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

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Abstract: The pollen content of three adjacent peat profiles has been analysed to study the development of pasture woodland in the small valley Combe des Amburnex (1300 m a.s.l.). Chronostratigraphy based on lowland pollen assemblages and radiocarbon dates was used to correlate and date the profiles. Forest and mire grazing occurred throughout at least the past two millennia. Before the ninth century the forest consisted of about equal parts of *Abies*, *Fagus* and *Picea*. Thereafter *Picea* increased and is today strongly dominant in the area, likely an effect of selective browsing. The central part of the valley obtained its modern structure of pastures and forests in the twelfth century, and the pasture woodland in general came into existence during the seventeenth century as an effect of extensive fire activity, possibly charcoal production. In the twentieth century grass and nutrient-demanding species increased relative to other herbs.

Key words: Cultural landscape, Jura Mountains, palaeoecology, forest history, pasture woodland, pollen analysis, Switzerland, late Holocene.

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, which are kept in this state by summer grazing and forest management (Gillet and Gallandat, 1996). This type of cultural landscape was probably once widespread across Europe, but today it is present only in limited areas because of modern agriculture and forestry practices.

The park-like landscape with its solitary spruces, well trimmed by cattle, has a high aesthetic value, and is important in both biological and economic respects. The mosaic landscape in general and the wooded pastures with their mixed vegetation in particular show a high biodiversity (Gallandat *et al.*, 1995). Traditional types of land use, now in modern forms, have in the recent decennia been complemented with tourism; hiking, cross-country skiing and picnicking in the picturesque landscape are particularly popular recreation activities.

This study is part of the project National Centre of Competence in Research (NCCR) Plant Survival, in which modern and historical ecology of pasture woodland are investigated in order to improve the scientific base of the management strategies for this type of landscape. The small valley Combe des Amburnex in the high part of the Jura Mountains is used as an investigation area for several different ecological studies. The major questions are how and to what degree the modern landscape pattern and species composition are dependent on historical land-use changes and/or internal dynamics.

The contribution of this paper is to assess a detailed long-term vegetation history and development of pasture woodland within the investigation area. Special weight is given to the spatial scale in order to understand the landscape patterns, in this case differences between the central and peripheral part of the valley. The period of concern is the past 2000 years, as this is relevant for the development of today's pasture–woodland landscape, but the past 100 years are considered of special importance as this time period provides the link between palaeoecological results and ecological investigations and models of the present vegetation.

The study is based on the analysis of pollen in three peat profiles. The sites are within 1 km of each other, which enables

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assessment of local changes in the landscape structure. Different basin sizes are used to improve the spatial resolution (eg, Björkman and Sjögren, 2003; Koff and Kangur, 2003). Most mires in the area are heavily grazed so the top part of the peat is compressed or disturbed. To enable comparison between the sites under such conditions a chronostratigraphy was established on the basis of low-land pollen assemblages (non extra-local pollen) and radiocarbon dates.

Study sites and regional settings

Geographical setting

The valley Combe des Amburnex at 1300 m altitude in the Jura Mountains 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 south-southwest, with weak winds from the north-northeast. 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/yr, 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 are sealed off with clay and fed by springs. Nearly half the area has a tree cover. The tree composition is dominated by *Picea*, while *Abies*, *Fagus* and a few *Acer* trees occur in areas protected from grazing, such as on stony ridges and in denser stands. The pastures are species-rich, and 550 vascular plant species have been listed in the valley and surrounding area (Vittoz, 1998).

The general Holocene vegetation history of the southwest Jura Mountains is well established (Wegmüller, 1966), as is the general development of the cultural landscape (Gauthier, 2004). Several palaeoecological investigations along the south-eastern edge of the mountain chain have been published (eg, 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.

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 in the same year by the Roman commander Julius Caesar and, heavily decimated, they were forced to return to their old lands (Caesar, −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 fifth century, but in the investigation area they had no major impact until the twelfth century. 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 northwest 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 south), in AD 1146 (Mottaz, 1982). Later written sources mention pastures in Combe des Amburnex in AD 1301, then owned by the village St Oyens, 8 km southeast (Rochat, 1995). In AD 1348 the plague (Black Death) severely reduced the population in this part of Europe.

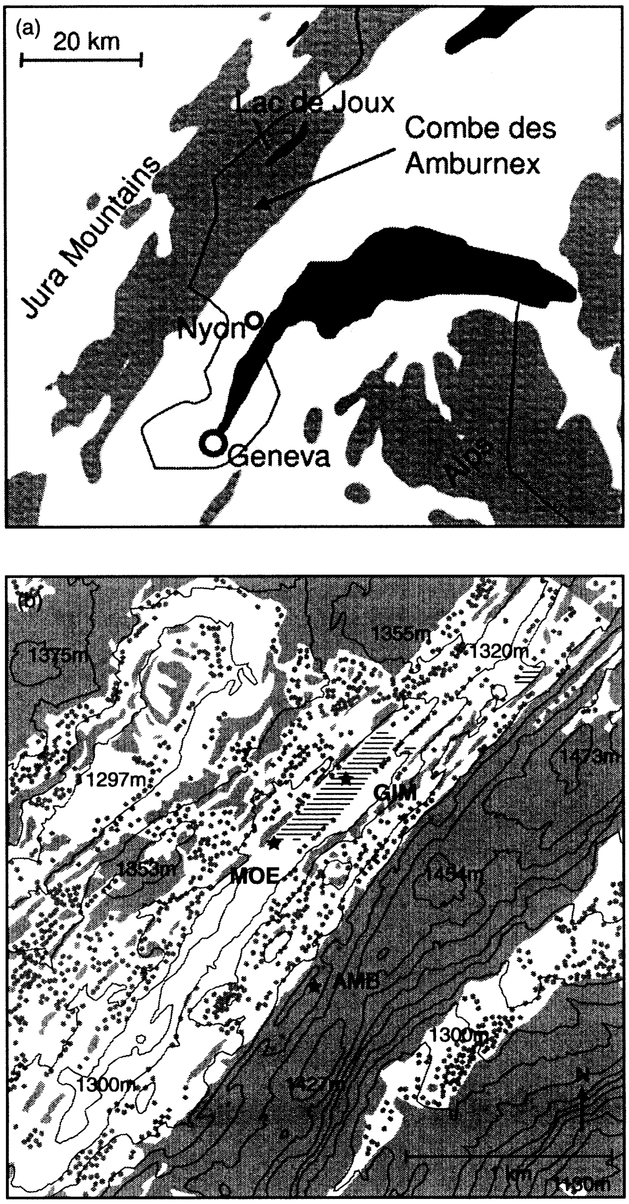

Figure 1 Overview map (a) and site map (b). a. Grey represents areas above 1000 m a.s.l. The thin line marks the border between France and Switzerland. b. Grey represents forest, small dots are single or small groups of trees, mainly *Picea*. Wetlands are marked with stripes, site locations are marked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

Major glass and iron production were 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 sixteenth century (Rochat, 1995). As glass and charcoal production increased in the eighteenth and nineteenth 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 nineteenth century. Old maps show that the treeless areas in Combe des Amburnex were about 10% larger in 1892–93 than today (*Die Siegfried Karten*, Marchairuz, section XVI, 2b). In 1902 different cantonal and federal laws finally allowed organized forestry, and in the 1950s–1970s separation of forest and pastures was promoted. Since 1973 the area has been under protection as part of the 70 km^2 Parc Jurassien Vaudois and it is kept open by a combination of summer grazing and selective forestry (Gillet and Gallandat, 1996).

Material and methods

Coring sites and field work

Three adjacent profiles were used. 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 southwestern edge of the same mire. This 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 bog (*c.* 0.2 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, ie, GIM for Sèche de Gimel, MOE for Le Moé and AMB for Les Amburnex.

The GIM core was obtained in 2003 with a gauge corer of 6 cm diameter. The first 0.5 m of the top drive 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 distant 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 was collected in 2002 as *c.* 50 cm deep monoliths.

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.

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 fuchsine. 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 × 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).

Biostratigraphy

Because of uneven peat accumulation the correlation between sites is based on biostratigraphy (Figure 2). Pollen assemblages from taxa not growing in the area (ie, extra-regional) and assumed not to have grown there in the past were used to establish the biostratigraphy. 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 be the same in all three sites (eg, 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 resulting from low extra-regional pollen sums (mean 110). The zonation is based on distinctive features within zones and at zone transitions (increases, decreases and amplitude). Features used for correlation are either recognized in two or in three of the profiles. 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 biostratigraphical zonation.

Characteristics used for the biostratigraphical zonation 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 *Castanea*. *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*, *Castanea*, *Pinus*, *Cannabis*, *Secale* and *Mercurialis annua* increase.

Zone 4, *Pinus* increases and *Secale* decreases. *Cannabis* makes a dip in the lower part of the zone but recovers.

Zone 5, *Carpinus*, *Juglans* and *Castanea* decrease.

Zone 6, *Carpinus* and *Pinus* make a dip. *Juglans* and *Castanea* peak. *Fraxinus* reappears.

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

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

Zone 9, *Fraxinus* increases.

Radiocarbon dating and chronozonation

The ages of the biostratigraphic zone boundaries are determined in two steps, resulting in chronozones. In step one site-specific ages are calculated on the basis of radiocarbon dates. In step two the ages of the zone boundaries are derived from the best fit of the site-specific ages.

A total of 30 samples have been ^{14}C-dated (Table 1). Calibration of pre-bomb samples (AD < 1950) was done by OxCal (Bronk Ramsey, 1995, 2001) with the IntCal98 calibration set (Stuiver *et al.*, 1998). Calibration of post-bomb dates (AD > 1950) is based on the peak and subsequent 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) were used. Post-bomb dates have an accuracy of 2–3 years (Goslar *et al.*, 2005). For the site-specific depth-age models (Figure 3) linear interpolation between calibrated dates was used (Table 1).

Some dates are problematic. MOE-33cm gives a too young age, probably because of contamination with post-bomb material. Too high ^{14}C-activity is often found in peat samples between AD 1930 and 1955 (Goslar *et al.*, 2005), which is explained by integration of younger material. Some ^{14}C dates are based on the peat fraction < 0.2 mm. Even though most modern and younger material was 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. For the age determination of an important transition in AMB at 32.5 cm, peat accumulation rates were considered (derived from pollen concentration).

The chronozones follow the biostratigraphic zones (Figure 2). The ages of the chronozones have been determined by comparison of site-specific ages in the three sites (Table 2),

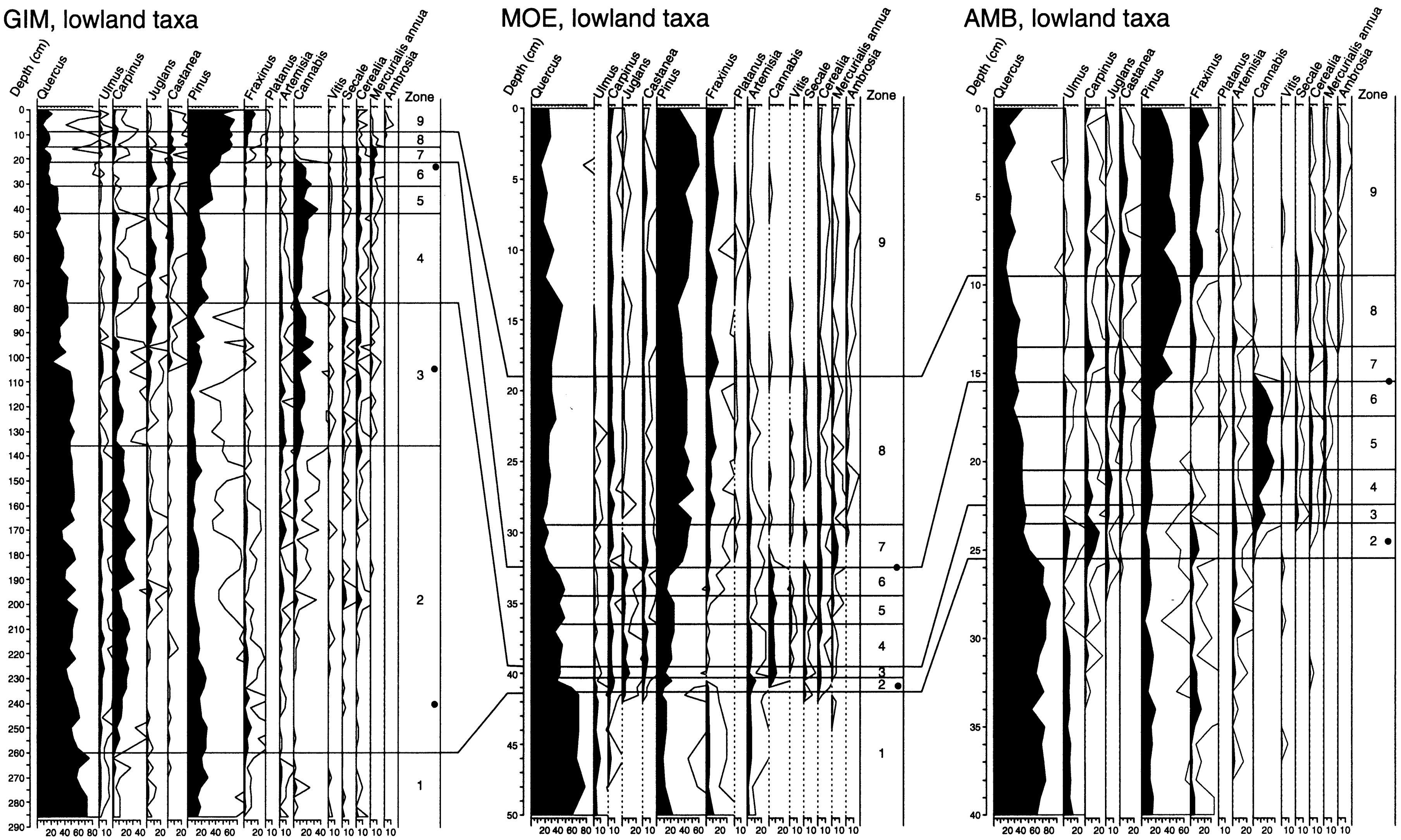

Figure 2 Pollen percentage diagrams from GIM, MOE and AMB for correlation based on the extra-regional (ie, non extra-local) pollen sum. Biostratigraphical zone boundaries are marked with lines and statistically determined PAZ boundaries are marked with solid circles. The zone boundaries drawn between the diagrams are for clarification purpose only

Table 1 Radiocarbon dates

Site	Depth	^{14}C-age (1σ)	Calibrated ^{14}C-age[a] (1σ)	Cal. age range	Date used[b]	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 < 0.2 mm
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 < 0.2 mm
AMB	32 cm B	−100±40 BP	*c.* AD 1950	*c.* AD 1950	Test sample	Poz-1716	Peat fraction > 0.2 mm
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 < 0.2 mm

[a] Underlined age-intervals are used for the depth–age models.

[b] 'Date used' are used for the site-specific depth–age models.

*Determination of the date used for the depth–age model is based primarily on within-profile stratigraphy.

**Determination of the date used for the depth–age model is based primarily on correlation between profiles.

***Possibly too young.

weighted according to the temporal resolution of the pollen diagram and the distance between dates. GIM is considered the most suitable in the Roman period and the Middle Ages (AD 1–1650), AMB in Modern Time (AD 1650–1900), and MOE in the late twentieth century (AD 1950–2000). The accuracy of the zone ages is approximately ±50 yr, and ±10 yr

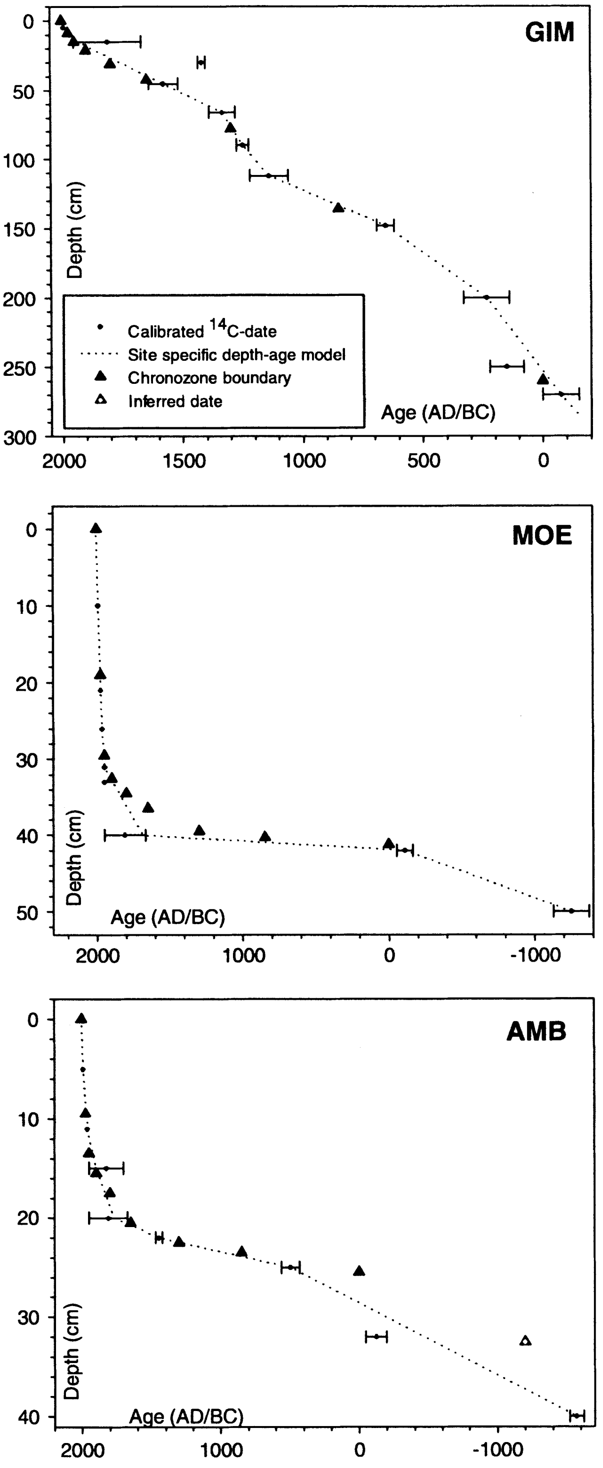

Figure 3 Calibrated ^{14}C-dates (1σ), site-specific depth–age models and chronozone boundaries for GIM, MOE and AMB. For AMB an indirect age determination is inferred from expected peat accumulation rate (based on pollen concentration). See text for details

in the twentieth century. Ages throughout the paper are based on the chronozones.

In MOE the site-specific depth–age model deviates considerably in some parts from the chronozone age. This might be due to partial mixing of the peat, which brought down younger material, and therefore also the pollen stratigraphy might be disturbed, and caution should be taken with the interpretation. Also the site-specific depth–age model for AMB shows in the lower part deviations from the chronozone ages. 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 this cannot be ruled out, considering the high degree of decomposition and compaction.

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

Pollen source area

The pollen load (the pollen deposited in a place) can be divided into different components 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 components (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 will be used in the present investigation, but some clarification is needed. The local pollen includes fen, bog and wetland plants that grow on or in direct connection with the mires studied. 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 component is, as usual, excluded from the pollen sum. The extra-local pollen load is here equalled with the component that derives from the relevant source area of pollen (RSAP), 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 700–800 m (Florence Mazier, personal communication, 2005), so the RSAP for the sites should be similar or somewhat larger depending on the basin sizes. The regional pollen component is here considered to be from the Jura Mountains above *c.* 1000 m, and the extra-regional component is thus the pollen that derives 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 are regional taxa (excluding *Pinus*), lowland taxa are extra-regional taxa (excluding highland taxa), and wetland taxa are 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 might have an increased pollen production (Aaby, 1988). As GIM comes from the middle part of the largest mire it can be assumed that it has a stronger regional pollen signal than MOE and AMB (eg, Janssen, 1966; Jacobson and Bradshaw, 1981).

Results and interpretation

The pollen data are presented in diagrams (Figures 4–6), and the main trends are described in the text below. In MOE partial mixing of the peat (and therefore the pollen) may have

Table 2 Intercept dates for site-specific depth–age models and biostratigraphical zone boundaries

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

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.

occurred at 32.5–40.25 cm depth (zones 2–6). Changes in the pollen values of *Abies*, *Fagus*, *Picea* and *Acer* are assumed to be mainly of extra-local origin. However, *Fagus* thrives on the lower slopes and in the lowland, ie, extra-regionally, so 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 lowlands make any interpretation uncertain (Ammann *et al.*, 1996; van der Knaap and Ammann, 1997). In fact AMB correlates rather well with the lowland locality Lobsigensee, *c.*100 km northeast (Ammann, 1989), which suggests that the extra-regional pollen component may be considerable. With some hesitation *Alnus*, *Corylus* and *Betula* will be treated as locally present in the lower parts of the profiles. 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*) 1:0.5 (Andersen, 1970). Characteristic features in the pollen diagrams are described and commented on below. After a general assessment of the development (based on the best represented sites) site-specific characteristics are presented.

Chronozone 1, > 1600–1 BC; closed forest with some human impact

The highland tree pollen assemblages show that the forest had approximately equal parts of *Abies*, *Fagus* and *Picea*, and some *Acer*, *Alnus*, *Betula* and *Corylus* might have occurred locally at the mire edge or scattered in the forest. In the early part of the period (> 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 (eg, *Plantago media* and *Plantago montana*) at all three sites show that open pastures are present. MOE: an increase in herb and grass pollen occurs in the last sample, but this cannot be dated exactly because of the low temporal resolution in this part of the profile. AMB: A local pollen assemblage dominated by Cyperaceae is succeeded around 1200 BC by dominance of 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.

Table 3 Comparison of biostratigraphic events (dates based on the chronozones) and the relevant biostratigraphy of Switzerland (van der Knaap *et al.*, 2000)

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

Chronozone 2, AD 1–850; closed forest with mire and forest grazing

Higher values of tree pollen indicate that the forest became more closed in the first centuries AD (AD 1–250). Pollen from *Alnus*, *Corylus* and *Betula* increased initially and then declined, suggesting a succession with pioneers. A short open phase AD 250–350 was followed by a new forest-regeneration phase AD 350–550, which shows a similar pattern of succession as the previous regeneration phase. After this the landscape slowly began to open up again (AD 550–850). Higher amounts of microscopic charcoal appeared AD 800, suggesting anthropogenic opening up of the surrounding landscape. GIM: 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 the chronozone. MOE: the peat is very compressed and a hiatus might be present. 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), indicate 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 (eg, a nearby pathway, waterhole or cottage), at some time during the chronozone. AMB: in contrast to MOE there are no clear signs of human impact during this period, suggesting limited use of peripheral areas.

Chronozone 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 became more dominated by *Picea*, which at this time probably constituted more than 50% of the forest cover. Lower pollen values for *Alnus*, *Corylus* and *Betula* suggest a reduction in these taxa. GIM: the amount of open pastureland, as reflected in the NAP, *Plantago lanceolata* and Poaceae pollen, is rather constant during most of the period (AD 850–1150) but expands in the latter

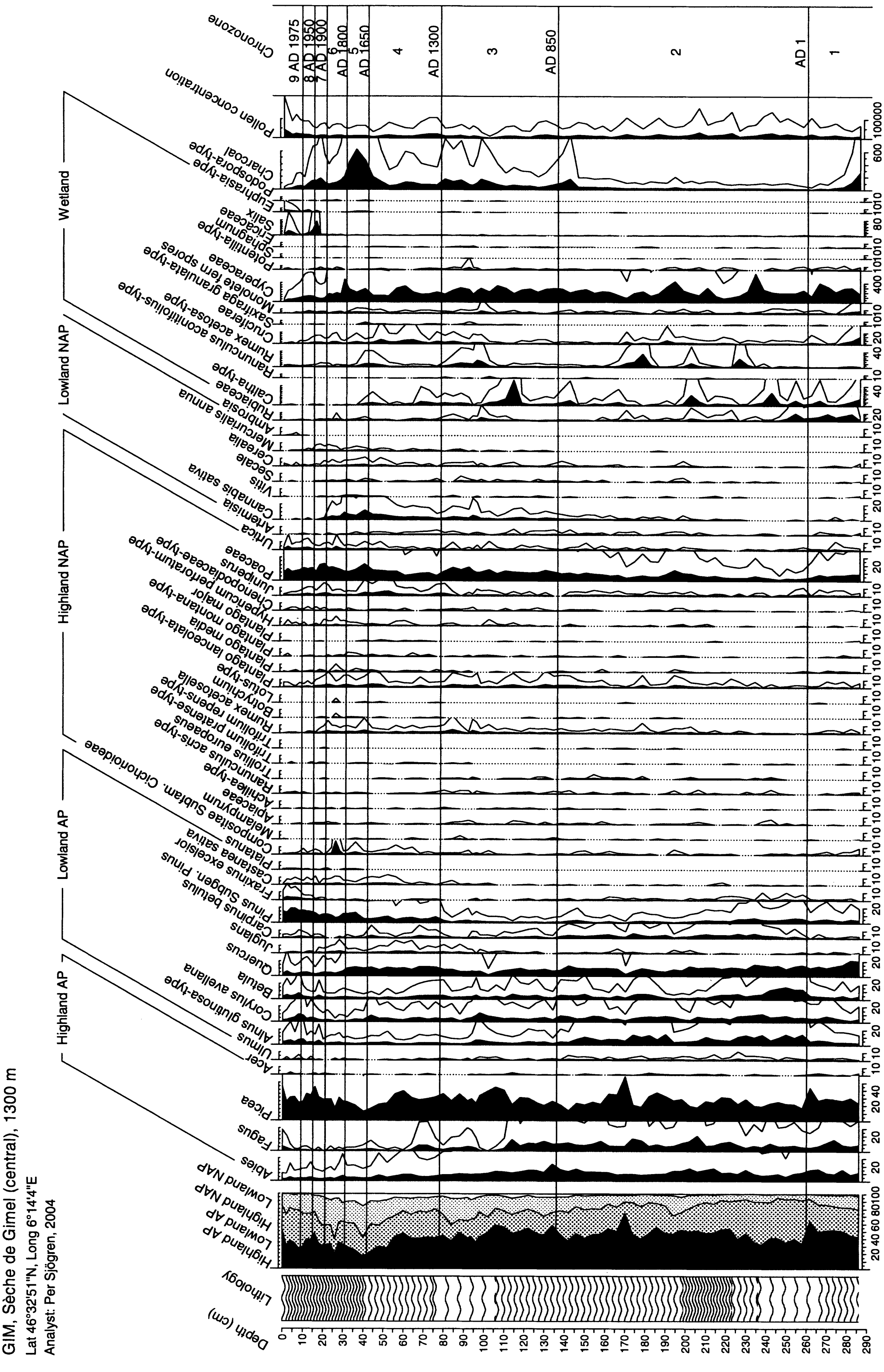

Figure 4 Pollen diagram for GIM in the middle part of Le Marais de Sèche de Gimel. The non-local (non-wetland) sum of pollen and spores has been used for percentage calculation. Some wetland (local) taxa in GIM are in MOE and AMB classified as highland taxa. Unfilled curves show × 5 exaggeration. Note that wetland and some non-pollen curves differ in scale. The lithology shows the degree of decomposition by increasingly close line spacing: 1, undecomposed peat; 2, peat; 3, decomposed peat; 4, strongly decomposed peat

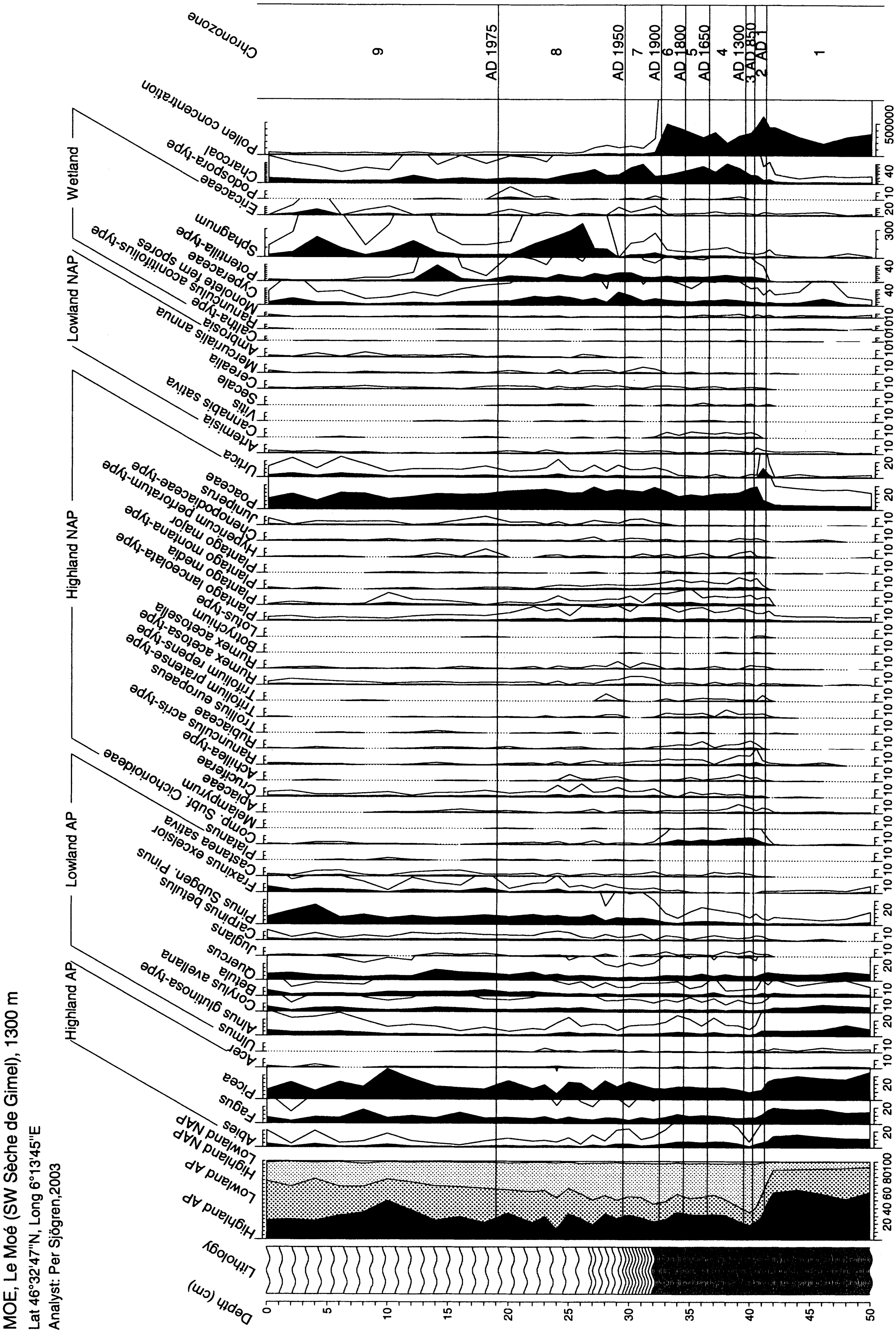

Figure 5 Pollen diagram for MOE in the southwestern part of Le Marais de Sèche de Gimel. See Figure 4 caption for explanation

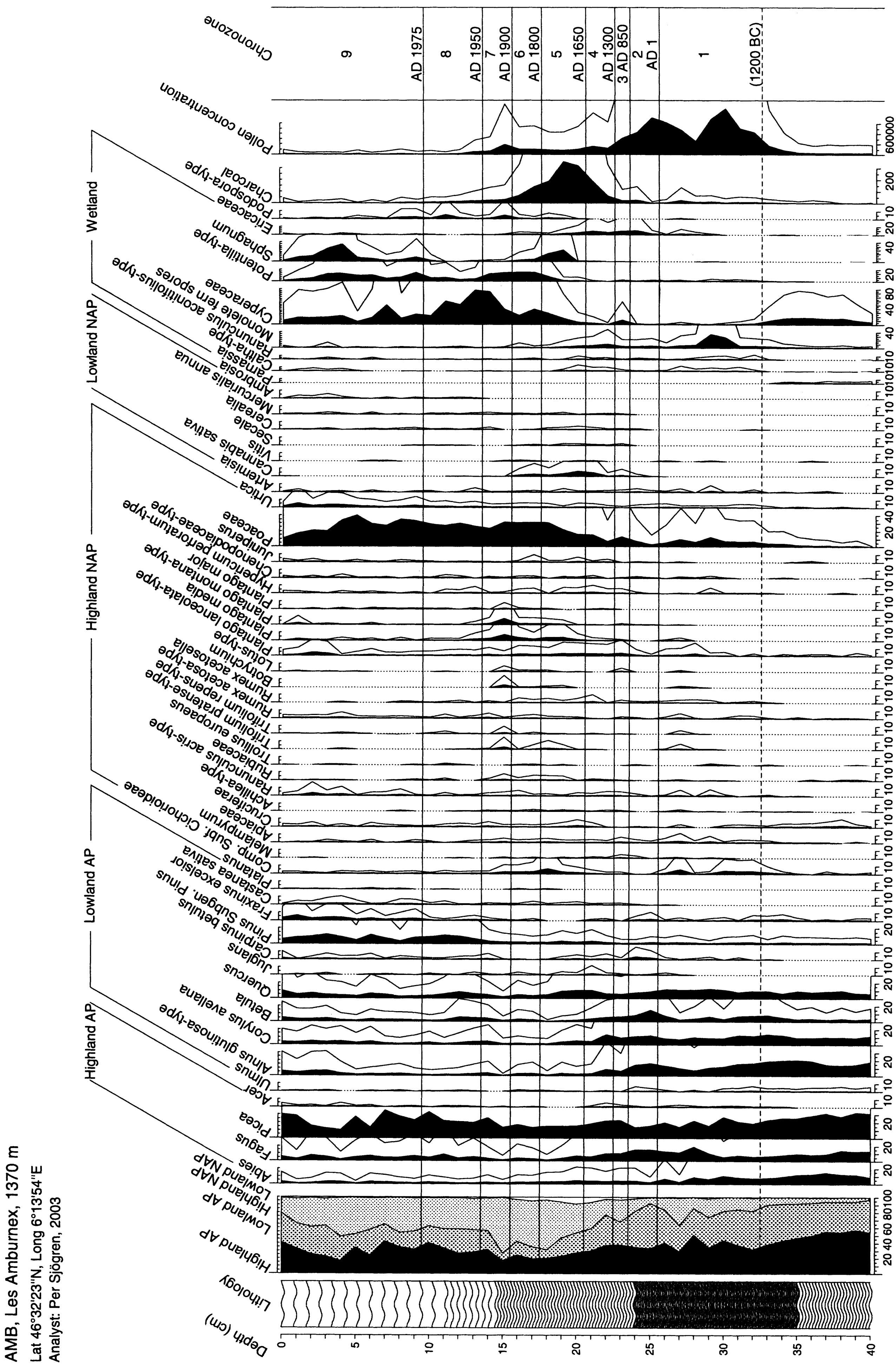

Figure 6 Pollen diagram for AMB, Les Amburnex mire. See Figure 4 caption for explanation

half (AD 1150–1300), and the central parts of the valley probably became as open as today.

Chronozone 4, AD 1300–1650; grazed forest and open pastures

The earlier part (AD 1300–1500) is marked by higher values of tree pollen. In the younger part (AD 1500–1650) there is a 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, and the decrease in NAP is primarily caused by well-dispersed pollen types such as *Plantago lanceolata*, Poaceae and *Juniperus*. Other NAP types are little or not affected at all. It thus seems that the central part of the valley was little affected by this regeneration phase. AMB: in contrast with GIM the increase in tree pollen in the early part of the zone primarily comes from *Alnus* and *Corylus*, trees that may have grown locally. In the younger part (AD 1500–1650) there is a decline in *Alnus*, *Corylus* and *Betula* pollen, suggesting a local reopening of the area around the site.

Chronozone 5–6, AD 1650–1800, AD 1800–1900; pasture woodland

Microscopic charcoal particles indicate major fire activity in the area, and a general openness comparable with today was probably reached in the eighteenth century. The largest lasting expansion of pastureland during this period seems to be in the peripheral areas, possibly because most useful land in the central part already had been turned into pastures. The more frequent occurrence of *Podospora* spores suggests an increased number of cattle. GIM: The zone starts with a peak in Poaceae and a dip in the *Picea* pollen frequencies. This may be the result of forest clearing. 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 chronozone 4. Locally the pollen values indicate that *Caltha* more or less disappeared while Cyperaceae increased, suggesting tussock formation. AMB: the Poaceae value doubles during the chronozone, and there is an increase in many herb pollen types, 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 were cleared away. Locally *Sphagnum* spores increases and peaks in AD 1700, followed by an increase in Cyperaceae and *Potentilla* pollen. The presence of *Podospora* spores suggests local cattle grazing.

Chronozones 7–9, AD 1900–1950, 1950–1975, 1975–2000; improved pasture woodland

The maximum openness and grazing pressure occur around AD 1900. During the twentieth century pollen values decline for most herbs except *Urtica*, and Poaceae pollen values remain high, which suggests increased nutrient levels. From here on an increase in lowland pollen from *Alnus*, *Corylus*, *Betula*, *Pinus* and *Fraxinus* occurs and suppresses the local and extra-local pollen signals. GIM: pollen and spore values of Cruciferae, ferns and Cyperaceae decrease after 1950, while peaks occur in *Salix* and *Euphrasia*-type pollen. MOE: pollen and spore values of Cyperaceae, *Potentilla* and *Podospora* decrease after AD 1975, suggesting a shift in local land use. AMB: a very high grazing pressure around AD 1900 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.

Discussion

Landscape development

After the open phase in the first centuries BC the following forest-regeneration phases can be detected: AD 1–250, AD 350–550, AD 1300–1500 and AD 1925–2000. Pasture-expansion phases are AD 250–350, AD 800–1300 and AD 1500–1900. Phases with maximum openness are AD 1200–1300 and AD 1700–1900.

During the early Middle Ages increasingly large areas in the central part of the valley were cleared, and in the thirteenth century the central part was probably as open as today. The general opening of the landscape occurred in the seventeenth and eighteenth centuries, and now a pasture-woodland landscape similar to present day came 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 for charcoal. An increased number of husbandry animals, most likely cattle, hampered forest regeneration. From AD 1925 a minor regeneration of the forest can be seen. This correlates well with the approximately 10% reduction of open land since the end of the nineteenth 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, while open pastures are little affected.

Forest composition and regeneration

An estimation of the natural forest composition at the end of the first millennium BC would be approximately 30% each of *Abies*, *Fagus* and *Picea*, 5% scattered *Acer* and 5% of *Alnus*, *Corylus* and *Betula*. 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. For *Alnus*, *Corylus* and *Betula* variations between the sites suggest local differences, and thereby local presence. *Picea* started to increase relative to *Abies* and *Fagus* in the ninth century, an increase that continued to AD 1950. In the thirteenth century it had increased to around 50% of the forest composition, and in the nineteenth century to 60%. *Picea* is relatively little browsed, and increased grazing pressure in the surrounding forests likely favoured it compared with other trees. The wooded pastures of today consist nearly entirely of *Picea*, and considering the increasing *Picea* dominance in the forest composition this vegetation type might have started to occur in the ninth century, and was most likely common in the twelfth century. Woodland pastures also started to occur across Europe at approximately the same time, ie, in the Middle Ages starting at the eighth century (Behre, 1988). *Alnus*, *Corylus* and *Betula* decreased from the ninth century and disappeared completely from the area in the seventeenth century. In the twentieth century *Picea* and *Fagus* expanded.

The opening of the landscape is shown to be a rather slow process, while forest regrowth is fast. 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. Forest regrowth typically starts with an increase in *Alnus*, *Corylus* and *Betula*, followed 100–200 years later by an increase in *Abies*, *Fagus* and *Picea*.

Pastures and herb composition

Pastureland in the last two millennia was 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 throughout and became even more dominating after AD 1900. During the twentieth century Poaceae pollen increased from *c.* one-half to two-thirds portion of NAP. Together with the increase in Poaceae an increase in *Urtica* suggests a nutrient enrichment of the area, probably as an effect of twentieth-century manuring.

Local mire development

Local development at the three localities is different and each is described separately.

GIM: the presence of Rubiaceae, *Rumex acetosa* and Cruciferae suggest that local grazing occurred throughout the past 2000 years. Increased peat-accumulation rates around the thirteenth century are likely an effect of a rise in the water-table following deforestation in the twelfth century. The local vegetation changed around AD 1700; *Caltha*, *Rumex acetosa* and Cruciferae decreased while Cyperaceae increased. These changes are associated with a more frequent occurrence of *Podospora* spores and increased fire activity, which suggest an increased number of cattle and a general deforestation. This general deforestation probably had a limited effect on the groundwater table as the central part of the valley was deforested already in the Middle Ages. Increased grazing pressure, especially trampling by heavy cattle, would have had a negative impact on the peat accumulation rate and might have caused tussock formation. It is also possible that the mire was ditched and drained, perhaps to improve grazing conditions. Ditches exists today but are partly overgrown and the drainage capacity is limited. Some major changes in the local vegetation also occurred around AD 1975. Cruciferae and Cyperaceae decreased while *Euphrasia* and *Salix* increased. The absence of earlier high values for *Euphrasia* and *Salix* suggest that they are invading the mire.

MOE: a marked increase in *Potentilla* occurred during the centuries around the birth of Christ and *Sphagnum* started to occur more regularly. These changes are associated with increased openness and grazing pressure, including the presence of *Podospora* spores. A strong peak in *Urtica* pollen coincides with the local changes in vegetation. This peak occurs before the presence of *Cannabis* pollen, making any dates younger than the eighth century unlikely. Herb and grass pollen are, at this point, rather low, which suggest that the changes are limited to the mire and local surroundings. *Urtica* thrives on disturbed and nutrient-rich soils, and the peak might have been caused by a nearby pathway or waterhole, perhaps in connection with forest grazing. MOE shows very high NAP values from shortly after this time and onwards, and this part of Sèche the Gimel was likely transformed into pastureland in the Middle Ages or even earlier. The peat at MOE shows very strong decomposition and partly mixing of the peat (AD 1–1900), which also suggests a very heavy local grazing pressure. From AD 1950 onwards the peat-accumulation rate increases rapidly, likely an effect of decreased grazing pressure (the area is today fenced and protected from grazing).

AMB: around 1200 BC (estimated age 1400–1000 BC) the local vegetation changed from Cyperaceae fen, including *Parnassia*, to one dominated by ferns. This change coincided with a marked increase in pollen concentration (increased peat decomposition) that perhaps reflects a lowering of the water-table. The period 1550–1150 BC is characterized by high lake levels in the Jura Mountains (Magny, 2004), and the end of this period coincides 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 in vegetation and decomposition rate in AMB. The pollen record shows weak increases in Poaceae and several herbs, including Compositae subfam. Cichorioideae, *Rumex acetosa*, *Rumex acetosella*, *Caltha* and *Ranunculus aconitifolius*, suggesting the development of a wet meadow or pasture (Behre, 1981). The local changes in mire vegetation coincided with a local opening of the forest, and human impact (forest grazing) is the most probably cause. Around AD 1700 there is a marked increase in pollen and spores from Cyperaceae, *Potentilla*-type and *Sphagnum*, while *Caltha*, *Ranunculus aconitifolius*-type, monolete ferns and Ericaceae decrease. Peak values in charcoal and increasing values of NAP suggest deforestation, and increased values of *Podospora* dung-spores and pollen from *Plantago media* and *Plantago montana*-type indicates a higher grazing pressure. The peat accumulation rate increases at the same time. Deforestation (higher water-table) and increased grazing pressure is likely responsible for the changes in the local vegetation, which is similar to the changes that occurred in MOE earlier.

Lowland vegetation

The percentage of *Quercus* pollen decreased during the first centuries AD and then rose again in the nineteenth century. *Carpinus* pollen frequencies reached their highest values AD 1–850. The *Carpinus* curve is consistent with that in the lowland (Rachoud-Schneider, 1998), but increased a few hundred years earlier than in many other parts of the Jura Mountains (eg, Wegmüller, 1966; van der Knaap *et al.*, 2000; Mitchell *et al.*, 2001; Gauthier, 2002). Around AD 850 a clear increase in *Cannabis sativa* pollen occurred. The highest values occurred AD 1650–1900, after which it declined sharply. Around AD 1300 the amount of *Pinus* pollen increases. This is likely related to the forest-regeneration phase that started at the same time. The percentage of *Pinus* pollen did not decrease after the landscape was opened up again, implying that either different parts of the landscape were deforested or that *Pinus*, after its initial establishment, was able to compete with existing trees or establish in earlier uncolonized areas.

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

Regional and historical context

Wegmüller (1966) studied four other sites by pollen analysis along the eastern edge of the Jura Mountains (Le Couchant at 1400 m, Creux du Croue at 1360 m, La Pile at 1220 m, La Maréchaude at 1590 m). All those sites recorded an opening in the first centuries BC, while the peat from the past 2000 years was missing or very compressed. This suggests that the peat development at those sites was similar to that at MOE and AMB. Pollen analysis of a sediment core from the large lake Lac du Joux *c.* 10 km north of the investigation area showed the same general pattern in expansion and regeneration phases (Wegmüller, 1966). A peat core from the Praz-Rodet bog (Mitchell *et al.*, 2001), 5 km to the northwest, shows some differences, but the main features can be recognized. 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 with the locally recorded forest-regeneration phases at AD 350–550 and AD 1300–1500. 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 by human activities (Gaillard, 1984). However, the vegetation history recorded in Lake Geneva itself (Rachoud-Schneider, 1998) shows that the main trends are similar between the lowland and Combe des Amburnex.

The forest-regeneration phase AD 1–250 was 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 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 compared with the lowland is the much larger impact of forestry in the high Jura Mountains during Modern Time, which together with summer grazing finally created the pasture woodland we see today.

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