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
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 cm² was cut from the peat monolith and divided into segments 1–3 cm long to give samples of 2–12 cm³, 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.

<table>
<thead>
<tr>
<th>Site</th>
<th>Locality and Region</th>
<th>Mire topography</th>
<th>Altitude (m a.s.l.)</th>
<th>Latitude Longitude</th>
<th>Area (ha)</th>
<th>Edge (m)</th>
<th>Depth (m)</th>
<th>Sampling surface</th>
<th>Mire vegetation</th>
<th>Landscape type</th>
<th>Forest vegetation</th>
<th>Grazing</th>
<th>Drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOE</td>
<td>Le Moé Vaud, Switzerland</td>
<td>raised</td>
<td>1300</td>
<td>46°32'47'' N 06°13'45'' E</td>
<td>12</td>
<td>20</td>
<td>&gt;2</td>
<td>Sphagnum lawn</td>
<td>Carex, Potentilla, Sphagnum</td>
<td>pasture woodland</td>
<td>Picea, Abies, Fagus</td>
<td>no (fenced)</td>
<td>water hole</td>
</tr>
<tr>
<td>AMB</td>
<td>Les Amburnex Vaud, Switzerland</td>
<td>raised</td>
<td>1370</td>
<td>46°32'23'' N 06°13'54'' E</td>
<td>0.25</td>
<td>15</td>
<td>&gt;2</td>
<td>Sphagnum lawn</td>
<td>Carex, Potentilla, Sphagnum</td>
<td>pasture woodland</td>
<td>Picea, Abies, Fagus</td>
<td>no (fenced)</td>
<td>20th cent. pipe</td>
</tr>
<tr>
<td>WE1</td>
<td>Weissbrunnalm 1 Ulental, South Tyrol</td>
<td>flat</td>
<td>2070</td>
<td>46°28'39'' N 10°49'27'' E</td>
<td>1.5</td>
<td>10</td>
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<td>Sphagnum hummock</td>
<td>Juniperus, Sphagnum, Carex</td>
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<td>Picea, Larix, Pinus cembra</td>
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<td>none</td>
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<tr>
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<td>2070</td>
<td>46°28'39'' N 10°49'27'' E</td>
<td>1.5</td>
<td>6</td>
<td>&gt;2</td>
<td>Sphagnum hummock</td>
<td>Carex, Potentilla, Sphagnum</td>
<td>pasture woodland</td>
<td>Picea, Larix, Pinus cembra</td>
<td>yes</td>
<td>none</td>
</tr>
<tr>
<td>FIS</td>
<td>Fischersee Ulental, South Tyrol</td>
<td>flat</td>
<td>2060</td>
<td>46°28'46'' N 10°49'40'' E</td>
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<td>12</td>
<td>&gt;2</td>
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<td>Picea, Larix, Pinus cembra</td>
<td>yes</td>
<td>none</td>
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<tr>
<td>ROA</td>
<td>Rosaninalm Lungau, Austria</td>
<td>sloping</td>
<td>1830</td>
<td>46°57'40'' N 13°47'20'' E</td>
<td>0.5</td>
<td>17</td>
<td>&gt;2</td>
<td>Sphagnum hummock</td>
<td>Carex, Potentilla, Sphagnum</td>
<td>pasture woodland</td>
<td>Picea, Larix, Pinus cembra</td>
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<tr>
<td>WEN</td>
<td>Wengerkopf Lungau, Austria</td>
<td>flat</td>
<td>1790</td>
<td>47°10'40'' N 13°52'40'' E</td>
<td>0.25</td>
<td>12</td>
<td>1.3</td>
<td>Sphagnum hummock</td>
<td>Carex, Potentilla, Sphagnum</td>
<td>grazed forest</td>
<td>Picea, Larix, Pinus cembra</td>
<td>yes</td>
<td>none</td>
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<tr>
<td>GUS</td>
<td>Gr. Überling Schattseite-Moor Lungau, Austria</td>
<td>flat</td>
<td>1750</td>
<td>47°10'20'' N 13°54'00'' E</td>
<td>12</td>
<td>100</td>
<td>&gt;2</td>
<td>Sphagnum hummock</td>
<td>Carex, Pinus mugo</td>
<td>grazed forest</td>
<td>Picea, Larix, Pinus cembra</td>
<td>no (fenced)</td>
<td>none</td>
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<tr>
<td>SIJ</td>
<td>Šijec Pokljuka, Slovenia</td>
<td>raised</td>
<td>1200</td>
<td>46°20'09'' N 14°00'00'' E</td>
<td>16</td>
<td>60</td>
<td>&gt;2</td>
<td>Sphagnum hummock</td>
<td>Ericaceae, Sphagnum</td>
<td>grazed forest</td>
<td>Picea</td>
<td>no</td>
<td>none</td>
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</table>
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 14C 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.
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%).
Table 3. Radiocarbon dates for peat samples from Sites WE2, FIS, ROA and GUS.

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

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.
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.

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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

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 (Grüning 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 regrowth 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 Gotthard 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 14C-plateau accentuates the problem of dating, as calibrated 14C-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.

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