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Stable carbon isotopes as indicators for micro-geomorphic changes in palsa peats

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Abstract

Palsa peats are unique northern ecosystems formed under an arctic climate and characterized by an unique biodiversity and ecology. The stability of the palsas are seriously threatened by climate warming which will change the permafrost dynamic and results in degradation of the mires. We used stable carbon isotope depth profiles in two palsa mires of Northern Sweden to track environmental change during the formation of the mires. Carbon isotope (δ^{13}C) depth profile of the yet undisturbed mire Storflaket indicated very low to no degradation of the peat in the water saturated depressions (hollows) but increased rates of anaerobic degradation at the Stordalen site. The latter might be induced by degradation of the permafrost cores in the uplifted areas (hummocks) and subsequent braking and submerging of the hummock peat into the hollows due to climate warming. Carbon isotope depth profiles of hummocks indicated a turn from aerobic mineralisation to anaerobic degradation at a peat depth between 4 to 25 cm. The age of these turning point was ^{14}C dated between 150 and 670 years and could thus not be caused by anthropogenically induced climate change. We found the uplifting of the hummocks due to permafrost heave the most likely explanation for our findings. We thus concluded that differences in carbon isotope profiles of the hollows might point to the disturbance of the mires due to climate warming or due to differences in hydrology. The characteristic profiles of the hummocks are indicators for micro-geomorphic change during permafrost up heaving.

1 Introduction

Global climate change is significantly threatening stability and functioning of permafrost soils in extended areas of the northern latitudes and/or at high altitudes (Luoto et al., 2004; Brown and Romanowsky, 2008). A thawing of permafrost soils will most likely result in a positive feedback mechanism due to accelerated degradation of soil organic matter (Schuur et al., 2009; Dorrepaal et al., 2009). Furthermore, biodiversity and functioning of these unique ecosystems are under immediate threat (Luoto et al., 2004).

One very unique northern ecosystem type are palsa peats, also called palsa mires. Palsa mires are a type of peat land typified by characteristic high mounds (called palsa or palsa *hummocks*), each with a permanently frozen core. During formation of the hummocks, the volumetric expansion following freezing of the underlying horizons uplift the peat out of the groundwater saturated zone. Between the hummocks are wet depressions (called *hollows)*, where permafrost is less extensive or absent. Palsa mires are common in high-latitude areas across the Northern Hemisphere including the northern parts of Scandinavia and characterized by a unique geochemistry and biodiversity (Railton and Sparling, 1973; Masing et al., 2010). Since these sensitive ecosystems are currently exposed to climate change (Åkerman and Johansson, 2008; Lemke et al., 2007), not only hydrology and vegetation composition but also degradation and mineralisation patterns will change. The latter should be reflected in stable carbon isotope patterns.

The depth distribution of stable carbon isotopes (^{12}C and ^{13}C) reflects the combined effects of plant fractionation processes and microbial decomposition (Krull and Retallack, 2000). The fractionation within the plant towards slowly decomposing substances depleted in ^{13}C and more easily degradable material relatively enriched in ^{13}C leads to a depletion of ^{13}C in the remaining, recalcitrant organic matter in the soil (Ågren et al., 1996). In contrast, the preferential respiration of ^{12}C from decomposers may lead to an enrichment of ^{13}C in the remaining soil organic matter (Ågren et al., 1996; Nadelhoffer and Fry, 1988). The balance between the latter two mechanisms will shape the carbon isotope depth profiles in soils, which then reflects the dominating fractionation mechanism.

The aim of this study was to scrutinize stable carbon isotope depth profiles in northern palsa peat complexes as indicators of environmental change and/or soil forming processes in space and time. Our hypothesis was that (i) hummocks and hollows should differ significantly in their stable isotope depth profiles and (ii) that vertical trends reflect hydrological and botanical conditions mainly controlling decomposition processes at the time when the peat was deposited.

2 Theoretical concepts to interpret δ^{13}C depth profiles in soils

Isotopic depth profiles in soils that are independent of vegetation changes (e.g. C3 to C4 plants or major changes in species composition) and independent of major changes in hydrology have been reported as different trends (Fig. 1).

2.1 Uniform depth trend in the δ^{13}C

This can be found in relatively young and/or poorly drained soils with little time for soil formation, and/or limited decomposition and thus limited fractionation (Fig. 1a). Several studies found uniform depth trends in water saturated peats with little or no fractionation of δ^{13}C (Kracht and Gleixner, 2000; Clymo and Bryant, 2008; Skrzypek et al., 2008). Clymo and Bryant (2008) showed that δ^{13}C of a 7 m deep Scottish bog was rather uniform because opposite fractionation effects of CO_2 and CH_4 formation resulted in similar δ^{13}C signatures of degradation product and sources (relative enrichment and depletion relative to source material, respectively). Thus, anaerobic decay with methane production, which requires low redox potential under anaerobic conditions (e.g. acetate fermentation) might also result in uniform δ^{13}C depth profiles.

2.2 A δ^{13}C depth trend towards slightly lower values

These are common for soils that are constantly waterlogged such as peat producing histosols (Fig. 1b; Krull and Retallack, 2000) but have significant anaerobic degradation. The slight decrease in δ^{13}C is due to preservation of slowly decomposing ^{13}C depleted substances like lignin (Benner et al., 1987). Since Spagnum species have phenolic compounds very similar to lignin (Nimz and Tutschek, 1977; Rasmussen et al., 1995; Farmer and Morrison, 1964), a similar fractionation pattern can be expected in sphagnum peats. Thus, if we see a depth trend towards lower δ^{13}C values this indicates an environment, where the enrichment of recalcitrant material dominates the isotopic profile.

2.3 Pronounced δ^{13}C increases with depth of up to 5‰

This pattern is typical for mature, well drained soils, because aerobic decomposition favours selective loss of ^{12}C (Fig. 1c; (Nadelhoffer and Fry, 1988; Beckerheidmann and Scharpenseel, 1989; Ågren et al., 1996). Clay minerals in deeper soil horizons also favour this pattern in preferentially adsorbing the heavier ^{13}C (Beckerheidmann and Scharpenseel, 1986), but the latter affect should negligible in the peats we investigate in this study.

2.4 Depth trends induced by major changes in plant species composition

The species effect can range from $\delta^{13}\mathrm{C} = -30‰$ for Calluna species to $-22‰$ for Sphagnum (Menot and Burns, 2001). Major changes in peat producing vegetation composition can be expected to be coupled to natural succession, changes in climate and/ or changes in peat hydrology, where the latter can be induced by permafrost thawing and subsidence of peat which was previously uplifted by permafrost heave.

2.5 Depth trends due to the Suess effect

The atmospheric composition of CO_2 has decreased from δ^{13}C values around $-6.4‰$ at the end of the eighteenth century to values around $-7.6‰$ in 1980 due to emissions from burning of fossil fuels, the so called Suess effect (Friedli et al., 1986). A further decrease to values of around $-8.1‰$ in 2002 was measured by Keeling et al. (2005). If this decrease in δ^{13}C of 1.7‰ over the last 150 years plays a crucial role for the δ^{13}C of peats, it will only be documented in the upper cm of the peat because of the high soil age of up to several hundreds/ thousands of years. In an investigation of wetland soils in the Swiss Alps (Urseren Valley, Kanton Uri, (Schaub and Alewell, 2009)) no considerable increase of δ^{13}C with depth was detected. However, depending on soil age a slight increase in δ^{13}C with depth due to the Suess effect might be possible in wetland soils.

3 Site description

The two studied sites, Storflaket (68°20′51″ N, 18°15′55″ E) and the eastern Stordalen mire (68°20′90″ N, 18°58′57″ E) are situated about 3 km apart within a large palsa peat complex in the Abisko valley, northern Sweden. Storflaket is characterized by a stable palsa plateau with a fairly homogenous thickness of about 0.5 m. The eastern Stordalen site is a partly degraded palsa system having an average peat depth around 0.5 m, but with large local variations. The thickness of the active layer, i.e. the seasonally thawing zone is in late September typically about 0.5 m in the hummocks and between 1 and 3 m in the hollows in both mires.

Permafrost heave drives the topography of the mires; higher uplifted palsas hummocks are typically situated between 1 to 3 m above the surrounding, less uplifted wetter areas. Hummocks are mainly dominated by nutrient poor vegetation such as dwarf shrubs (*Empetrum hemafroditum, Betula nana*), lichens (*Cladonia* ssp) and mosses (*Sphagnum fuscum, Dicranum elongatum*), indicating ombrotrophic conditions, i.e. a disconnection from the groundwater source. In the hollows formed beneath the hummocks common plants are *Carex rostata* and *Eriophorum angustifolium* indicating groundwater inputs of nutrients and thus minerotrophic conditions (Malmer et al., 2005).

The depth of the active layer has been monitored in the Abisko valley since 1978. This monitoring shows an average increase in the active layer between 1978 to 2006 by about 1 cm yr^{-1} and a recent phase (since the mid-1990) of accelerated thawing (Åkerman and Johansson, 2008). In the time between 1970 and 2000 a large expansion of wet fen communities has been documented in Stordalen (Malmer et al., 2005) but not in Storflaket (Åkerman and Johansson, 2008), making the latter mire more representative of an un-degraded palsa system.

4 Methods

Peat cores were taken in September 2007 at seven sites with 4 cores each at the Storflaket and the Stordalen mire representing stable hummocks ($n = 4$) and hollow peat ($n = 3$). Peat cores were collected using a Wardenaar peat corer (Wardenaar, 1987) for the upper ~ 0.5 m and a Russian peat corer for deeper peat layers. The peat cores were cut in the field in 0.01 to 0.05 m sections and stored in air tight plastic bags. A resampling of the mires was done in June 2009 for two of the hollows (HoSD1, HoSD2), because core sections where either not distributed evenly or no sample material was left over for stable isotope analysis. Additionally, five palsa hummock profiles (HuSD6, HuSD7, HuSF10, HuSF11) where sampled close to the former locations of HuSD5 and HuSF9, respectively, to validate the isotope patterns of the 2007 samples. For location of the sampled profiles please see map in Fig. 2.

Stable carbon isotope analyses were accomplished using a continuous flow isotope ratio mass spectrometer (DELTA^{plus} XP, Thermo Finnigan, Bremen, Germany) coupled with a FLASH Elemental Analyzer 1112 (Thermo Finnigan, Milan, Italy) combined with a CONFLO III Interface (Thermo Finnigan, Bremen, Germany) following standard processing techniques. Stable isotope ratios are reported as δ^{13}C values [‰] relative to V-PDB defined in terms of NBS 19 = 1.95‰. The long term reproducibility for all standards is better than 0.1‰.

C-14 was measured at the Radiocarbon Laboratory of the University of Arizona following the method of Polach et al. (1973). Samples were treated with 1N HCl to remove carbonate, then with 2% NaOH solution to remove any alkali-soluble organic carbon fraction. Finally, samples were rinsed with very dilute HCl until the sample pH was about 5. The residual sample was dried, and then combusted in a stream of pure oxygen gas. The resultant CO_2 was purified by passage through cryogenic and chemical traps. It was reacted with Li metal at 500 °C to produce Li_2C_2. The Li_2C_2 was reacted with water at room temperature to yield C_2H_2 gas, which was trimerized on a Cr^6+ catalyst to give benzene. The benzene was stripped from the catalyst at

approx. +80 °C and diluted to 3 g if necessary with pure benzene of petrochemical origin, containing no radiocarbon. Three mL of benzene was mixed with butyl-PBD scintillant, and radioactive decays were counted in a liquid scintillation spectrophotometer. (We use 2 Quantulus 1220 Spectrometers and a Wallac Rackbeta Spectrometer).

The bomb ^{14}C model from Harkness et al. (1986) was used to calculate mean residence times (MRTs) of the bulk soil (for a detailed description of the model calculation see Leifeld and Fuhrer (2009)).

Peat accumulation rates have been calculated from C^{14} MRTs in the respective depth of samples.

5 Results and discussion

5.1 Isotope depth profiles in the hummocks

From eight investigated hummocks six show a very clear pattern: an increase of δ^{13}C isotope profiles up to a certain depth (called here "turning points") and then a decrease to more lighter values in the deeper horizons (Fig. 3). The increase in δ^{13}C with depth is regardless of the peak depth always around Δ^{13}C = 3.2–4‰ (Table 1). The increase with depth in the upper horizons can not be explained by the Suess effect, since this would only correspond to an increase of approximately 1.7‰. Furthermore, the Suess effect should have occurred in the last 50 years, but the age of the turning points is considerably older (Table 1). Also, isotope depth profiles of the hollows did not indicate that the Suess effect had a significant influence on the depth profiles of the mires. However, the increase with depth of about 3.2–4‰ in the hummocks down to the turning point corresponds to δ^{13}C increases with depth of well drained soils where aerobic decomposition favours selective loss of ^{12}C (type 3 in Fig. 1; Nadelhoffer and Fry, 1988; Beckerheidmann and Scharpenseel, 1989).

The deeper horizons of the investigated hummocks follow more the pattern expected in hollows with anaerobic degradation (type 2 in Fig. 1; Krull and Retallack, 2000;

Benner et al., 1987). All sampled depths were clearly above the permafrost layer and well within the active layer and none of the hummock samples were from a permanently water saturated horizon. The stable isotope profile might indicate that at a certain point in time the metabolism changed from anaerobic to aerobic degradation. The most likely explanation for this change would be that the permafrost lifted hollow peat material out of the groundwater level zone. It is important to consider that 80–90% of organic matter decomposition in bogs takes place in the Acrotelm (Clymo, 1984; Zaccone et al., 2008). Thus, the turning point may represent a situation where aerobic decomposition with corresponding shift in δ^{13}C is replaced by often anoxic situations with selective preservation of lignin or phenolic compounds from Sphagnum. Even if the herbaceous species contain only small amounts of lignin it may make up the vast majority of organic matter below the turning point because of selective preservation. Loisel et al. (2009) determined similar patterns in boreal hummocks and (Zaccone et al., 2008) for the preservation of phenolic compounds in temperate ombrotrophic mountainous peats.

Samples representing the turning point were age dated with ^{14}C radiocarbon dating. MRTs range from 155 years at 4 cm depth at the Stordalen mire, to 670 years in 25 cm depth at the Storflaket mire (Table 1). Thus, if the turning points in the isotope depth profiles indicate environmental change or any kind of disturbance, this happened not at a large regional but rather at a small local scale at different points in time. MRTs indicate relatively homogenous peat accumulation rates in both mires between 0.3 and 0.6 mm yr^{-1}.

Pancost et al. (2003) determined a strikingly similar depth pattern for Sub-Boreal Dutch raised bogs. However, they dated the turning points to the transition from a relatively warm and dry continental climate during the Sub-Boreal to a more humid and cold oceanic climate during the early part of the Sub-Atlantic approximately 2900 to 2500 years ago.

5.2 Possible explanation for turning points in the hummocks

5.2.1 Preferential leachate of relatively young organic substances

Other studies have observed a 1–3‰ return of the δ^{13}C depth profiles to more negative values in the lower B and C horizon of mineral soils which has been explained with a chromaticgraphic-like effect with lower clay content in the deeper soil layers and thus a greater percentage of relatively young, and undecomposed organic substances compared to clay rich horizons with older, decomposed organo-mineral complexes (Beckerheidmann and Scharpenseel, 1989). The leaching of organic substances down the profile is called podsolisation in mineral soils. However, we investigated peat soils with a percentage of organic substance mostly $> 80\%$ in all horizons. Thus, a leaching of organic substances down the profile should hardly influence bulk δ^{13}C of deeper horizons to such an extent.

5.2.2 Change in vegetation

Carbon isotopes of ombrotrophic peat bog plants differ between species. This species effect has been determined for Arctic environments between −20‰ (mosses) and −29‰ (Carex species; Skrzypek et al. 2008). Thus, a change in species composition could theoretically explain all observed changes in our depth profiles if we would assume major changes in vegetation. The maximal variation in δ^{13}C values seen between hummocks and hollows at our sites range between −24.6 to −29.2‰ (see values at depth = 0 cm in Figs. 3 and 4). The average δ^{13}C value of today's living vegetation at our sites is -25.9 ± 1.1‰ in the hollows and -28.2 ± 0.8‰ in the hummocks. Thus, a change from fen hollow peat towards ombrotrophic hummock peat with time are expected to generate decreasing δ^{13}C value similar to the type 3 trend (Fig. 1).

Changes in vegetation would occur due to (a) changes in hydrology (e.g. uplifting of the palsas, submerging by erosion) or (b) through dramatic climatic change. The latter is not very likely because the turning points are (i) pretty sharp (meaning within a few cm of the profiles and thus within a few decades) and (ii) quite recent but before anthropogenically induced climate change started. Thus we can rule out major climatic changes being responsible for soil forming profiles in the upper 30 cm of the profiles. Geomorphic processes (palsa uplifting, thermocast erosion and submerge of material) may be the reason for the turning points in the δ^{13}C depth profiles. These geomorphic processes would cause major changes in hydrology and in vegetation.

Previous investigations of the vegetation at the sites confirm our results. In Stordalen, peat hollow has been dominated by spaghum communities since the onset of peat formation (Malmer and Wallen, 1996), making the δ^{13}C unlikely to change in the peat as a result of major vegetation shifts in the past. However, the peat in the hummocks developed from a carex dominated fen peat with woody debris into a drier ombrotrophic peat with Calluna and Spaghnum (Malmer and Wallen, 1996; Kokfelt et al., 2010). Such vegetation change is expected to give rise to a depth trend similar to the type 3 trend in Fig. 1 and might thus explain the upper profiles of the hummocks.

5.2.3 Change in hydrology

A change in hydrology can change the carbon isotopic composition beyond the change of vegetation or the change from aerobic to anaerobic degradation. Higher water table depth causes an enrichment in δ^{13}C because a water film on the leaves will act as diffusion barrier for CO_2. The latter will result in lower fractionation factors during CO_2 uptake and thus a relative enrichment in the plants under high water saturation or vice versa a relative depletion under low water saturation ((Price et al., 1997) for Sphagnum; (Pancost et al., 2003) for bulk peat with changes of + 4‰ from dry to wet; (Loisel et al., 2009)). If a shift in hydrology is the explanation for the δ^{13}C depth profile this would indicate an increase in water saturation up to the turning point and then a decrease again. Thus, considering this effect the turning point of δ^{13}C in the hummocks would, even though for different reasons, indicate the same change in hydrology as discussed above: high or even increasing water saturation during the peat formation of the lower horizons and then, from the turning point upwards a decrease or lower water saturation

during the peat formation in the upper horizons. This is also in agreement with the time period when the Stordalen mire is assumed to have turned ombotrophic, likely due to permafrost induced up-lift of the palsa features (Rydberg et al., 2010).

5.2.4 Influence of methane and melting of permafrost

Rask and Schoenau (1993) have stated that a δ^{13}C enrichment with depth or in space might not only point to aerobic mineralisation but also to times/zones with strong CH_4 production. The latter will lead to a preferential release of the light $^{12}CH_4$ and an enrichment in the remaining organic matter (basically the same effect but stronger signals as aerobic mineralisation). However, increased methane release and subsequent methane oxidation (methanotrophy) can also lead to recycling of light $^{12}CO_2$ and a shift to lighter values in the resulting organic material (Krull, 1999; Krull and Retallack, 2000; Krull et al., 2000). Increased methane release has been attributed to melting of permafrost in depth profiles of paleosols (Krull et al., 2000). Overall we would not expect CH_4 production or recycling to produce such consistent patterns in the depth profile but a much greater scattering of the δ^{13}C data. However, some of the variances in the δ^{13}C data might be due to this effect.

5.3 Isotope depth profiles in the hollows

The δ^{13}C profiles of all investigated hollows (Fig. 4) are congruent with depth patterns reported previously for water logged soils (Benner et al., 1987; Krull and Retallack, 2000). The δ^{13}C depth profile of the hollow at Storflaket (HoSF8) is more or less uniform indicating slow to totally suppressed decomposition rates (Krull and Retallack, 2000). This profile would also be compatible with organic matter formation under the regime of methanogenesis (see above, Clymo and Bryant, 2008). The water table in Storflaket is closer to the peat surface in the hummocks than in Stordalen (Klaminder et al., 2008). Thus, oxygen supply can be supposed to be very limited in the hollows of Storflaket which would explain the stable isotope profile which indicates low degradation rates at low redox potential favouring processes like methanogenesis. Furthermore, Storflaket in general and the sites we sampled for this study specifically, were (based on observations in the field) not strongly affected by thawing of the permafrost and succeeding degradation of hummocks yet.

The δ^{13}C profiles of the hollows at Stordalen (HoSD1 and HoSD2) decrease towards slightly lower values with depth which is typical for decomposition under anaerobic conditions with the remaining recalcitrant organic substances dominating the δ^{13}C signature (Ågren et al., 1996; Benner et al., 1987; Krull and Retallack, 2000). Thus, Stordalen hollows seem to have relatively higher decomposition rates favouring a stronger accumulation of ^{13}C depleted compounds such as lignin or phenols and/or generally a higher redox regime where processes like methanogenesis play a minor role compared to the hollow profile sampled in Storflaket. Hollows at Stordalen seem seriously affected by thawing, breaking and submerging of peat chunks from hummocks at the edge to the bigger hollows (see also Klaminder et al. (2008)). The new supply of hummock peat material in the hollows might increase degradation processes in the hollows, thus explaining the different δ^{13}C profile at Stordalen with relatively heavier values in the upper horizons and a slight decrease with depth. Furthermore, water flow at the investigated Stordalen sites is much more active, thus some (even though limited) oxygen transport into the hollows is not unlikely.

6 Conclusions

It is very likely that we see the influence of permafrost melting due to climate change in the δ^{13}C depth profiles of the hollows in Stordalen. However, the distinct δ^{13}C patterns in the hummocks (e.g. the “turning points”) can not be attributed to global climate change, because age of turning points is older than anthropogenically induced climate change. Further, age of turning points vary at a very small local scale. Thus, a geomorphic induced change in the hydrology of the mires, e.g. the uplifting of the palsa is a more likely explanation for the observed patterns. We thus conclude:

1. The difference in depth profile between hollows in Storflaket and Stordalen might indicate the difference in site disturbance due to climate change or due to the different hydrology of the sites (less groundwater movement in Storflaket compared to Stordalen).
2. The most likely explanation of the depth profiles of the hummocks is a change in degradational metabolism due to a change in hydrology (likely followed by vegetation changes) induced by permafrost uplifting. However, since the age of the turning points is roughly between 150 and 700 years, there is no indication that anthropogenically induced climate change is responsible for this pattern in the hummocks.

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Table 1. Turning points, C^{14} ages at turning point as mean residence time in years (MRT), peat accumulation rates per year, stable carbon isotope value of the turning point and the increase in stable carbon isotopes in the upper layer (Δ^{13}C). n.s. = Harkness et al. (1986) model unsolvable.

Site	Turning point (cm depth)	MRT (yrs)	Peat acc.rates mm yr^{-1}	δ^{13}C‰ at turning point	Increase in upper layer (Δ^{13}C‰)
HuSD4	−12	215	0.6	−25.57	3.36
HuSD3	–				
HuSD5	−4	155	0.3	−25.02	3.33
HuSD6	−4	n.s.		−25.40	3.38
HuSD7	−14	246	0.6	−25.54	3.24
HuSF9	−25	671	0.4	−24.95	3.29
HuSF10	–				
HuSF11	−15	212	0.7	−24.99	4.09

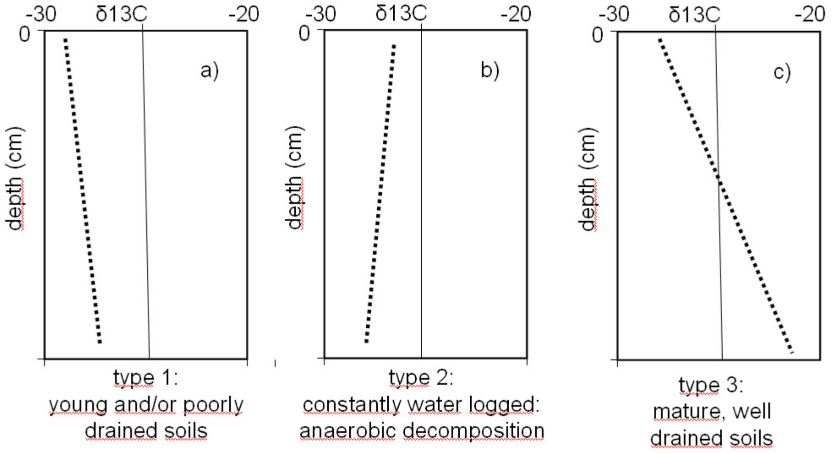

Fig. 1. Theoretical concept of isotope depth profiles in soils under regimes of differing metabolisms due to differences in water saturation and/or age.

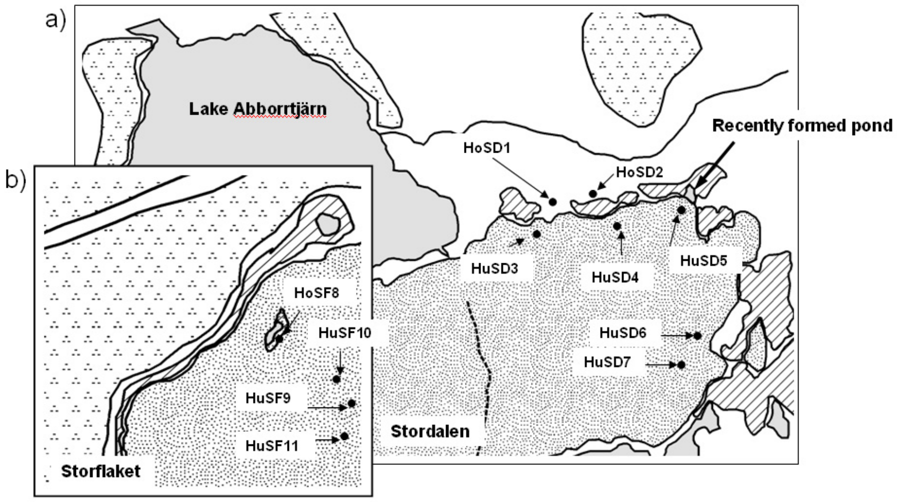

Fig. 2. Map showing the coring sites at **(a)** Stordalen and **(b)** Storflaket mires. Cores are labeled Ho = Hollow, Hu = Hummock, SD = Stordalen, SF = Storflaket and in ascending order from 1 to 11 according to the sampling sequence.

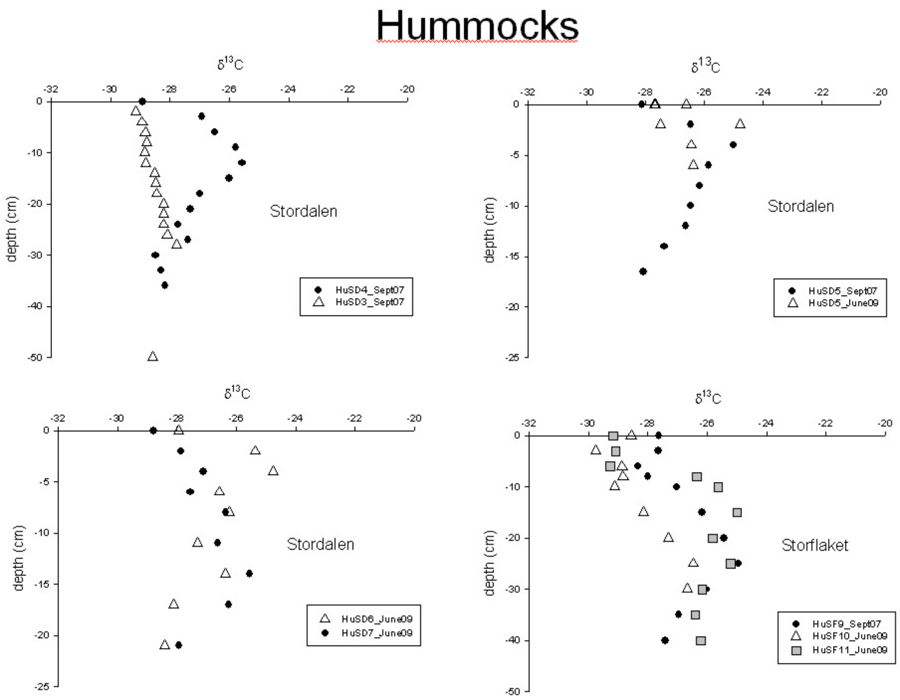

Fig. 3. Isotope depth profiles of the investigated hummocks. δ^{13}C in ‰.

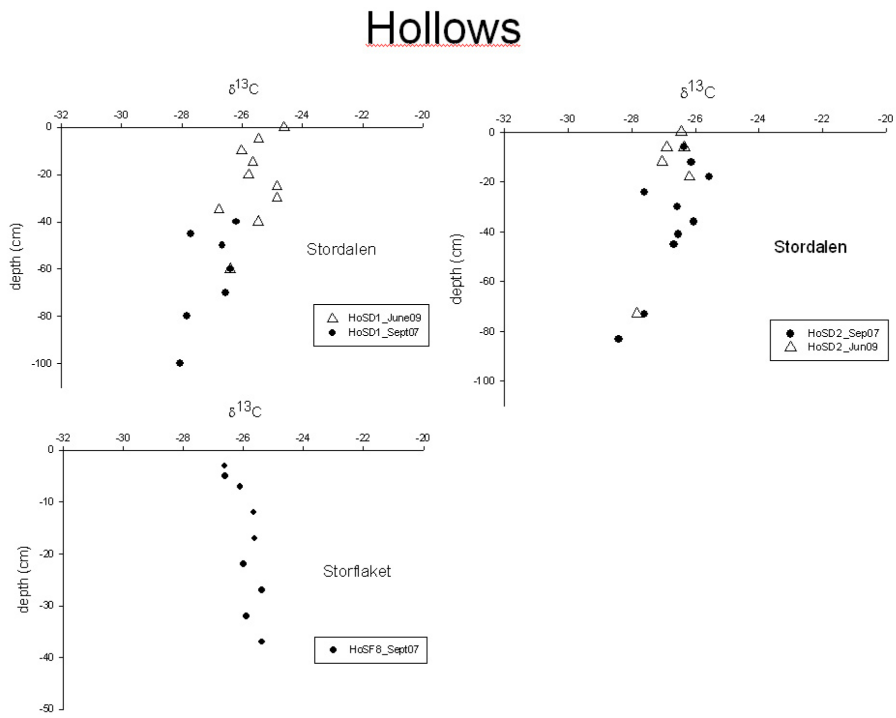

Fig. 4. Isotope depth profiles of the investigated hollows. δ^{13}C in ‰.