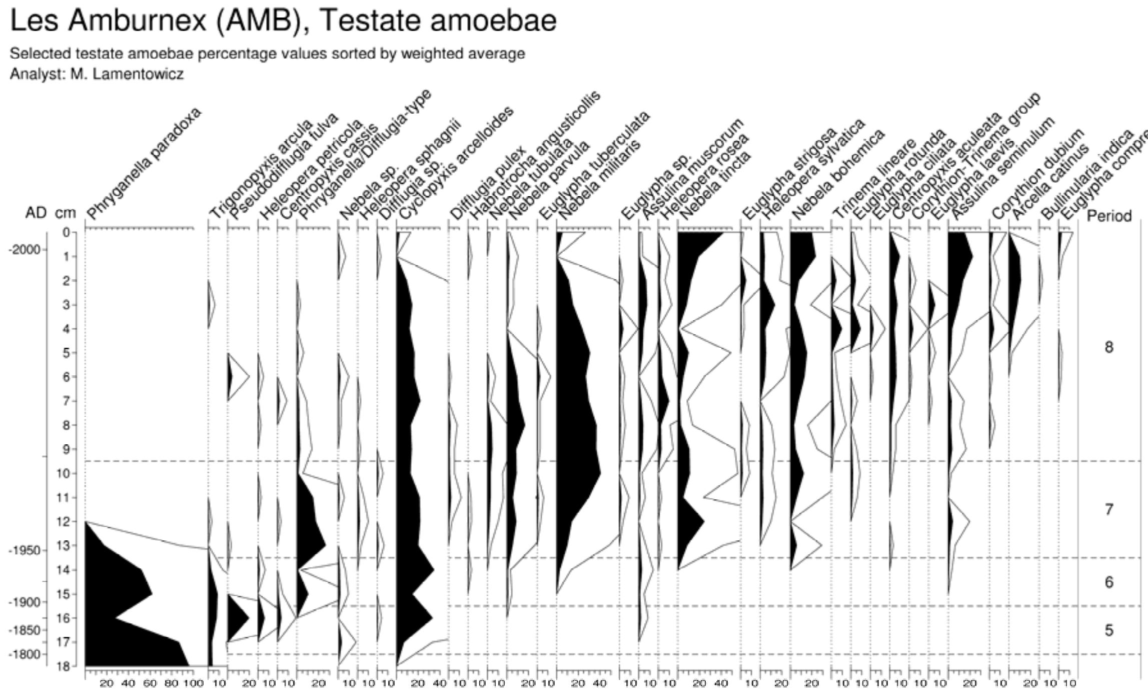


Fig. 2 Percentage diagram of selected testate amoebae and rotifera (*Habrotrocha angusticollis*). Taxa are sorted after weighted average. Finer lines show 5x exaggeration of the percentage values.

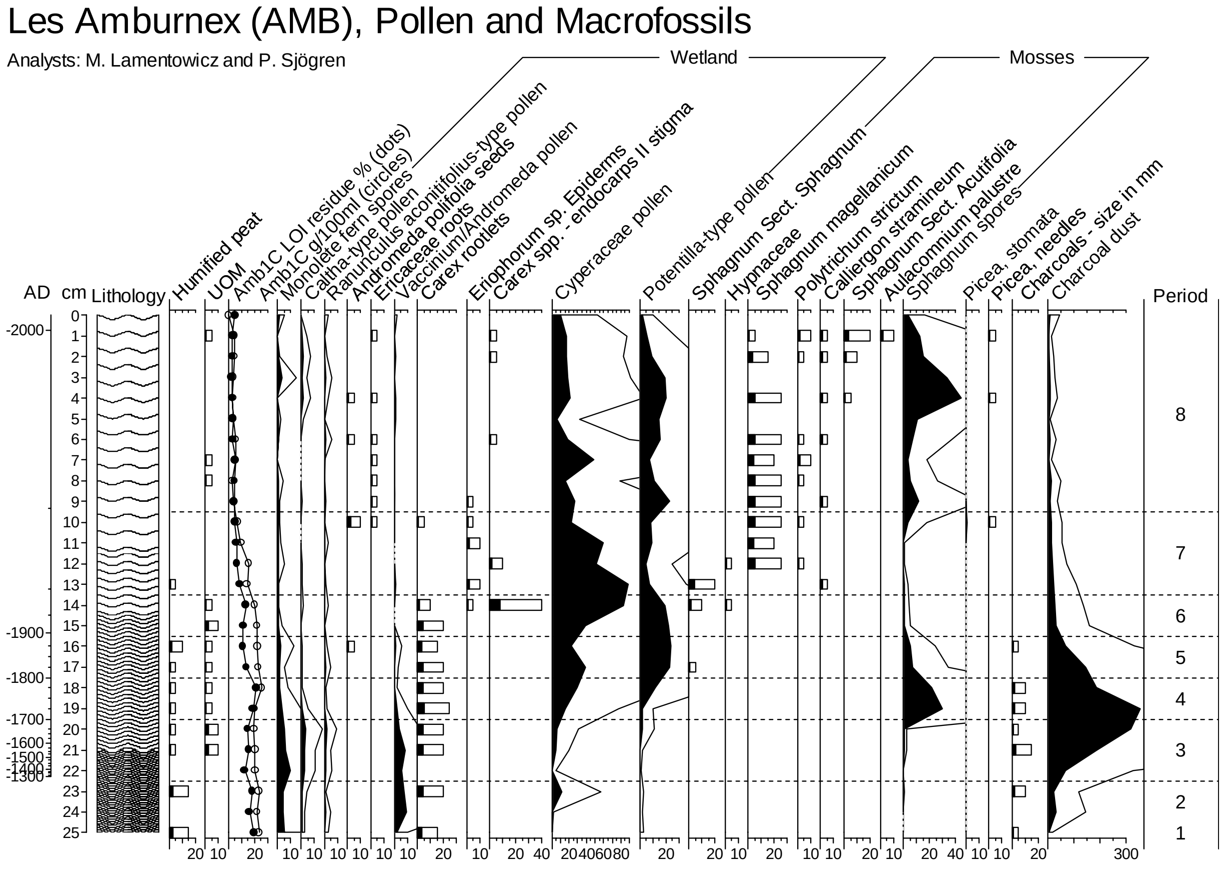


Fig. 3 Diagram of macrofossils, peat characteristics and pollen percentages of local plants. Percentage values of pollen are based on the sum of upland pollen and spores. Macrofossils are in absolute counts or on a scale from 1-5 (1 = <5%, 2 = 5-25%, 3 = 25-50%, 4 = 50-75%, 5 = 75-100%). Finer lines and unfilled boxes show 5x exaggeration. The lithology shows strongly decomposed (close line spacing), decomposed, slightly decomposed and undecomposed (broad line spacing) peat. UOM = unidentified organic material.

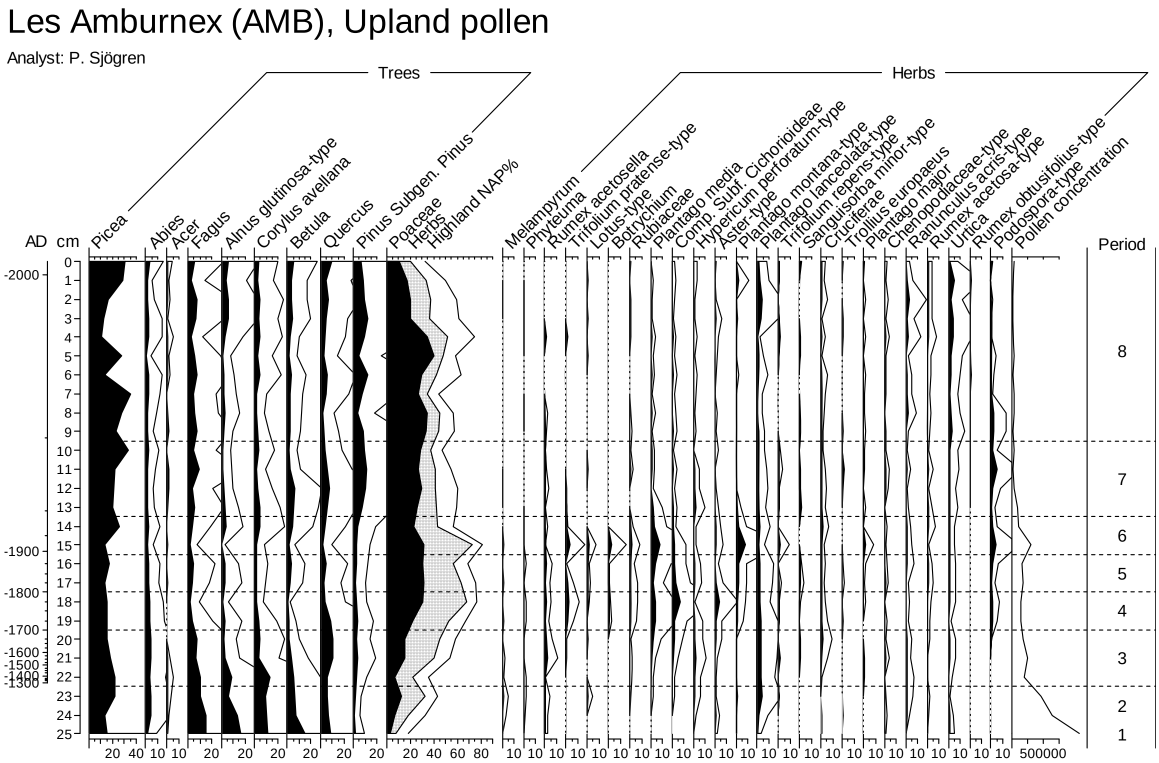


Fig. 4 Percentage diagram of upland pollen types. Highland NAP % is based on the sum of highland pollen and spores (in the modern situation). Percentage values are based on the sum of upland pollen and spores. Only *Picea*, *Abies*, *Acer* and *Fagus* occur locally (c. 5 km) today. Herb taxa are sorted after weighted average.

Table 1 Summary of results. Local water table is inferred from testate amoeba, moss types and degree of decomposition. Peat growth rate is based on the depth-age model (Sjögren 2005). Stand scale vegetation is based on the most important taxa of the macrofossils. Mire vegetation is derived from the most important taxa of the wetland pollen. Openness is inferred from the highland NAP. Climate is inferred from Moberg et al. (2005), and Casty (2005). Periods follow major changes in the testate amoeba, macrofossil and pollen values.

AD	Water table	Growth r.	Stand vegetation	Mire vegetation	Openness	Climate	Period
1975-2000	Decreasing	Very high	*Sphagnum*, *Vaccinium*, *Picea*	Cyperaceae, *Potentilla*, *Sphagnum*	Open	Warming	8
1950-1975	Decreasing	High	*Sphagnum*, *Eriophorum*, *Picea*	Cyperaceae, *Potentilla*, *Sphagnum*	Open	Warm	7
1900-1950	High (variable)	Moderate	*Carex*, *Sphagnum*	Cyperaceae, *Potentilla*	Very open	Warming	6
1800-1900	High (variable)	Moderate	*Carex*	Cyperaceae, *Potentilla*, *Sphagnum*	Very open	Cold	5
1700-1800	Increasing	Low	*Carex*	Cyperaceae, *Potentilla*, *Sphagnum*	Open	Cold	4
1300-1700	Low	Very low	*Carex*	Ferns, *Vaccinium*, *Caltha*	Half open	Cooling	3
500-1300	Low?	Very low	*Carex*	Ferns, *Vaccinium*, Cyperaceae	Half open	Warm	2
c. 500	Very low?	Very low	*Carex*	Ferns?	Closed	Cold	1

Period 5, AD 1800-1900

The first leaves of *Sphagnum* are recorded, indicating increasing acidity. During the 19th century *Cyclopyxis arcelloides* increases. This taxon prefers moderately moist habitats, and the high values in the late 19th century and early 20th century indicate a wet phase. This phase coincides rather well with the openness maximum around AD 1900 indicated in the pollen record, and the reduction in forest cover is the most likely cause of the increased water table (decreased evapotranspiration).

Period 6, AD 1900-1950

After a grazing maximum at the turn of the century *Picea* pollen starts to increase. This is possibly an effect of the first generation of *Picea* trees established on the mire reaching maturity.

Period 7, AD 1950-1975

Pollen from Cyperaceae peaks around AD 1950. The occurrence of *Carex* spp. - endocarps II stigma in the same interval indicates that this is a local increase. No *Carex* rootlets are found above this level. *Phryganella*/*Difflugia* type seems to be connected with a transitional zone between *Cyperaceae* and *Sphagnum* habitats. Also *Nebela tubulata* could be regarded as accompanying *Sphagnum* encroachment and disappear when *Sphagnum* starts to dominate the microsite. *Nebela tubulata* is found on regenerating *Sphagnum* mires in the Swiss Jura (EAD Mitchell pers. comm.). S*phagnum* Sect. Sphagnum and *S. magellanicum* become dominant in vegetation structure 1950 AD, so the water table was relatively high as *S. magellanicum* is a lawn species. Janssens (1989) as well as Dierßen & Dierßen (2001) show that this species has its optimum at a depth to water table (DWT) around 19 cm. After AD 1950 testate amoebae species indicate a gradually decreasing pH and a water table corresponding to hummock development

Period 8, AD 1975-2000

Dominance of *Nebela militaris* and a decline of *Cyclopyxis arcelloides* show a decrease in the water table and pH in the 1970's, at the same time as *Sphagnum* spores reappear. The pH decreased to approximately 4. In the 1990's *Sphagnum* Sect. Acutifolia and *Aulacomnium palustre* appear, indicating a further water-table decrease and a hummock development. *Arcella catinus*, *Assulina muscorum*, *A. seminulum* and *Nebela tincta* also show the water table lowering. The continued *Sphagnum* growth leads to more ombrotrophic conditions with decreased pH, and the levelling of the mire surface lead to a relative reduction of the water table as the hollows disappear.

3.1. Discrepancy between proxies

The comparison between pollen and macrofossil data reveals some discrepancies between the two proxies: 1) In the upper part of the peat (periods 6 and 7) *Sphagnum* leaves and stems are present but no or very few spores; and 2) In the uppermost part (periods 7 and 8) Ericaceae roots, *Vaccinium* twigs and *Andromeda* seeds occur without any response in the Ericaceae pollen values. This shows that some taxa can be locally present without any pollen or spore signal, at least for periods <50 years. A possible explanation is that the local mire conditions can be favourable for vegetative growth without pollen and spore production.

4. Discussion

Around AD 1300 the degree of peat decomposition decreased and *Caltha* appeared, suggesting more open and wetter conditions. The presence of *Vaccinium* indicates that the mire still is rather dry. The most profound changes in mire vegetation occurred around AD 1700 (i.e. the transition from period 3 to 4) and resulted in a vegetation similar to today: *Caltha*, *Ranunculus aconitifolius*, ferns and *Vaccinium* decrease, while Cyperaceae, *Potentilla*, and *Sphagnum* (spores) increase. Charcoal particles and dust have very high values around the transition, tree pollen decreases and *Podospora* fungal spores start to appear. Testate amoebae and plant macrofossils (low humification) from the end of the 18th century suggest an increased but varying water table (cf. *Phryganella paradoxa* co-occurring with *Trigonopyxis arcula*). About AD 1950 a third major change occurs with large changes in testate amoebae (cf. *Phryganella paradoxa* and *Trigonopyxis arcula* decrease, while most *Heleopera* and *Nebela* species increase), indicating a strong shift in the water table and pH. S*phagnum* Sect. Sphagnum and *S. magellanicum* becomes dominant.

We stipulate four potential causes for these changes in the mire development: 1) deforestation; 2) grazing; 3) local human impact; and 4) climatic change. These are discussed below.

4.1. Deforestation

Deforestation of the surrounding landscape might have raised the water table because of reduced evapotranspiration. The connection between deforestation and a rise in water-table has been clearly shown (Moore & Willmot 1976). But the opposite might occur if the mire is unconnected to the surrounding groundwater level, as is the case in the nearby Joux valley (Mitchell et al. 2001). The drier conditions following deforestation might in this case be caused by increased wind exposure of the mire surface. Upland pollen suggests an increase in landscape openness in the 18th century, concurrent with major changes in the mire vegetation. The high values of charcoal particles and dust around c. AD 1500-1900 with a strong peak c. AD 1700 is likely related to the fuel-demanding charcoal and glass production and would imply deforestation of wide areas. A small glass industry was established a few km east of the site in AD 1698 and was active until AD 1708 (Piguet 1998), i.e. about the same time as the most profound changes in the mire and surrounding landscape occurred. Some of the charcoal might come from burning of brushwood in connection with clearance.

4.2. Grazing

Grazing and trampling can damage the mire, and local grazing might well be the main cause for the high degree of decomposition of the peat. On the other hand, grazing is needed to hinder tree regeneration and maintain an open landscape with a high groundwater table. Upland pollen show that grazing increases in the 18th century and declines around AD 1950, coinciding with major changes in the mire vegetation. *Podospora* dung fungal spores, which are associated with cowpats, start to occur at approximately the same time, suggesting that the number of cattle increased. Heavy cattle do not mind grazing in wetlands and might have created *Carex* tussocks, today present in other parts of the area. The peak in Cyperaceae pollen at AD 1950 occurs directly after the phase of maximum land-use, and thus it seems to be an effect of decreased grazing pressure. The mire is as mentioned fenced today, and can have been so for a long time, which of course also would limit grazing on the mire.

Reduced grazing would allow higher pollen production as Cyperaceae are not damaged prior to flowering (Segerström & Emanuelsson 2002). With reduced trampling *Sphagnum* could form peat in the areas between the tussocks, resulting in the recorded succession of wet lawn to relative dry hummock. The modern surface is flat and consists of a mosaic of Cyperaceae, *Potentilla* and *Sphagnum* patches (the peat profile is extracted from a *Sphagnum* patch), which can be the stage following tussock vegetation. A similar succession of peat regeneration is described by e.g. Grosvernier et al. (1995), who also stresses the importance of the microstructure for peat regeneration. It is likely that many of the vegetation changes around and after AD 1950 are stages of mire regeneration following reduced trampling, such as the phase with *Eriopohorum* epiderms. Among testate amoebae *Nebela tubulata* indicates a less disturbed mire surface.

4.3. Local human impact

In some cases special human activities have affected the mire but not the surrounding landscape. One important use of mires in the Jura Mountains was, and is, water extraction for husbandry animals on summer grazing, as water sources are scarce due to the permeable bedrock. This use of mires leads to a lowering of the water table and increased trampling. Water has been lead from the Amburnex mire to the nearby farm since the beginning of the 20th century (Vittoz 1997).

A lowered water table might also have been desirable in order to improve grazing on the mire and surrounding area. An effective way of lowering the water table is plantation of *Picea*. A grown *Picea* can use up to 100 l water on a sunny summer day (Zweifel & Häsler 2001). The *Picea* stand on the mire seems to have been established when the grazing pressure was high (a felled tree was dated to late 19th century). It is possible that the *Picea* trees were deliberately planted and / or nurtured (protected from grazing). An alternative explanation is that the mire was fenced already around AD 1900 when water extraction by the nearby farm begun. *Picea* could then establish itself on the mire when grazing stopped. Today small trees are removed to hinder continuing *Picea* expansion on the mire (Vittoz 1997).

4.4. Climatic impact

The general climatic deterioration of the Little Ice Age c. AD 1300-1850 and increasing water table in mid-European lakes from c. AD 1400 (Magny 2004) coincides with a decreased decomposition rate and a higher water table in the mire. The most profound change in the mire development c. AD 1650-1750 coincides with the Maunder Minimum in solar activity (AD 1645-1715; Eddy 1977) and with glacier advances in the Alps AD 1600-1900 (maxima c. AD 1650 and AD 1850; Wanner et al. 2000). The changes of the mire vegetation in the 20th century might be an effect of global warming with increasing temperatures during the century (except for a relative stable plateau AD 1950-1975) and decreased summer precipitation after AD 1970 (Casty 2005). The climatic deterioration and subsequent warming might have enhanced the effects of human impact, or it might have affected the land-use strategies and thus indirectly the mire development.

4.5. Concluding remarks

The multiproxy approach allowed a general assessment of the different causes for the mire development. The most important findings are summarized in table 1 and below:

1 - Deforestation, grazing regime, local human activity and climate all seem to had an impact on the mire development.

2 - Deforestation increased the water table through lowered evapotranspiration from c. AD 1300 and especially from c. AD 1700. Important human activities that lead to deforestation were fire related, i.e. charcoal production, glass production and brushwood burning. Increased cattle densities hindered forest regeneration.

3 - Grazing and trampling might be responsible for the generally strong decomposition of the peat. Around AD 1700 a change of the husbandry composition towards cattle and increased grazing pressure and might have caused *Carex* tussock formation on the mire. Reduced grazing and trampling from AD 1950 resulted in *Sphagnum* peat growth in the hollows that during the 1990's levelled out the mire surface and it starts to gain hummock characteristics.

4 - Local human activities such as water extraction, fencing and possible *Picea* plantation most likely have an impact on the mire development, especially during the 20th century.

5 - Major climatic deterioration (14th century, 17th century) and global warming (20th century) are in phase with the local mire development, and climatic change either induced land-use change that affected the mire or reinforced its effects.

6 - This study shows the complexity and interdependence of factors that affect the development of a mire ecosystem. No single factor can be determined as the driving factor, because different factors enhance or compensate each other on different levels.

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