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A multi-proxy, high-resolution record of peatland development and its drivers during the last millennium from the subalpine Swiss Alps

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ABSTRACT

We present a record of peatland development during the last 1000 years from Mauntschas mire in the eastern Swiss Alps (Upper Engadine valley; 1818 m a.s.l.) inferred from testate amoebae (pH and depth to the water table (DWT) reconstructions), stable oxygen isotopes in *Sphagnum* ($\delta^{18}O$; proxy for water vapour pressure) and carbon isotopes in *Sphagnum* ($\delta^{13}C$; proxy for mire surface wetness), peat accumulation rates, charcoal (indicating local burning), pollen and spores (proxies for human impact), and plant macrofossils (reflecting local vegetation and trophic state). Past human impact on the local mire conditions was strong but fluctuating during AD 1000—1570 (±50 yr; depth—age model based on 29 ^{14}C AMS dates) with local irrigation of nutrient-enriched water and grazing. Human impact was minor AD 1570—1830 (±30 yr) with partial recovery of the local mire vegetation, and it was absent AD 1830 (±30 yr)—present when hummock formation took place. Correlations among DWT, pH, $\delta^{13}C$, and $\delta^{18}O$, carried out both with the raw data and with linear trends removed, suggest that the factors driving peatland development changed over time, since only testate amoeba-based pH and DWT co-varied during all the three aforementioned periods. $\delta^{18}O$ correlates with $\delta^{13}C$ only in the period AD 1830—present and with DWT only during AD 1570—1830, $\delta^{13}C$ correlates with DWT only during AD 1000—1570. Part of this apparent instability among the four time series might be attributed to shifts in the local mire conditions which potentially formed very different (non-analogue) habitats. Lack of analogues, caused, for example, by pre-industrial human impact, might have introduced artefacts in the reconstructions, since those habitats are not well represented in some proxy transfer functions. Human impact was probably the main factor for peatland development, distorting most of the climate signals.

Keywords: Last millennium, Multi-proxy, High resolution, Palaeoecology, Peatland, Alps, Climate, Human impact

1. Introduction

Two main factors lead to ecosystem change in Alpine peatlands: climate change and human action (Grünig, 1994; Körner, 2003). Ongoing global warming is dramatically changing mountain ecosystems. In the European Alps, for example, glaciers are shrinking and current snow conditions differ considerably from those that existed 50 years ago (Laternser and Schneebeli, 2003;

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Wipf et al., 2009). Peatland ecosystems accumulate records of their own developmental history; thus, they may represent a valuable archive of hydro-climatic changes and human impact (Charman, 2002; Booth et al., 2005). Among them, peatlands in mountains are generally given little attention, even though they differ markedly from lowland peatlands (Succow and Joosten, 2001) and were shown to be sensitive to climate change and human impact on decadal to millennial time scales. During the last few centuries, most mires in the Alps were repeatedly impacted by human action (Sjögren et al., 2007), but some were shown to be controlled by climate during the twentieth century (van der Knaap and van Leeuwen, 2003).

This study focuses on change in a peatland in the European Alps during the last millennium, with special attention to the drivers of that change. More specifically, we are interested in linking peatland development (vegetation, hydrology, peat accumulation) to climate and human impact. One objective is to find climate signals, as the mire lies close to the forest-limit ecotone where climate may be limiting for a number of organisms and processes. We aim at high temporal (near-annual) resolution, as this brings phenomena to light that are otherwise missed (van der Knaap et al., 2000; van der Knaap and van Leeuwen, 2003).

To study effects of climate change and human impact on peatland development, we use multiple proxies providing information on different environmental variables at different spatial and temporal scales (Lotter, 2003; Hájek et al., 2006). Testate amoebae and stable isotopes in mosses, for example, tend to respond to different aspects of wetness: the former respond predominantly to mire surface wetness (Mitchell et al., 2008), the latter to evaporation stress (Moschen et al., 2009; Hangartner, 2010). $\delta^{18}O$ was found to react sensitively to altitudinal climate parameters especially in *Sphagnum* (Ménot-Combes et al., 2002; Hangartner, 2010), whereas the $\delta^{18}O$ signal in some vascular plants is mainly driven by local conditions such as relative humidity and evaporation and transpiration rates. $\delta^{13}C$ in *Sphagnum* was found to correlate with temperature (Skrzypek et al., 2007) and with summer surface wetness; it was also shown to reflect the seasonality of precipitation (Nichols et al., 2009). Differences in spatial scale arise when including proxies transported by wind, such as pollen, spores, and charcoal. These proxies reflect environmental changes from within a few meters to many kilometers (Sugita, 1994; Sjögren et al., 2010; van der Knaap et al., in press). In contrast, most macrofossils remain where they were formed, as they represent the material the peat is built of (*Sphagnum* and other mosses, roots, stems). Only leaves of vascular plants and fertile parts may have moved horizontally, but over shorter distances than the smaller, air-borne pollen and spores. A comparison between micro- and macro-remains might thus help to disentangle local from regional changes in vegetation (Birks and Bjune, 2010), which is important for separating climatic from human impacts on peatland development (de Jong et al., 2010). Multi-proxy studies at this resolution are still very rare globally (Lamentowicz et al., 2010a). This is the first high-resolution multi-proxy study of an Alpine peatland (Lamentowicz et al., 2010c).

2. Study site

Mauntschas mire is located near St. Moritz in the Upper Engadin valley, south-eastern Swiss Alps (46° 29′ 24.7" N, 9° 51′ 16.7" E, 1818 m a.s.l., 10 ha in size) (Fig. 1). Part of the mire surface is fed by calcium-rich spring-water. The studied peat section was collected in August 2003 from an area characterized by low hummocks, where the surface is ombrotrophic but deeper layers are calcium-rich. As a result, shallow-rooted, ombrotrophic vascular plants grow mixed with deep-rooted vascular plants which indicate more minerotrophic conditions. Lamentowicz et al. (2010a) provides a detailed description of the study site.

3. Material and methods

3.1. Sampling methods

On 6 August 2003, a 130 cm deep peat monolith was collected with a spade from a *Sphagnum* hummock (diameter ca. 3 m, located in wet peat lawn) in the undisturbed part of Mauntschas. The monolith was stored in the dark at 4 °C and, in February 2004, carefully sampled with scissors and knives at near-annual resolution following the preliminary depth—age model of Goslar et al. (2005). The peat section was studied from the surface down to a depth of 100.5 cm. Sample depths are identical for all proxies, except for 29.2—48.4 cm where two contiguous sub-sections were sampled, one for testate amoebae and macrofossils, the other for

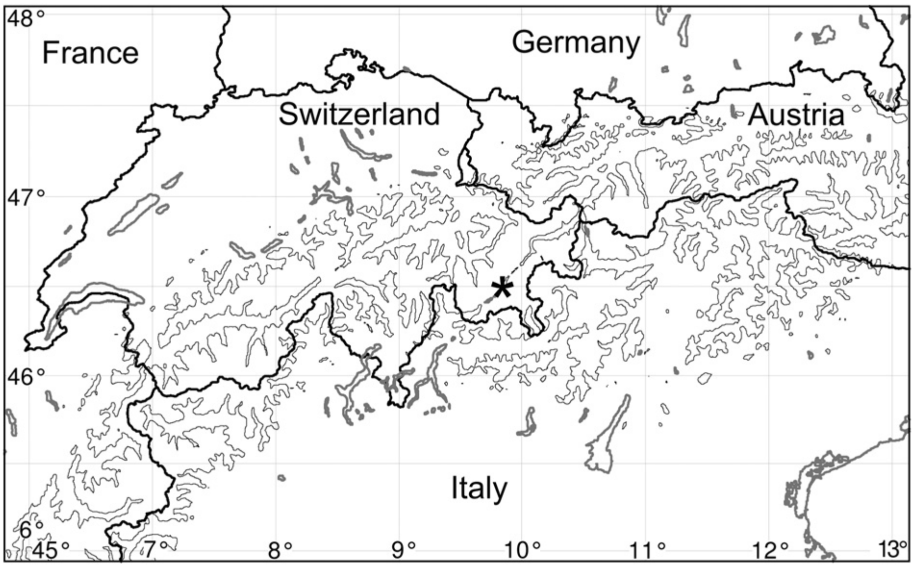

Fig. 1. Map of study site. The study site Mauntschas mire is shown by asterisk. Thick black lines are country boundaries. Thick grey lines are shores. Thin black lines show 1800 m a.s.l. (elevation of study site). Latitude and Longitude are indicated.

the additional proxies. This led to sample depth differences of 0.1 cm between the sub-sections. Five samples yielded insufficient material for one or the other proxy analysis. The 17 samples below 97.1 cm depth were only analysed for pollen and stable isotopes. The total data set includes 335 samples for testate amoebae, 351 for stable isotopes, 354 for pollen, and 132 for macrofossils. Lamentowicz et al. (2010a) provides additional information on the sub-sampling.

3.2. Analytical methods

Goslar et al. (2009) described the depth–age modelling. In the depth–age model, the 2σ uncertainty of sample ages does not exceed ±2 yr for the interval AD 1950–2002, ±30 yr for the interval AD 1550–1950, and ±50 yr before AD 1550.

Testate amoeba samples were washed over sieves of 20 and 300 μm mesh size using only water; the fraction 20–300 μm was used for extracting testate amoebae (Lamentowicz et al., 2010a). The testate amoebae were identified and counted at ×200 and ×400 magnification. Taxonomy followed Ogden and Hedley (1980), Grospietsch (1990), Meisterfeld (2001a, b) and Clarke (2003); some difficult taxa were discussed with other specialists in testate amoeba taxonomy.

Previous studies of stable isotopes in mires indicate that individual plant taxa respond differently to environmental gradients, so that species-specific studies are required for palaeoclimate reconstructions (Ménot-Combes et al., 2002; Moschen et al., 2009). But even within a single *Sphagnum* species, branches and stems have a significant offset (Loader et al., 2007), with more homogeneous values for branches than for stems (Kaislahti Tillman et al., 2010). Thus, the stable isotopes δ^{13}C and δ^{18}O were measured separately on bulk *Sphagnum* stems and *Sphagnum* branches. Above 81.5 cm depth (AD 1625), *Sphagnum* stems were further separated in 'dark solid' (mostly *Sphagnum fuscum*) and 'light flaccid' (other *Sphagnum* species), but in deeper (older) levels this distinction was not feasible due to stronger decomposition of the material and all stems were assigned to 'light flaccid' which they resembled most. Extraction of α-cellulose has been recommended if enough material is available (Ménot and Burns, 2001; Kaislahti Tillman et al., 2010), but this is not always needed since the offset in stable isotopes between raw and cellulose-extracted material is generally quite constant. In this study, insufficient material was available for the extraction of α-cellulose. Whenever sufficient material was available, each studied level was measured on two samples of 0.5 mg, others were measured on a single sample of 0.5 mg when available, or less if necessary. The uncertainty in the isotope ratio is expressed as one standard deviation (1σ) of the double measurements. As these values are multiples of the analytical error, they mainly express the uncertainty of the measurements due to isotopic variation in the sample material. Hangartner (2010) provides more detailed information on the methods.

The time series of δ^{18}O and δ^{13}C from the three types of *Sphagnum* material were combined to single δ^{18}O and δ^{13}C time series based on the following criteria:

(i) Double measurements on *Sphagnum* branches were selected when available ($n = 144$) and were offset to double dark-solid *Sphagnum* stem measurements (offsets based on samples that have both types of measurements: 0.014 for δ^{18}O and −1.57 for δ^{13}C based on $n = 134$).
(ii) In the remaining samples, double dark-solid stem measurements were selected when available ($n = 159$; no offset).
(iii) In the remaining samples, double light-flaccid *Sphagnum* stem measurements were selected when available ($n = 36$) and were offset to double dark-solid stem measurements (offset 0.30 for δ^{18}O and 0.27 for δ^{13}C based on $n = 18$).
(iv) In the remaining samples, single dark-solid stem measurements were selected when available ($n = 11$; no offset); the δ^{18}O value at 36.3 cm is an outlier and was replaced by the average of adjacent values.

The final isotope sequences have 351 values, 340 based on double measurements and 11 on single measurements (Fig. 5).

The samples for pollen, spores, and microscopic charcoal were cleaned using standard procedures including 6 min of KOH (10%, 90 °C), sieving (0.25 mm screen), 2 min of acetolysis, and 3 min of KOH (10%, 60 °C). For quantification, each sample was spiked with *Lycopodium* (Stockmarr, 1971). Identification of microfossils followed van der Knaap et al. (2000). Charcoal particles >10 μm were counted together with the microfossils. Kamenik et al. (2009) described the methods in more detail.

Plant macrofossils were analysed from the sieve residues of testate amoeba analysis; macrofossil analyses below 13 cm depth were carried out on mixtures of contiguous samples in order to obtain sufficient volume for analysis (Amesbury et al., 2011). Macrofossils were extracted from the samples by boiling in 5% KOH, followed by sieving over 125 μm mesh size. Macrofossils were scanned using a binocular microscope (10–50×), and identified using an extensive reference collection of plant material (Mauquoy and van Geel, 2007). Identifications checked by colleagues include *Hyphum jutlandicum* by Andy McMullen (Aberdeen, UK). Volume percentages were estimated for all components with the exception of seeds, *Sphagnum* spore capsules, and charcoal particles, which were counted and expressed as the number (n) present in each sample.

3.3. Numerical methods

Following the example of Lamentowicz et al. (2008), testate amoebae were used to reconstruct both surface wetness (as the depth to the water table = DWT) and pH. Transfer functions were based on Weighted Averaging, resulting in a Root Mean Square Error of Prediction (RMSEP) of 3.5 cm ($r^2 = 0.89$) for DWT (Lamentowicz et al., 2010a) and of 0.4 ($r^2 = 0.86$) for pH (Mitchell et al., submitted for publication). Surface wetness and pH are significantly correlated in the training set. To facilitate statistical comparisons with other proxies, depth differences between testate amoeba samples and the other proxies in the 29.2–48.4 cm interval (see section 2.2 on sub-sampling) were compensated by shifting the former downwards by 1 mm ($n = 61$).

The depth–age model (Goslar et al., 2009) provides the sediment-accumulation rates (cm yr^{-1}, and its inverse, yr cm^{-1}), which were square-root transformed to stabilize the variance.

Counts of pollen, spores, and microscopic charcoal were converted to accumulation rates (PAR = particles cm^{-2} yr^{-1}), also called influx. Indicators for human impact were summarized into three groups after stabilizing their variance by square-root transformation: dung-related fungal spores (first group in Fig. 3); microscopic charcoal; and hay-meadow pollen (third group in Fig. 3), which are pollen types indicative of local irrigation with nutrient-enriched water (Calthion plant communities, now virtually absent from the entire valley of study). A pollen-based reconstruction of mean April–November temperatures was developed by applying the calibration model of Kamenik et al. (2009) to non-detrended pollen percentages. Since human impact might have led to artefacts in this reconstruction, we tried to reduce anthropogenic influence with information from hay-meadow pollen indicative of irrigation (see above). Hay-meadow pollen was not included in the percentage calculation of the six pollen types the reconstruction was based on. The pollen-based reconstruction and hay-meadow

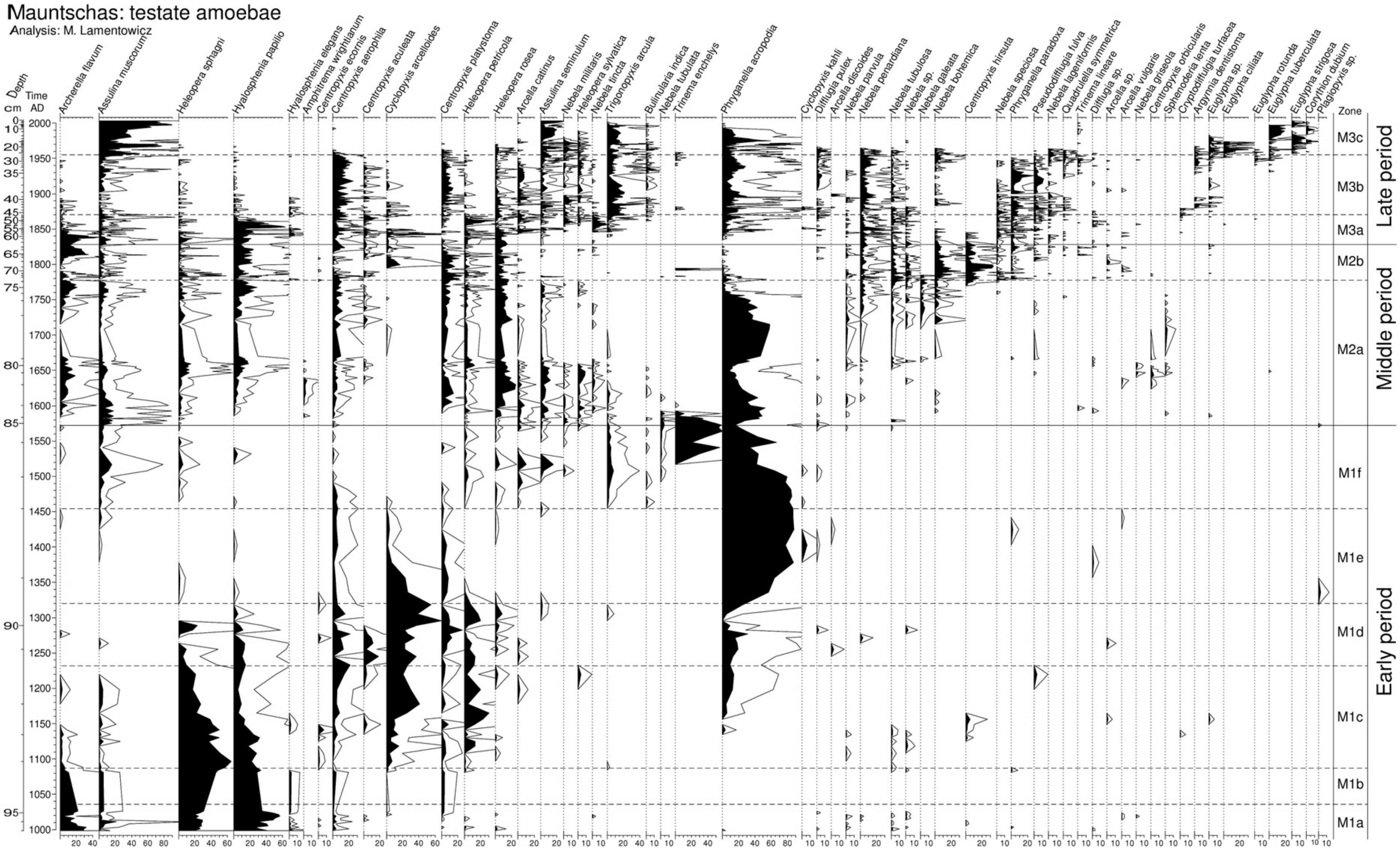

Fig. 2. Testate amoebae. Percentages, Periods and zones are identical in Figs. 2–5. Analysis: M. Lamentowicz.

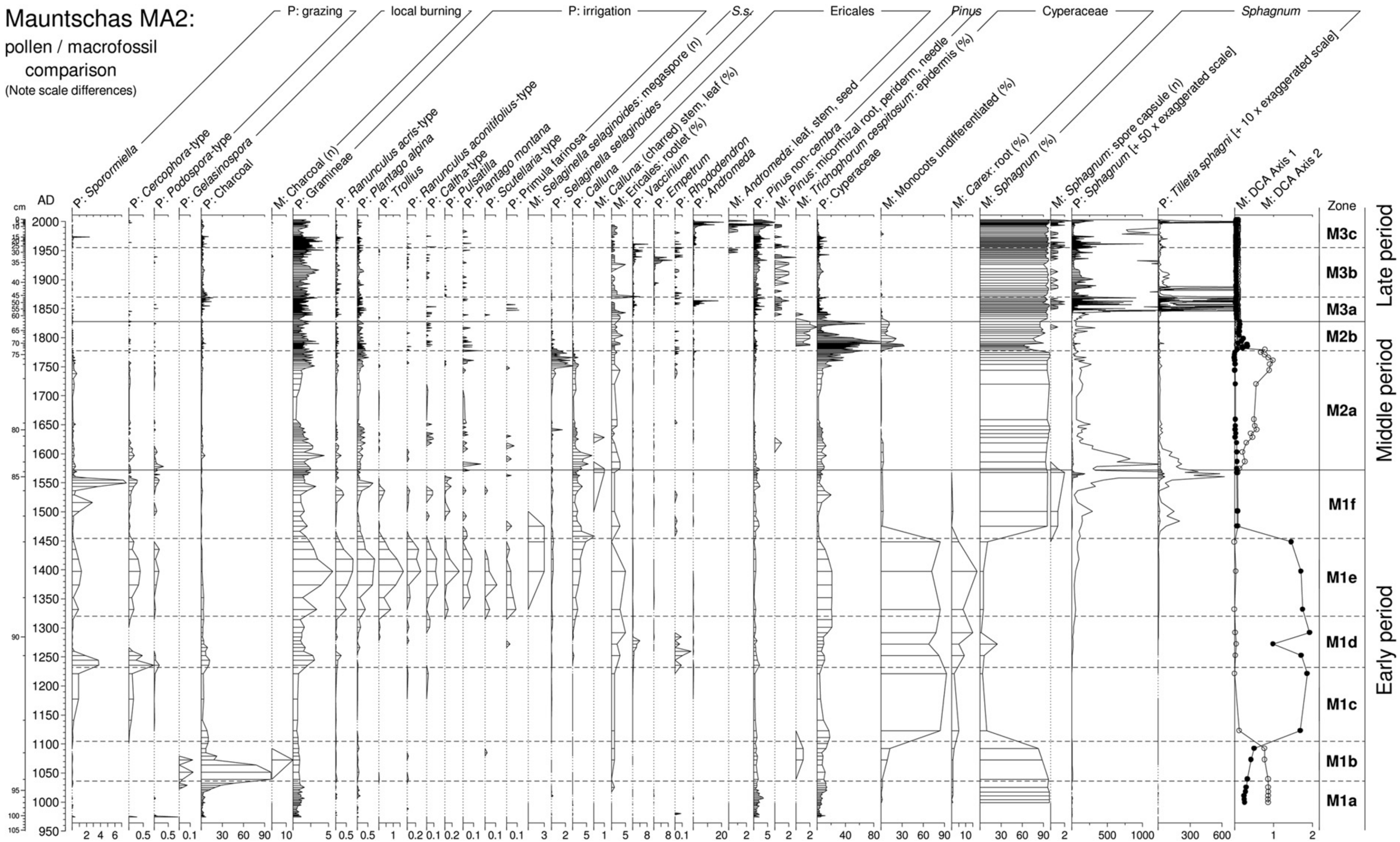

Fig. 3. Selected microfossils counted on pollen slides and summarized macrofossils. P: microfossils counted on pollen slides (particles mm^{-2} yr^{-1}). M: macrofossils, summarized from Fig. 4. Individual samples are shown by depth bars in curves. The P groups 'grazing' and 'irrigation' are summarized in Fig. 5. Group 'S.s.' includes *Selaginella selaginoides*. Periods and zones are identical in Figs. 2–5. Analyses: Jacqueline van Leeuwen (pollen and spores), Dmitri Mauquoy (macrofossils), and W.O. van der Knaap (charcoal in pollen slides).

pollen percentages were thus independent from each other. We eliminated changes in the pollen-based reconstruction, which might have been caused by human impact on the underlying six pollen types, by fitting a linear, Ordinary Least Squares regression model with pollen-based temperature depending on hay-meadow pollen ($R^2 = 0.18$, overall $P < 0.001$). The residuals from this model are independent from hay-meadow pollen and, most likely, from human disturbances. The two temperature reconstructions (with and without human impact) were rescaled to equal mean and variance of April–November temperature during the instrumental period (AD 1864–2003).

To simplify comparison, selected plant macrofossils were grouped in similar taxonomic units as those of pollen (Fig. 3). Plant macrofossils were summarized by Detrended Correspondence Analysis (DCA) (Fig. 5).

Selected proxies were smoothed for visual comparison using a 25-year triangular low-pass filter, which corresponds to the coarsest temporal resolution per sample (Fig. 5). Exploratory data analysis was, however, based on the original data, since smoothing would have removed information on high frequency changes, which we considered to be important when comparing proxies on short time intervals. To facilitate the comparison between the different proxies, samples were grouped into three stratigraphic units or time periods (Figs. 2–5, Table 1). The splits between the periods were based on visual examination of similarities among the curves of DWT, pH, $\delta^{13}C$, and $\delta^{18}O$: The boundary between the early and middle period was based on the observation that during the early period, these proxies show similarities both at low and high frequencies (decreasing values up to AD 1300, then increasing to 1520, then decreasing to 1570), while during the middle period, the same proxies show clear differences (Fig. 5). The boundary between the middle and late period was set at the level where all four proxies show different trends (coinciding with finer temporal resolution).

Similarities among the same proxies were further tested with Pearson's correlation using the programme PAST (v. 1.96; Hammer et al., 2001). Correlations were based on raw data (neither smoothed nor regularized) with and without linear detrending, thus considering potentially different signals in short-term (decadal – centennial) changes and long-term trends. Statistical analyses were carried out on the complete time series and on each of the three main periods (early, middle, and late).

4. Results and interpretation

Figs. 2–4 show the stratigraphies of testate amoebae, dung-related spores tracing local grazing, indicators for local burning, hay-meadow pollen reflecting irrigation, a selection of micro- and related macrofossils, and peat composition. Fig. 5 summarizes low-pass filtered proxies.

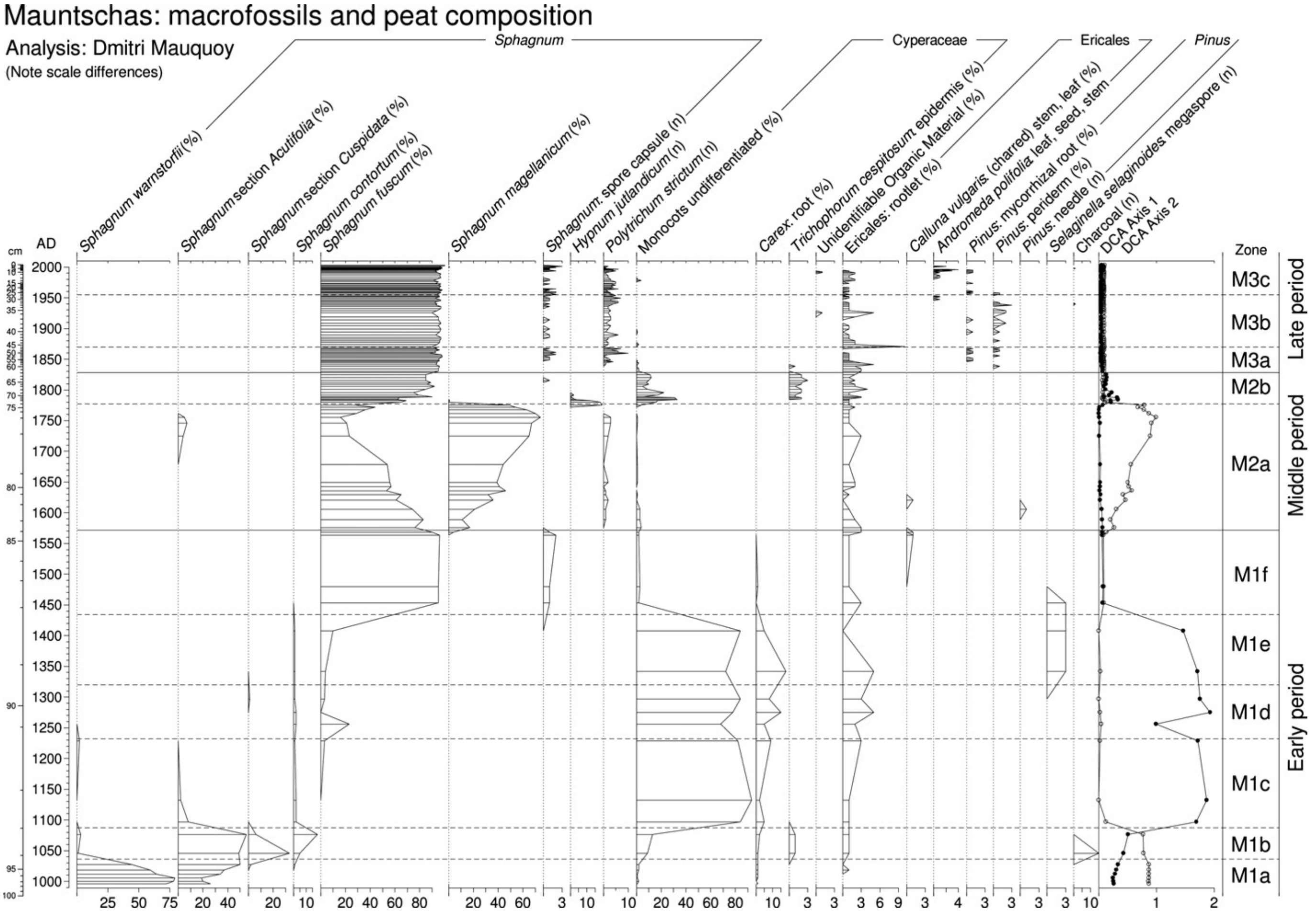

Fig. 4. Plant macrofossils and peat composition. (%) following a name denotes volume percentage, (n) the count for the entire analysed samples. Individual samples are shown by depth bars in curves. Omitted are Ericales stem (AD 1966–2000 only) and *Carex* nutlet (1 occurrence). Combined are: *Calluna vulgaris* charred stem, stem, and leaf; *Andromeda polifolia* leaf, seed, and stem; and two size classes of charcoal (1 piece >2 mm in AD 1940, <0.5 mm elsewhere). Note scale differences. Periods and zones are identical in Figs. 2–5. Analysis: Dmitri Mauquoy.

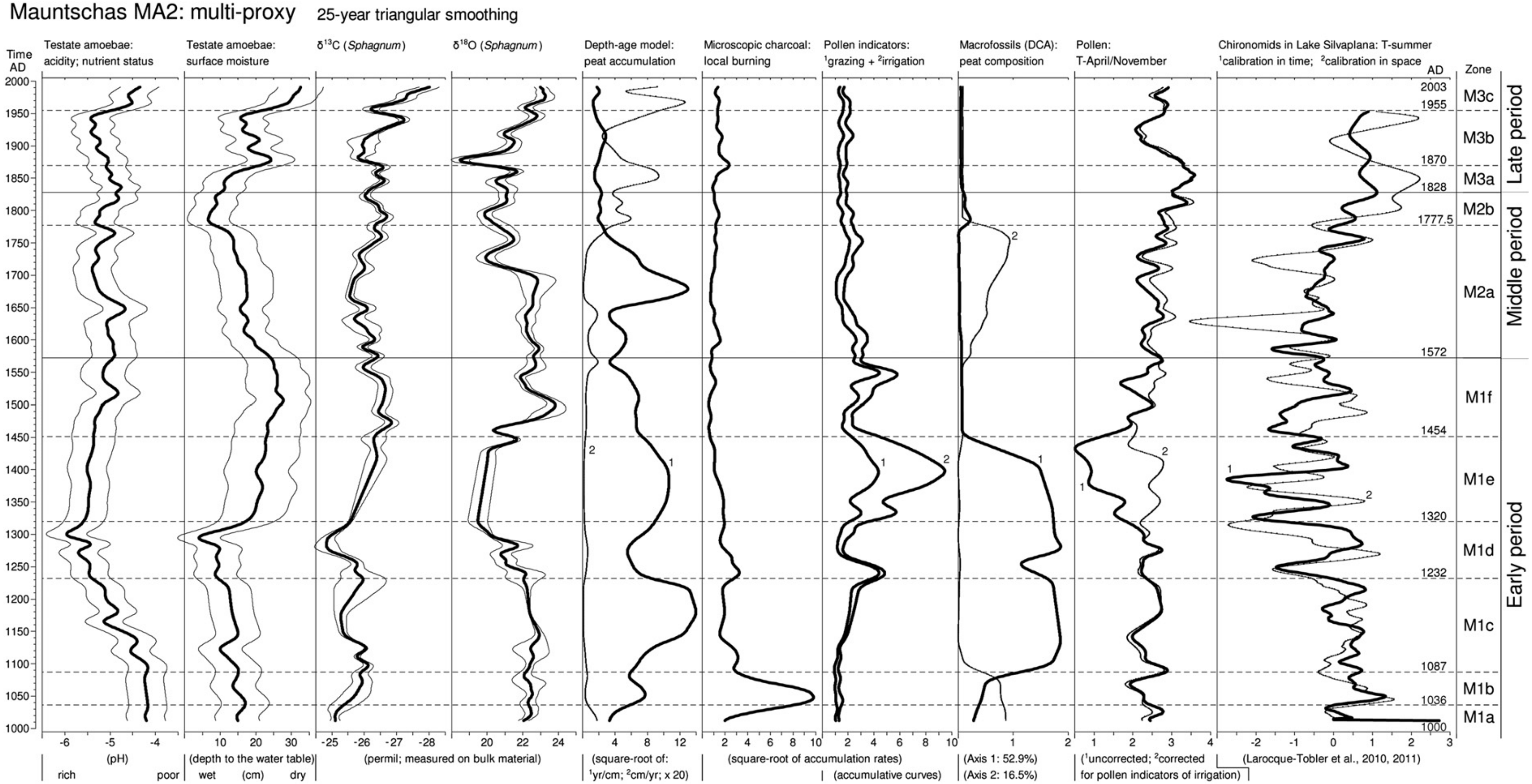

Fig. 5. Summary curves of the proxies. The reconstructions of pH and depth to the water table (DWT) are shown with their bootstrap error intervals (thin lines). Thin lines flanking $\delta^{18}O$ and $\delta^{13}C$ measurements are 1σ standard deviations of two measurements per level. The depth–age model provides peat accumulation rates (cm yr^{-1}) and its inverse (yr cm^{-1}). Charcoal is microscopic charcoal in pollen slides; accumulation rates are particles mm^{-2} yr^{-1}. The pollen indicators 'grazing' and 'irrigation' summarize curves shown in Fig. 3; accumulation rates are grains mm^{-2} yr^{-1}. DCA axes 1 and 2 of macrofossils track the changes in peat composition (cf. Fig. 4). The pollen-based reconstruction of mean April–November temperatures follows Kamenik et al. (2009); the thin line is corrected for indicators of irrigation. The chironomid-based temperature reconstruction (far right) is based on a nearby lake (Larocque-Tobler et al., 2010, 2011). Periods and zones are identical in Figs. 2–5.

Table 1
Zonation scheme of Figs. 2–5.

Period	Zone	Top age[a]	Bottom age[a]
Late period	M3c	AD 2003	AD 1955
	M3b	AD 1955	AD 1870
	M3a	AD 1870	AD 1828
Middle period	M2b	AD 1828	AD 1777.5
	M2a	AD 1777.5	AD 1572
Early period	M1f	AD 1572	AD 1454
	M1e	AD 1454	AD 1320
	M1d	AD 1320	AD 1232
	M1c	AD 1232	AD 1087
	M1b	AD 1087	AD 1036
	M1a	AD 1036	AD 999[b]

[a] Ages are approximate, with uncertainties according to the depth–age model.
[b] AD 970 for pollen-based proxies and isotopes.

4.1. *The individual proxies*

4.1.1. *Past mire wetness and acidity*

Assemblages of testate amoebae (Fig. 2) were used to reconstruct past surface wetness (as water table depth) and past acidity (pH; a measure of general base richness; Hájková et al., 2008) at the exact sampling locality (Fig. 5). Zones M1a and M1b are characterized by wetness indicators such as *Hyalosphenia papilio* and *Archerella flavum* and other species associated with *Sphagnum* such as *Heleopera sphagnii*. At the beginning of zone M1c *H. sphagnii* reaches a maximum, and *Centropyxis aerophila* and *Cyclopyxis arcelloides* indicate increased wetness and pH. The reconstructed wet conditions of zone M1d are mainly based on *C. arcelloides*. In zone M1e the increasing dominance of *Phryganella acropodia* indicates gradually drier conditions. During zone M1f, continued dry conditions are indicated by the dominance of *P. acropodia* and *Trinema enchelys,* and the diversity started to increase. In zone M2a *H. papilio* indicates an increase in wetness, and the diversity further increased. The higher abundance of *A. flavum* and *Assulina muscorum* are typical for a higher abundance of *Sphagnum* (Lamentowicz et al., 2010b). Increasingly minerotrophic conditions (higher pH) are marked by *Nebela penardiana*, *Sphenoderia lenta*, *Centropyxis aculeata*, *C. aerophila*, and *Centropyxis platystoma*. Zone M2b had very wet conditions; *Centropyxis hirsuta*, *H. papilio*, and several other species suggest even shallow water conditions with floating mosses. The surface became markedly drier during zone M3a, due to the local development of a *Sphagnum* hummock (compare with macrofossils). The mire became again wetter in the course of zone M3b, but also more minerotrophic (higher pH; decline of both *A. flavum* and *H. papilio*). In this geographic region *Difflugia pulex* is an indicator of minerotrophy (Lamentowicz et al., 2010b) rather than of dry conditions as found in other regions (Lamentowicz et al., 2008). The surface became markedly drier in zone M3c; the water table today is the lowest of the entire last millennium. The main drought indicators in this zone are *Trigonopyxis arcula*, *P. acropodia*, *A. muscorum*, *Assulina seminulum*, and *Euglypha* spp. Further indications for drought are the decline of *C. aerophila*, *C. platystoma*, and *Quadrulella symmetrica*. The link between surface wetness and pH throughout the millennium suggests that the wetness had its source in groundwater, which is rich in carbonates, rather than in rainwater. Only the bottom (zones M1a and M1b) and top (zone M3c) were sufficiently acid to suggest ombrotrophic conditions.

4.1.2. *Climate information in stable isotopes*

Stable carbon and oxygen isotopes were measured with the aim of obtaining climate information. Mean values of $\delta^{13}C$ and $\delta^{18}O$ measured in *Sphagnum* species in Switzerland follow the known altitudinal gradient (Ménot and Burns, 2001; Ménot-Combes et al., 2002). They may therefore be governed by the decreasing partial pressure of CO_2 ($\delta^{13}C$) and the altitudinal dependence of the isotopic composition of precipitation ($\delta^{18}O$). Both isotopes are highly correlated between *Sphagnum* branches and stems, though branch values clearly have a smaller range. According to Hangartner (2010), correlations of $\delta^{13}C$ from Mauntschas with temperature, precipitation, and relative humidity are not significant, in contrast to those of $\delta^{18}O$ that exhibit at least partly significant values; the strongest correlation is obtained for $\delta^{18}O$ and water vapour pressure (related to the relative humidity). Branch $\delta^{18}O$ appeared to be more sensitive to climate than stem $\delta^{18}O$. For the correlations, Hangartner (2010) used the meteorological data AD 1864–2003 from the nearby station of Segl Maria as well as monthly gridded climate data AD 1901–2003 (grid cells of 0.5° Latitude and Longitude; CRU TS 3.0, http://www.cru.uea.ac.uk/cru/data/hrg/, Brohan et al., 2006). For the last millennium, similar results were obtained for $\delta^{18}O$ and reconstructed pH ($r = 0.53$, after excluding the extremely low $\delta^{18}O$ values for AD 1871–1885). The correlation increases to $r = 0.8$ for a 25-year running mean as shown in Fig. 5.

4.1.3. *Past human impact at the local scale*

Palynomorphs, plant macrofossils, and charcoal were used to reconstruct past human impact. The spatial scale of reconstructed events can in part be assessed from the relation between macrofossils and microfossils of the same taxonomic origin. Simultaneous occurrence in a zone indicates that the plants grew at the sampling spot. This is the case with *Selaginella selaginoides* and various taxa within the Ericales. However, the data do not allow setting a threshold of spore or pollen values indicative of local presence or absence of the plants. This implies that scattered pollen or spore occurrences can be strictly local, but are not necessarily so. Cyperaceae pollen was always found, but became fairly low when Cyperaceae macrofossils were absent. When no Cyperaceae macrofossils were found, Cyperaceae plants must still have grown within a distance of a few metres at the most, as there is hardly a peatland in Europe without Cyperaceae and Mauntschas mire today abounds with them from dry to wet and from poor to rich habitats. Among *Sphagnum* species, *S. fuscum* has by far the highest spore production. *Tilletia sphagni* spores are closely associated with *Sphagnum* spores, as could be expected (van Geel, 1978).

Among the three different indicators of human impact, dung-related fungal spores (first group in Fig. 3) point to large mammals that occurred close to the sampling spot in several periods. Dominance of *Sphagnum* macrofossils (zones M1a–M1b and M1f–M3c) and a lack of fodder-related macrofossils suggest, however, that the exact sampling spot was never covered by dung, as *Sphagnum* plants would not tolerate a dung cover. Macro-charcoal is found only when microscopic charcoal is abundant (>50 pieces mm^{-2} yr^{-1}), with the exception of one single large stray charcoal piece around AD 1940. Microscopic charcoal in zone M1b in association with *Gelasinospora* and macroscopic charcoal (second group in Fig. 3) show that burning was nearby (van Geel and Aptroot, 2006), though continued accumulation of peat indicates that the fire was not at the exact sampling spot. Pollen characteristic for mineral-rich fen (third group in Fig. 3) indicate close proximity of this type of vegetation (especially in zone M1e), since these plants have low pollen dispersal capacities. This contrasts with the mineral-poor, dense Cyperaceae fen with some *Sphagnum* shown by macrofossils at the sampling spot for zones M1c/e, and with the absence of mineral-rich fen plants among the macrofossils. We hypothesise that the high diversity and abundance of rich-fen pollen in zone M1e away from its place of origin was mainly caused by surface-water runoff transporting pollen, but not macrofossils, over a relatively short distance from the rich fen. Among the pollen indicators for irrigation, especially *Trollius europaeus*, *Caltha palustris*, *Pulsatilla alpina*, *Scutellaria galericulata*, and *Primula farinosa* have low dispersal capacities. Such pollen types usually have irregular (spiky) local representations, explicable as stochastic dispersal related to wind gusts at the microscale, pollen-carrying insects, or flower parts such as complete anthers (e.g., van der Knaap et al., 2000). The pollen types indicative of rich fen in zone M1e, however, all have very similar trends. This indicates pollen transport by water rather than by wind or insects. These trends remain essentially the same for pollen percentages (not shown), so they are not likely to be an artefact caused by an unrealistic depth–age model.

4.2. Multi-proxy reconstruction of local vegetation, peat growth, and hydrology

As demonstrated above, our proxies (Figs. 2 and 3, and 4, summarized in Fig. 5) allow a detailed reconstruction of past vegetation and peat formation at a spatial scale that is essentially local; surface wetness, acidity, stable isotopes in *Sphagnum*, peat-accumulation rates, and the bulk of the macrofossils, which make up the peat matrix (*Sphagnum* and other mosses, Cyperaceae, Ericales rootlets, and *Pinus* roots), reflect the situation at the sampling spot. Pollen, spores, both microscopic and macroscopic charcoal, and above-ground vascular-plant macrofossils mirror the situation of an area of up to several metres away from the sampling spot, even though a minor and therefore negligible part of these fossils may derive from larger distances. *Pinus* non-*cembra*, Gramineae, Cyperaceae, and *Plantago alpina* pollen have a continuous background deposition derived from longer distances; other pollen types with good dispersal properties, mainly trees, are not discussed in this paper (interested readers are referred to Kamenik et al., 2009 and van der Knaap et al., in press). In the following, the quoted ages are approximate according to the uncertainty of the depth–age model.

4.2.1. Early period

4.2.1.1. AD 1000–1087 (zones M1a and M1b). The dominant *Sphagnum* species (Fig. 4) indicate poor fen with groundwater influence at the surface, rather than ombrotrophic bog that is fed only by rainwater. Surface wetness (based on testate amoebae) and the rate of peat accumulation were intermediate and stable, and there was no sign of human impact on the peat growth or on local vegetation (based on pollen indicators). Even the close fire around AD 1050 (zone M1b) does not seem to have influenced the local mire vegetation.

4.2.1.2. AD 1087–1232 (zone M1c). The local situation changed dramatically: *Sphagnum* virtually disappeared, monocotyledons dominated (macrofossils), and around AD 1140 the peat accumulation rate dropped strongly. The association of the mostly undifferentiated monocots with *Carex* roots and Cyperaceae pollen suggests that the monocots were mainly Cyperaceae and even *Carex*. The peat surface became less acidic (testate amoebae), which suggests increased nutrients. We interpret this as a change in hydrology from little horizontal water movement to a stronger one, through *Carex*-dominated fen as it occurs today in other, more nutrient-rich places of the mire. Microfossils indicate a beginning or moderate increase of human impact by way of cattle grazing. A possible scenario is that grazing changed the vegetation from *Sphagnum* to *Carex* dominance, which, in turn, improved the fodder quality on the mire. It is even possible that the inferred change in hydrology was deliberately induced by humans with this aim.

4.2.1.3. AD 1232–1320 (zone M1d). Peaks among grazing indicators, surface wetness, pH, and peat accumulation contrast with the relatively dry, nutrient-poor conditions suggested by pollen maxima among the Ericales (*Vaccinium*, *Rhododendron*). Most likely, these Ericales grew on ombrotrophic peat and/or deforested soil just outside the mire. Microscopic charcoal suggests some burning. Altogether, the evidence suggests human impact that was stronger than in the preceding period (water management for improving the fodder quality, small-scale deforestation along the mire combined with a moderate use of fire such as burning of branches, and cattle grazing closer to the sampling site than before).

4.2.1.4. AD 1320–1454 (zone M1e). The mire became much drier (testate amoebae) and peat accumulation rates reached a minimum. Drying of the mire surface and compaction of the peat was probably caused by trampling, which is often associated with local grazing (Sjögren et al., 2007) as indicated by *Selaginella selaginoides.* Still, a variety of plants typical for periodically flooded, nutrient-rich meadow (third group in Fig. 3) grew very close to the site, while Ericales, characterising dry, nutrient-poor mire (see preceding period), dropped to background values. Possibly, cattle were stabled overnight close to the mire, and the collected manure was used to enrich the water flow directed to irrigate parts of the mire with the aim of increasing fodder or hay production.

4.2.1.5. AD 1454–1572 (zone M1f). The indicators both for grazing and for irrigation declined and the peat accumulation rate (cm yr^{-1}) increased again to levels of the period AD 1235–1320 (zone M1d), which indicates that fewer cattle were around and irrigation came to an end. This period has two main differences with the above-mentioned period: the mire surface was dry (testate amoebae), and *Sphagnum fuscum* dominated (forming lawns or hummocks in relatively dry, ombrotrophic conditions) rather than Cyperaceae (macrofossils). We infer that cessation of irrigation with nutrient-enriched water caused drier and nutrient-poorer conditions at the sampling site, which enabled *S. fuscum* to grow, causing further drying of the surface.

4.2.2. Middle period

4.2.2.1. AD 1572–1777.5 (zone M2a). According to testate amoebae, the mire became gradually wetter, while *Polytrichum strictum* suggested dry conditions at the sampling site (Bayfield, 1973). A temporary admixture with *Sphagnum magellanicum* (macrofossils) indicates more acidic conditions. Peat accumulation was very slow around AD 1660–1700.

4.2.2.2. AD 1777.5–1828 (zone M2b). Indicators for human impact were scarce, the mire was very wet (testate amoebae, absence of *P. strictum*), and peat accumulated rapidly. Still, *S. fuscum* and *Trichophorum cespitosum*, usually occurring on dry mires, dominated the peat-forming vegetation.

4.2.3. Late period

4.2.3.1. AD 1828–2003 (zones M3a/M3c). The mire surface became drier until AD 1870 (zone M3a), wetter around AD 1920–1955 (zone M3b), and drier up to the present day (zone M3c), reaching the driest conditions for the last millennium (testate amoebae). The abundance of *P. strictum* suggests a dry mire surface.

4.3. Peatland development and its forcing factors

Here, we explore similarities and differences among the time series of pH, DWT (depth to the water table), δ^{13}C, and δ^{18}O (Fig. 5) to determine drivers of peat development. Table 2 lists all pair-wise correlations between the four time series (with and without linear

Table 2
Correlations among stable isotopes and amoebae-inferred pH and depth to the water table (DWT) during three time periods[a].

	Data not detrended			Linear trend removed		
	pH	DWT	$\delta^{13}C$	pH	DWT	$\delta^{13}C$
Late period: AD 1828–2003 (N=174)						
$\delta^{18}O$	−0.18*	+0.20**	**−0.39*****	+0.07	**−0.46*****	−0.24**
$\delta^{13}C$	+0.26**	**−0.29*****		+0.04	+0.07	
DWT	**−0.71*****			**−0.67*****		
Middle period: AD 1572–1828 (N=91)						
$\delta^{18}O$	**−0.40*****	**+0.77*****	+0.28**	**−0.48*****	**+0.57*****	+0.14
$\delta^{13}C$	−0.10	+0.30**		−0.10	+0.13	
DWT	**−0.42*****			**−0.68*****		
Early period: AD 999–1572 (N=66)						
$\delta^{18}O$	**−0.42*****	+0.18	+0.10	**−0.52*****	+0.25*	+0.11
$\delta^{13}C$	−0.29*	**−0.62*****		+0.06	**−0.41*****	
DWT	−0.06			**−0.76*****		
Entire sequence: AD 999–2003 (N=331)						
$\delta^{18}O$	**−0.28*****	**+0.32*****	**−0.19*****	**−0.26*****	**+0.29*****	**−0.14*****
$\delta^{13}C$	+0.05	**−0.32*****		−0.02	−0.11*	
DWT	**−0.51*****			**−0.51*****		

[a] Correlation coefficients based on non-smoothed, irregular time series. DWT (depth to the water table) is assumed to reflect surface wetness, so low values indicate wet conditions, high values indicate dry conditions. Asterisks denote statistical significance (*** at $p < 0.001$; ** at $p < 0.01$, and * at $p < 0.05$). The correlation strength is further visualized by using bold or regular typeface.

detrending) in the early, middle, and late time period and in the entire sequence.

The following general observations can be made on the basis of the results presented in Table 2. The only correlation that holds through all time periods is the one between amoebae-inferred pH and amoebae-inferred depth to the water table (DWT), which is always strong apart from that for non-detrended data during the early period. The ecological significance of this correlation is, however, difficult to judge because pH and DWT are inferred from the same proxy (testate amoebae). The two variables are significantly correlated in the training set, and this correlation might propagate into the two reconstructions. Correlations between stable oxygen isotopes and amoebae-inferred pH are strong in the early and middle period but insignificant in the late period. Correlations between stable carbon isotopes and amoebae-inferred pH are always of low significance. Most time series have stronger correlations when not detrended. Correlations for the entire millennium are generally close to the average of those for the individual time periods except for $\delta^{13}C$ and $\delta^{18}O$.

4.3.1. *Early period (AD 999–1572)*

Amoebae-inferred pH and DWT have many features in common even though their long-term trend is opposite (Table 2, Fig. 5). A plausible explanation for the shared features is that minerals and surface water have the same source. This would be the case when fluctuations in surface wetness depend more on groundwater (high pH) than on rainwater (low pH), so that wetter means richer in minerals. Human impact may have caused a long-term divergence of the trends, for example by a general increase of nutrients in the landscape. Nutrient enrichment may have increased the pH directly, but also indirectly by causing shifts in *Sphagnum* species (Fig. 4) that have different capacities to acidify their environment (Kooijman and Bakker, 1994).

In spite of the strong correlation between the two testate-amoeba-derived reconstructions, amoebae-inferred DWT correlates only with $\delta^{13}C$ and amoebae-inferred pH only with $\delta^{18}O$. The two stable isotopes do not correlate with each other. Correlations hold when linear trends are removed. Assuming that strong correlations reflect common forcing, we hypothesize that surface wetness and $\delta^{13}C$ are both driven by precipitation and evaporation temperature (e.g. Moschen et al., 2010; Kaislahti Tillman et al., 2010), while acidity and $\delta^{18}O$ are not affected by these environmental factors. The strong pH/$\delta^{18}O$ correlation might be related to shifts in the abundance of different *Sphagnum* species and/or changes in water sources (Fig. 4; Aravena and Warner, 1992). Table 3 summarizes the potential forcing factors for the four time series.

4.3.2. *Middle period (AD 1572–1828)*

During the middle period, human impact decreased markedly compared to the early period (see above). The strong correlation between the non-detrended time series of amoebae-inferred pH and DWT supports our hypothesis that human impact decoupled the long-term development of acidity and surface wetness during the early period.

The correlation between amoebae-inferred pH and $\delta^{18}O$ remains strong (Table 2) even though no more than two *Sphagnum* species were found (Fig. 4). In turn, the correlation strength between $\delta^{13}C$ and amoebae-inferred DWT decreases, while the correlation strength between $\delta^{18}O$ and amoebae-inferred DWT increases. This discrepancy suggests a shift in environmental forcings. It coincides with a shift in *Sphagnum* species indicating changed hydrological conditions. While the early period had *Sphagnum* species typical for fens and bog hollows (Fig. 4: the first four taxa), the middle period had a species combination typical for *Sphagnum* lawn or hummock (*S. fuscum* and *S. magellanicum*; also *P. strictum*), probably changing the isotopic fractionation (Ménot-Combes et al., 2002).

4.3.3. *Late period (AD 1828–2003)*

Apart from the correlation among amoebae-inferred pH and DWT, which might be affected by correlations among the two variables in the training set (see above), correlations change

Table 3
Potential drivers behind the correlations among four time series during the early period (AD 999–1572).

Drivers	$\delta^{18}O$	pH	DWT	$\delta^{13}C$
Water source (surface/precipitation)		X	X	
Human impact (direct: minerals)[a]		X	–	
Human impact (indirect: shifts in *Sphagnum* species)	X	X		
Temperature (relative humidity; evapotranspiration)			X	X

The time series are re-arranged compared to Table 2 to highlight their relationships with potential drivers. X denotes presence of the driver;– denotes absence of the driver.

[a] Nutrient enrichment might suppress the acidity/surface-wetness relationship, as suggested by untransformed data.

drastically from the middle to the late period, suggesting a drastic shift in forcing factors. We hypothesise that *S. fuscum*, the only *Sphagnum* species involved in the late period, started to grow above the surrounding surface water level through the process of hummock formation (see the surface-wetness curve in Fig. 5), so that direct precipitation became the main water source.

4.4. The climate signal in the proxies

Four temperature reconstructions are shown (Fig. 5, far right), two mean April–November temperature time series inferred from selected pollen from our site with and without correction for human impact (see Material and Methods) and two summer temperature time series inferred from chironomids from nearby Lake Silvaplana (6.6 km to the south-west, same valley, same elevation). The latter two, which are inferred from the same chironomid assemblages, are based on either calibration-in-space (Larocque-Tobler et al., 2010) or calibration-in-time (Larocque-Tobler et al., 2011). The close distance between the two sites and their positions in the same valley at the same elevation ensures that they essentially experienced the same climate. Trends among the pollen-based and the chironomid-based reconstructions are similar only during approximately AD 1500–1850, which is the period after Medieval human impact and before hummock formation. Before this time period, the uncorrected pollen-based reconstruction indicates a cold period around AD 1320–1450, whereas the pollen-based reconstruction corrected for human impact records relatively constant temperatures for the entire period AD 1000–1500, contrasting with the chironomid-based reconstruction, which shows clear trends and strong fluctuations. Even though we tried to reduce effects of human impact on the pollen-based reconstruction (i) by excluding pollen types indicative of human action and (ii) by statistical methods, we still attribute differences among the reconstructions to human disturbances in the pollen. Given the information from the other proxies, human impact on vegetation was stronger than we had anticipated from the apparently undisturbed nature of the study site today.

Despite the fact that we did not find any significant correlation between δ^{13}C in *Sphagnum* and the instrumental records of relative humidity, precipitation, and temperature from the nearby meteorological station (Hangartner, 2010), we found that δ^{13}C correlates strongly with amoebae-inferred DWT for the early period (AD 999–1572). This indicates a common driver, probably a temperature-related climate factor. δ^{18}O, on the other hand, correlates significantly with measured relative humidity for the summer to autumn months ($p < 0.05$) and even better agreements are obtained with the water vapour pressure time series AD 1901–2003. These correlations are supported by a similar trend of the testate amoeba *Phryganella acropodia* known as a dryness indicator (Fig. 2).

5. Discussion and conclusions

5.1. Peatland development

Our high-resolution, multi-proxy record of Mauntschas mire revealed that human impact was much more important for the ecological functioning of this mountain peatland than we anticipated. We found phases of notable human impact on the mire prior to ca. AD 1454 in the form of grazing and irrigation for hay making, and outside the mire by wood cutting and burning. The mire vegetation could partly recover after ca. AD 1454 and is still recovering today. This history of human impact could unfold only because of very high-resolution sampling. Multi-proxy analysis inevitably leads to multi-scale reconstructions, both spatially and temporally: Testate amoebae and stable isotopes in *Sphagnum* function at a strictly local scale and respond to change within months to years, most macrofossils are also strictly local but respond slower in accordance with plant growth rates, presumably in years to decades, and pollen represents a large range of scales and response times. Still, the multi-proxy approach helped us to obtain a more comprehensive picture of past environmental changes. Results from pollen, macrofossils, and testate amoebae appear tightly linked: pollen and macrofossil analysis complemented each other (Birks and Birks, 2000), and the testate-amoeba-based reconstructions of acidity (nutrient status) and surface wetness (water table depth) could be used to further unravel the history of local peat growth, local hydrology, and local human impact.

Correlation analysis for three separate time periods (AD 999–1572, 1572–1828, and 1828–2003), revealed potential links between reconstructed surface acidity (nutrient status), reconstructed surface wetness, stable carbon isotopes in *Sphagnum*, and stable oxygen isotopes in *Sphagnum*. Acidity and surface wetness appeared tightly linked in all periods, pointing to groundwater supply as the shared forcing factor. The following ecological setting was inferred for the early period: human impact was the common forcing factor for acidity and δ^{18}O, and temperature for surface wetness and δ^{13}C. δ^{18}O and δ^{13}C had no common forcing during this period. Among all three periods, δ^{18}O and δ^{13}C had correlation coefficients with surface wetness and with each other that were fundamentally different. Similarly, the correlation of δ^{18}O with acidity held for the early and middle periods only. So none of the pairs of time series that include a stable isotope had a common forcing factor that lasted through all three time periods. We hypothesize that these differences between the time periods were caused by peatland development: enriched by minerals during the early period due to grazing and irrigation, partial recovery during the middle period due to a marked decline of human impact on the mire, and final hummock formation during the late period.

5.2. Climate signals in the proxies

A basic problem of reconstructing climate variables from sediment proxies in cultural landscapes such as the Swiss Alps (the valley of study was already inhabited since about 1950 BC; Gobet et al., 2003) is that the distinction between human and climate signals is biased towards the human signal. The reason for this bias is that the human signal has the potential to be unequivocal, which in our study was the case when the nutrient status is affected, e.g. when pollen indicators for anthropogenic grasslands or dung-related spores are present. The climate signal, on the other hand, does not have exclusive indicators and is therefore rarely unequivocal and in our study often confounded with the human signal. Shifts in mire hydrology or in forest dynamics might be climatic or anthropogenic, even when human causes are not prominent in the data, and the human action itself might have been triggered by climate change. The climate signal in cultural landscapes remains therefore often masked, even when climate is the dominant driver. Nevertheless, we list here a couple of potentially climate-related issues.

Now that human impact and local hydrology are found to be so important for the peatland development of Mauntschas mire (see above), the question arises what kind of climate signal is still preserved in the proxies. Kamenik et al. (2009) found a strong link between mean April–November temperatures and pollen assemblages in a sub-decadally resolved part of the sequence (AD 1864–2003), which we interpret as temperature forcing on the flowering capacities of the plant populations rather than fluctuations in population density. In a comparable pollen study, van der Knaap and van Leeuwen (2003) came to the same conclusions for the last century in the northern and central Swiss Alps. Records of multi-decadal temporal resolution like that of the early and middle period of Mauntschas mire (before ca. AD 1770), however, can not register sub-decadal variability in pollen production, so information on flowering capacity is lost and population dynamics becomes the dominant signal, the latter being prone to human impact. To estimate the relative strengths of the two signals, we compared the mean April–November temperature reconstruction based on pollen with an independent summer-temperature reconstruction based on chironomids from a nearby lake. The two reconstructions yielded rather different results. An effort to partial out human impact by correcting the reconstruction using pollen indicating human impact resulted in a flat curve, far from the chironomid-based climate reconstruction. This suggests that human impact distorted the climate signal during the early and middle period. Dominance of human impact on peat formation during the last few centuries is the rule in the Alps; in an earlier study we found that most mires have a hiatus or a layer of extremely slow peat accumulation due to cattle grazing mainly during the nineteenth century AD (Sjögren et al., 2007). Mauntschas mire has an uninterrupted peat accumulation during the entire last millennium; however, its present-day appearance of pristine mire appears to be representative for the last five centuries at the most.

Some information on climate might still reside in the reconstructed surface wetness, as Mauntschas mire is located in a subcontinental part of the Alps, where moisture tends to limit peat formation. Nevertheless, in calibrations of our surface wetness reconstruction with measured climate (AD 1864–2002) by Lamentowicz et al. (2010a) we found better correlations with temperatures than with precipitation. It is widely thought that oceanic peatlands are driven by precipitation and continental peatlands by temperature (e.g. Charman et al., 2009; Słowińska et al., 2010), but this remains to be tested by additional observational and experimental studies in different biogeographic areas. Our findings suggest that in Mauntschas mire proxies for water-table depth (testate amoebae, stable isotopes p.p.) are less efficient in reconstructing precipitation quantitatively, but rather reflect the moisture of the soil and atmosphere.

A way to cope with the problem of interacting temperature and rainfall might be using parameters which take both into account. Booth (2010), for example, tested the correlation between the ‘Palmer Drought Severity Index’ and the water table as inferred from testate amoebae and Booth et al. (2006) used water-table fluctuations to reconstruct dry and wet episodes in lowland bogs. Snowmelt, however, complicates the record further in a subalpine peatland such as Mauntschas mire (1800 m a.s.l.). We have observed that melting snow supplied the peatland with water long after the end of winter. Snowmelt runoff may well have been stronger during the Little Ice Age than today, and evapotranspiration lower due to lower temperatures. This

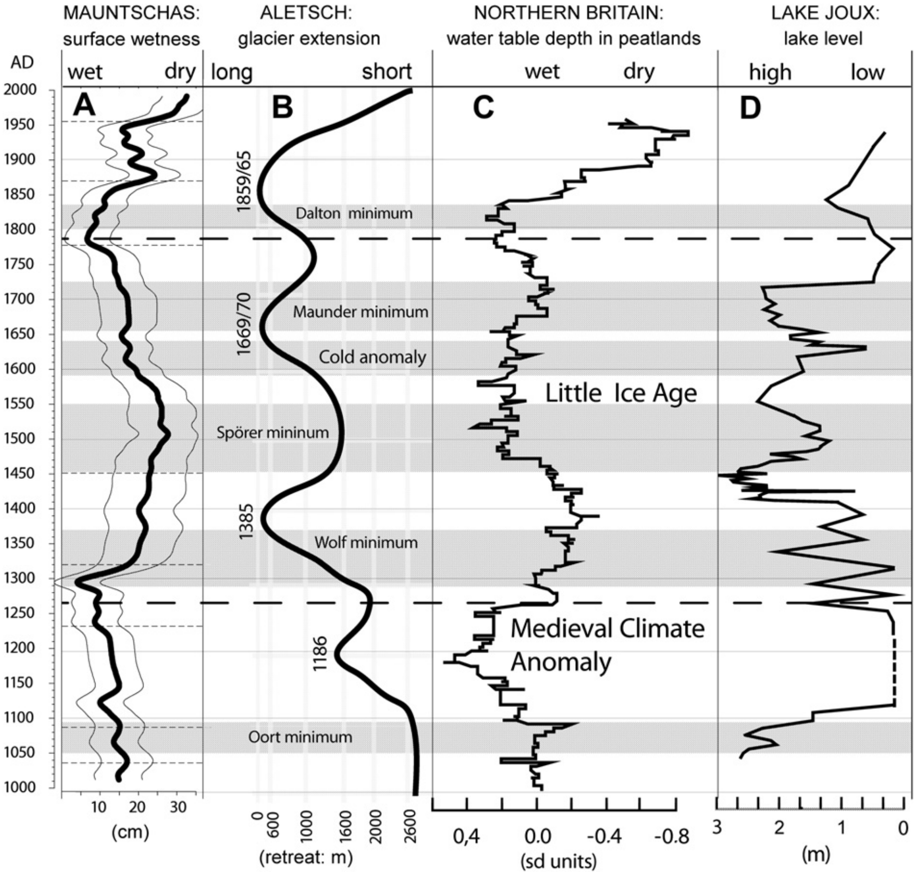

Fig. 6. Comparison of amoebae-inferred DWT (surface wetness) in Mauntschas mire with other studies.The delimitation of the Medieval Climate Anomaly and the Little Ice Age follows Larocque-Tobler et al. (2010). A – Surface wetness is amoebae-inferred DWT (depth to the water table) in Mauntschas mire (this study); B – Movements of the Aletsch glacier (central Swiss Alps) (Holzhauser et al., 2005); C – Water-table changes in ombrotrophic peatlands in northern Britain (Charman et al., 2006); D – Lake-level changes in Lake Joux (Jura Mts, Switzerland) (Magny et al., 2008).

might help explain the increased surface wetness reconstructed for the Little Ice Age and the dry surface for the Medieval Warm Period.

The depth to the water table (DWT) reconstructed from testate amoebae yields some tentative relationships with published climate-related events. Several phases of reconstructed low DWT (wet peat surface) coincide with independent, large scale indications for cool and/or wet climate. The wet conditions reconstructed for the period around AD 1300 coincide with the Wolf solar minimum (AD 1280–1340; Wigley, 1988; Foukal, 1990) when climate change had impacts on natural systems in this part of Europe, such as the increasing trend of the Great Aletsch Glacier in the central Swiss Alps (Holzhauser et al., 2005), increasing lake levels of Lake Saint Point in the Jura Mountains (Magny et al., 2010), and the strikingly high titanium content in Lake Le Bourget in the north-western French Alps indicative of sedimentary input (Jacob et al., 2008). The wet phase reconstructed for ca. AD 1750–1825 coincides with other events indicative of increased wetness, including the Dalton minimum in solar irradiance (Bard et al., 2000), glacier advance in the Alps (Holzhauser et al., 2005), and lake-level change in Lake Saint Point in the French Jura Mts (Magny et al., 2010) and in Lake Le Bourget (Arnaud et al., 2005). A next wet phase reconstructed for AD 1920–1955 also coincides with glacier advance in the Alps (Holzhauser et al., 2005). These coincidences suggest that the peatland surface wetness retains links with climate-driven moisture conditions of the landscape in spite of human impact. This needs, however, confirmation in further studies, as it contrasts with our findings that the local mire hydrology was modified by human action prior to AD 1550 and by hummock formation afterwards.

In Fig. 6, we compare our amoebae-inferred DWT (surface wetness) in Mauntschas mire with three other reconstructions related to water availability. The first three reconstructions are superficially similar for the Medieval Climate Anomaly in showing a declining trend, and all four reconstructions decline after AD 1750 and then increase after the mid-nineteenth century. In general, however, the four reconstructions seem largely unrelated. For Mauntschas mire surface wetness and Aletsch glacier extensions, winter precipitation was shown to be a common driver. Still, other forcing factors, such as summer temperatures for Aletsch glacier extensions and human impact for Mauntschas mire surface wetness, seem to blur expected common signals. From a spatial point of view, the same is true for mire surface wetness from Mauntschas and the northern British mires. We would expect anti-correlated signals due to large scale (NAO) forcing, yet other large scale processes, for example the transport of wet air masses from the Mediterranean region or blocking over Eastern Europe, apparently disrupt expected common signals.

The correlations between $\delta^{18}O$ in *Sphagnum* and relative humidity or water vapour pressure are the only significant relationships found between our isotope ratio measurements and climate variables measured at nearby stations. The significant correlations between $\delta^{13}C$ in *Sphagnum* and reconstructed mire surface wetness might indicate that carbon isotope fractionation depends strongly on the water level. In-depth investigation of the carbon incorporation process will be needed to find out why this could be so, in which the relative proportions of the carbon in *Sphagnum* derived from the air and from the acidic water are of special interest.

Summarizing, the multi-proxy approach has helped us much better understand the functioning of a sub-continental Alpine mire in terms of its hydrology and nutrient status primarily in relation to human impact, and has yielded a few hints on the impact of climate change.

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