The occurrence of an upper decomposed peat layer, or "kultureller Trockenhorizont", in the Alps and Jura Mountains

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SUMMARY

Many European mires show a layer of increased decomposition and minerogenic content close to the mire surface. Although the phenomenon is widely recognised, there have been few investigations of its distribution, cause and effect. In this study, nine peat profiles from the Alps and Jura Mountains in central Europe were studied to assess general trends in the upper peat stratigraphy. Analyses of pollen and fungal spore content in two profiles indicates that near-surface changes in decomposition are related to recent historical changes in grazing intensity of the surrounding landscape. Reduced trampling pressure and/or decreased nutrient input allowed partial *Sphagnum* regeneration in the western Alps and Jura Mountains from AD 1940–60, and in the eastern Alps from AD 1820–60. The results are considered in the context of climate and land use, and future implications for mire development in a changing environment are discussed. Many high-altitude mires in the area are now in a *Sphagnum* peat re-growth state, but future land use and climatic change will determine whether they will develop towards raised bog or forest carr.

KEY WORDS: dry bulk density, grazing, mire conservation, histosol, loss on ignition.

INTRODUCTION

When peat profiles are examined it is not uncommon to find, somewhere within the uppermost half metre, a dark layer that is many times enriched in clay, silt, or even sand. Although this has been known for a long time, no generally accepted explanation has yet emerged. Granlund (1932) observed this layer in many south Swedish raised bogs and explained it in terms of climatic conditions, whilst von Bülow (1929) claimed that human impact was the cause of the "kultureller Trockenhorizont" that he found in German raised bogs. Since these early observations, very little attention has been paid to the phenomenon (but see Franzén 2006). The majority of investigations - with a few exceptions, e.g. Chambers *et al*. 2007a,b - have focused on a single site only, and in most cases the strong decomposition of the top layers has been regarded as a distracting nuisance rather than an interesting object of study in itself. This was initially true also for our study, which searched out high-elevation peat profiles as sources of high-resolution environmental records for the past several centuries, but we consistently encountered the "problem" in all the mires visited and decided to investigate its cause.

The pan-European occurrence of a near-surface decomposed peat layer suggests a general effect; but there may be variations in dynamics, specific processes, patterns, causes, and consequences between different parts of Europe related to climate, soils, land use, *etc*. Our study concentrated on the Alps and the Jura Mountains and can thus be regarded as a regional investigation of a more widespread and at least Europe-wide phenomenon that has so far escaped adequate scientific attention.

The main goals of this paper are to:

1) describe general stratigraphical trends within the uppermost *ca*. half metre of peat;
2) determine the cause(s) of the phenomenon; and
3) discuss the implication(s) for peat growth and mire protection.

METHODS

Site selection

The nine sites investigated lie on a west-east transect from the Jura Mountains to the Austrian and Slovenian Alps (Figure 1, Table 1). Their altitudes range from 1200 to 2100 m a.s.l. All are in marginal (outfield) areas, more than 500 m above major settlements. The Jura Mountains sites MOE and AMB are situated in pasture woodland which is a mosaic of open pasture, wooded pasture, and forest dominated by *Picea* with some *Abies* and *Fagus*. Sites WE1, WE2, and FIS in the South Tyrolean

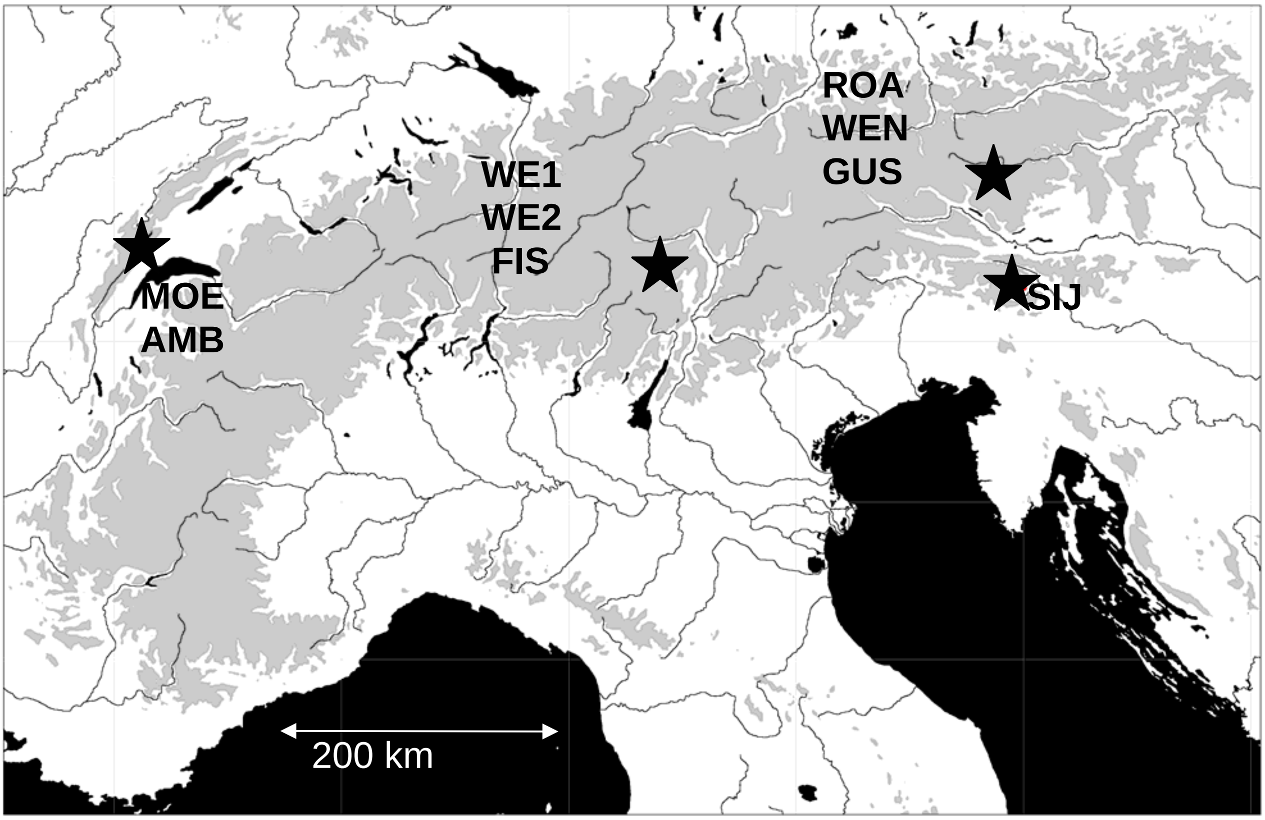

Figure 1. Overview map showing the locations of study sites. Grey shading indicates land above 1000 m altitude (mostly the eastern Jura Mountains and the Alps).

Alps are situated in pasture surrounded by grazed forest. The Austrian Alpine sites WEN and GUS are surrounded by grazed forest, whilst Site ROA lies in open pasture with patches of forest nearby. The forest near the South Tyrolean and Austrian sites is dominated by *Picea* with admixed *Larix* and *Pinus cembra*. Site SIJ in the Slovenian Alps is surrounded by dense *Picea* forest.

At each site, several test profiles were extracted using a 3 cm diameter gouge corer and examined to find the least decomposed peat profiles. A single peat monolith was then collected from a location where degree of decomposition was low for the mire as a whole and the vegetation consisted of healthy (growing) *Sphagnum*. Thus the profiles that were sampled represented the least decomposed and most rapidly growing parts of the mires, where layering was least pronounced. Elsewhere in each mire, the decomposed layer was generally more distinct and the upper, well-preserved layer shallower than in the cores that were collected. Indeed, large parts of most of the mires were haplotelmic (*cf*. Ingram 1978), with the most decomposed layer at the surface and hardly any evidence of current peat growth.

Laboratory work

The peat profiles were characterised in terms of dry bulk density and ash content; and pollen and spore analysis was carried out on the samples from Sites MOE and WEN. For measurements of dry bulk density (dry weight per unit fresh peat volume, units g cm^{-3}) a vertical strip of peat with surface area 2–3 cm^2 was cut from the peat monolith and divided into segments 1–3 cm long to give samples of 2–12 cm^3, choosing larger sample volumes within this range for less compacted peat. The samples were dried in open containers slightly above room temperature for one week before weighing for dry bulk density calculations (*cf*. Aaby 1986). Ash content (ash percentage of dry weight, or loss-on-ignition residue) was determined for the same samples. The samples were dried at 105°C overnight, weighed, and then combusted at 550°C for 4 hours (*cf*. Heiri *et al*. 2001). Pollen samples were prepared using the standard acetolysis method (Berglund & Ralska-Jasiewczowa 1986, Faegri *et al.* 1989). Pollen type classification followed Moore *et al.* (1991) and dung-related fungal spores were classified according to van Geel *et al*. (2003).

Table 1. Site descriptions. Edge = distance from the sampling point to the nearest edge of the mire; Depth = total depth of peat at the sampling point; Sampling surface = surface morphology at the sampling location; Mire vegetation = dominant species on the mire surface; Forest vegetation = common tree species in the surrounding area (*Picea* is dominant in all cases); Grazing = the current grazing regime; Drainage = known type of drainage.

Site	Locality and Region	Mire topography	Altitude (m a.s.l.)	Latitude Longitude	Area (ha)	Edge (m)	Depth (m)	Sampling surface	Mire vegetation	Landscape type	Forest vegetation	Grazing	Drainage
MOE	Le Moé Vaud, Switzerland	raised	1300	46°32'47" N 06°13'45" E	12	20	>2	*Sphagnum* lawn	*Carex*, *Potentilla*, *Sphagnum*	pasture woodland	*Picea*, *Abies*, *Fagus*	no (fenced)	water hole
AMB	Les Amburnex Vaud, Switzerland	raised	1370	46°32'23" N 06°13'54" E	0.25	15	>2	*Sphagnum* lawn	*Carex*, *Potentilla*, *Sphagnum*	pasture woodland	*Picea*, *Abies*, *Fagus*	no (fenced)	20th cent. pipe
WE1	Weissbrunnalm 1 Ultental, South Tyrol	flat	2070	46°28'39" N 10°49'27" E	1.5	10	>2	*Sphagnum* hummock	*Juniperus*, *Sphagnum*, *Carex*	pasture woodland	*Picea*, *Larix*, *Pinus cembra*	yes	none
WE2	Weissbrunnalm 2 Ultental, South Tyrol	flat	2070	46°28'39" N 10°49'27" E	1.5	6	>2	*Sphagnum* lawn	*Carex*, *Potentilla*, *Sphagnum*	pasture woodland	*Picea*, *Larix*, *Pinus cembra*	yes	none
FIS	Fischersee Ultental, South Tyrol	flat	2060	46°28'46" N 10°49'40" E	0.5	12	>2	*Sphagnum* hummock	*Carex*, *Potentilla*, *Sphagnum*	pasture woodland	*Picea*, *Larix*, *Pinus cembra*	yes	none
ROA	Rosaninalm Lungau, Austria	sloping	1830	46°57'40" N 13°47'20" E	0.5	17	>2	*Sphagnum* hummock	*Carex*, *Potentilla*, *Sphagnum*	pasture woodland	*Picea*, *Larix*, *Pinus cembra*	yes	none
WEN	Wengerkopf Lungau, Austria	flat	1790	47°10'40" N 13°52'40" E	0.25	12	1.3	*Sphagnum* hummock	*Carex*, *Potentilla*, *Sphagnum*	grazed forest	*Picea*, *Larix*, *Pinus cembra*	yes	none
GUS	Gr. Überling Schattseit-Moor Lungau, Austria	flat	1750	47°10'20" N 13°54'00" E	12	100	>2	*Sphagnum* hummock	*Carex*, *Pinus mugo*	grazed forest	*Picea*, *Larix*, *Pinus cembra*	no (fenced)	none
SIJ	Šijec Pokljuka, Slovenia	raised	1200	46°20'09" N 14°00'00" E	16	60	>2	*Sphagnum* hummock	Ericaceae, *Sphagnum*	grazed forest	*Picea*	no	none

Radiocarbon dating

Peat age was determined by AMS radiocarbon dating. Pre-bomb samples (AD <1950) were calibrated using OxCal (Bronk Ramsey 1995, 2001) with the IntCal98 calibration set (Stuiver *et al*. 1998). Post-bomb dates (AD >1950) were calibrated using changes in atmospheric ^{14}C following the nuclear weapons test peak in the early 1960s (Nydal & Lövseth 1983). The measurements from Vermunt (Levin *et al*. 1994) and Schauinsland (Levin & Kromer 1997) were used for post-bomb calibration. Post-bomb dates after *ca*. AD 1955 are considered to have an accuracy of around 2–3 years, although correlations between sections with age differences of no more than one year are possible (Sjögren *et al*. 2006). Dates calibrated to *ca*. AD 1950 may in reality be from the age interval AD 1930–1955 because of peat integration (Goslar *et al*. 2005).

The depth-age models for Sites WE2, FIS, ROA and GUS are based on linear interpolation/extrapolation of the midpoints of the calibrated time ranges (at 1 σ for pre-bomb dates). For MOE and AMB, deviations from the midpoints of the calibrated time ranges are allowed on the basis of correlation with nearby sites (for details see Sjögren 2006). The dates used for the depth-age models for WE1, WEN, and SIJ are based on the calibration software PozCal (Goslar *et al*. 2005).

RESULTS

Ash content and dry bulk density

Ash content and dry bulk density are shown in Figure 2. For increased comparability between sites, the depth scales have been set to zero at the level of the most pronounced change in dry bulk density. Every site shows a similar pattern, as follows. Dry bulk density is very low in the uppermost part of the peat profile. Below this is a 3–8 cm plateau of slightly increased values, then a strong increase to the highest dry bulk density in the next 5–20 cm. Below this, dry bulk density decreases to slightly lower values. Ash content follows the same pattern except that it declines more abruptly below the peak, only 3–10 cm below the 0-line. On the basis of these patterns, five different layers are recognised, and these are labelled A to E from the surface downwards (Table 2).

After the growth of peat-forming material, its dry bulk density is modified by compaction, decomposition and minerogenic influx. Ash content is affected by decomposition but not by compaction, and is especially sensitive to minerogenic influx because the organic component has considerably lower density than the minerogenic component. Thus an increase in the ratio of ash content to dry bulk density indicates an increase in the content of minerogenic material. During pollen analysis of the samples from Sites MOE, AMB, WEN and SIJ, elevated contents of minerogenic material (sand, silt and clay) were observed in Layer C, coinciding with the peak in ash content. The concentration of minerogenic material is affected by minerogenic influx and the peat accumulation rate. Because the peat accumulation rate is constant or increasing upwards in most parts of the profiles (see the depth-age models in Figure 3), an elevated ratio of ash content to dry bulk density indicates elevated minerogenic influx.

Peat accumulation rates

Radiocarbon dates for Sites WE2, FIS, ROA and GUS are presented in Table 3. Similar information for the other five sites is given by Goslar *et al*. (2005) (WE1, WEN, SIJ) and Sjögren (2006) (MOE, AMB). Depth-age relationships for all nine sites are shown in Figure 3.

The strongest increase in peat accumulation rate takes place at the 0-cm line in each depth-age model. In the western sites this level is dated to the mid-20th century AD (MOE 1945, AMB 1950, WE1 1960, WE2 1960, FIS 1945), whilst in the eastern sites it occurs in the early-to-mid-19th century AD

Table 2. General pattern of layers in the peat profiles. Depths are in centimetres relative to the transition from decomposed to well-preserved peat, as in Figure 2.

Layer	Soil layer	Depth of lower limit	Depth of upper limit	Ash content	Dry bulk density	Accumulation rate of peat	Description
A	acrotelm	-3 to -8	-12 to -61	very low	very low	fast	loose *Sphagnum*
B	acrotelm	0	-3 to -8	low	low	fast	*Sphagnum*
C	catotelm	3 to 10	0	high	high	intermediate	decomposed, dust
D	catotelm	5 to 20	3 to 10	low	high	slow	decomposed, compacted
E	catotelm	-	5 to 20	low	low	(intermediate)	rather decomposed

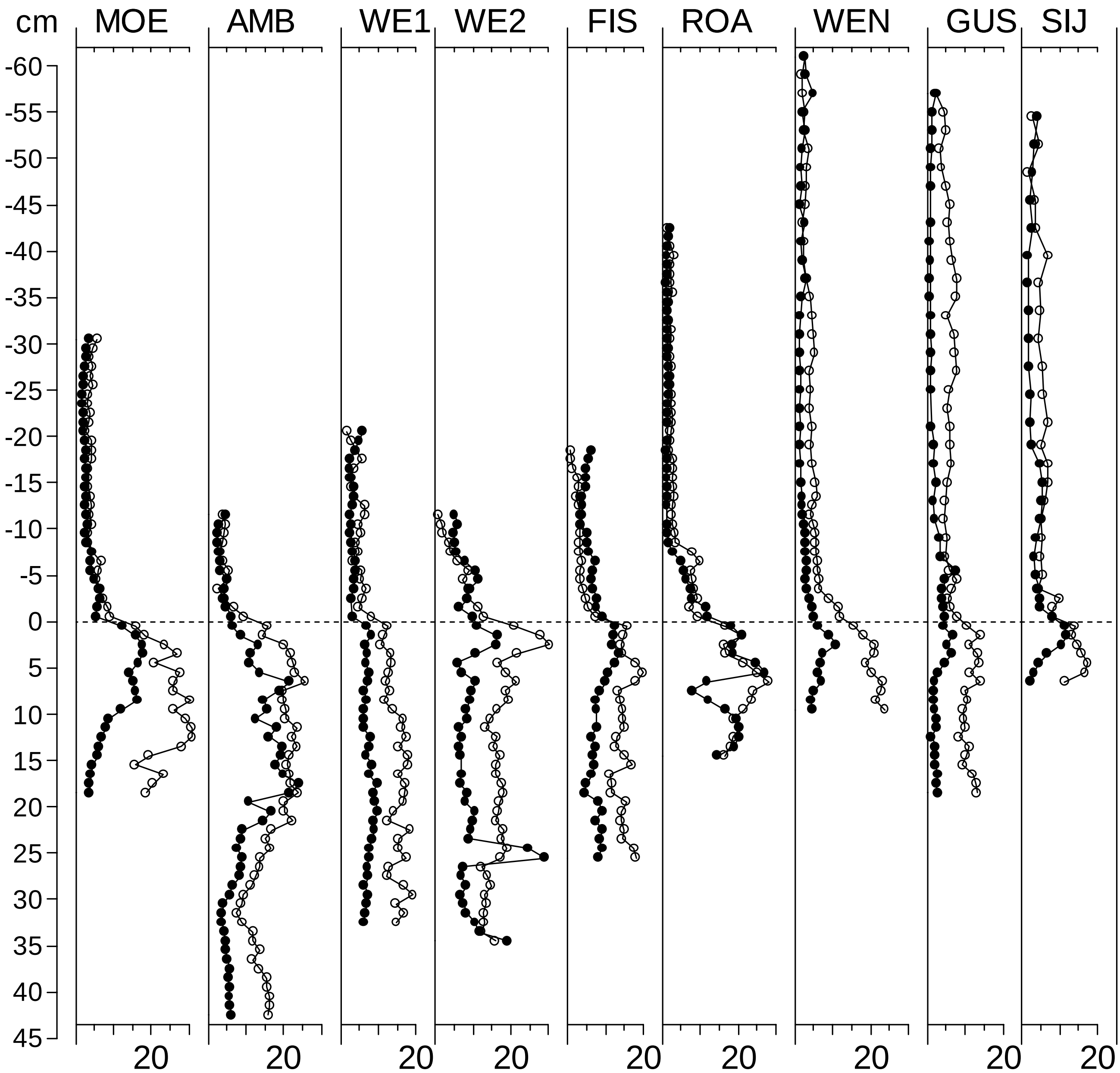

Figure 2. Comparison between sites of profiles of ash percentage (dots ●) and dry bulk density (circles ○; units centigram cm^{-3}). Dry bulk density is expressed in units of 0.01 g cm^{-3} so that the profiles can be presented together. The transition from decomposed to well-preserved peat is marked by the dashed line, and depth is measured relative to this line. The lowest negative depth for each profile indicates the peat surface.

(WEN 1820, GUS 1825, SIJ 1855). The depth-age model for ROA (intercept age AD 1630) is inconclusive as there are too few ^{14}C-dates; the transition to faster peat growth here may have occurred during the same time period as at the other sites (AD 1800–1950). The peat accumulation rate is lowest in the deeper parts of the profiles, but starts to increase a few centimetres below the 0-cm line. Peat accumulation rates seem to have been elevated during the first millennium BC, but this time period is represented only at MOE and AMB.

Pollen analysis

In the pollen diagrams (Figure 4), non-arboreal pollen (NAP; sum of herb, grass, and shrub pollen), *Plantago media/montana* (*P. media* + *P. montana*) pollen, and dung-related fungal spores (*Cercophora* type + *Podospora* type + *Sporormiella*) are calculated as percentages of the sum of pollen and spores from dry-land plants. The same sum is used to calculate the pollen concentration. *Plantago media/montana* is not shown for WEN, where the values were consistently low (<1%).

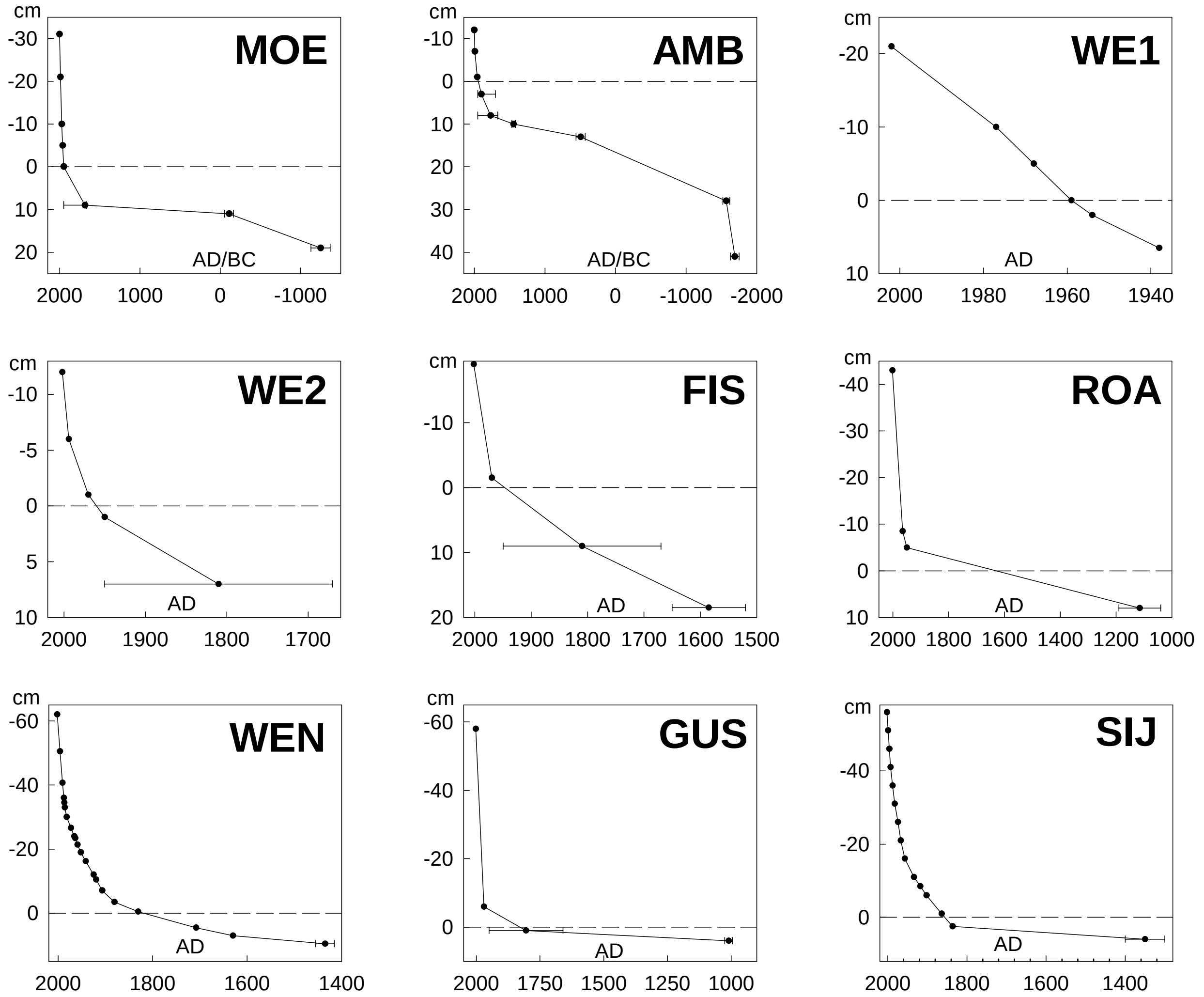

Figure 3. Depth-age relationships for the nine study sites (see Table 1 for key). The transition from decomposed to more well-preserved peat is marked by a dashed line and depth is shown relative to this transition, the smallest negative depth coinciding with the peat surface. For MOE and AMB, '0' on the horizontal axis indicates midnight on 31 December in the year 1 BC.

Table 3. Radiocarbon dates for peat samples from Sites WE2, FIS, ROA and GUS.

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

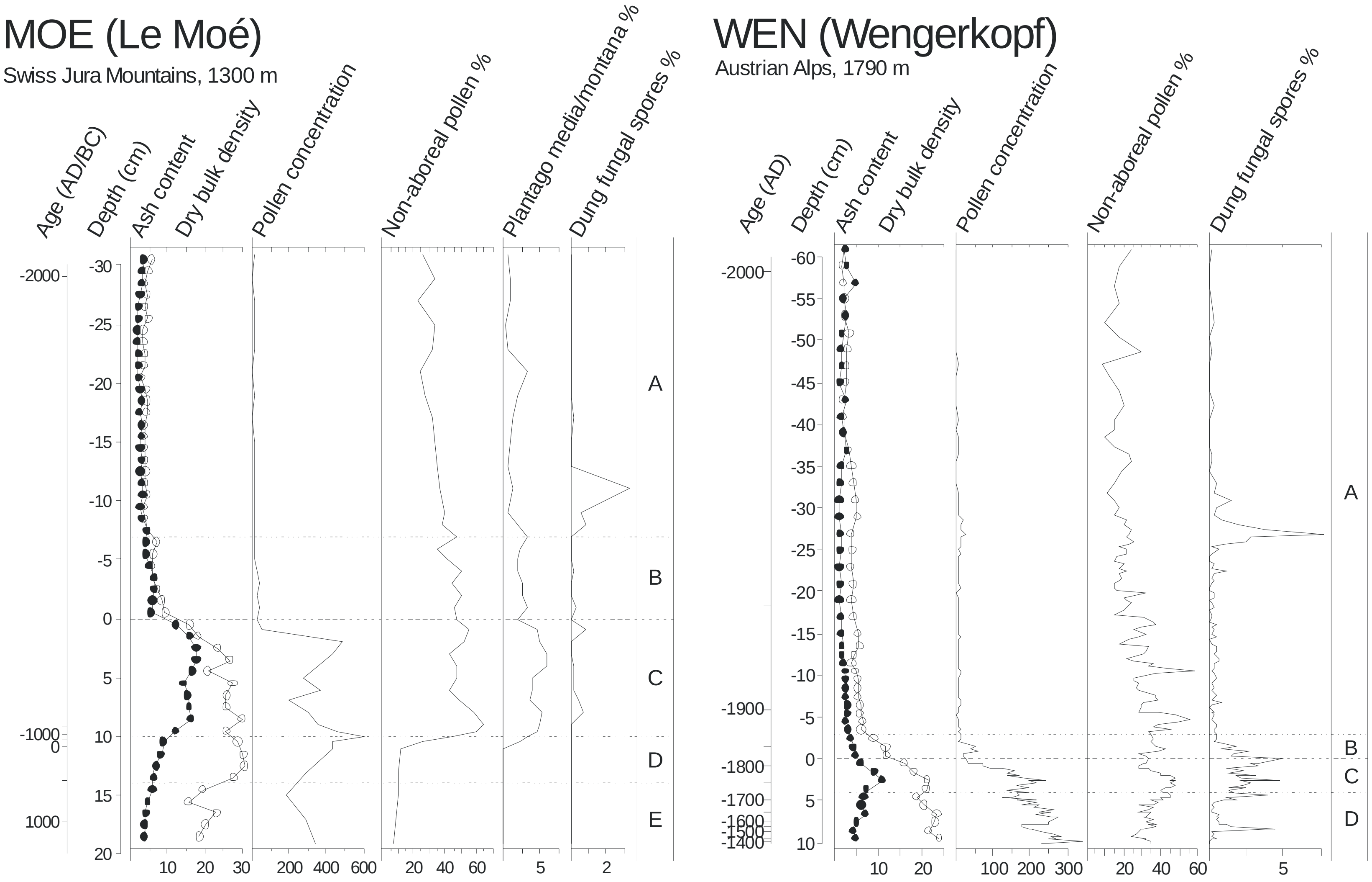

Figure 4. Selected data from the western site MOE and the eastern site WEN (Figure 1). Ash content is indicated by dots (●, %) and dry bulk density by circles (○, centigram cm^{-3}). Pollen and spore values are expressed as percentages of the total upland pollen and spore content. Pollen concentrations are expressed as 1000s of upland pollen grains per cm^3. Depth is expressed relative to the transition from decomposed to more well-preserved peat, and the lowest negative depth indicates the peat surface. Zonation follows Table 2.

Pollen concentrations reflect variations in pollen accumulation, mechanical compaction and decomposition of the organic matrix (which also results in compaction). Pollen accumulation (pollen deposition per unit time and surface area) is unlikely to vary by more than a factor of 2–3 except in conjunction with drastic changes in the peat-forming vegetation (*cf*. Hicks 1998, 2001; van der Knaap *et al*. 2001), and there is also a limit to how much the material can be mechanically compacted. It can therefore be assumed that high pollen concentrations are caused primarily by decomposition. The pollen concentration curves for both MOE and WEN correlate well with the dry bulk density curves.

The percentages of non-arboreal pollen are used to assess changes in the general openness of the landscape. A clear increase can be seen at the base of layer C, and this coincides with increases in minerogenic influx and dung-related fungal spores. After (above) this peak, a slow and shaky decline occurs until the late 20th century, when the non-arboreal pollen percentages level out. Dung-related fungi occur primarily on cowpats and indicate cattle activity. At MOE they first appear at the transition from Layer D to Layer C, and at WEN they clearly increase at the same transition. Low frequencies of dung-related fungal spores also occur in the uppermost parts of the profiles, reflecting continued cattle activity. The single peaks in the upper fast-growing parts of both profiles (*Podospora*-type at MOE, *Sporormiella* at WEN) are ascribed to single dispersal events from a cowpat lying close to the sampling location. The same phenomenon has been observed elsewhere (van der Knaap *et al*. 2000, van der Knaap & van Leeuwen 2003).

DISCUSSION

General patterns in the peat stratigraphy

The two soil layers that are generally distinguished in mires are the acrotelm and the catotelm (Ingram 1978). Decomposition of peat occurs primarily in the acrotelm (the periodically water-saturated surface layer) and depends on the rate at which the material passes into the underlying (permanently saturated) catotelm (Clymo 1965). Within the catotelm, the decomposition rate is very low. Thus the degree of peat decomposition is strongly influenced by the position of the water table at the time of peat formation (Aaby & Tauber 1974), although high-amplitude water level fluctuations can affect deeper layers (Tallis 1983).

The average dry bulk density of the uppermost (commonly 10–30 cm thick) layer of *Sphagnum* peat is usually 0.02–0.04 g cm^{-3}, below which it increases rapidly to 0.1 g cm^{-3}. There is only a limited - perhaps 20% - increase in bulk density thereafter (Clymo 1983). Thus a 'natural' or 'normal' *Sphagnum* peat profile consists of rather decomposed peat with an abrupt transition to less decomposed peat near the surface. On the basis of degree of decomposition, the top layers (A and B) of the nine peat profiles described in this study can be assigned to the acrotelm, with bulk density 0.035–0.065 g cm^{-3} (mean 0.045 g cm^{-3}); and the deeper layers C, D, and E to the catotelm, with bulk density 0.15–0.25 g cm^{-3} (mean 0.20 g cm^{-3}). These values are considerably higher than 'normal' (*cf.* Clymo 1983). For the acrotelm this can be partly explained by the species composition (high proportion of vascular plants), the presence of twigs and the likelihood that part of the transition to the catotelm is included. The high dry bulk density of the catotelm may indicate that it does not consist of pure *Sphagnum* peat, and/or that its degree of decomposition is higher than normal.

The peat stratigraphy observed in our sections can be interpreted in two alternative ways. First, apart from the high dry bulk density values, the sequence of layers C–B–A displays the expected pattern for *Sphagnum* peat accumulation and Layer B, with intermediate decomposition, can be regarded as transitional. Secondly, the sequence might be the transition between the two types of peat formed when there is a shift from high to low peat decomposition so that the mire grows in thickness. In the latter case the acrotelm/catotelm transition either happens to coincide with the transition in peat types, or is as yet poorly developed stratigraphically and represented by the B/A layer transition. The hypothesis of two types of peat is strongly supported by the very high decomposition and very low peat accumulation in layers D and C, which indicates less favourable peat accumulation conditions than in the surface layers B and A. The inferred change in peat growth conditions occurred around AD 1940–60 in the western sites (Jura mountains and western Alps), and around AD 1820–1860 in the eastern Alps; this regional synchrony suggests some external forcing.

Causes of variation in peat decomposition

We discuss here six possible explanations for the presence of a decomposed peat layer near the surface; namely climate, minerogenic influx, trampling/grazing, forest cover, drainage, and autogenous responses.

Climate
Several investigations have shown a connection between peat decomposition and climate change (e.g. Walker & Walker 1961, Aaby & Tauber 1974, Nilssen & Vorren 1991, Chambers *et al*. 1997, Mauquoy *et al*. 2002, Roos-Barraclough *et al*. 2004). Slow peat decomposition is generally associated with cold and wet climate.

Minerogenic influx
The pollen and spore data show that increased minerogenic influx coincides with grazing and human activity (Figure 4). Peaks in ash or dust content have been attributed to windblown dust from agricultural or pastoral activity in many studies (Bahnson 1973, Kramm 1978, Vuorela 1983), although climate (i.e. storminess) can be important in sandy coastal areas (Björk & Clemmensen 2004, de Jong *et al*. 2006). Dust and sand can be blown in from areas where the vegetation cover has been damaged (e.g. clearances, pastures, pathways, slopes and water holes) or transported directly onto mires on the hooves of husbandry animals. In some cases, sand has even been spread deliberately on mire surfaces in order to improve agricultural or pasture productivity. Increased minerogenic influx to the mire surface will change the nutrient balance and may increase the rate of decomposition, eventually affecting sub-surface layers (*cf*. Franzén 2006). It has also been shown that increased nitrogen input has a detrimental effect on *Sphagnum* growth, and may well cause changes towards another type of vegetation (Nordin & Gunnarsson 2000, Gunnarsson *et al*. 2004). Increased nutrient levels may thus directly hamper *Sphagnum* growth and thereby cause stagnation in peat accumulation.

Trampling/grazing
Trampling of the mire surface by animals can hinder plant growth, or even destroy the vegetation cover (especially *Sphagnum* carpets) and so expose the peat surface to the atmosphere. Trampling damage is most intense where animals congregate, for example close to water holes. It may be caused not only by husbandry animals but also by game under some circumstances, as at the Aletschwald Nature Reserve in the central Swiss Alps where large numbers of game animals seek refuge from hunting (Bodenmann & Eiberle 1967, Müller 1972, van der Knaap & van Leeuwen 2003). Another important effect of trampling is the mechanical compaction of peat, which has a direct effect on dry bulk density. Also, peat decomposition may increase due to the associated enhancement of micro-relief, because water will collect in trampling holes and hoof prints leaving the peat between the depressions prone to drying and decomposition. High concentrations of grazing animals on the mire will also increase dunging which, at least locally, might contribute to over-fertilisation causing sensitive ombrotrophic species to vanish.

Forest cover
Deforestation of the landscape will reduce general evapotranspiration and thus raise the water table (*cf*. Moore & Willmot 1976). The surface wind speed will on the other hand increase, and this can have a drying effect on the mire surface, although this seems to be most important when the hydrology of the mire is independent of the surrounding groundwater level (Mitchell *et al*. 2001). Human activity has affected forest cover in the alpine region since prehistoric times (Vorren *et al*. 1993), with maximum deforestation during the 19th century (Grünig 2002, Hürlimann 2004). Grazing is generally the most common agent keeping the landscape open, but lumbering became increasingly important up to the mid-19th century.

Drainage
Drainage of mires for pasture and meadow improvement or for water extraction has been common even in the high parts of the Jura Mountains and the Alps, especially during the second half of the 19th century when the demand for pasture and hay meadows was high (Bätzing 2003). After drainage the peat may shrink and develop a more or less impermeable dried-out surface skin (Tallis 1983).

Autogenous responses
Compaction and decomposition of the upper peat layers reduces the permeability of the peat so that surface runoff will increase, especially on animal tracks. In severe cases this can lead to erosion of the mire surface. Restricted uptake of water would modify the autogenous responses of the peat mass to changes in water supply (Tallis 1983), thus making the mire surface more susceptible to summer drought.

Regional mire development
From considering the various possible causes of change in peat decomposition, it is quite evident that human impact is an important factor. Pastoralism would cause increased trampling and nutrient input on the mire and so increase decomposition. Drainage is often carried out when the grazing intensity increases or is high, so that it is difficult to separate the effects of grazing and drainage on peat development. A water hole or drier area of mire surface would also attract animals and thus locally

increase trampling. On the other hand, grazing reduces forest cover so that, in most cases, the water table would rise and impose a lower rate of decomposition. It is thus possible that low grazing pressure on the landscape (deforestation) would be beneficial for peat growth while high-intensity land use (trampling, nutrient input, drainage) would be detrimental. Autogenous responses may then increase peat decomposition further. The analysis of pollen and fungal spores from MOE and WEN also shows a clear association between high grazing intensity and a more open landscape. The slowness of the decline in non-arboreal pollen after the maximum grazing phase is understandable as re-growth of trees takes time, and non-arboreal pollen production may increase temporarily when grazing intensity falls (Groenman-van Waateringe 1993).

Climate seems to have little or no effect on the decomposition of the upper peat. The highly decomposed peat in layers C and D was formed largely within the period of cold climate from the 14th to the 19th century, i.e. during the Little Ice Age *sensu lato*. The general climatic trend in the Alps over the last 150 years shows increasing temperatures with no clear trend in precipitation apart from somewhat drier conditions during the last three decades (Auer *et al*. 2001, Begert *et al*. 2005, Casty *et al*. 2005). We therefore conclude that climate change is highly unlikely to be the cause of the increase in peat accumulation observed in the top layers A and B. The apparent lack of climatic forcing on peat characteristics does not rule out climatic impact, but the main forcing factor must be sought elsewhere, i.e. in the particularly strong human impact in the region during the study period.

Thus, the most probable explanation for the observed pattern in peat stratigraphy (Table 2) is high grazing intensity (trampling, nutrient input and possibly drainage) at or directly after the time when Layer C was formed. This added minerogenic material to Layer C and caused compaction and decomposition of the underlying Layer D. The deeper peat (Layer E) was less affected, but the shortness of our peat cores and our incomplete knowledge of earlier periods of human activity make it difficult to determine the 'natural' state. Layer B is the result of resumption of peat growth when trampling was reduced, promoted by higher water tables associated with deforestation and/or collapse of drainage systems. Its higher dry bulk density relative to Layer A is probably due to auto-compaction, possibly enhanced by the special nutrient and groundwater conditions imposed by the subjacent compact and mineral-rich peat of Layer C. Layer A consists of undamaged, well preserved *Sphagnum* peat.

Regional land use history

Neolithic groups were already present in the Alps and the Jura Mountains during the 5th millennium BC. Human impact increased over time and peaked in the Late Bronze Age and Early Iron Age. After a drop in high-altitude activity during the Roman Period around the birth of Christ, human impact increased again during the Middle Ages (e.g. Wegmüller 1966, Sjögren 2006, Moe & Fedele 2007).

The opening of the Gotthardt pass in the sixteenth century made commerce with North Italy and the harbour of Genoa possible. This may mark the transition from sustainable farming to market-oriented farming. Hard cheese was particularly in demand for rations on long sea journeys because of its high nutritional value and keeping qualities. The rise in demand for hard cheese from the mid-18th century resulted in increased pressure on the alpine pastures. During the 19th century the cheese production centres moved down the valleys but the mountain pastures remained crucial for grazing young cattle, and even more so after a second boom in cheese exports after AD 1860 (Lexikon der Schweiz 2006). Historically, the strongest grazing pressure in the western and central Alps occurred around the end of the 19th century. During the latter half of the 20th century the number of husbandry animals decreased rapidly and today reforestation, or "Verbuschung", is occurring all over the Alps and Jura Mountains (e.g. van der Knaap *et al*. 2000).

Two phases of re-initiated peat growth can be seen in the peat profiles, during the early and mid-19th century (*ca*. AD 1820–1860) in the eastern sites, and the mid-20th century (*ca*. AD 1940–1960) in the western sites. Large peat hummocks in the eastern Alps may have been protected from trampling by their own size and by *Juniperus* and other shrubs growing on them, and from drought by the high water retention capability of hummock-forming *Sphagnum* species (Overbeck 1963).

Consequences for the environmental archive

The damaging effect of trampling and drainage on peat development has major implications for palaeoecological studies in terms of 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 of contamination increases. The uneven and slow peat accumulation also makes it difficult to construct accurate depth-age models for the last 500-2000 years. The Little Ice Age ^{14}C-plateau accentuates the problem of dating, as calibrated ^{14}C-dates have multimodal probability distributions. Age control can be improved by combining the probability functions of many dates (*cf*. PozCal, Goslar *et al.* 2005), or if ^{14}C dates are used in combination with correlation of pollen-assemblage characteristics with less affected peat/sediment profiles (*cf*. Sjögren 2006). 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 (e.g. Roos-Barraclough *et al*. 2004). The only solutions are to use carefully selected sites in remote areas or to rely on less-affected proxies, e.g. pollen percentage data.

The presence of hummocks that are almost 200 years old on an otherwise near-haplotelmic mire surface also has implications for understanding the formation of little-humified peat layers. The present C/B boundary can be regarded as a recurrence surface (*cf*. Granlund 1932) where peat growth began at least 200 years earlier than on other parts of the same surface. Uneven peat growth over the mire surface could thus give rise to differences of at least 200 years in dating a little-humified peat layer if the present data are used as an analogy. This may partly explain the wide range of dates that can be obtained for stratigraphically similar layers of undecomposed peat (e.g. Nilsson 1964).

Consequences for mire preservation

An important ecological observation is that most mires at high elevation in the Jura Mountains and the Alps have been severely damaged by human activities, either recently or during the 19th or 20th century. Compaction and decomposition of the upper peat layers has changed the water and nutrient conditions of these mires, and increased influx of minerogenic material has altered the soil conditions further. During the latter half of the 20th century the number of husbandry animals in the Alps has declined considerably and this has allowed regeneration of *Sphagnum* and the resumption of peat formation in some mires. Thus it seems that a decrease in grazing pressure leads relatively quickly to re-growth of *Sphagnum* peat and thereby, in the long run, to full restoration of the “natural” (pre-human) state of the mire. However, a few points that recommend a more cautious view of the future development of high-altitude mires in the Alps and the Jura Mountains are listed below.

1) There have been severe changes in many of the mires so that even if drainage, grazing, and trampling were to stop completely, the changes in nutrient levels and hydrology will persist for a long time, perhaps permanently changing the mire conditions (*cf*. Goodall 1983).
2) A dry, nutrient-rich mire surface below the tree line is prone to invasion by woody species which promote evapotranspiration. This will damage the mire further, turning it slowly into wet forest.
3) Forest cover is increasing in large parts of the Alps and Jura Mountains, primarily as a result of reduced grazing pressure. A less open landscape will increase evapotranspiration and lower the water table, creating drier mire conditions.
4) Warmer and possibly drier climate following human-induced global warming will affect mire conditions both directly through increased evapotranspiration and indirectly by permitting a higher forest limit and more warmth-demanding species. Also, *Sphagnum* is sensitive to climate change (*cf*. Barber *et al*. 1994, Gunnarsson *et al*. 2004) so there are possible consequences for species composition and growth rate.
5) Past and present land use under different climatic settings has affected high-altitude mires for a very long time. Species composition, hydrology and nutrient levels are therefore far from natural, and all mires in the study region have probably been affected for thousands of years. The biological and aesthetic values of today’s Alpine wetlands are thus the result of a long and continuing tradition of summer grazing, and these values might be lost if the mires are allowed to return to their “natural” state - although other values will surely be created.

In conclusion, it is possible for the mires to develop in three directions from their present condition: into bogs (low disturbance, high water table); into wet forests (low disturbance, low water table); or to remain in their present state (moderate disturbance, high water table). Development towards bog can be observed in conjunction with decreasing grazing pressure at present, but the expected reforestation and a warmer climate may alter this trend. The number of cattle that are summer-grazed in the mountains is a crucial factor, and this is largely determined by agricultural policies.

ACKNOWLEDGEMENTS

We thank Myriam Angehrn for the LOI analysis and Florencia Oberli for laboratory preparation/analysis. Robert Krisai provided logistic support and valuable comments on the manuscript. Also, two anonymous reviewers are acknowledged for their interesting comments and suggestions for improvement. This paper contributes to the Swiss National Science Foundation (SNF) project NCCR Plant Survival, and the European Union projects PINE - Predicting Impact on Natural Ecotones (EVK2-CT-2002-00136) and Millennium - European climate of the last millennium (EU 6FP Integrated Project No: 017008).

REFERENCES

Aaby, B. (1986) Palaeoecological studies of mires. In Berglund, B.E. (ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology*, J. Wiley & Sons, Chichester, 743–774.

Aaby, B. & Tauber, H. (1974) Rates of peat formation in relation to degree of humification and local environment, as shown by studies of a raised bog in Denmark. *Boreas,* 4, 1–17.

Auer, I., Böhm, R. & Schöner, W. (2001) Austrian long-term climate 1767-2000 – Multiple instrumental time series from central Europe. *Österreichishe Beiträge zu Meteorologie und Geophysik*, 25, 1–147.

Bahnson, H. (1973) Spor af muldflugt i keltisk jernalder påvist i højmoseprofiler (Traces of soil erosion from the Celtic Iron Age determined in raised bogs). *Danmarks Geologiske Undersøgelse Årbog*, 1972, 7–12 (in Danish).

Barber, K.E., Chambers, F.M., Maddy, D., Stoneman, R. & Brew, J.S. (1994) A sensitive high-resolution record of late Holocene climatic change from a raised bog in northern England. *The Holocene*, 4, 198–205.

Bätzing, W. (2003) *Die Alpen – Geschichte und Zukunft einer europäischen Kulturlandschaft* (*The Alps – History and Future of a European Cultural Landscape*). Verlag C.H. Beck, München (in German). 431 pp.

Begert, M., Schlegel, T. & Kirchhofer, W. (2005) Homogeneous Temperature and Precipitation Series of Switzerland from 1864 to 2000. *International Journal of Climatology*, 25, 65–80.

Berglund, B.E. & Ralska-Jasiewczowa, M. (1986) Pollen analysis and pollen diagrams. In: Berglund, B.E. (ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology*, J. Wiley & Sons, Chichester, 455–484.

Björk, S. & Clemmensen, L.B. (2004) Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess in southern Scandinavia? *The Holocene*, 14, 677–688.

Bodenmann, A. & Eiberle., K. (1967) Über die Auswirkungen des Verbisses der Gemse im Aletschwald (About the effect of grazing of gemse (wild goat) in Aletschwald). *Schweizerische Zeitschrift für Forstwesen,* 118, 461–470 (in German).

Bronk Ramsey, C. (1995) Radiocarbon Calibration and Analysis of Stratigaphy: The OxCal Program. *Radiocarbon,* 37, 425–430.

Bronk Ramsey, C. (2001) Development of the Radiocarbon Program OxCal. *Radiocarbon*, 43, 355–363.

Casty, C., Wanner, H., Luterbacher, J., Esper, J. & Böhm, R. (2005) Temperature and precipitation variability in the European Alps since 1500. *International Journal of Climatology*, 25, 1855–1880.

Chambers, F.M., Barber, K.E., Maddy, D. & Brew, J. (1997) A 5500-year proxy-climate and vegetational record from blanket mire at Talla Moss, Peebleshire, Scotland. *The Holocene*, 7, 391–399.

Chambers, F.M., Mauquoy, D., Cloutman, E.W., Daniell, J.R.G. & Jones, P.S. (2007a) Recent vegetation history of Drygarn Fawr (Elenydd SSSI), Cambrian Mountains, Wales: implications for conservation management of degraded blanket mires. *Biodiversity and Conservation*, 16 (in press).

Chambers, F.M., Mauquoy, D., Gent, A., Pearson, F., Daniell, J.R.G. & Jones, P.S. (2007b) Palaeoecology of degraded blanket mire in South Wales: data to inform conservation management. *Biological Conservation*, 137, 197–209.

Clymo, R.S. (1965) Experiments on breakdown of *Sphagnum* in two bogs. *Journal of Ecology*, 53, 747–758.

Clymo, R.S. (1983) Peat. In: Gore, A.J.P. (ed.) *Ecosystems of the World*, *4A*, *Mires: Swamp, Bog, Fen and Moor*, Elsevier, Amsterdam, 159–224.

de Jong, R., Björk, S., Björkman, L. & Clemmensen, L. (2006) Storminess variation during the last 6500 years as reconstructed from an ombrotrophic peat bog in Halland, SW Sweden. *Journal of Quaternary Science*, 21, 905–919.

Faegri, K., Kaland, P.E., Krzywinski, K. & Iversen, J. (1989) *Textbook of Pollen Analysis*, *Fourth Edition.* Wiley, Chichester, 328 pp.

Franzén, L.G. (2006) Increased decomposition of subsurface peat in Swedish raised bogs: are temperate peatlands still net sinks of carbon? *Mires and Peat*, 1, 03, 1–16. Online at: http://www.mires-and-peat.net.

Goodall, D.W. (1983) Conclusion - the future of mires. In: Gore, A.J.P. (ed.) *Ecosystems of the World*, *4B*, *Mires: Swamp, Bog, Fen and Moor – Regional Studies*, Elsevier, Amsterdam, 395–396.

Goslar, T., van der Knaap, W.O., Hicks, S., Andric, M., Czernik, J., Goslar, E., Räsänen, S. & Hyötylä, H. (2005) Radiocarbon dating of modern peat profiles: pre- and post-bomb ^{14}C variations in the construction of age-depth models. *Radiocarbon,* 47, 115–134.

Granlund, E. (1932) De svenska högmossarnas geologi (Geology of the Swedish raised bogs).

Sveriges Geologiska Undersökning C, 26, 1–193 (in Swedish).

Groenman-van Waateringe, W. (1993) The effects of grazing on the pollen production of grasses. *Vegetation History and Archaeobotany*, 2, 157–162.

Grünig, A. (2002) The development of agriculture in Switzerland at first glance. In: Berger, T. *et al*. (eds.) *Mountains of the World*. Proceedings of the World Mountain Symposium (WMS 2001), 30.9–4.10 2001, Interlaken. Swiss Agency for Development and Co-operation (SDC), 10 pp. (CD-ROM).

Gunnarsson, U., Granberg, G. & Nilsson, M. (2004) Growth, production and interspecific competition in *Sphagnum*: effects of temperature, nitrogen and sulphur treatments on a boreal mire. *New Phytologist*, 163, 349–359.

Heiri, O., Lotter, A.F. & Lemcke, G. (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology*, 25, 101–110.

Hicks, S. (1998) Fields, boreal forests and forest clearings as recorded by modern pollen deposition. *Paläoklimaforschung*, 53–66.

Hicks, S. (2001) The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. *Review of Palaeobotany and Palynology*, 117, 1–29.

Hürlimann, K. (2004) Schlussbericht - Projekt «Holznot» (18/19 Jahrhundert) (Final report of the project “Wood destitution” (18/19 century)). Departement Umweltwissenschaften, Prof. Forsteinrichtung und Waldwachstum, Swiss Federal Institute of Technology Zurich, Zurich, 159 pp. (in German).

Ingram, H.A.P. (1978) Soil layers in mires: Function and terminology. *Journal of Soil Science*, 29, 224–227.

Kramm, E. (1978) Pollenanalytische Hochmoor-untersuchungen zur Floren- und Siedlungs-geschichte zwischen Ems unt Hase (Pollen-analytical investigations of raised bogs between Ems and Hase). *Abhandlungen aus dem Westfälischen Museum für Naturkunde*, 40, 1–49 (in German).

Levin, I. & Kromer, B. (1997) *$^{14}CO_2$ records from Schauinsland*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A.

Levin, I., Kromer, B., Schonch-Fisher, H., Bruns, M., Münnich, M., Berdau, D., Vogel, J.C. & Münnich, K.O. (1994) *$^{14}CO_2$ record from Vermunt*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Lexikon der Schweiz (consulted MONTH 2006) http://www.lexhist.ch/externe/protect/textes/d/D13951-1-1126.html (in German).

Mauquoy, D., Engelkes, T., Groot, M.H.M., Markesteijn, F., Oudejans, M.G., van der Plicht, J. & van Geel. B. (2002) High-resolution records of late-Holocene climate change and carbon accumulation in two north-west European ombrotrophic peat bogs. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 186, 275–310.

Mitchell, E.A.D, van der Knaap, W.O., van Leeuwen, J.F.N., Buttler, A., Warner, B.G. & Gobat, J-M. (2001) The palaeoecological history of the Praz-Rodet bog (Swiss Jura) based on pollen, plant macrofossils and testate amoebae (Protozoa). *The Holocene*, 11, 65–80.

Moe, D. & Fedele (2007) Vegetational changes and human presence in the low-alpine and subalpine zone in Val Febbraro, upper Valle di Spluga (Italian central Alps), from the Neolithic to the Roman period. *Vegetation History and Archaeobotany*. DOI 10.1007/s00334-006-0088-0.

Moore, P.D., Webb, J.A. & Collinson, M.E. (1991) *Pollen Analysis*. Second Edition, Blackwell Scientific Publications, Oxford, 216 pp.

Moore, P.D. & Willmot, A. (1976) Prehistoric forest clearence and the development of peatlands in the uplands and lowlands of Britain. *Proceedings of the 5th International Peat Congress, Poznan, Poland,* 21–25 September 1976, II, 7–21. International Peat Society, Jyväskylä, Finland.

Müller, E. (1972) Wald und Wild im Aletschwaldreservat (Forest and wildlife in the Aletschwald nature reserve). *Schweizerische Zeitschrift für Forstwesen*, 123, 572–581 (in German).

Nilssen, E. & Vorren, K-D. (1991) Peat humification and climate history. *Norsk Geologisk Tidsskrift*, 71, 215–217.

Nilsson, T. (1964) Entwicklungsgeschichtliche Studien im Ageröds Mosse, Schonen (Studies of development history in the Ageröd bog, Scania). *Lunds Universitets Årskrift*, N.F. 2, Bd. 59, Nr 8, 1–34 (in German).

Nordin, A. & Gunnarsson, U. (2000) Amino acid accumulation and growth of *Sphagnum* under different levels of N deposition. *Écoscience*, 7, 474–480.

Nydal, R. & Lövseth, K. (1983) Tracing bomb ^{14}C in the atmosphere, 1962–1980. *Journal of Geophysical Research*, 88, 3621–3642.

Overbeck, F. (1963) Aufgaben botanisch-geologischer Moorforschung in Nordwestdeutschland (Geobotanic mire research projects in northwest Germany). *Bericht der Deutschen botanischen Gesellschaft*, 76B, 2–12 (in German).

Roos-Barraclough, F., van der Knaap, W.O., van Leeuwen, J.F.N. & Shotyk, W. (2004) A Late Glacial and Holocene record of climate change and possible modern anthropogenic influences from a Swiss humification profile. *The Holocene*, 14, 7–19.

Sjögren, P. (2006) The development of pasture woodland in the southwest Swiss Jura Mountains over 2000 years, based on three adjacent peat profiles. *The Holocene*, 16, 210–223.

Sjögren, P, van Leeuwen, J.F.N., van der Knaap, W.O. & van der Borg, K. (2006) The effect of climate variability on pollen productivity, AD 1975-2000, recorded in a *Sphagnum* peat hummock. *The Holocene*, 16, 277–286.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J. & Spurk, M. (1998) Intcal98 radiocarbon age calibration, 24 000–0 cal BP. *Radiocarbon*, 40, 1041–1083.

Tallis, J.H. (1983) Changes in wetland communities. In: Gore, A.J.P. (ed.) *Ecosystems of the World*, *4A*, *Mires: Swamp, Bog, Fen and Moor*, Elsevier, Amsterdam, 311–348.

van der Knaap, W.O. & van Leeuwen, J.F.N. (2003) Climate/pollen relationship AD 1901–1996 in two small mires near the forest limit in the northern and central Swiss Alps. *The Holocene*, 13, 809–828.

van der Knaap, W.O., van Leeuwen, J.F.N. & Ammann, B. (2001) Seven years of annual pollen influx at the forest limit in the Swiss Alps studied by pollen traps: relations to vegetation and climate. *Review of Palaeobotany and Palynology*, 117, 31–52.

van der Knaap, W.O., van Leeuwen, J.F.N., Fankhauser, A. & Ammann., B. (2000) Palynostratigraphy of the last centuries in Switzerland based on 23 lake and mire deposits: chronostratigraphic pollen markers, regional patterns, and local histories. *Review of Palaeobotany and Palynology*, 108, 85–142.

van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., van Reenen, G. & Hakbijl, T. (2003) Environmental reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. *Journal of Archaeological Science*, 30, 873–883.

von Bülow, K. (1929) Allgemeine Moorgeologie – Einführung in das Gesamtgebiet der Moorkunde (General mire geology – introduction to mire research). *Handbuch der Moorkunde*, 1. Gebrüder Borntraeger, Berlin, 308 pp. (in German).

Vorren, K-D., Mørkved, B. & Bortenschlager, S. (1993) Human impact on the Holocene forest line in the Central Alps. *Vegetation History and Archaeobotany*, 2, 145–156.

Vuorela, I. (1983) Field erosion by wind as indicated by fluctuations in the ash content of *Sphagnum* peat. *Bulletin of the Geological Society of Finland*, 55, 25–33.

Walker, D. & Walker, P.M. (1961) Stratigraphic evidence of regeneration in some Irish bogs. *Journal of Ecology*, 49, 169–185.

Wegmüller, S. (1966) Über die spät- und postglaziale Vegetationsgeschichte des südwestlichen Juras (About the late- and post-glacial vegetation history of south-western Jura). *Beiträge zur Geobotanischen Landesaufnahme der Schweiz*, 48, 1–143 (in German).

Submitted 26 April 2007; revisions 15 June 2007
Editor: Olivia Bragg

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