Peatland degradation indicated by stable isotope depth profiles and soil carbon loss

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Jan Paul Krüger

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Prof. Dr. Christine Alewell (Dissertationsleiterin)

Prof. Dr. Karsten Kalbitz (Korreferent)

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Prof. Dr. Jörg Schibler

(Dekan)

Summary

Peatlands play a significant role in the global carbon cycle. Since the last glacial maximum, peatlands in the northern hemisphere have accumulated organic matter as peat with about 550 Pg carbon in their soils. The degradation of peatlands either by anthropogenic activities or by changing climatic conditions results in changes of the biogeochemical cycles. Increasing temperatures, especially in the high northern latitudes, lead to the accelerated permafrost thaw and the degradation of palsa peatlands and may lead to a positive carbon-climate feedback. Peatland drainage induces oxic conditions and causes increasing carbon dioxide emissions resulting in a decline of soil organic carbon. In Europe more than 50 % of the former peatland area has been drained for agricultural or forestry use contributing a significant proportion to the national greenhouse gas emissions.

The main objectives of this study were to use depth patterns of stable isotopes, both carbon and nitrogen, as indicators of peatland degradation, and to calculate the carbon balance of degraded peatlands by different profile-based methods. Various depth profiles from peatlands in Northern Sweden, Central Finland and Northern Germany were sampled to investigate these research questions. These peatlands present different causes of peatland degradation, including changes in climatic conditions in the subarctic region, drainage for forestry in the boreal region and drainage for grassland management in the temperate region.

The natural abundance of stable isotopes, particularly stable carbon and nitrogen isotopes, is a commonly used indicator in soil sciences to investigate biogeochemical processes in soils and soil degradation. Depth profiles of stable carbon isotopes generally reflect organic matter dynamics in soils with an increase of $\delta^{13}C$ with depth during aerobic decomposition and stable or decreasing $\delta^{13}C$ values with depth during anaerobic decomposition of organic matter. In addition, the $\delta^{15}N$ values are assumed to increase with depth in degraded peatlands due to aerobic decomposition and show uniform depth patterns under anaerobic decomposition in natural peatlands.

In the palsa peatlands in Northern Sweden, stable carbon isotope depth profiles indicated changes in the decomposition processes over time. Recent degradation due to accelerated permafrost thaw as well as historical changes in decomposition processes from anaerobic to aerobic are displayed in the $\delta^{13}C$ depth profiles. The historical changes indicated the uplifting of the palsa peatlands by permafrost. Furthermore, the time of the permafrost uplifting was determined by peat accumulation rates between 100 and 800 years ago. In addition, stable nitrogen isotope depth profiles indicated the change in decomposition processes and showed perturbation of the soil when relating to C/N ratios. The mean ages of permafrost uplifting of the two palsa peatlands identified by the stable nitrogen isotope depth profiles fall in the period of the Little Ice Age.

A land use gradient was investigated in Northern Germany including a near-natural wetland, an extensively managed and an intensively managed grassland site, which have all formed in the same peatland complex. Vertical depth profiles of $\delta^{13}C$, $\delta^{15}N$, ash content, C/N ratio, bulk density and radiocarbon ages were studied to identify peat degradation and to calculate carbon loss. The $\delta^{13}C$ depth profiles indicated aerobic decomposition in the upper horizons at all sites. Moreover, depth profiles of $\delta^{15}N$ differed significantly between the sites with increasing $\delta^{15}N$ values of the upper horizons concurrent to increasing land use intensity due to differences in peat decomposition and fertilizer application.

There are different methods and approaches to determine the carbon balance of degraded peatlands. The profile-based methods compare the degraded soil with a reference soil. Differences in biogeochemical soil parameters, such as ash content, bulk density and radiocarbon age, are used by the profile-based methods to estimate the soil carbon balance of degraded peatland sites.

Peat and carbon loss could be quantified by the combination of ash content and bulk density and is supported by the radiocarbon ages. Increasing carbon loss with increasing land use intensity was calculated by two different profile-methods with 11.5, 18.8-38.2 and 42.9-52.8 kg C m^{-2} at the near-natural site, the extensively used grassland site and the intensively used grassland site, respectively. However, current greenhouse gas fluxes measured by the chamber technique indicated a carbon gain at the near-natural site, a neutral carbon balance at the extensive used grassland site and a carbon source at the intensive used grassland site. The historical carbon balance was assessed by the profile-based methods whereas the present changes in the carbon balance are captured by the flux measurements. Moreover, the combination of both approaches pointed out that the carbon balance of the peatland has changed over time. All biogeochemical soil parameters indicated peat degradation at all investigated sites along the land use gradient, however, at varying degrees.

In Finland more than half of the peatland area was drained during the 20th century for forestry use. The Lakkasuo peatland, Central Finland, includes a minerotrophic and an ombrotrophic part, both of which were partially drained for forestry. In addition to the $\delta^{13}C$ depth profiles, four different profile-based methods were applied, using differences in ash content or radiocarbon dated peat samples to calculate the carbon balance of the soil. The $\delta^{13}C$ depth profiles indicated that both undrained sites are in a natural state and that both drained sites are enriched in ^{13}C in the topsoil indicating aerobic decomposition. At the minerotrophic drained site all four profile-based methods indicated a carbon loss but of different magnitude (0.058 to 0.272 kg C m^{-2} yr^{-1}). However, at the ombrotrophic drained site both radiocarbon methods suggested a carbon gain (0.139 to 0.182 kg C m^{-2} yr^{-1}) whereas the two other methods indicated a carbon loss (0.061 to 0.270 kg C m^{-2} yr^{-1}). The results confirm that in boreal peatlands drainage for forestry leads to a higher risk of losing carbon when the peatland is minerotrophic.

This thesis demonstrates that examining stable carbon isotopes is a useful way of identifying peatland degradation by various causes, and this approach can be used as indicator of the natural state of a peatland. The carbon balance calculations by different profile-based methods help determining the long-term carbon changes of degraded peatlands since the beginning of peatland drainage.

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CHAPTER 1

Introduction

1.1 Peatlands and the carbon cycle

Peatlands cover about 4 million km^2 worldwide, approximately 3 % of the Earth's terrestrial surface area (Gorham, 1991; Limpens et al., 2008; Yu et al., 2011). Nevertheless, they are an important pool in the global carbon (C) cycle, storing about 600 Pg carbon in their soils (Yu et al., 2010; Jungkunst et al., 2012). This is comparable to the present carbon in the atmosphere (Ciais et al., 2014). Most of the peatland area is situated in the high northern latitudes (>45°N) particularly in the boreal and subarctic regions (Gorham, 1991; Yu et al., 2011; Jungkunst et al., 2012) with about 500 to 550 Pg carbon in their soils (Yu et al., 2010; Jungkunst et al., 2012) representing about 15-30 % of the worlds soil carbon pool (Limpens et al., 2008). The tropics, storing about 50 to 88 Pg carbon in their soils, and the southern hemisphere, primarily Patagonia, storing about 15 Pg carbon in their soils, contribute less to the global peatland carbon pool (Yu et al., 2010; Page et al., 2011).

Peatlands in the northern hemisphere have accumulated organic matter as peat since the last glacial maximum (Yu et al., 2011; Yu, 2012). With the biomass production being higher than the decomposition of organic material, peatlands accumulate carbon in a natural state (Turunen et al., 2002). In these water-saturated soils, anoxic conditions inhibit organic-matter decomposition and favour peat accumulation (Clymo, 1984) and methane emissions. The overall net carbon accumulation during the Holocene was between 0.02-0.03 kg C m^{-2} yr^{-1} (Turunen et al., 2002; Frolking and Roulet, 2007; Strack et al., 2008). The net radiative forcing of northern peatlands is a net cooling of about 0.2 to 0.5 W m^{-2} (Frolking and Roulet, 2007). A high water table is required for peat accumulation whereas low water levels (occurring because of drainage or a change in climate conditions) lead to mineralisation of organic matter and the release of carbon from the soil to the atmosphere as CO_2 (Clymo, 1984; Ise et al., 2008; Fenner and Freeman, 2011).

Due to their high carbon density and the large carbon reservoir of these ecosystems peatlands are an important component of the global carbon cycle. With a view to the rising concentrations of greenhouse gases, especially CO_2, the carbon storage function of peatlands is crucial: these ecosystems could release a huge amount of carbon to the atmosphere due to drainage and management of peatlands. In 2008, for instance, the global CO_2 emissions from drained peatlands was about 1.3 Pg CO_2 (Joosten, 2010). In view of changes in climatic conditions they can have positive or negative climate feedbacks. Warming without moisture stress is suggested to increase the net primary production more than the peat decomposition and to enhance long-term peat carbon sequestration, leading to a negative climate feedback (Loisel et al., 2012; Loisel and Yu, 2013). However, rising air temperatures and changes in precipitation patterns could significantly influence the biogeochemical cycles of peatlands with an acceleration of carbon emissions from these soils and a potentially disturbance of these ecosystems, resulting in a positive climate feedback (Ise et al., 2008; Dise, 2009; Dorrepaal et al., 2009).

1.2 Degradation of peatlands in different climatic regions

Degradation of peatlands is a change from natural conditions to a disturbed status of the peatland due to anthropogenic activities, such as drainage and land use change, or because of changes in climatic conditions. Peatland degradation alters the biogeochemical processes and changes the carbon balance of the soil. In the last century, more than 50 % of the peatland area in Europe was converted mainly for agricultural or forestry purposes (Joosten and Clarke, 2002; Byrne et al., 2004). Drainage of peatlands induces oxic conditions and an increase in carbon dioxide emissions, resulting in a net loss of carbon to the atmosphere (Maljanen et al., 2001). Therefore, peatland sites used for agriculture or peat extraction are significant sources of greenhouse gases (Maljanen et al., 2010). Moreover, peatlands are important wildlife habitats, play a major function in maintaining freshwater quality and are essential for geochemical and paleo archives, which will be altered/ destroyed by peatland degradation.

In the northern discontinuous **permafrost region** climate warming has accelerated carbon emissions from these soils. This was measured by the chamber technique (Dorrepaal et al., 2009) and presents contrary results to paleoecological studies, which suggest increasing net primary production under warmer conditions (Beilman et al., 2009; Yu et al., 2009; Loisel and Yu, 2013). Rising air temperatures, particularly in the high latitudes, leads to the thawing of permafrost and an increase of active layer thickness (Åkerman and Johansson, 2008) and affects the distribution of palsa peatlands. For palsa peatlands it is projected that the area suitable for these ecosystems will most likely be lost by the end of this century (Fronzek et al., 2006; Fronzek et al., 2010; Bosiö et al., 2012). While it is certain permafrost thaw will release carbon into the atmosphere and will accelerate climate change, the magnitude of this effect is highly uncertain to date (Schuur and Abbott, 2011). The alteration of palsa peatlands with a drastic change in vegetation patterns with a decline in dry hummocks due to permafrost thaw will change the carbon balance of this ecosystem, potentially decreasing CO_2 emissions and increasing CH_4 emissions (Bosiö et al., 2012).

In the **boreal region** a substantial proportion of peatlands in Fennoscandia and Russia was drained for forestry use with a total area of more than 100 000 km^2 (Minkkinen et al., 2008). In Finland, for instance, more than half of the peatland area was drained during the 20th century, mainly for forestry use (Laine et al., 2006). Mean emission factors for ombrotrophic drained peatlands for forestry in the boreal region are 0.02 kg C m^{-2} yr^{-1} whereas minerotrophic emit about 0.1 kg C m^{-2} yr^{-1} (IPCC, 2013a). The impact of draining boreal peatlands for forestry is a controversial debate because usually drained peatlands are carbon sources, but some studies show that these peatlands are still carbon sinks after drainage mainly due to increased wood, root and litter production (Minkkinen et al., 1999; Lohila et al., 2011; Ojanen et al., 2013). However, peatland drainage in the boreal region for grassland or cropland purpose usually changes a peatland from a carbon sink into a carbon source (carbon loss of 0.26 kg C m^{-2} yr^{-1} and 0.68 kg C m^{-2} yr^{-1}, respectively) (Couwenberg, 2009; IPCC, 2013a).

In the **temperate region** most of the peatland area has been drained and is managed as agriculture or grassland (Joosten and Clarke, 2002). Mean greenhouse gas emissions from peatlands in the temperate region under grassland use are 0.6 kg C m^{-2} yr^{-1} for deeply drained areas and 0.4 kg C m^{-2} yr^{-1} for shallowly drained peatlands (IPCC, 2013a). Ranked by land use intensity, intensively managed grasslands emit about 2.8 kg CO_{2eq} m^{-2} yr^{-1} and extensively managed grasslands emit between 0.2 and 2.0 kg CO_{2eq} m^{-2} yr^{-1} (depending on the water table) (Drösler et al., 2013). Near-natural peatlands are almost climate-neutral (Drösler et al., 2013). However, dry bogs which are affected by past drainage activities emit up to 1.0 kg CO_{2eq} m^{-2} yr^{-1} (Drösler et al., 2013). In Germany, for instance, 75 % of the greenhouse gas emissions from peatlands are attributed to agricultural use (Höper, 2007), and more than half of the greenhouse gas emissions from managed peatlands originate from grassland sites (Drösler et al., 2008). In total, greenhouse gas emissions from peatland soils account for about 5 % of Germany`s national greenhouse gas emissions (Drösler et al., 2013).

1.3 Indicators of peatland degradation

1.3.1 Qualitative indicators of peatland degradation

Stable carbon and nitrogen isotopes in depth profiles as indicators of peatland degradation

Both of the elements carbon and nitrogen consist of two stable isotopes. The two naturally occurring stable carbon isotopes are ^{12}C which forms 98.89 % of the carbon on Earth and ^{13}C with about 1.11 % of carbon (Fry, 2007). The naturally occurring stable nitrogen isotopes are ^{14}N which forms 99.64 % of the Earth's nitrogen and ^{15}N which represents about 0.36 % (Fry, 2007).

The natural abundance of these stable isotopes is an indicator in soil science to investigate biogeochemical processes in the soils and soil degradation (Krull and Retallack, 2000; Robinson, 2001; Schaub and Alewell, 2009; Conen et al., 2013; Meusburger et al., 2013). Stable carbon (and stable nitrogen) isotope ratios are usually presented as the ratio of ^{13}C:^{12}C (^{15}N:^{14}N) and reported as parts per mil (‰) comparing it to a reference standard Pee Dee Belemnite (PDB) for carbon (see equation 1.1) and the atmospheric nitrogen for nitrogen.

$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right)\text{sample}}{\left(\frac{^{13}C}{^{12}C}\right)\text{standard}} - 1 \right) * 1000‰ \qquad (1.1)$$

Depth profiles of stable carbon isotopes, which are not influenced by a vegetation change from C_3 to C_4 plants show fractionation trends in $\delta^{13}C$ values with depth (Nadelhoffer and Fry, 1988). These soils can be divided into three different $\delta^{13}C$ depth patterns (Krull and Retallack, 2000) which can be used as indicators of soil degradation.

These three different **stable carbon isotope** depth patterns are used as qualitative indicators of peatland degradation (Alewell et al., 2011) and are briefly introduced below.

(i) In natural peatlands with low decomposition rates, the $\delta^{13}C$ values can be almost constant with depth. This is because oxygen availability is low in water-saturated soils, the decomposition of organic material is reduced, and therefore isotopic fractionation is small (Clymo and Bryant, 2008; Skrzypek et al., 2008). Another possibility is that in peatlands where methane is produced the fractionation effects of CO_2 and CH_4 production might cancel out which can result in a uniform depth pattern of $\delta^{13}C$ values (Clymo and Bryant, 2008).

(ii) Lower $\delta^{13}C$ values in the deeper parts of the profile, compared to the source material (vegetation signal), are common for water-saturated soils (Krull and Retallack, 2000). The decrease of $\delta^{13}C$ occurs because of the relative enrichment of ^{13}C depleted recalcitrant material, such as lignin dominating the $\delta^{13}C$ values (Benner et al., 1987; Alewell et al., 2011).

(iii) Under aerobic conditions, decomposers prefer to use the lighter ^{12}C for respiration (Nadelhoffer and Fry, 1988). Because of this, ^{13}C accumulates more in the remaining organic material and the $\delta^{13}C$ value increases with depth (Nadelhoffer and Fry, 1988; Ågren et al., 1996). Increasing $\delta^{13}C$ values with depth of up to 5 ‰ are typical for well drained or mineral soils (Nadelhoffer and Fry, 1988).

In peatlands mainly two **stable nitrogen isotope** depth patterns exist: one with a constant $\delta^{15}N$ value with depth and the other one with increasing $\delta^{15}N$ values with depth.

(i) Stable nitrogen isotope depth profiles in natural ombrotrophic peatlands are assumed to scatter around 0 ‰ because atmospheric nitrogen is the primary source of nitrogen in these ecosystems (Jones et al., 2010; Broder et al., 2012). The $\delta^{15}N$ values of about 0 ‰ are characteristic of nitrogen-limited ecosystems (Skrzypek et al., 2008). However, plant species in peatlands can vary substantially in their $\delta^{15}N$ signature from -11.3 ‰ to +2.7 ‰ (Asada et al., 2005b), which can influence the $\delta^{15}N$ signature of the remaining peat material.

(ii) Under aerobic conditions the decomposition rate of soil organic matter is accelerated, resulting in a greater loss of the lighter isotope (^{14}N) compared to the heavier isotope (^{15}N) (Nadelhoffer and Fry, 1988). This is because decomposers preferentially use the lighter ^{14}N (Högberg, 1997; Robinson, 2001; Skrzypek et al., 2008). This nitrogen isotope fractionation during decomposition of organic matter leads to an enrichment of ^{15}N in the remaining soil organic matter and increases the soil ^{15}N with depth and age (Nadelhoffer and Fry, 1988; Nadelhoffer et al., 1996). Therefore, $\delta^{15}N$ values in oxic soils as well as in drained and/or degraded peatlands are supposed to increase with depth due to nitrogen mineralisation (Nadelhoffer et al., 1996; Kohzu et al., 2003).

In intensively managed ecosystems, the application of mineral and/or organic fertilizer, with their different isotopic signals (Bateman and Kelly, 2007), additionally alters the stable nitrogen isotope signature in peatland soils.

Further biogeochemical soil parameters as qualitative indicators of peatland degradation

Further biogeochemical soil parameters in depth profiles can be used as qualitative indicators of peatland degradation and to determine the change in decomposition processes of peatlands. The radiocarbon age determined by ^{14}C analyses, the C/N ratio, the bulk density and the mineral or ash content is changing significantly due to peatland degradation.

The ^{14}C is the most important radiogenic isotope of carbon and it occurs on Earth about 0.0000000001 % with a half-life of 5730 years (Godwin, 1962). In natural peat profiles the radiocarbon signature shows an increasing age with depth (Shotyk et al., 1998) due to peat accumulation over time. Peatland drainage results in a loss of peat that has been accumulated for the last hundreds or thousands of years. Loss of the younger, more recently accumulated carbon from the upper layers to the atmosphere changed the ^{14}C depth profile towards higher ages at the peat surface.

Peatland degradation causes not only peat oxidation and loss of carbon to the atmosphere but it also changes the bulk density and mineral (or ash) content in the peat profile. A higher decomposition of organic matter typically occurs due to peatland drainage, resulting in an increase in bulk density and an increase in ash content (Minkkinen and Laine, 1998b; Grønlund et al., 2008).

The C/N ratio indicates the degree of decomposition of the peat material (Malmer and Holm, 1984; Kuhry and Vitt, 1996). Little decomposed peat has larger C/N ratios, reflecting the former plant material, whereas the C/N ratio decreases in more strongly decomposed peat because of a preferential loss of carbon over nitrogen during microbial decomposition.

1.3.2 Quantitative indicators of peatland degradation

As peatlands are an important carbon pool and have a high potential of carbon loss due to degradation the carbon budget of these soils is of vital interest. There are several approaches to determine the quantitative carbon balance of natural and degraded peatlands (Van den Akker et al., 2016). Broadly they can be divided into process and inventory studies (Simola et al., 2012).

Process studies investigate the gas exchange of the soil or the whole ecosystem (Lindroth et al., 1998; Lohila et al., 2011; Meyer et al., 2013; Ojanen et al., 2013; Hommeltenberg et al., 2014). Process studies are using eddy covariance technique or chamber measurements. Through chamber measurements the heterotrophic and autotrophic respiration is used to calculate the loss or gain of carbon from the peatland (Beetz et al., 2013; Beyer and Höper, 2015). The eddy covariance method is a micro-metrological technique which uses vertical turbulent fluxes within the atmospheric boundary layers and measures for example the CO_2 fluxes between the ecosystem and the atmosphere (Baldocchi et al., 1988; Sagerfors et al., 2008; Olefeldt et al., 2012). In both these methods the flux exchange of other greenhouse gases like methane and nitrous oxide can be measured. For a full carbon budget of peatlands by the chamber measurements or by the eddy covariance method further carbon losses via leaching such as dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) or via gas fluxes such as methane (CH_4) need to be considered (Nilsson et al., 2008; Beyer and Höper, 2015). Additionally, exports of carbon and nitrogen by harvesting or mowing and the import by fertilizer and/or manure application must be considered at utilised agricultural sites for the annual carbon (and nitrogen) budget.

Inventory studies using profile-based methods examine the long-term changes in carbon stocks (Minkkinen et al., 1999; Simola et al., 2012; Pitkänen et al., 2013). Depending on the approach, different biogeochemical soil parameters of degraded soils are compared to a reference soil.

There are several approaches to determine the soil carbon balance of drained peatlands by soil profile-based methods. In general soil profile-based studies can be divided into (i) a resampling of a study site where peat profiles between present-day and historical situation are compared (Grønlund et al., 2008; Simola et al., 2012) or (ii) a space-by-time approach where soil parameter of peat profiles of paired undrained and drained parts of the same peatland are compared (Minkkinen et al., 1999; Pitkänen et al., 2013).

Carbon loss of degraded peatlands can also be calculated by subsidence measurements (Grønlund et al., 2008; Hooijer et al., 2012), changes in bulk density (Leifeld et al., 2011b) or by differences in the mineral content (ash content) of the peat profiles (Grønlund et al., 2008; Rogiers et al., 2008; Leifeld et al., 2011a). The two latter are combined in the so called combined method (Leifeld et al., 2014) in which the physical primary subsidence due to compaction and the chemical secondary subsidence due to the oxidative loss of organic matter can be estimated (Ewing and Vepraskas, 2006). This approach assessed the previous soil carbon stocks and peat thickness and estimated with this the carbon loss of the degraded peatland.

Another approach for determining the effect of peatland drainage on the soil carbon balance is the comparison of the carbon stocks of drained and undrained parts of the same peatland. This could be done, for instance, by comparing the carbon stocks above a same layer defined by an abrupt change in pollen ratios, by a synchronous charcoal layer (Laine et al., 1992) or by a layer of the same age, determined by radiocarbon analyses.

All profile-based methods assess the average carbon balance over the last several decades or centuries since the onset of peatland drainage.

1.4 Aims and outline of the thesis

The main aims of the thesis were to assess stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) in depth profiles as indicators of peatland degradation and to estimate the carbon loss of degraded peatlands by different profile-based methods. Thematically the thesis is subdivided into two main parts (figure 1.1): (i) qualitative indicators of peatland degradation (chapters 2, 3, 4 and 6) and (ii) quantitative estimation of the soil carbon balance of degraded peatlands (chapters 4, 5 and 6). The regional foci of the thesis are on peatland degradation in the subarctic region (chapter 2 and 3), the boreal region (chapter 6) and the temperate region (chapter 4 and 5) of Europe (figure 1.2).

Chapter 2 focused on stable carbon isotopes in depth profiles as indicators of palsa degradation and palsa uplifting by permafrost near **Abisko**, Northern Sweden (Abisko in figure 1.2). It was hypothesized that the stable carbon isotope depth profiles differ significantly between the degraded and non-degraded sites due to differences or changes in decomposition processes. Therefore, several transects, including degraded and non-degraded sites, in three different palsas were sampled. Palsa peatlands are projected to be lost by the end of this century due to increasing temperatures and permafrost thawing. The development of palsa including the uplifting by permafrost is therefore crucial for prospective distribution of this ecosystem. It was furthermore hypothesized that the uplifting by permafrost of the hummocks (uplifted peat material by permafrost) is indicated by stable carbon isotope depth patterns.

In **Chapter 3** the relation of $\delta^{15}N$ to C/N ratio (Conen et al., 2013) was used to detect disturbance of the soil depth profiles in the palsa peatland due to permafrost uplifting. It was hypothesized that the relation of $\delta^{15}N$ to C/N ratio indicated a disturbance of the soil at the depth where the peat was uplifted by permafrost. The uplifting changes the decomposition processes in the palsas and the time of permafrost uplifting can be identified by $\delta^{15}N$ depth profiles in combination with peat accumulation rates. Therefore, several depth profiles of two palsas (hummocks) from the subarctic, **Abisko**, Northern Sweden (Abisko in figure 1.2) were analysed on stable nitrogen isotopes and on the C/N ratio.

Chapter 4 investigated stable isotopes, both $\delta^{13}C$ and $\delta^{15}N$, and carbon losses along a land use gradient in a temperate bog near **Cuxhaven**, Northern Germany (Cuxhaven in figure 1.2). It was hypothesized that the stable isotope depth profiles change from a constant signal under natural conditions to increasing values with depth on the degraded sites. Furthermore, increasing carbon losses are assumed to occur along with increasing land use intensity. Vertical depth profiles of $\delta^{13}C$, $\delta^{15}N$, ash content, C/N ratio and bulk density, as well as radiocarbon ages were sampled to identify peat degradation and to estimate carbon loss along a land use gradient with a near-natural wetland, an extensively managed grassland and an intensively managed grassland site, all formed in the same bog complex.

The carbon balance of drained peatlands in central Europe is of major interest because the carbon losses of these ecosystems contribute a great amount to the national greenhouse gas budget. In **Chapter 5** a comparison of three different methods for calculating the carbon balance along a land use gradient in a temperate bog near **Cuxhaven**, Northern Germany (Cuxhaven in figure 1.2) was conducted. It was hypothesized that the highest carbon losses occur on the most intensive used site. Two soil profile-based methods (one using carbon accumulation rates and one using differences in ash content) were compared to greenhouse gas measurements using closed chambers as presented in Beetz et al. (2013).

The impact of draining boreal peatlands for forestry on the soil carbon balance is an object of controversial debate because some peatlands are still carbon sinks after drainage. In **Chapter 6** four different profile-based methods were applied for calculating carbon changes in peatland soils drained for forestry in the boreal region. The **Lakkasuo** peatland (Lakkasuo figure 1.2), Central Finland, has a minerotrophic and an ombrotrophic part, both of which have partially been drained for forestry. A pair-wise comparison between the two nutrient statuses was conducted. It was hypothesized that the nutrient status plays a crucial role on the impact of draining boreal peatlands for forestry on the soil carbon loss with higher losses at the nutrient-rich sites. Furthermore, it was hypothesized that the $\delta^{13}C$ depth profiles at the undrained sites show a uniform depth trend, indicating the natural status of these sites, and therefore, these sites can be used as reference sites for the carbon balance calculations.

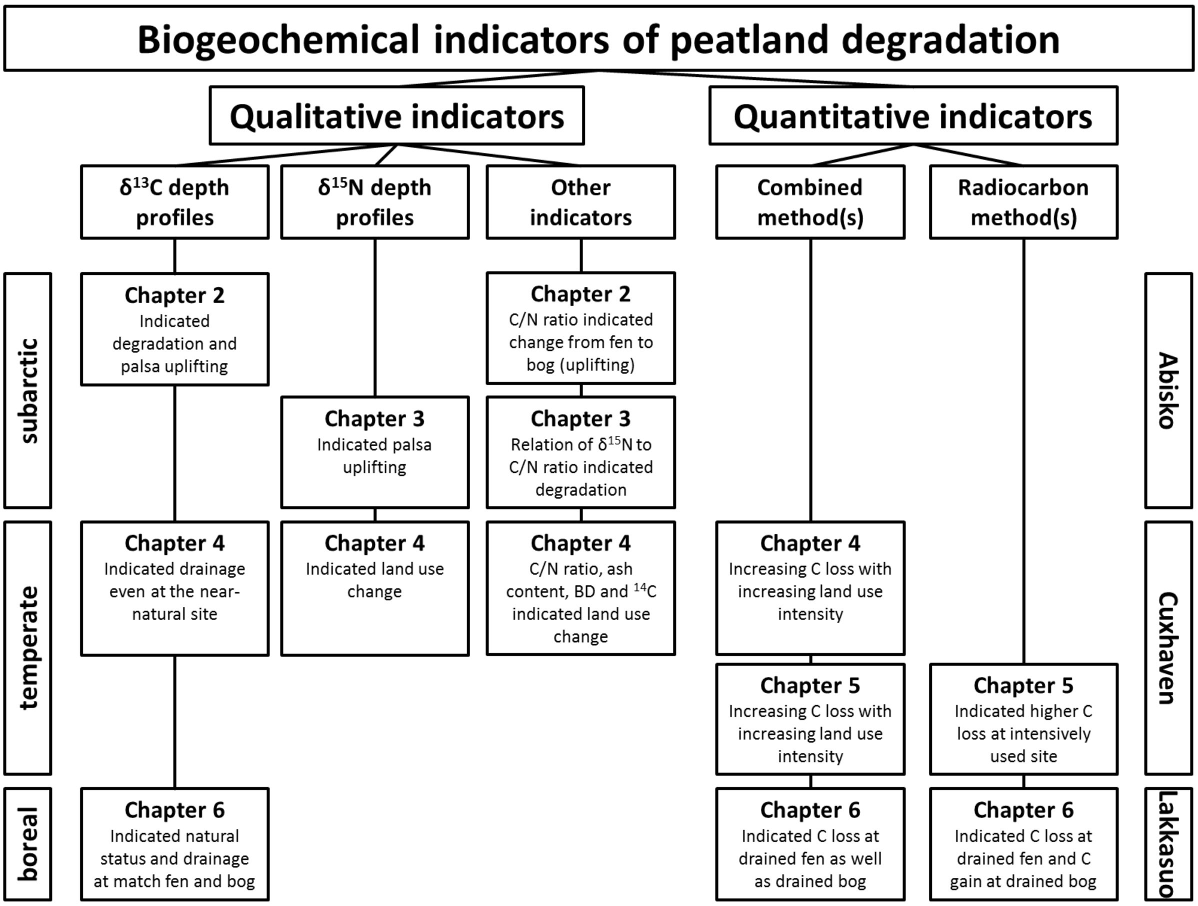

Figure 1.1: Overview of the thesis with the chapters 2-6 dealing with the qualitative and quantitative indicators of peatland degradation in the subarctic (Abisko), the temperate (Cuxhaven) and the boreal region (Lakkasuo).

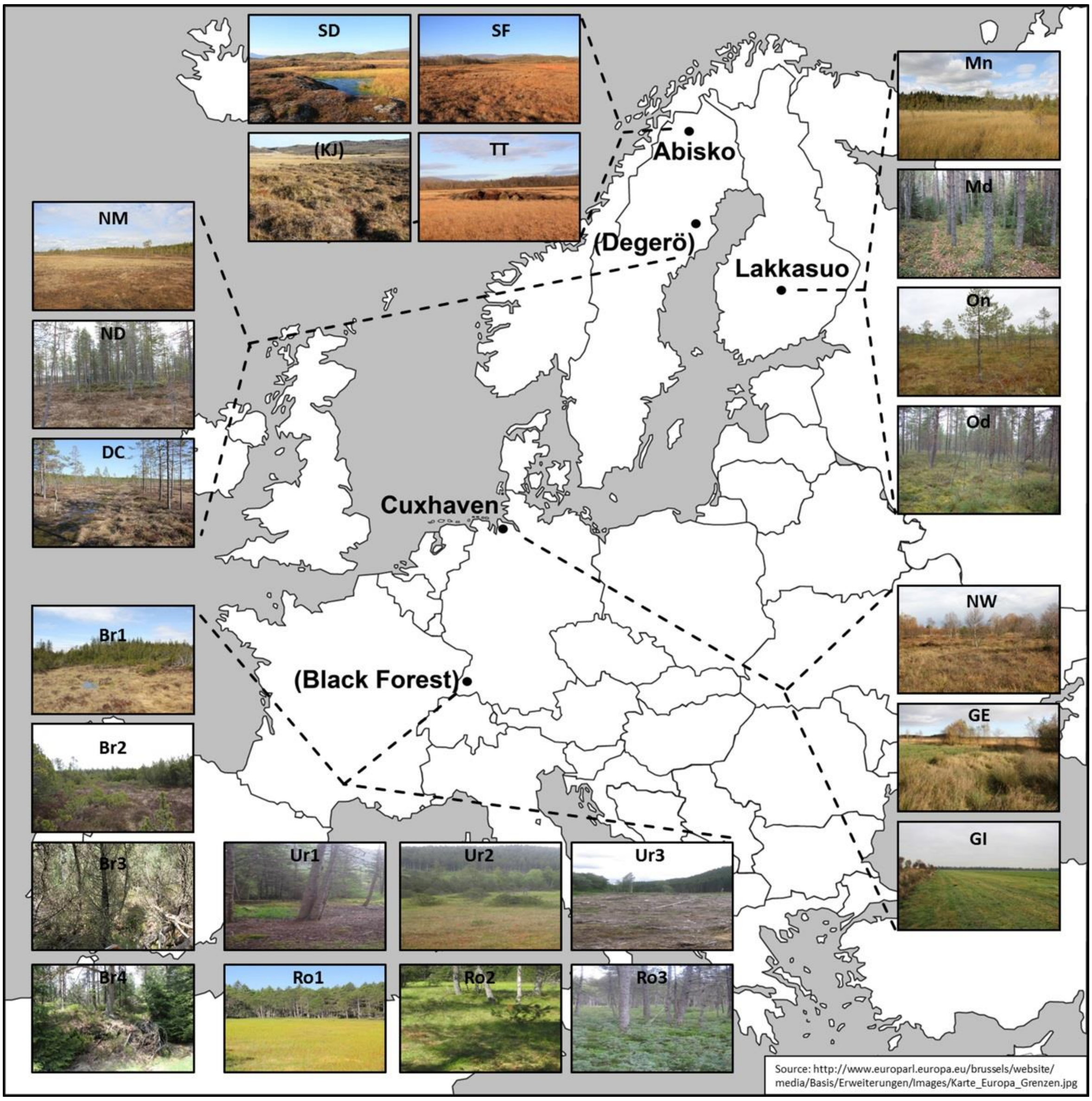

Figure 1.2: Overview of the peatlands which were investigated in the project. In Abisko, Northern Sweden, three palsa peatlands, Stordalen (SD), Storflaket (SF) and Torneträsk (TT) were investigated. The Lakkasuo peatland, Central Finland, comprises a natural minerotrophic (Mn) and a drained minerotrophic (Md) part as well as a natural ombrotrophic (On) and a drained ombrotrophic (Od) part. The Ahlenfalkenberger Moor, near Cuxhaven, Northern Germany, contains a near-natural wetland site (NW), an extensively used grassland site (GE) and an intensively used grassland site (GI). These entire sites are introduced in detail in the corresponding chapters. Further sites which are not included in the main chapters of this thesis but data are presented in the appendix 2 are: the Kattajokken (KJ) peatland near Abisko, Northern Sweden; the Degerö-Stormyr peatland, Sweden, with a natural mire site (NM), a natural dry site (ND) and a site near a drainage channel (DC); the Breitlohmisse, Northern Black Forest, Southern Germany, comprising a natural open bog (Br1), a site with heath vegetation (Br2), and two sites near a drainage channel a strongly degraded (Br3) and a low degraded (Br4); the Ursee Moor, Southern Black Forest, Southern Germany, consists of a dry site at the edge of the peatland (Ur1), a wet site at the center (Ur2) and a former forest site which was burned several years ago (Ur3); the Rotmeer Moor, Southern Black Forest, Southern Germany, comprised an open bog site (Ro1), a semi-dry but growing site (Ro2) and a dry site (Ro3).

Further investigated study sites which are not included in this thesis

In this PhD project further peatlands (Breitlohmisse, Rotmeer Moor and Ursee Moor in the Black Forest, Southern Germany; Degerö-Stormy in Sweden; Kattajokken in Northern Sweden) were investigated to assess the effect of peatland degradation on stable isotope depth profiles. Three peatlands from the temperate region (Black Forest, Germany), one peatland from the boreal region (Degerö-Stormyr, Sweden) and one from the subarctic (Kattajokken, Northern Sweden) are briefly introduced and the main aims of the studies are presented.

In the **Black Forest**, Southern Germany (Black Forest in figure 1.2), three temperate peatlands were investigated to evaluate stable isotope depth profiles as indicators of peatland degradation and peatland growth.

The peatland called **Breitlohmisse** (Br) in the Northern Black Forest comprised four different types of sites: a near-natural bog, a peatland with heath vegetation indicating drier conditions and two different sites at the edge of the peatland near a drainage channel, one strongly degraded and one just slightly degraded. It is assumed that the near-natural bog shows a uniform depth pattern of $\delta^{13}C$ and that the $\delta^{13}C$ depth profiles indicate degradation at the other sites but to different degree.

At the **Rotmeer Moor** (Ro) in the Southern Black Forest a moisture gradient with three different sites was sampled: an open bog site, a site which is assumed to grow and another site which is drier. It is therefore hypothesized that the $\delta^{13}C$ depth profiles represent the moisture gradient and that $\delta^{13}C$ depth pattern at the assumed growing site indicates a natural peatland. The stable isotope data will be compared to peat humification degrees and macrofossil analyses and will be included in the manuscript by Alewell et al. which is in preparation.

At the **Ursee Moor** (Ur) in the Southern Black Forest three different sites were sampled: one site at the edge of the peatland with dry conditions possibly influenced by the surrounding pasture management, one other site at the centre of the peatland with wet conditions and the third site is a former dry forest site on the peatland which was burned down several years ago. We assume an influence of the nutrient input on the decomposition rates consequently on the stable isotope depth patterns of the site on the edge of the peatland. Furthermore, it is hypothesized that the $\delta^{13}C$ depth patterns of the wet site represent a natural peatland, but is potentially also influenced by the surrounding pasture management, and the third site is strongly degraded due to the burning which is indicated by the stable isotope depth patterns. Figures of stable carbon and nitrogen isotopes in depth profiles as well as the radiocarbon data from the peatlands of the Black Forest are presented in the appendix (figure A2.1 – figure A2.10 and table A2.1).

To investigate the influence of draining a boreal peatland on the stable isotope depth profiles, three different sites at the boreal peatland **Degerö-Stormyr** near Vindeln, Sweden (Degerö in figure 1.2) were investigated. One site represents the natural peatland in the center. The other two sites are drier, with one located at the edge of the peatland near a ridge, and one close to a drainage channel. It is assumed that the stable isotope depth patterns differ significantly between the three sites and that the anthropogenic drainage had a greater impact on the stable isotope depth profiles compared to the naturally dry. Figures of stable carbon and nitrogen isotopes in depth profiles are presented in the appendix (figure A2.11 - figure A2.13).

At the subarctic peatland **Kattajokken** (KJ) near Abisko, Northern Sweden (Abisko in figure 1.2), three hummocks and three hollows were sampled. Neither of them has a permafrost core contrary to the other sites near Abisko, where permafrost is influencing the small-scale topography of the palsa peatlands. It is hypothesized that the stable isotope depth profiles present a different depth pattern compared to the subarctic sites with permafrost and that the $\delta^{13}C$ depth profiles of the hollows indicating wet conditions contrary to the profiles from the hummocks indicating dry conditions. Figures of stable carbon and nitrogen isotopes in depth profiles from the investigated hummocks and hollows of the Kattajokken peatland are presented in the appendix (figure A2.14 – figure A2.15).

CHAPTER 2

Degradation changes stable carbon isotope depth profiles in palsa peatlands

Krüger, J. P.[1], Leifeld, J.[2], and Alewell, C.[1]

[1]Environmental Geosciences, University of Basel, Bernoullistrasse 30, 4056 Basel, Switzerland

[2]Agroscope Reckenholz-Tänikon Research Station ART, Reckenholzstrasse 191, 8046, Zürich, Switzerland

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Abstract

Palsa peatlands are a significant carbon pool in the global carbon cycle and are projected to change by global warming due to accelerated permafrost thaw. Our aim was to use stable carbon isotopes as indicators of palsa degradation. Depth profiles of stable carbon isotopes generally reflect organic matter dynamics in soils with an increase of $\delta^{13}C$ values during aerobic decomposition and stable or decreasing $\delta^{13}C$ values with depth during anaerobic decomposition. Stable carbon isotope depth profiles of undisturbed and degraded sites of hummocks as well as hollows at three palsa peatlands in northern Sweden were used to investigate the degradation processes. The depth patterns of stable isotopes clearly differ between intact and degraded hummocks at all sites. Erosion and cryoturbation at the degraded sites significantly changes the stable carbon isotope depth profiles. At the intact hummocks the uplifting of peat material by permafrost is indicated by a turning in the $\delta^{13}C$ depth trend and this assessment is supported by a change in the C/N ratios. For hollows isotope patterns were less clear, but some hollows and degraded hollows in the palsa peatlands show differences in their stable carbon isotope depth profiles indicating enhanced degradation rates. We conclude that the degradation of palsa peatlands by accelerated permafrost thawing can be identified with stable carbon isotope depth profiles. At intact hummocks $\delta^{13}C$ depth patterns display the uplifting of peat material by a change in peat decomposition processes.

2.1 Introduction

Peatlands cover only 3 % of the global land surface, but they are an important component in the global carbon (C) cycle (Joosten and Clarke, 2002; Yu et al., 2011). Most of the peatland carbon (between 450 and 700 Pg) is stored in the boreal and subarctic regions (Gorham, 1991; Yu et al., 2011; Jungkunst et al., 2012), so this region contains as much carbon as is currently stored in the atmosphere (Lal, 2008). Peatlands in the northern permafrost zone, where palsa mires are widespread, have accumulated more than 270 Pg carbon in their soils (Tarnocai et al., 2009).

The existence of palsa mires is linked to climate conditions in the discontinuous permafrost region with low mean annual temperature, low annual precipitation and/or strong winds (Luoto and Seppälä, 2003; Luoto et al., 2004a). On wind exposed sites with a thin or even lacking snow cover a frozen core is built up (Luoto and Seppälä, 2002). The characteristics of palsa mires are mounds and plateaus called hummocks, which have been raised by the frozen core and thus lost connection to the groundwater. The uplifted peat surface above the surroundings leads to nutrient-poor and ombrotrophic conditions (Luoto et al., 2004a). The wetter parts (hollows) between the hummocks or surrounding parts have a high water table with sometimes minerotrophic conditions. Palsa mires are growing peatlands with different stages of development (Seppälä, 2003). With increasing active layer depth (annual thawing soil layer) their hummocks lose stability and start to collapse at the edges by block erosion and subsidence (de Jong et al., 2010) and could create thermokarst ponds (Luoto and Seppälä, 2003).

Global climate change with rising air temperatures particularly in the high latitudes leads to thawing of permafrost and an increase of the active layer thickness (Lemke et al., 2007; Åkerman and Johansson, 2008). In the Torneträsk region, northern Sweden, the active layer thickness has increased on average by 0.7 to 1.3 cm per year in the past 3 decades (Åkerman and Johansson, 2008). This process affects the hydrology, vegetation composition, C balance and other biogeochemical processes in the palsa peatlands (Christensen, 2004; Malmer et al., 2005; Bäckstrand et al., 2010; Olefeldt and Roulet, 2012). The degradation of palsa mires is likely to continue with the projected climate change and the carbon exchange between the peatlands and the atmosphere will be altered (Dorrepaal et al., 2009; Schuur et al., 2009).

It is projected that in the next decades the palsa vegetation will shift from dry hummock to moist hummock due to permafrost thawing (Bosiö et al., 2012). This change impacts the carbon exchange of the mire with a decrease in the efflux of CO_2 and an increase in the efflux of CH_4, the sum of which is predicted to be equivalent to a slight decrease in CO_2 equivalent emissions (Bosiö et al., 2012). Based on climate models it is estimated that the area suitable for palsa mires will decline by more than half by the 2030s and likely all suitable areas will disappear by the end of 21st century (Fronzek et al., 2006; de Jong et al., 2010; Fronzek et al., 2010).

Stable carbon isotopes are a widespread tool to analyse biochemical processes in soils. The ratio of ^{12}C and ^{13}C has been used to study soil degradation in different environments (oxic and wetland soils Schaub and Alewell (2009); palsa mires Alewell et al. (2011)). Depth profiles of stable carbon isotopes reflect organic matter dynamics (Krull and Retallack, 2000). The metabolic fractionation in plants produces slowly decomposing or recalcitrant substances like lignin which are low in ^{13}C (Benner et al., 1987; Ågren et al., 1996). On the other hand, decomposers used preferentially ^{12}C

for respiration which might lead to an enrichment of ^{13}C in the remaining soil organic matter (Ågren et al., 1996; Alewell et al., 2011). As such, changes in metabolic pathways (aerobic to anaerobic), or reaction rates should alter stable carbon isotope signatures of soils. Based on a theoretical concept of $\delta^{13}C$ in peatland soils outlined below three main types of $\delta^{13}C$ depth profiles were established and degradation hypotheses were developed.

The aim of this study was to use stable carbon isotope depth profiles as indicators of palsa degradation. Our hypotheses were as follows: (I) undisturbed palsa hummocks and degraded palsa hummocks differ significantly in their stable carbon isotope depth profiles. (II) A change from increasing to decreasing $\delta^{13}C$ values at the intact hummocks indicates the uplifting of the hummocks by permafrost. (III) Degraded hollows show a higher variation of stable carbon isotopes in their depth profile compared to undisturbed hollows indicating degradation processes.

2.2 Theoretical concept of $\delta^{13}C$ in peatland soils

The depth profiles of $\delta^{13}C$ in soils which are not influenced by a change from C3 to C4 vegetation might be described by three main depth patterns (Fig. 2.1). The theoretical concept by Alewell et al. (2011) has been adapted to the two main soil types of our study hummock (type A) and hollow (type B) of palsa peatlands. Additionally, the degraded status of both types is shown (type B and type C).

Depth profiles of intact hummocks (type A) are characterised by so-called “turning points” which indicate the uplifting of the hummocks by permafrost (Alewell et al., 2011). The $\delta^{13}C$ signal increases in the upper part of the profile to a certain depth and then decreases to lower values. In the upper part mostly aerobic decomposition with preferential loss of ^{12}C compared to ^{13}C has increased the $\delta^{13}C$ signal. Below this turning point the $\delta^{13}C$ signal decreases with depth and shows a depth pattern similar to degraded hollows with anaerobic decomposition and an enrichment of recalcitrant material in the deeper parts.

Degraded hummocks show a uniform depth trend of $\delta^{13}C$ (type B) or a zigzag pattern, because cryoturbation of hummock material mixed the soil material (Repo et al., 2009; Marushchak et al., 2011). The characteristic isotopic depth profile of intact hummocks has been merged to a constant signal lacking any depth trend in the soil profile.

A uniform depth trend is also found in intact hollows (type B) with little or no fractionation of $\delta^{13}C$. This trend is characteristic of water-saturated soils (Clymo and Bryant, 2008) with low redox conditions and little time for decompositional fractionation to occur (Krull and Retallack, 2000). In peatland soils where methane could be produced, the opposite fractionation effects of CO_2 and CH_4 production resulted in a uniform depth trend of $\delta^{13}C$ values (Clymo and Bryant, 2008). Another possibility is that the $\delta^{13}C$ values of the source material (vegetation) have been preserved due to anoxic conditions in the peat and no isotopic fractionation occurred.

A trend to lower $\delta^{13}C$ values with depth is found in degraded hollows (type C) with anaerobic composition. The decrease in $\delta^{13}C$ values with depth is due to a relative enrichment of slowly decomposing substances depleted in ^{13}C (Benner et al., 1987). The degraded hollows are characterised by added hummock material which was eroded from the edges of the hummocks. The latter could increase degradation processes in the hollows and alter stable isotope depth profiles with an enrichment of recalcitrant material dominating the $\delta^{13}C$ values (Benner et al., 1987; Alewell et al., 2011). The $\delta^{13}C$ value decreases with depth and has lower values in the deeper part of the profile compared to the source material (vegetation signal).

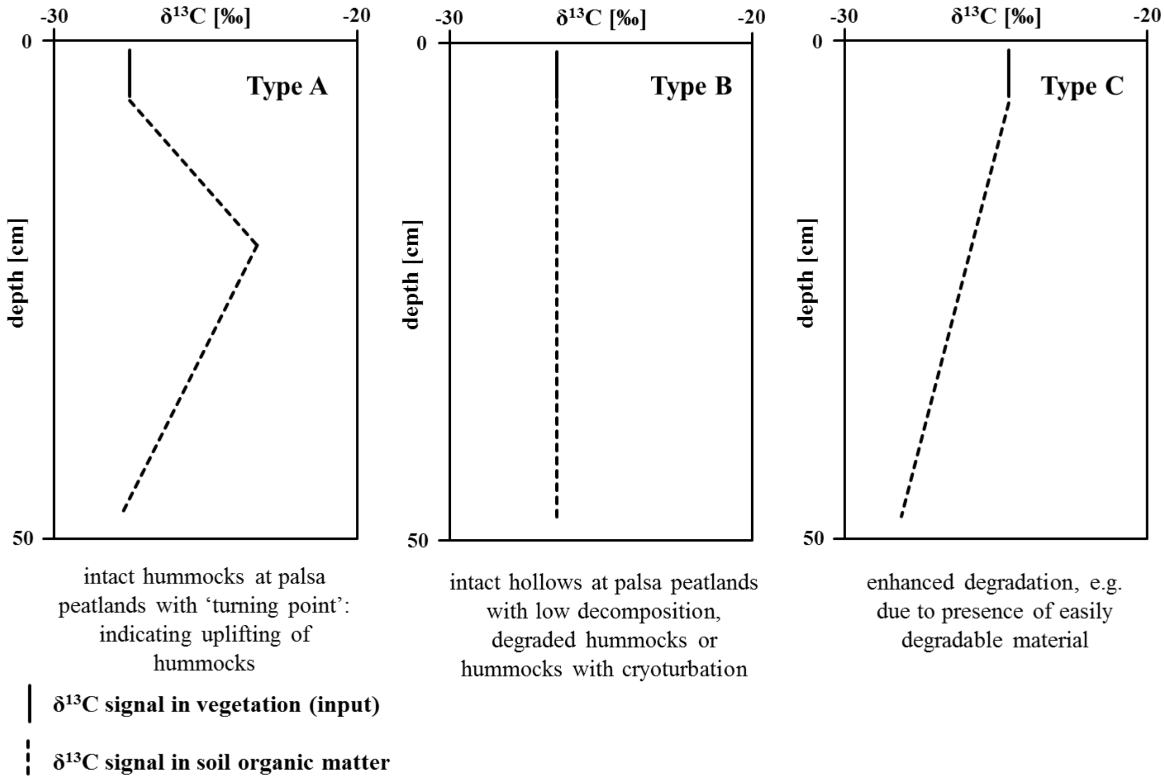

Figure 2.1: Theoretical concept depth profiles of $\delta^{13}C$ in peatland soils with hummocks (type A), degraded hummocks (type B), hollows (type B) and degraded hollows (type C) (modified from Alewell et al., 2011).

2.3 Material and methods

2.3.1 Sites

We sampled three palsa peatlands which are situated in the Torneträsk valley near Abisko (68°21'N, 18°49'E) in northern Sweden. The region is in the discontinuous permafrost zone 200 km north of the polar circle. Onset of peatland formation has been dated at ca. 4700 and ca. 6000 cal BP in the southern and northern part, respectively, of the Stordalen peatland (Kokfelt et al., 2010). All peatlands have drier, elevated parts with underlying permafrost called hummocks and adjacent, deeper and wetter parts called hollows. Permafrost aggradation was estimated to start at the peatlands in this region several hundred years ago (Malmer and Wallen, 1996; Kokfelt et al., 2010). The active layer, the annual thawing zone of the permafrost, usually reaches its greatest thickness in late September and is about 0.5 to 0.6 m deep at the hummocks and over 1.0 m in the hollows.

The Stordalen peatland (SD) is situated 10 km east of Abisko. A large part of the Stordalen peatland is a peat plateau elevated above the surrounding wet area. Malmer et al. (2005) classified three main plant communities, whereas Johansson et al. (2006) illustrate more site classes including the transition communities. In this study we focused on the elevated, dry hummock and on the wet hollow parts of the Stordalen peatland. The dry palsa hummocks are dominated by dwarf shrub (e.g. *Empetrum hermaphroditum*) and lichens (*Cetaria* spp. and *Cladonia* spp.) (Olefeldt et al., 2012) and the wetter hollows by *Sphagnum* and *Carex* vegetation where the water table is close to the surface. Additional information of the sites, including defined species names, can be found in Malmer et al. (2005) and Johansson et al. (2006). In this peatland hummocks have a silt layer below the peat material. In some parts this layer starts already at 15-20 cm depth.

The Storflaket peatland (SF) is located about 3 km west of the Stordalen peatland, closer to Abisko between the road E10 and the railway. The peatland is also characterised by a dry palsa plateau with dwarf shrub (*Empetrum nigrum*) and lichen vegetation and with some wetter parts dominated by *Sphagnum* mosses (*S. fuscum* and *S. balticum*) (Lund et al., 2009) and *Carex* vegetation. A few cracks with block erosion along the edges are present. The peat plateau is surrounded by wet areas with tall graminoid vegetation and open water.

The Torneträsk peatland (TT) is situated in the Abisko valley 40 km east of Abisko between the road E10 and the lake Torneträsk. Large isolated palsas (up to 1.5 m) with dwarf shrub (*Empetrum nigrum*) and lichen vegetation and with *Sphagnum* and *Carex* vegetation in between characterise this peatland. The palsas are small dome-shaped palsas with strong degradation on the edges with cracks and block erosion.

2.3.2 Climate

Climate data have been recorded since 1913 at the Abisko Research Station with a mean annual air temperature of -0.6°C and mean annual precipitation of 304 mm for the period 1913-2003.The precipitation at the two peatlands Stordalen and Storflaket does not differ significantly from the climate station (Johansson et al., 2006). Annual precipitation at Torneträsk is with 476 mm higher compared to the two other peatlands (Åkerman and Johansson, 2008). For the period 1961-1990 mean annual temperature is 0.2°C lower at Torneträsk compared to Stordalen and Storflaket (Åkerman and Johansson, 2008).

2.3.3 Peat samples

Peat cores were collected at the three palsa peatlands from September to October 2012. Samples were taken in small transects (Fig. 2.2) from hummock (hu) to hollow (ho) with degraded hummock (hud) and degraded hollow (hod) in between. We defined undisturbed hummocks as elevated palsas with no visible cracks or erosion. In contrast, degraded hummocks show clear cracks and erosion and are situated mainly at the edges of the palsas with partly water-saturated soil, but with typical hummock vegetation (dwarf shrub and lichen). Undisturbed hollows are represented by water-saturated parts of the peatlands with no influence of hummocks and their eroded material. Degraded hollows are hollows influenced by the eroded hummock material close to the degraded hummocks, but with distinct hollow vegetation (*Sphagnum* and *Carex*). Each of these transect sites are represented by three cores (n=3). Samples of palsa peatlands were taken with a Russian peat auger (Eijkelkamp, Netherlands) or with a cylindrical soil auger (Giddings Machine Company, US) down to the permafrost (hummocks) or about 0.5 m deep (hollows). The peat cores were embedded in plastic shells, wrapped with plastic foil and transported directly to the lab. Cores were cut into 0.02 to 0.04 m sections in the lab and oven-dried at 40-50°C for 72 h. The procedure was done on the day of sampling. Samples were transported and stored until preparing for drying at air temperature, but peat was dried directly after sampling. All samples were ground and homogenised in a vibrating ball mill (MM 400, Retsch, Germany). Stable carbon isotopes, organic C and total N concentrations were measured with isotope ratio mass spectrometer (Thermo Finnigan Delta plus XP coupled with a Flash EA 1112 Series elemental analyser; both instruments supplied by Thermo-Finnigan, Waltham, MA, USA) following standard processing techniques. Stable carbon isotope ratios are reported as $\delta^{13}C$ in [‰] relative to the V-PDB standard. The instrumental standard deviation for $\delta^{13}C$ is 0.1%. The C/N ratio represents the atomic relationship between carbon and nitrogen content of the peat material. Active layer depth was determined at hummocks manually by a 1 cm diameter steel rod inserted into the soil. Measurements were done in late September-early October which is the time of maximum thaw of the permafrost.

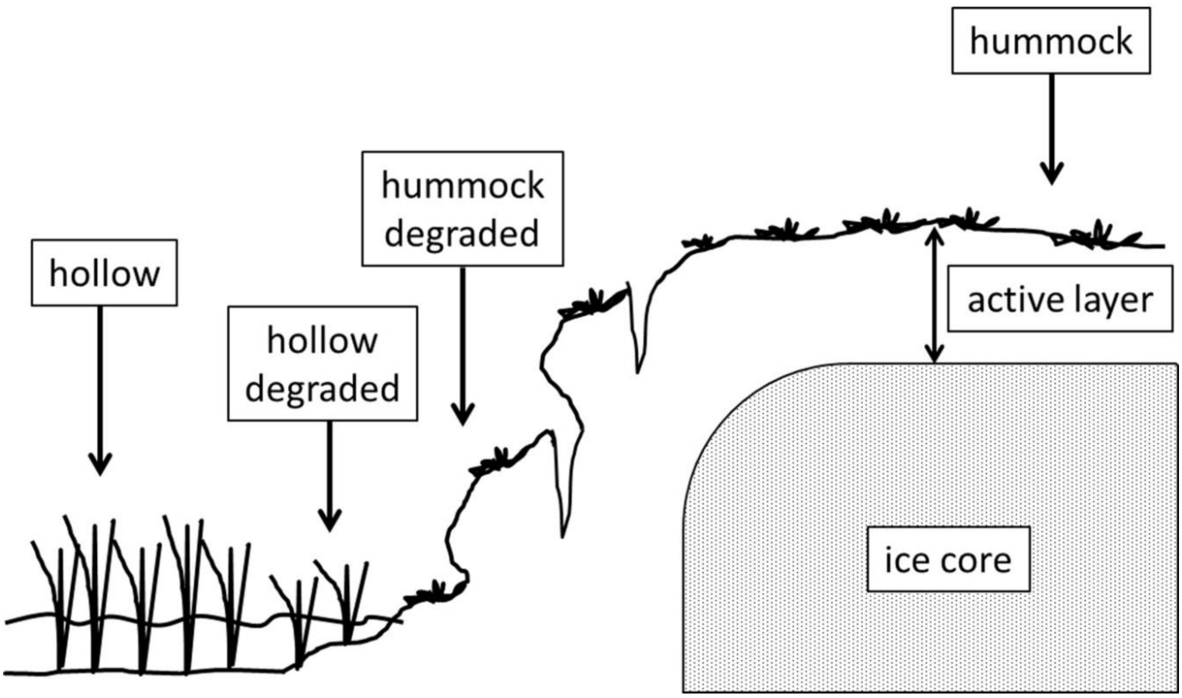

Figure 2.2: Transect of the sampling at the palsa peatlands with an approximately distance of 4.0 to 8.0 meter between the outer sampling points.

2.4 Results and discussion

Stable carbon isotope values of peat profiles from the three palsa peatlands in all studied sites varied between -21.2 ‰ and -29.1 ‰ and are in the range of other peatland studies (Price et al., 1997; Hornibrook et al., 2000; Ménot and Burns, 2001; Jones et al., 2010; Alewell et al., 2011; Andersson et al., 2012; Broder et al., 2012; Esmeijer-Liu et al., 2012). However, the different sites at the palsa peatlands showed distinct depth profiles of stable carbon isotopes indicating different processes during peat accumulation and decomposition.

2.4.1 Hummocks

Eight out of nine hummocks show a depth pattern of $\delta^{13}C$ with a turning point, i.e. a profile with an increase of $\delta^{13}C$ in the upper part and a decrease to lower ^{13}C values in the deeper part with the lowest measured $\delta^{13}C$ value in the profile at the turning point (Fig. 2.3). Regression analysis indicates a clear (in some profiles a significant) change from increase to decrease of $\delta^{13}C$ values with depth (Table 2.1).

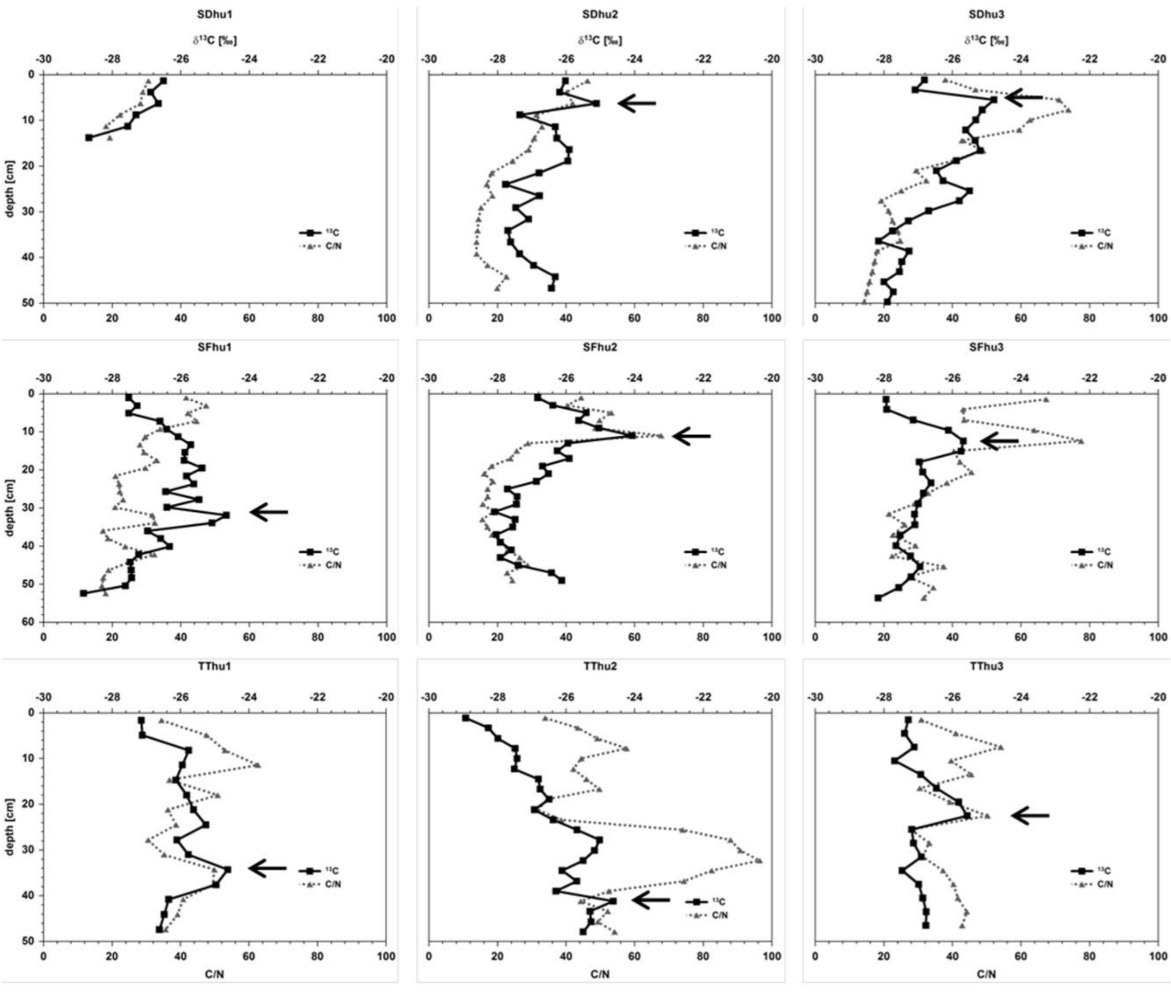

Figure 2.3: $\delta^{13}C$ and C/N ratio in depth profiles of hummocks (hu) at Stordalen (SD), Storflaket (SF) and Torneträsk (TT) peatland. Turning points in the profiles are indicated with black arrows.

Table 2.1: Regression analyses of $\delta^{13}C$ and depth at hummocks (hu) and hummocks (hud) degraded of the peatlands Stordalen (SD), Storflaket (SF) and Torneträsk (TT) with 'turning points' and calculated ages of the "turning points".

	Sites		Turning point: Depth (cm)	Turning point: $\delta^{13}C$ (‰)	Turning point: Calc. age	Coefficient of determination (R^2): Upper part		Coefficient of determination (R^2): Deeper part	
Non-Degraded	Stordalen	SDhu 1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		SDhu 2	5.5	-24.7	126	n=3	$0.61^{n.s.}$	n=16	$0.21^{n.s.}$
		SDhu 3	6.3	-25.1	110	n=3	$0.65^{n.s.}$	n=21	0.83***
	Storflaket	SFhu 1	31.9	-24.7	580	n=16	0.58***	n=11	0.81***
		SFhu 2	11.0	-24.1	200	n=6	0.92**	n=20	$0.18^{n.s.}$
		SFhu 3	12.4	-25.7	225	n=5	0.94**	n=16	0.67***
	Torneträsk	TThu 1	34.3	-24.6	660	n=11	0.61**	n=5	0.86*
		TThu 2	41.2	-24.6	792	n=19	0.80***	n=4	$0.78^{n.s.}$
		TThu 3	22.5	-25.6	433	n=8	0.75**	n=9	$0.07^{n.s.}$
Degraded	Stordalen	SDhud 1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		SDhud 2	9.0	-24.9	180	n=3	$0.83^{n.s.}$	n=10	0.52*
		SDhud 3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Storflaket	SFhud 1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		SFhud 2	29.0	-25.3	527	n=8	0.69*	n=3	$0.86^{n.s.}$
		SFhud 3	13.0	-24.5	236	n=7	$0.20^{n.s.}$	n=12	0.63**
	Torneträsk	TThud 1	25.0	-24.6	481	n=7	0.86**	n=7	$0.37^{n.s.}$
		TThud 2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		TThud 3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.s. = not significant, *p<0.05, **p<0.01, ***p<0.001, n.d. = not detected, calc. age (years) = age calculated based on results from Alewell et al. (2011), with mean peat accumulation rates for Stordalen (0.5 mm yr^{-1}) and Storflaket (0.55 mm yr^{-1}) and mean of both peatland for Torneträsk (0.52 mm yr^{-1}) peatland.

The turning point depth varies between the three peatlands from lowest depth at Stordalen (about 6 cm) to medium at Storflaket (between 11 and 31 cm) and deepest at Torneträsk (22 to 41 cm depth). The $\delta^{13}C$ signal at turning points in all peatlands is approximately -25.0 ‰. Based on the peat accumulation rates determined in Alewell et al. (2011), the age of the turning points in this study is about 120 years at Stordalen, between 200 and 580 years at Storflaket and up to almost 800 years at Torneträsk (Table 2.1). The turning point ages are comparable to ^{14}C dated ages in Alewell et al. (2011) of 155 to 671 years for Stordalen and Storflaket. Thus, the Suess effect played a minor role in the palsa peat profiles, because the turning points are much older and it will only be documented in the upper centimetre of the profile (Alewell et al., 2011). The increase of $\delta^{13}C$ with depth is comparable to well-drained soils where aerobic decomposition favours selective loss of ^{12}C (Nadelhoffer and Fry, 1988). The change from minerotrophic to ombrotrophic conditions of the Stordalen mire, which are caused by the uplift of the palsas due to permafrost, is supposed to have occurred also in the time period mentioned above (Rydberg et al., 2010). In line with our results at Stordalen peatland (turning point ca. 120 years), Kokfelt et al. (2010) detected palsa formation at the Stordalen site at ca. 120 cal BP. However, permafrost aggradation started at Stordalen over 800 years ago, and since then ombrotrophic conditions have dominated the peatland (Malmer and Wallén, 1996). The differences in turning point ages between the three sites may indicate different times of the uplifting of the palsas and a shift from anaerobic to aerobic decomposition. Small-scale differences in climate conditions (precipitation, temperature, wind exposure) could lead to different timing of permafrost uplift. In view of palsa formation, the higher age of the turning points at Torneträsk peatland compared to the two other peatlands could be explained by an earlier uplifting of the hummocks and is congruent with the formation of considerably bigger hummocks. Simultaneously the visible advanced degradation of the palsas at Torneträsk indicates a collapsing palsa and a higher development status of the palsa peatland (Seppälä, 2006), which might be explained by an advanced influence from climate change in this region.

Table 2.2: Correlation analyses (Spearman's) between $\delta^{13}C$ and C / N ratio with correlation coefficient and error probability at hummocks in the three palsa peatlands.

sites		n	r	p
	SDhu 1	6	0.89	0.03
Stordalen	SDhu 2	19	0.82	0.00
	SDhu 3	23	0.80	0.00
	SFhu 1	26	0.17	0.39
Storflaket	SFhu 2	25	0.64	0.00
	SFhu 3	20	0.32	0.16
	TThu 1	15	0.36	0.19
Torneträsk	TThu 2	22	0.58	0.01
	TThu 3	16	0.29	0.28

All profiles, with one exception, show highest C/N ratios in the upper 10 to 15 cm (Fig. 2.3), which is congruent with the results from Rydberg et al. (2010). They investigated a core at Stordalen peatland with a change from ombrotrophic to minerotrophic conditions at about 15 cm depth. C/N ratio decreases at this depth from high to lower values. Kokfelt et al. (2010) measured high C/N ratios in the uppermost part and even higher in the sequence just below. In the deeper sequences they detected low C/N ratios, which is congruent with our results. From the eight hummocks showing a turning point, seven have highest C/N ratios at or above the turning point, indicating ombrotrophic conditions. In contrast, low C/N ratios in peatlands indicate minerotrophic conditions (Andersson et al., 2012), and therefore this change at the turning points could be another indicator of the uplifting of hummocks by permafrost. The absentee change in C/N ratios from high to lower values at Torneträsk peatland may indicate that the Torneträsk peatland was not strongly influenced by groundwater, and therefore no minerotrophic conditions occurred (Broder et al., 2012).

Low C/N ratios are in parallel with low $\delta^{13}C$ values, and vice versa (Fig. 2.3). All sites show a positive correlation between $\delta^{13}C$ and C/N ratios (Table 2.2) although the strength of correlation varies. A correlation between C/N ratios and ^{13}C values in peat soils was also found by Hornibrook et al. (2000). A close correlation indicates that decomposition is driving the stable isotope values (Jones et al., 2010). However, Esmeijer-Liu et al. (2012) found no correlation between C/N and ^{13}C values in a peat core. In forest soils values of $\delta^{13}C$ were mostly low in more strongly decomposed soil, because decomposition processes favour selective loss of ^{12}C and an enrichment of ^{13}C in the remaining material (Nadelhoffer and Fry, 1988). The correlation of organic matter C/N ratios and decomposition processes has been shown in other studies with a relatively higher loss of peat carbon compared to nitrogen during decomposition (Malmer and Holm, 1984; Kuhry and Vitt, 1996).

Mean active layer depth at hummocks is greatest at Stordalen (58 cm), less deep at Storflaket (52 cm) and shallowest at Torneträsk (49 cm) peatland. In contrast, in a previous study in 2008 mean active layer thickness was shallower at Stordalen (50 cm) compared to Torneträsk (56 cm) (Keuper et al., 2012). Either the Torneträsk palsas have been subsided and the active layer depth has decreased or Stordalen has been degrading faster recently. Another possibility is that the absolute thawing depth and relative differences are an annual fluctuating phenomenon (Åkerman and Johansson, 2008).

2.4.2 Degraded hummocks

In comparison to intact hummock profiles most of the degraded hummocks show no clear depth pattern such as a turning point or a change from increasing $\delta^{13}C$ values to decreasing $\delta^{13}C$ values with depth (Fig. 2.4). The majority of depth profiles of degraded hummocks show a uniform depth trend or a zigzag pattern of $\delta^{13}C$ without clear direction. However, some of the degraded hummocks show a similar depth pattern in their $\delta^{13}C$ values with a turning point (Table 2.1) similar to the intact hummocks (SDhud2, SFhud2, SFhud3, TThud1). The uniform depth pattern could indicate the degradation of former intact hummocks caused by cryoturbation of the peat material. Continued warming in the Arctic could accelerate cryoturbation (Repo et al., 2009;

Marushchak et al., 2011) and hence increase degradation processes of palsa peatlands. Aerobic decomposition in palsa peatlands leads to selective preservation of recalcitrant and oxidised C in the soil organic matter (Pengerud et al., 2013). Advanced degradation of palsa hummocks leads to a transport of recalcitrant material into the surrounding hollows. The pattern in the degraded hummock profiles which are similar to those of intact hummocks may be related to a recent degradation of these areas and until now with no degradation signs in the $\delta^{13}C$ profile. The two intact depth profiles at the Storflaket peatland at visibly degraded sites could indicate the recent degradation at this palsa peatland with no change in the isotope signal until now. The recent degradation is supported by a previous study of Klaminder et al. (2008), who found no degradation at the Storflaket peatland 5 years ago.

At the Stordalen peatland the influence of the underlying silt layer can be seen in two out of three profiles with very low C content (below 20 %) and higher bulk density (up to 0.5 $g\,cm^{-3}$) in the deepest parts of the profile. This supports the cryoturbation consideration indicated by the homogeneous $\delta^{13}C$ depth pattern. The underlying organic-rich silt layer refers to permafrost-free conditions and was dated ca. 2800 cal BP (Kokfelt et al., 2010).

Degraded hummock profiles have low C/N ratios (on average 12-27 % lower than intact hummocks) especially in their deeper parts (C/N ratio < 20) with the exception of the degraded hummocks at Torneträsk. Various studies have shown that the C/N ratio is lower in more strongly decomposed peat (e.g. Malmer and Holm, 1984; Kuhry and Vitt, 1996), because nitrogen is relatively enriched compared to carbon. In N-limited ecosystems, such as peatlands, decomposition leads to a relatively higher loss of C compared to N, because organisms respiring organic substances will retain the N in the systems. Low C/N ratios in cryoturbated peatlands were also found by Repo et al. (2009) because of significantly higher nitrogen content (about 2 %) compared to typical peat plateaus and likely a higher decomposition rate. The latter is supported by higher respiration rates of incubated peat material at degraded sites compared to intact sites (Turetsky, 2004; Pengerud et al., 2013).

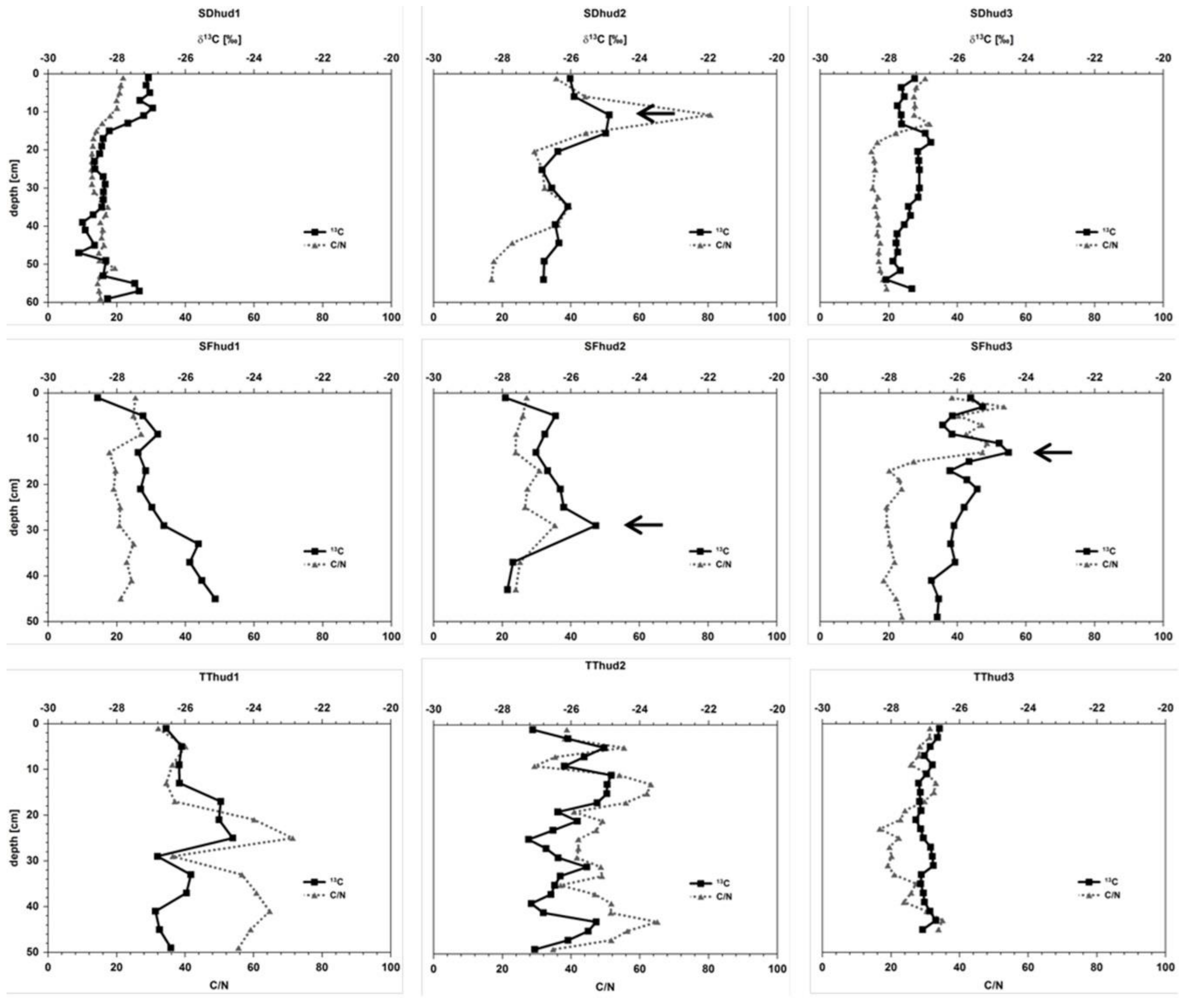

Figure 2.4: $\delta^{13}C$ and C/N ratio in depth profiles of degraded hummocks (hud) at Stordalen (SD), Storflaket (SF) and Torneträsk (TT) peatland. Turning points in the profiles are indicated with black arrows.

2.4.3 Hollows

Most of the hollows at the three palsa peatlands show a quite uniform depth trend of $\delta^{13}C$ with low variation of $\delta^{13}C$ (Fig. 2.5). In six out of nine depth profiles, the variation coefficient of $\delta^{13}C$ values is very low (Table 2.3) indicating uniform depth patterns. Uniform depth patterns are characteristic of water-logged soils, such as peatland soils, with little time for soil formation and/or limited decompositional fractionation (Krull and Retallack, 2000; Clymo and Bryant, 2008). Such conditions preserve the original isotopic signature (Krull and Retallack, 2000). Opposite fractionation effects of CO_2 and CH_4 formation in peatlands under low redox conditions with methane production may also result in a uniform depth trend of $\delta^{13}C$ in the remaining material (Clymo and Bryant, 2008).

One of the hollows at Storflaket (SFho2) has a depth pattern comparable to the degraded hollow profiles with decreasing $\delta^{13}C$ values with depth (see degraded hollows). Two profiles (SDho3 and SFho3) show an increase to heavier signatures with depth indicating slow aerobic decomposition in the hollows (Krull and Retallack, 2000; Alewell et al., 2011).

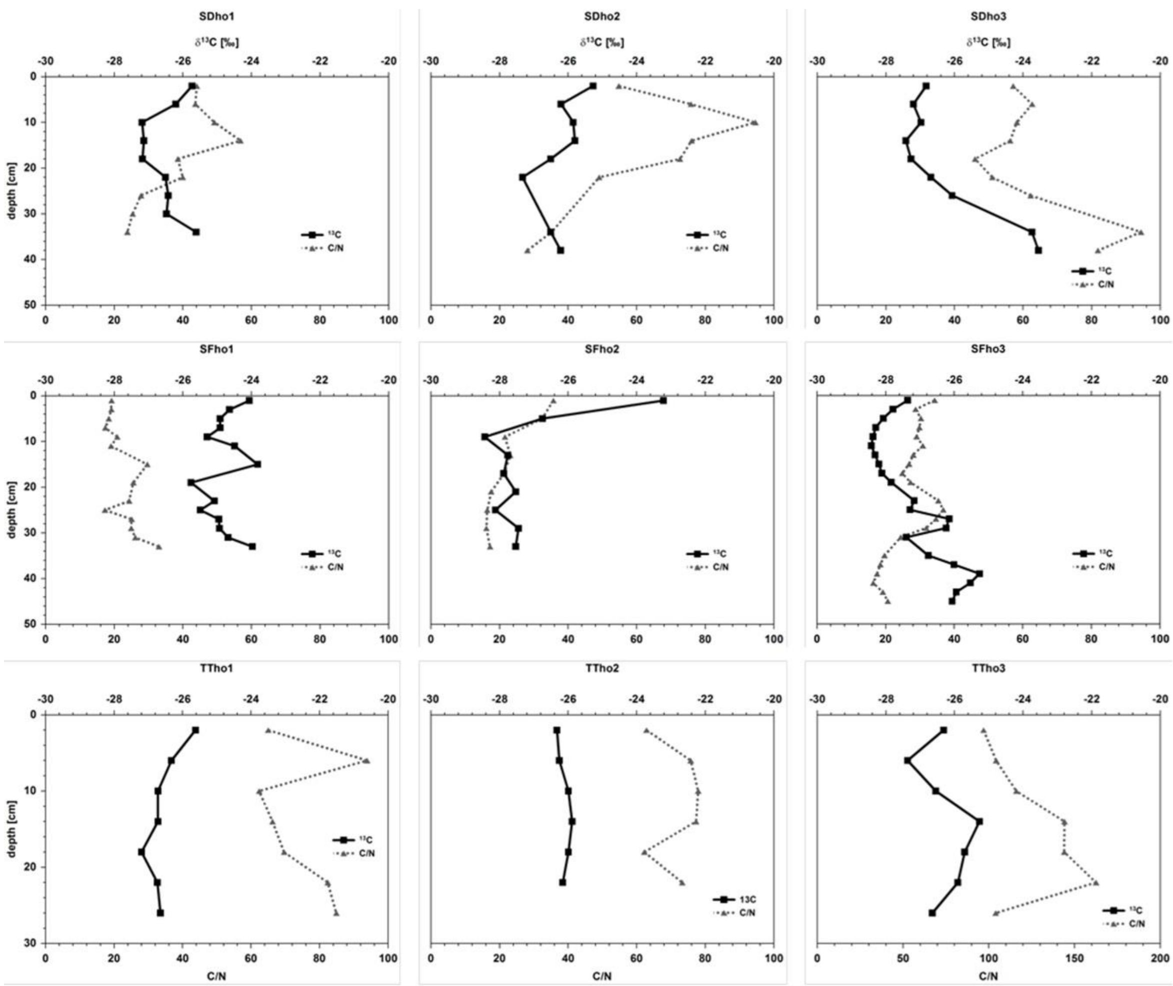

Figure 2.5: $\delta^{13}C$ and C/N ratio in depth profiles of hollows (ho) at Stordalen (SD), Storflaket (SF) and Torneträsk (TT) peatland.

Table 2.3: Coefficient of variation (CV) of $\delta^{13}C$ [‰] at hollows and degraded hollows.

	Stordalen						Storflaket						Torneträsk					
	non-degraded			degraded			non-degraded			degraded			non-degraded			degraded		
	ho1	ho2	ho3	hod1	hod2	hod3	ho1	ho2	ho3	hod1	hod2	hod3	ho1	ho2	ho3	hod1	hod2	hod3
n	9	8	9	25	20	23	14	9	21	10	11	20	7	6	7	9	12	12
CV (%)	2.2	2.3	5.7	5.1	4.4	2.0	2.3	5.7	3.8	3.6	2.8	3.2	1.8	0.7	2.7	4.8	8.0	7.9

In some profiles C/N ratios peak at 10 to 15 cm depth. This indicates the accumulation of fresh, little decomposed organic material (Kuhry and Vitt, 1996). C/N ratios at Torneträsk peatland are particularly high with values around 100, an indicator of strong ombrotrophic conditions

(Andersson et al., 2012). In general, the hollow profiles show higher C/N ratios compared to the degraded hollows, indicating that the peat material is less decomposed.

2.4.4 Degraded hollows

Degraded hollows at Torneträsk peatland show a decreasing depth pattern in the upper part congruent with the depth profile of type C (Fig. 2.6) and a uniform depth trend in deeper layers (type B). These profiles of Torneträsk peatland indicate an anaerobic degradation of the degraded hollow sites with significant differences in the stable isotope depth pattern compared to the intact hollows. Two profiles at Stordalen (SDhod1, SDhod2) show a similar depth pattern like the degraded hollows at Torneträsk. This could be due to the ongoing accelerated degradation of these palsa peatlands. However, at Storflaket no clear depth pattern of $\delta^{13}C$ at degraded hollows was found. The missing clear depth pattern at Storflaket could be due to low degradation of the palsa peatland and the hollows until now. Klaminder et al. (2008) detected no degradation in their study at Storflaket, whereas Alewell et al. (2011) found low degradation. In 2012 we found visible degradation with cracks and block erosion on the edges at this palsa peatland. However, this recent degradation of the hummocks might not be imprinted in the stable isotopes yet. The variation coefficient of $\delta^{13}C$ values at degraded hollows compared to intact hollows (Table 2.3) is higher at Torneträsk peatland indicating larger variability of $\delta^{13}C$ values and advanced degradation processes in these hollows. No significant higher variation coefficients at degraded hollows were found at Stordalen and Storflaket peatland.

In the degraded hollows the metabolic fractionation in plants may produce recalcitrant substances low in ^{13}C (Benner et al., 1987; Ågren et al., 1996). Owing to the high water table and probably permanent anoxic condition, the decomposition of organic matter is low. Therefore, the associated fractionation process with the preferential use of ^{12}C for respiration by decomposers and an enrichment of ^{13}C during decomposition is limited (Ågren et al., 1996). These degraded hollows are particularly affected by the (block) erosion of the thawing hummock. The additional hummock material could increase degradation rates in the hollows with a stronger accumulation of recalcitrant material depleted in ^{13}C in the deeper layers (Alewell et al., 2011) and thus explain the different $\delta^{13}C$ depth patterns between degraded and intact hollows. In the deeper parts the isotope signal is similar to that of the undisturbed hollows. Hollows contain a significant amount of labile C currently stabilised by anaerobic conditions (Pengerud et al., 2013). With degradation of palsas additional peat material is transported from hummocks into hollows and could alter the oxygen conditions and hence the decomposition processes in the hollows.

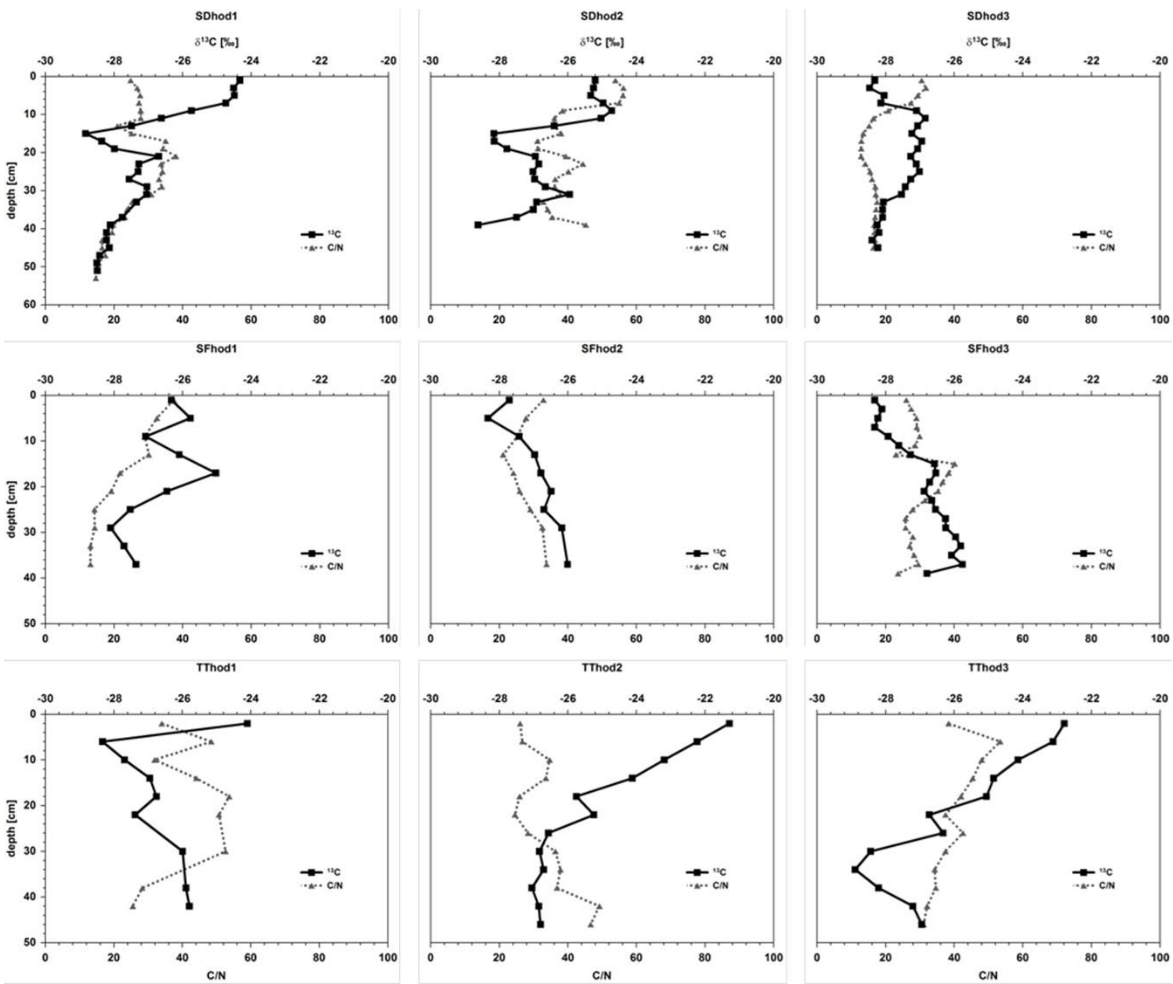

Figure 2.6: $\delta^{13}C$ and C/N ratio in depth profiles of degraded hollows (hod) at Stordalen (SD), Storflaket (SF) and Torneträsk (TT) peatland.

2.5 Conclusions

In the studied palsa peatlands, depth profiles of stable carbon isotopes show typical patterns related to their metabolism and degree of degradation. A changing climate in this region with continuous permafrost thawing altered the topography of the palsa peatlands, which induced a change in isotope depth profiles.

(I) The $\delta^{13}C$ depth profiles of hummocks differ significantly from the degraded hummocks. All but one intact hummock show a depth pattern with an isotopic turning point, i.e. change from increasing to decreasing $\delta^{13}C$ values. Most of the degraded hummocks have no turning point and display a more or less uniform depth profile of $\delta^{13}C$ indicating degradation and cryoturbation processes in these areas.

(II) The change from increasing to decreasing $\delta^{13}C$ values at hummocks indicates most likely the time of uplifting of the hummocks by permafrost above the surrounding areas with aerobic decomposition in the upper and anaerobic decomposition in the deeper part. The hypothesis of uplifting is supported by the higher C/N ratios above the turning point and lower values below, indicating ombrotrophic and minerotrophic conditions, respectively.

(III) Five out of six degraded hollows at two palsa peatlands show a predicted depth pattern of degraded hollows. $\delta^{13}C$ values at degraded hollows decrease with depth indicating an accumulation of recalcitrant material with depth as an indicator of anaerobic degradation in these peatlands. No clear differences were found at the Storflaket peatland, which might be due to the more recent influence of degradation.

A degradation of hollows in the palsa peatlands with altered decomposition conditions is indicated by the $\delta^{13}C$ in some of the profiles. $\delta^{13}C$ depth profiles of palsa peatlands in the hummock parts show the patterns of our established hypothesis of palsa degradation.

Acknowledgements

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CHAPTER 3

Permafrost uplifting in palsa peatlands identified by stable isotope depth profiles and relation of $\delta^{15}N$ to C/N ratio

Krüger, J. P.[1], Conen, F.[1], Leifeld, J.[2], and Alewell, C.[1]

[1]Environmental Geosciences, University of Basel, Bernoullistrasse 30, 4056 Basel, Switzerland

[2]Climate/Air Pollution Group, Agroscope, Reckenholzstrasse 191, 8046 Zürich, Switzerland

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Abstract

Palsas peatlands have an ice core and are common in discontinuous permafrost regions. Elevated parts of palsa peatlands, called hummocks, were uplifted by permafrost out of the zone influenced by groundwater. Here we relate $\delta^{15}N$ values to C/N ratios along depth profiles of hummocks in two palsa peatlands (Stordalen and Storflaket) to identify alterations in these soils. Nine out of ten profiles show a perturbation at the depth where peat was uplifted by permafrost. The perturbation of the peat by uplifting as well as the potential nutrient input by the adjacent hollows can be detected in soil $\delta^{15}N$ values when related to the C/N ratio at the same depth. Furthermore, the uplifting of the hummocks by permafrost could be detected by the $\delta^{15}N$ depth pattern with highest $\delta^{15}N$ values at the so called turning point. The $\delta^{15}N$ values increase above and decrease below the turning point when permafrost started uplifting. Onset of permafrost aggradation calculated from peat accumulation rates was between 80 to 545 years ago with a mean of 242 (±66) years for Stordalen and 365 (±53) years for Storflaket peatland. The mean peat ages of permafrost aggradation fall within the period of the Little Ice Age. Depth profiles of $\delta^{15}N$, when related to C/N ratio, are suitable to detect perturbation as well as uplifting of hummocks by permafrost in palsa peatlands.

3.1 Introduction

The distribution of palsa peatlands in discontinuous permafrost regions is projected to decrease dramatically due to the strong warming in the high northern latitudes (Fronzek et al., 2006; de Jong et al., 2010). The thawing permafrost due to increasing temperatures could release the vulnerable carbon (C) from these peatlands (Dorrepaal et al., 2009; Schuur et al., 2009; Treat and Frolking, 2013). In addition, the perturbation of palsa peatlands in the subarctic has ecological consequences for these specific peatland ecosystems (Luoto et al., 2004b).

Natural abundances of stable isotopes are not only a widespread tool to investigate biogeochemical processes in oxic soils (Nadelhoffer et al., 1996; Högberg, 1997; Robinson, 2001; Conen et al., 2013; Meusburger et al., 2013) or peatlands (Jones et al., 2010; Alewell et al., 2011; Andersson et al., 2012; Krüger et al., 2014; Krüger et al., 2015b) but might also help to detect perturbation of soils and ecosystems in general (Robinson, 2001; Conen et al., 2013). Studies from northern Sweden have shown that $\delta^{15}N$ could be correlated to nitrogen (N) losses from forest ecosystems (Högberg, 1990; Högberg and Johannisson, 1993). Boeckx et al. (2005) used the relationship between $\delta^{15}N$ and total N as an ecosystem indicator to assess ecosystem resilience against disturbance.

Changes in N cycling, i.e. loss or gain of N, results in the loss or gain of ^{15}N depleted forms leading to larger or smaller $\delta^{15}N$ values in soil than usual. Under aerobic conditions the decomposition rate of soil organic matter is accelerated, resulting in a greater loss of the lighter isotope (^{14}N) compared to the heavier isotope (^{15}N) (Nadelhoffer and Fry, 1988). Decomposers preferentially use the lighter ^{14}N which leads to a relative enrichment of ^{15}N in the remaining soil organic matter (Högberg, 1997; Robinson, 2001). Another influencing factor of the soil $\delta^{15}N$ value could be the mycorrhizal N transfer to plants which leads to a ^{15}N enrichment (Hobbie and Hobbie, 2008). However, this enrichment cannot account for all $\delta^{15}N$ patterns, and other soil processes such as discrimination during decomposition must influence the $\delta^{15}N$ signal in the soil (Hobbie and Ouimette, 2009). Because of a relatively higher release of C over N during organic matter decay C/N ratio decrease with decomposition (Nadelhoffer and Fry, 1988).

The characteristics of palsas are mounds or plateaus with an ice core, called hummocks, elevated above the surrounding, wetter area. The uplifted position leads to nutrient-poor and ombrotrophic conditions (Luoto et al., 2004b) as they are out of the influence of the groundwater. There are several techniques, for example macrofossil analysis or pollen and peat stratigraphy, in combination with radiocarbon dating to determine the time of palsa uplifting (Seppälä, 2005). Recently stable carbon isotopes in combination with peat accumulation rates have been used for determining the uplifting of palsa peatlands by permafrost (Alewell et al., 2011; Krüger et al., 2014). A combination of both macrofossil analysis and isotopic measurements have been proved as suitable for reconstructing the ecological conditions in a palsa peatland (Andersson et al., 2012).

Recently, Conen et al. (2013) used the relation of soil $\delta^{15}N$ to C/N ratio from different regions in northern Eurasia to detect a priori perturbation of the soil in these ecosystems. On unperturbed sites soil $\delta^{15}N$ values cover a relatively narrow range at any particular C/N ratio (Conen et al., 2013). The accelerated organic matter mineralisation will change the $\delta^{15}N$ value and alter the relationship of the $\delta^{15}N$ vs. C/N ratio of the soil according to the concept by Conen et al. (2013) and will indicate soil perturbation. The aims of this study were to apply the concept that Conen et al. (2013) developed for oxic mineral soils to palsa peatlands in order to detect perturbation of these soils and to identify permafrost aggradation by $\delta^{15}N$ depth profiles. We expect an enrichment of ^{15}N at the time, respectively depth, when permafrost lifted the peat material above the influence of groundwater because of an accelerated mineralisation resulting in a loss of isotopic lighter N (Fig. 3.1) indicating the perturbation of the soil. Furthermore, we expect a change in the C/N ratio as the peat material has different ecological conditions before and after the uplifting (Fig. 3.1). We hypothesize that with the application of the concept by Conen et al. (2013), relating $\delta^{15}N$ to C/N ratio, (I) the perturbation of hummocks in the palsa peatlands can be detected due to changes in decomposition processes by permafrost uplifting (II) the time of permafrost uplifting of the hummocks can be identified by combining $\delta^{15}N$ depth profiles with peat accumulation rates.

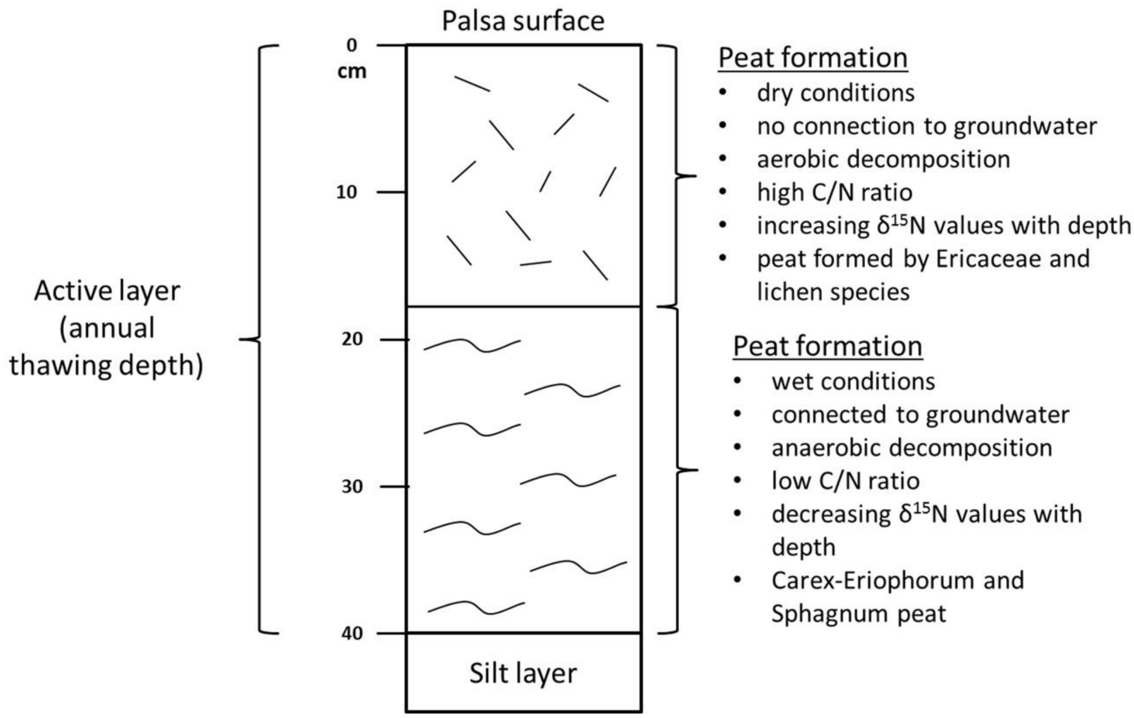

Figure 3.1: Schematic figure of a palsa profile. Peat formation occurred under dry and aerobic decomposition in the upper part of the profile (after uplifting by permafrost) and under wet and anaerobic decomposition in the deeper part of the profile (before permafrost aggradation). All peat material was lifted up by permafrost out of the influence of the groundwater.

3.2 Material and methods

We took soil samples from two palsa peatlands, Stordalen and Storflaket, which are situated in the Torneträsk valley near Abisko (68°21'N, 18°49'E) in northern Sweden. The region is located in the discontinuous permafrost zone 200 km north of the polar circle. Onset of peatland formation has been dated at about 4700 and about 6000 cal. years BP in the southern and northern part of the Stordalen peatland, respectively (Kokfelt et al., 2010). All peatlands in this study have drier, elevated parts with underlying permafrost, called hummocks, and adjacent, deeper and wetter parts, called hollows. The investigated hummocks are physical separated from the groundwater due to permafrost aggradation. Permafrost onset was estimated to start at the peatlands in this region about 700 to 800 years ago (Malmer and Wallén, 1996; Kokfelt et al., 2010). The active layer, the annually thawing zone of the permafrost in hummocks, is about 0.5 to 0.6 m deep and it usually reaches its greatest thickness in late September. In September and October 2012, peat cores were collected from hummocks at the two palsa peatlands, in three replicates per site (detailed site and sampling description in Krüger et al. (2014)). Samples described by Alewell et al. (2011) that were taken in June 2009 from the same two palsa peatlands were also used for this study. Samples were taken with a cylindrical soil auger (Giddings Machine Company, Windsor, CO 80550, USA) down to the thaw depth. Cores were cut into 2 cm sections in the lab and oven dried at 40°C for 72 h. All samples were ground and homogenised in a vibrating ball mill (MM 400, Retsch, 42781 Haan, Germany). Samples from 2012 were analysed for stable nitrogen isotopes, organic C and total N concentrations with a isotope ratio mass spectrometer (Thermo Finnigan Delta plus XP coupled with a Flash EA 1112 Series elemental analyser; both instruments supplied by Thermo-Finnigan, Waltham, MA, USA) following standard processing techniques. Stable nitrogen isotope as well as C and N content analyses (samples from 2009) 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 nitrogen isotope ratios are reported as δ^{15}N in [‰] relative to the atmospheric nitrogen standard with instrumental standard deviation of 0.15 %. The C/N ratio represents the atomic relationship between organic carbon and total nitrogen content of the peat material.

The turning point is defined as the highest δ^{15}N value of the depth profile with increasing values above and decreasing values below. Regression analysis of δ^{15}N and depth was carried out with the software R2.15.1 (R Core Team 2012). Ages of the turning points were determined based on peat accumulation rates for hummocks reported in Alewell et al. (2011), with mean peat accumulation rates of 0.5 mm yr^{-1} for hummocks at Stordalen and 0.55 mm yr^{-1} for hummocks at Storflaket peatland. To test for perturbation of each sample, the relation between δ^{15}N and C/N ratio was analysed by applying the equation (3.1) from Conen et al. (2013):

$$\delta^{15}\mathrm{N}\ [‰] = \frac{46.16}{\sqrt{C/N}} - 8.76 \qquad (3.1)$$

Samples, for which the measured δ^{15}N value deviates by more than +/- 2.4 ‰ from the δ^{15}N value predicted by this equation from the C/N ratio of the sample, are defined as perturbed. Other samples are defined as unperturbed.

3.3 Results and discussion

Samples from the two palsa peatlands in northern Sweden show $\delta^{15}N$ values from -5.2 to 5.7 (‰) and C/N ratios from 14 to 160 (Fig. 3.2). The $\delta^{15}N$ values are in the range of peatlands from the subarctic/arctic region (Jones et al., 2010; Andersson et al., 2012) and of soils with tundra vegetation (Nadelhoffer et al., 1996). The $\delta^{15}N$ of the soil pool is only determined by the isotopic composition of the inputs and losses of this system (Amundson et al. 2003). Within this system many different fractionation effects, such as mycorrhizal N transfer, denitrification or gaseous losses, can have an impact on the isotopic composition (Hobbie and Ouimette, 2009). Peat C/N ratios cover a wide range, greater values are found in the upper part of the profiles and smaller values in deeper parts (Krüger et al., 2014). Greater C/N ratios are typical for ombrotrophic peatlands or peat sequences which accumulate during ombrotrophic conditions whereas smaller C/N ratios are common for minerotrophic conditions (Andersson et al., 2012). This is comparable to the species common for palsas (*E. vaginatum)* and bogs (*Sphagnum spp.*) which have mean (±SD) C/N values of 39±24 and 46±18, respectively, and species common for fens like *Eriophorum angustifolium* and *Carex spp.* with C/N values of about 19±0.4 and 25±3, respectively (Hodgkins et al., 2014). Thus, a change in ecological conditions and hence vegetation can affect the C/N ratio of the remaining peat material. The $\delta^{15}N$ values of most samples are within the uncertainty envelope of +/-2.4 ‰ of Eq. 3.1, whereas some are situated outside, indicating perturbation of the latter (Fig. 3.2). Samples above the uncertainty envelope of the equation indicate a rapid N loss, whereas samples below indicate a rapid N gain. A rapid N loss is most likely due to the change in decomposition processes (anaerobic to aerobic conditions) of the peatland by permafrost uplifting. Under anaerobic conditions there is little mineralisation, hence little NH_4^+ is released. Consequently, very little N is lost in form of (isotopically light) NO_3^-, N_2O, or N_2. As a result, the $\delta^{15}N$ values of the soil are close to the $\delta^{15}N$ of the (isotopically light) input material (plants). As the material becomes oxic due to palsa formation, mineralisation accelerates, various forms of (isotopically light) N get lost (NO_3^-, N_2O, N_2) and the remaining material becomes enriched in ^{15}N. According to Eq. 3.1 all depth profiles, except one, indicate perturbation at the soil depth of the turning point (Fig. 3.3). Samples directly above the turning points are also mostly classified as perturbed samples. They indicate a loss of ^{15}N-depleted forms resulting in larger $\delta^{15}N$ values with decreasing C/N ratios and indicate continuing influences of change to the peat biogeochemistry due to uplifting by permafrost. Most of the youngest samples, close to the profile surfaces are classified as unperturbed, indicating that the ecosystem has adapted to the new conditions in the hummocks. A rapid N gain with samples being below the uncertainty envelope of mainly deeper soil samples in the profiles could be due to the proximity of these samples to the underlying silt layer and potential cryoturbation. With this, a mixing of the peat and silt material lowers C/N ratios, but probably maintains the $\delta^{15}N$ value. Furthermore, lateral water flow from the surrounding minerotrophic hollows may enhance the N concentration in deeper parts of the palsa complex. The relation of $\delta^{15}N$ and C/N ratio in depth profiles indicate the change in N cycling of these two palsa peatlands during and after the formation of hummocks.

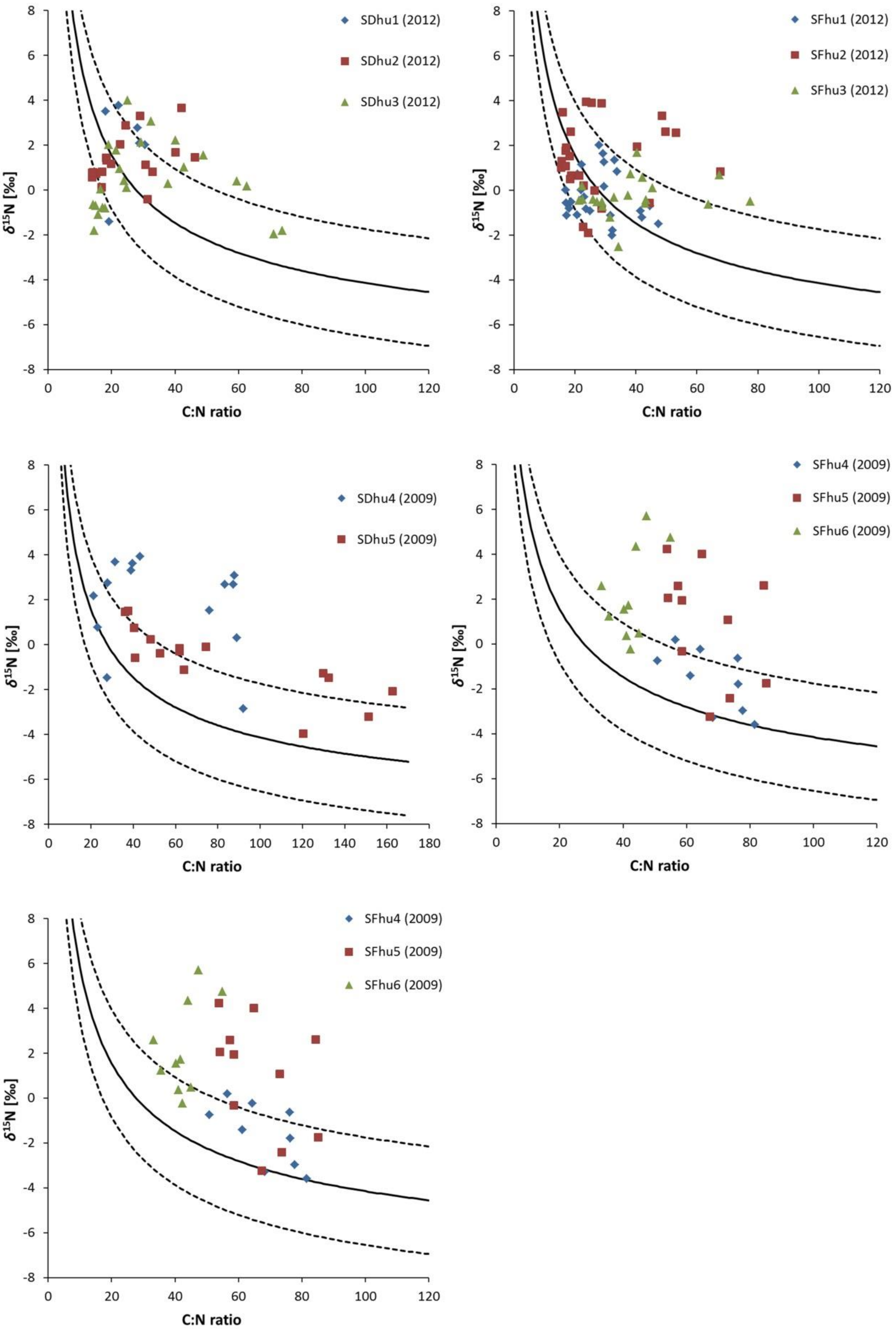

Figure 3.2: Relationship between $\delta^{15}N$ and C/N ratio at the hummocks in the Stordalen (SD) and Storflaket (SF) palsa peatland in northern Sweden. The relationship by Conen et al. (2013) was used to classify unperturbed samples (located inside the uncertainty envelope) versus perturbed samples (located outside the uncertainty envelope).

The uplifting of the hummocks leads to a change in decomposition processes in the soil and is indicated by a so called turning point. These soil depth patterns of $\delta^{15}N$ are also possible in ecosystems where N is not a limiting factor (Hobbie and Ouimette, 2009) but in peatlands N is usually a limiting nutrient. Six out of eight and five out of six profiles at Stordalen and Storflaket, respectively, reveal a $\delta^{15}N$ depth pattern with a turning point (Fig. 3.3). The change from increasing to decreasing $\delta^{15}N$ values with depth is supported by a linear regression analyses in the upper and deeper part of the profiles (Tab. 3.1). All regression analyses in the upper part present a positive relationship between $\delta^{15}N$ and depth and all in the deeper part, except one, a negative relationship. This indicates the uplifting of the hummocks by permafrost and a change from anaerobic to aerobic decomposition (Alewell et al., 2011; Krüger et al., 2014). The application of stable isotope depth profiles for identifying palsa uplifting is an easy technique and could be a suitable alternative to the pollen or macrofossil analyses. The increase of $\delta^{15}N$ values by about 2 to 6 ‰ in the upper part down to the turning point corresponds to the increase of $\delta^{15}N$ values with depth in oxic tundra soils (Nadelhoffer et al., 1996). Higher decomposition of soil organic matter results in N isotope fractionation with more positive $\delta^{15}N$ values in older soil organic matter and a decrease in the C/N ratio (Nadelhoffer and Fry, 1988). Highest $\delta^{15}N$ values at depth where peat was uplifted by permafrost could also be detected in a Russian peatland and is supported by the composition of the plant macrofossils and other geochemical measurements in the peat profile (Andersson et al., 2012). The change from fen to bog due to permafrost aggradation was evident in macrofossil and isotopic measurements confirming the usability of these proxies for paleo-ecological reconstruction (Andersson et al., 2012). The uplifting of peat material and a corresponding change from minerotrophic to ombrotrophic conditions is supported by the high C/N ratios in the upper part and low C/N ratios in deeper parts of the peat profiles (Krüger et al., 2014). In some other peat cores from Stordalen the same C/N patterns were found with a drastical change in the C/N ratio from large to small values at a certain depth which was interpreted as a change from minerotrophic to ombrotrophic conditions (Kokfelt et al., 2010; Rydberg et al., 2010). The high C/N ratios in the upper part of the profiles of our study are the result of low N concentrations of the soil indicating ombrotrophic conditions, because these ecosystems receive low N input, only from atmospheric deposition (Jones et al., 2010).

The $\delta^{15}N$ values at turning points varied from 2.4 to 4.2 ‰ and 1.7 to 5.7 ‰ for Stordalen and Storflaket palsa peatland, respectively (Tab. 3.1). The $\delta^{15}N$ value in a permafrost raised peatland in Russia was 5.5 ‰ in the associated depth (Andersson et al., 2012), which is in the range of our study. The turning point ages of the present study, based on the peat accumulation rates determined by Alewell et al. (2011), are between 80 and 508 years ago at Stordalen (mean 242 years) and between 243 and 545 years ago at Storflaket (mean 365 years) (Tab. 3.1). The younger ages at Stordalen compared to Storflaket are in accordance with the results in Alewell et al. (2011) and Krüger et al. (2014) based on stable carbon isotope depth profiles in combination with peat accumulation rates. At Stordalen the beginning of palsa development was dated between 120 and 800 years before present (Malmer and Wallén, 1996; Kokfelt et al., 2010; Rydberg et al., 2010), which is in the range of our calculated uplifting of hummocks. This indicates that permafrost onset was mainly during a prolonged cold period during the Little Ice Age (Bradley and Jonest, 1993) when most of the modern palsas have been formed (Oksanen, 2005; Zuidhoff and Kolstrup, 2000). Different turning point depths, and with this different timing of permafrost uplifting could be due to small-scale differences in geomorphology and thus exposition and climate conditions (precipitation, temperature, wind exposure). The missing turning points at some profiles from 2009 could be due to the early sampling in June with still incomplete thawing of the active layer resulting in low sampling depth of only down to approximately 25 cm.

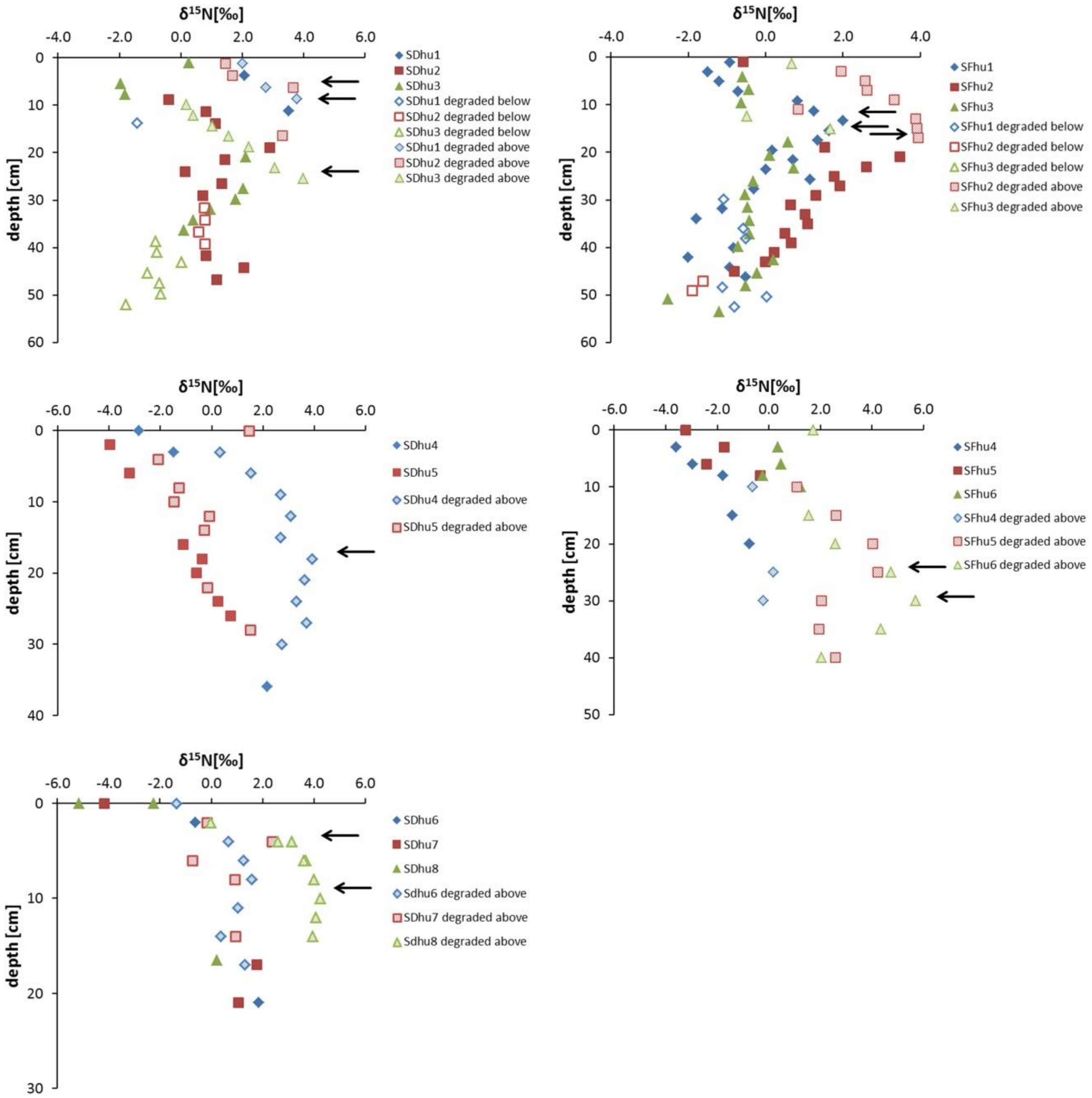

Figure 3.3: $\delta^{15}N$ depth profiles of hummocks in the Stordalen and Storflaket palsa peatland in northern Sweden. Perturbation of the soil samples were tested by applying the equation by Conen et al. (2013) with the relationship between $\delta^{15}N$ and C/N ratio (Fig. 1). Unperturbed samples are located inside the uncertainty envelope and are displayed as filled symbols in the depth profiles. Samples, which are below the uncertainty envelope are displayed as blank symbols and samples above the uncertainty envelope as striped symbols. Arrows indicate the turning points of the profiles.

Table 3.1: Regression analyses of $\delta^{15}N$ (‰) and depth (cm) at hummocks of the Stordalen and Storflaket palsa peatlands with depth, $\delta^{15}N$ value and calculated peat age at turning points.

Site	Core (sampling year)	Turning point Depth (cm)	$\delta^{15}N$ (‰)	Age# (years)	Mean (±SE) age# (years)	Correlation coefficient Upper part		Deeper part	
Stordalen	$SDhu1_{(2012)}$	8.8	3.8	175	242 (±66)	$0.94^{n.s.}$	n=4	$-0.89^{n.s.}$	n=3
	$SDhu2_{(2012)}$	6.3	3.7	126		$0.91^{n.s.}$	n=3	$-0.26^{n.s.}$	n=17
	$SDhu3_{(2012)}$	25.4	4.0	508		0.87^{***}	n=11	-0.89^{***}	n=13
	$SDhu4_{(2009)}$	18.0	3.9	360		0.92^{**}	n=8	-0.89^{**}	n=7
	$SDhu5_{(2009)}$	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	n.d.
	$SDhu6_{(2009)}$	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	n.d.
	$SDhu7_{(2009)}$	4.0	2.4	80		$0.99^{n.s.}$	n=3	$0.12^{n.s.}$	n=7
	$SDhu8_{(2009)}$	10.0	4.2	200		0.88^{**}	n=10	$-0.84^{n.s.}$	n=4
Storflaket	$SFhu1_{(2012)}$	13.4	2.0	243	365 (±53)	0.92^{**}	n=7	-0.71^{***}	n=20
	$SFhu2_{(2012)}$	17.0	4.0	309		0.73^{*}	n=9	-0.93^{***}	n=17
	$SFhu3_{(2012)}$	15.1	1.7	275		$0.29^{n.s.}$	n=6	-0.76^{**}	n=15
	$SFhu4_{(2009)}$	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	n.d.
	$SFhu5_{(2009)}$	25.0	4.2	455		0.96^{***}	n=8	$-0.61^{n.s.}$	n=4
	$SFhu6_{(2009)}$	30.0	5.7	545		0.87^{**}	n=9	$-0.99^{n.s.}$	n=3

n.d. = not detected, n.s. = not significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, # based on peat accumulation rates from Alewell et al. (2011) with mean peat accumulation rates of 0.5 mm yr^{-1} for Stordalen and 0.55 mm yr^{-1} for Storflaket peatland.

3.4 Conclusions

The concept of soil perturbation indicated by the relation of $\delta^{15}N$ to C/N ratios was developed for oxic soils (Conen et al., 2013) and was applied in this study for subarctic palsa peatlands. A rapid N loss and a rapid N gain, respectively, is indicated by the curved relationship between $\delta^{15}N$ and C/N ratio and the position of the sample above or below the uncertainty envelope. Permafrost onset in these palsa peatlands could be detected by stable isotope depth profiles in combination with peat accumulation rates. The relationship between $\delta^{15}N$ and C/N ratio indicated a change in N cycling of this ecosystem due to the uplifting by permafrost. Hence the concept seems applicable also to palsa peatlands. Further, the data support our concept of uplifting of the hummocks and subsequent permafrost onset in these peatlands during the Little Ice Age. Stable isotope depth profiles and a concept for identifying soil perturbation in combination with ^{14}C age dated samples are a suitable technique for determining palsa uplifting by permafrost.

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CHAPTER 4

Biogeochemical indicators of peatland degradation – a case study of a temperate bog in northern Germany

Krüger, J. P.[1], Leifeld, J.[2], Glatzel, S.[3], Szidat, S.[4], and Alewell, C.[1]

[1]Environmental Geosciences, University of Basel, Bernoullistrasse 30, 4056 Basel, Switzerland

[2]Agroscope Reckenholz-Tänikon Research Station ART, Reckenholzstrasse 191, 8046, Zürich, Switzerland

[3]Department of Geography and Regional Research – Geoecology, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria

[4]Department of Chemistry and Biochemistry & Oeschger Centre for Climate Change Research, University of Bern, Freiestrasse 3, 3012 Bern, Switzerland

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Abstract

Organic soils in peatlands store a great proportion of the global soil carbon pool and can lose carbon via the atmosphere due to degradation. In Germany, most of the greenhouse gas (GHG) emissions from organic soils are attributed to sites managed as grassland. Here, we investigated a land use gradient from near-natural wetland (NW) to an extensively managed (GE) to an intensively managed grassland site (GI), all formed in the same bog complex in northern Germany. Vertical depth profiles of $\delta^{13}C$, $\delta^{15}N$, ash content, C/N ratio and bulk density, as well as radiocarbon ages were studied to identify peat degradation and to calculate carbon loss. At all sites, including the near-natural site, $\delta^{13}C$ depth profiles indicate aerobic decomposition in the upper horizons. Depth profiles of $\delta^{15}N$ differed significantly between sites with increasing $\delta^{15}N$ values in the top soil layers paralleling to an increase in land use intensity owing to differences in peat decomposition and fertilizer application. At both grassland sites, the ash content peaked within the first centimetres. In the near-natural site, ash contents were highest in 10-60 cm depth. The ash profiles, not only at the managed grassland sites, but also at the near-natural site indicate that all sites were influenced by anthropogenic activities either currently or in the past, most likely due to drainage. Based on the enrichment of ash content and changes in bulk density, we calculated the total carbon loss from the sites since the peatland was influenced by anthropogenic activities. Carbon loss at the sites increased in the following order: NW<GE<GI. Radiocarbon ages of peat in the topsoil of GE and GI were hundreds of years, indicating the loss of younger peat material. In contrast, peat in the first centimetres of the NW was only a few decades old, indicating recent peat growth. It is likely that the NW site accumulates carbon today but was perturbed by anthropogenic activities in the past. Together, all biogeochemical parameters indicate a degradation of peat due to (i) conversion to grassland with historical drainage and (ii) land use intensification.

4.1 Introduction

Peatlands comprise the most important soil organic carbon (C) pool, storing more than 600 Pg C (Yu et al., 2011; Jungkunst et al., 2012). In these water-saturated soils, anoxic conditions hinder organic-matter decomposition and favour peat accumulation (Clymo, 1984). Drainage of peatlands induces oxic conditions and causes increasing carbon dioxide emissions (Maljanen et al., 2001) resulting in a net loss of carbon to the atmosphere. Over the last century, more than 50 % of the peatland area in Europe has been converted mainly to agriculture or forestry (Byrne et al., 2004). In Germany, 75 % of the greenhouse gas (GHG) emissions from organic soils are attributed to agricultural use (Höper, 2007) and more than half of the GHG emissions from managed peatlands originate from grassland sites (Drösler et al., 2008). Together, GHGs from organic soils comprise 5.1 % of Germany`s national total emissions (Drösler et al., 2013).

In the temperate zone GHG emissions from peatlands under grassland use average 0.6 kg C m^{-2} yr^{-1} for deeply drained and 0.4 kg C m^{-2} yr^{-1} for shallowly drained peatlands (IPCC, 2013a). Ranked by land use intensity, intensively managed grasslands emit 2.8 kg CO_{2eq} m^{-2} yr^{-1} and extensively managed grasslands emit between 0.2 and 2.0 kg CO_{2eq} m^{-2} yr^{-1} (depending on the water table) (Drösler et al., 2013). Near-natural bogs are almost climate-neutral, but dry bogs emit up to 1.0 kg CO_{2eq} m^{-2} yr^{-1}(Drösler et al., 2013).

To study soil degradation in different environments, stable carbon and nitrogen isotopes are a useful tool (Alewell et al., 2011; Conen et al., 2013; Krüger et al., 2014; Meusburger et al., 2013; Schaub and Alewell, 2009). In two recent studies in the subarctic region, stable carbon isotope depth profiles were shown to be a meaningful indicator of peatland degradation as well as of the uplifting by permafrost (Alewell et al., 2011; Krüger et al., 2014).

In a natural peatland with low decomposition rates, the $\delta^{13}C$ signature is almost constant with depth because in water-saturated soils the oxygen availability is low, decomposition of organic material is reduced and therefore isotopic fractionation is small (Clymo and Bryant, 2008; Skrzypek et al., 2008; Alewell et al., 2011). However, under conditions of anaerobic decomposition, $\delta^{13}C$ may slightly decrease with depth because substances such as lignin, which require aerobic conditions for their decomposition, are relatively enriched in ^{13}C (Benner et al., 1987; Alewell et al., 2011). Under aerobic conditions, decomposers preferentially use the lighter ^{12}C for respiration. Hence, the heavier ^{13}C accumulates in the remaining organic matter and the $\delta^{13}C$ value increases with depth (Nadelhoffer and Fry, 1988; Ågren et al., 1996). Increasing $\delta^{13}C$ values with depth are typical for well-drained or mineral soils (Nadelhoffer and Fry, 1988; Alewell et al., 2011). With a switch from anaerobic to aerobic conditions, peatland drainage is suggested to induce a change from a uniform $\delta^{13}C$ depth profile to increasing $\delta^{13}C$ values with depth (Fig. 4.1).

Because atmospheric N is the primary source of N in a natural terrestrial ecosystem, $\delta^{15}N$ values in bogs are assumed to scatter around 0 ‰ (Fig. 4.1) (Jones et al., 2010; Broder et al., 2012). However, plant species in intact peatlands vary substantially in their $\delta^{15}N$ signature from -11.3 ‰ to +2.7 ‰ (Asada et al., 2005b), which could influence the $\delta^{15}N$ signature of the remaining peat material. A second source of variability comes from nitrogen isotope fractionation during decomposition, leading to an enrichment of ^{15}N in the remaining material and an increase in soil

^{15}N with depth and age (Nadelhoffer and Fry, 1988; Nadelhoffer et al., 1996). Therefore, $\delta^{15}N$ values in oxic soils increase with depth (Fig. 4.1) (Nadelhoffer et al., 1996; Kohzu et al., 2003). We hypothesize that in drained and/or degraded peatlands, too, owing the above-mentioned processes, $\delta^{15}N$ values increase with depth (Fig. 4.1). In intensively managed ecosystems, the application of mineral and/or organic fertilizer, with their different isotopic signals (Bateman and Kelly, 2007), additionally alters the stable nitrogen isotope signature in soil.

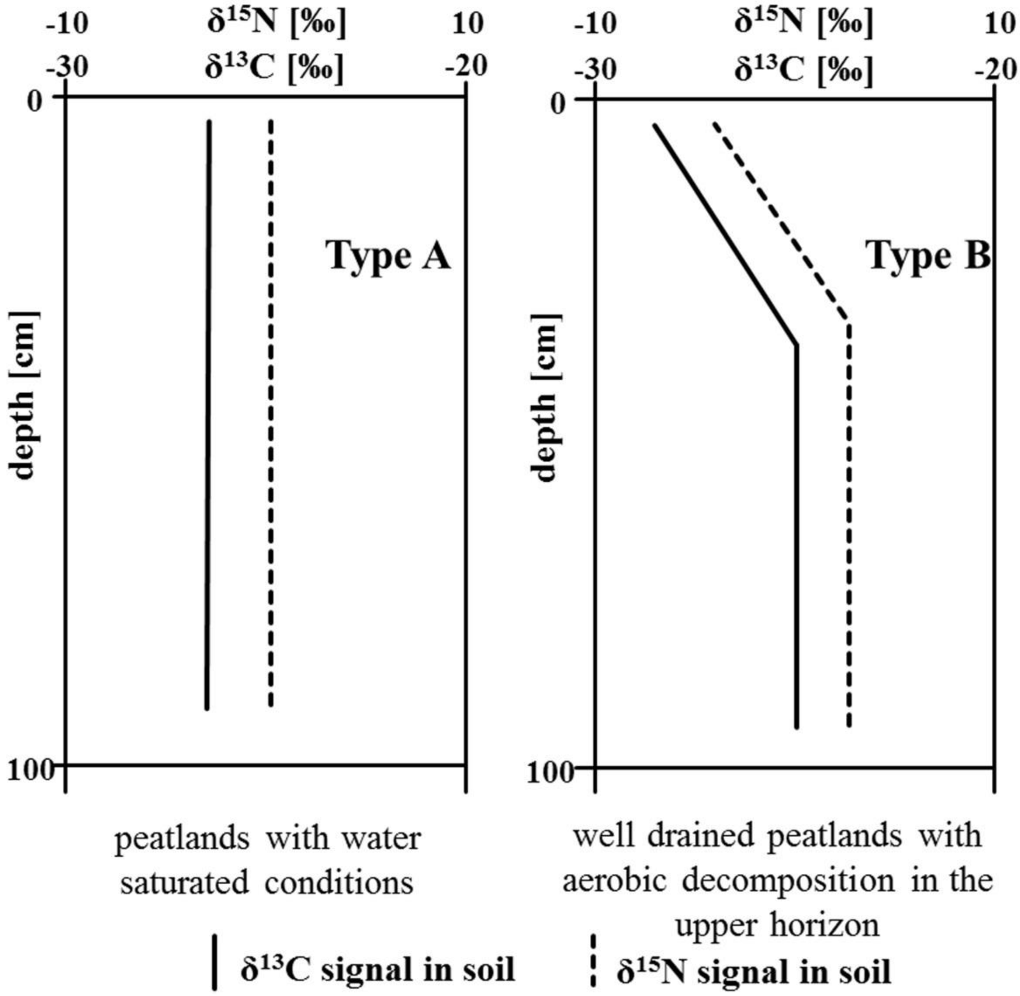

Figure 4.1: Theoretical concept of $\delta^{13}C$ and $\delta^{15}N$ depth profiles in natural (left) and degraded (right) peatlands.

In natural peat profiles the radiocarbon signature shows an increasing age with depth (Shotyk et al., 1998) due to peat accumulation in the course of time. Owing to the loss of peat which has been accumulated in the last several hundreds or thousands of years, a degrading peatland, with a loss of the younger, more recently accumulated C of the upper layers to the atmosphere, changes the ^{14}C depth profile towards higher ages near the peat surface.

The C/N ratio indicates the degree of the decomposition of the peat material (Malmer and Holm, 1984; Kuhry and Vitt, 1996). Peat that is only decomposed a little has larger C/N ratios, reflecting the former plant material, whereas the ratio becomes smaller in strongly decomposed peat owing to a preferential loss of C over N during microbial decomposition.

A simple but reliable estimate of C loss from cultivated peatlands can be obtained based on differences in ash content throughout the peat profile (Grønlund et al., 2008; Rogiers et al., 2008; Leifeld et al., 2011a). These methods are based on the premise of the accumulation of mineral matter (or “ash”) with peat oxidation, i.e. preferential loss of organic vs. mineral matter. In a pristine state of a bog, where mineral input solely derives from the atmosphere, we assume a relatively homogeneous ash depth profile. Drainage induces peat oxidation and net CO_2 emission, leading to peat subsidence and a relative enrichment of ash content in the upper layers, where decomposition is strongest. A so-called combined method (Leifeld et al., 2014) makes use of differences in bulk density and ash content in the profile in order to estimate not only C loss but also volumetric changes in the peat. It distinguishes between primary (settling) and secondary (oxidation) subsidence of the peat after drainage (Ewing and Vepraskas, 2006).

The main goal of our study was to test whether stable isotopes of carbon and nitrogen can be used as indicators of peatland degradation along a gradient of land use and drainage intensity and whether we could estimate carbon loss a posteriori. We apply the above concepts to a typical and well-studied peatland complex, the Ahlen-Falkenberger peatland, in northern Germany. Our hypotheses are as follows:

(I) The $\delta^{13}C$ depth profile changes from a constant signal under near-natural conditions to increasing $\delta^{13}C$ values with depth in degrading peatlands.

(II) Higher decomposition of the peat in the degraded sites leads to an enrichment of ^{15}N values in the upper layers.

(III) C losses are higher in the intensively managed compared to the extensively managed grassland.

Analysis of other indicators, such as radiocarbon age, ash content and C/N ratio, will be used for the validation of the interpretation of the stable isotope depth profiles.

4.2 Material and methods

4.2.1 Site description

The study area is located in Lower Saxony, north-western Germany, close to the North Sea coast. The peat bog complex called Ahlen-Falkenberger peatland (53°41’N, 8°49’E) is one of the largest peat bog complexes in northern Germany. The climate is humid Atlantic with a mean annual precipitation of 925.7 mm and a mean annual temperature of 8.5°C (reference period 1961–1990; German Weather Service, 2010). Bog formation began at about 6000 years BP on a former fen area (Schneekloth, 1970). From the late 17th century onwards, peat was extracted at the edges of the bog. Drainage activities started at the beginning of the 20th century. In the middle of the 20th century, over 50 homesteads were established in the Ahlen-Falkenberger peatland and land use was intensified (Ahrendt, 2012). Industrial peat extraction at the Ahlen-Falkenberger peatland began in 1957 (Schneekloth, 1981) and was terminated in the 1990s, when a conservation area was established (Beckmann and Krahn, 1991; Beller et al., 1994). About 60 % of the remaining former bog is currently used as grassland, and only a small area in the centre of the peat bog complex (approx. 5 %) was never drained or cultivated and remains as a natural peat bog today (Höper, 2007). In this area, vegetation is dominated by cross-leaved heath (*Erica tetralix* L.), flat-topped bog moss (*Sphagnum fallax* (Klinggr.)) and common cotton grass (*Eriophorum angustifolium* Honck.). We consider this near-natural wetland (NW) to be unmanaged. Further, we studied two areas of the former bog which are drained and today are managed as grassland: the extensive grassland (GE) is neither fertilized nor manured and only cut once per year; the intensive grassland (GI) is cut four to five times per year and fertilized with mineral fertilizer and manure (see details for the years 2008/2009 in Beetz et al. 2013). Liming and cattle grazing was never performed on these sites. GI is drained by pipes as well as drainage ditches, whereas GE is only drained by ditches, which were closed in 2003/2004. At the NW site, the water table was around the soil surface with a variation of -10 to 5 cm in 2012 and fluctuated between the surface and 40 cm depth (GE) and between the surface and 80 cm depth (GI) (Frank et al., 2014). Across the former bog complex, peat thicknesses range from 330 cm in cultivated to 515 cm in uncultivated, near-natural areas (Beetz et al., 2013). Recent GHG flux measurements at the Ahlen-Falkenberger peatland (2007-2009) indicate that site NW was C neutral in one year (-0.002 kg C m^{-2} yr^{-1}) and accumulated C in the next year (-0.124 kg C m^{-2} yr^{-1}) (Beetz et al., 2013). The net ecosystem carbon balance at site GE was positive in one (0.088 kg C m^{-2} yr^{-1}) and negative in the following year (-0.147 kg C m^{-2} yr^{-1}) (Beetz et al., 2013). GI was a carbon source for both years with C loss of about 0.548 to 0.817 kg C m^{-2} yr^{-1} (Beetz et al., 2013).

4.2.2 Soil sampling and analyses

In November 2012, three peat cores per site were collected in the Ahlen-Falkenberger peatland at NW, GE and GI (n=3) (Fig. A1.1). We took our cores close to the same locations from earlier studies by Beetz et al. (2013) and Frank et al. (2014). Peat samples were taken in the first 50 cm with a soil corer (Giddings Machine Company, US) and in deeper parts with a Russian peat corer (Eijkelkamp, Netherlands) down to approximately 1 m. Cores were embedded in plastic shells, wrapped with plastic foil and transported directly to the lab. Cores were cut into 2 cm sections and oven-dried at 40-50°C for 72 h. All samples were ground and homogenized in a vibrating ball mill (MM 400, Retsch, Germany). Stable carbon and stable nitrogen isotopes as well as C and N content were measured by combined mass spectrometry coupled to an SL elemental analyser (Integra2, Sercon, UK). The C/N ratio represents the mass relationship between the carbon and nitrogen content of the bulk peat material. Stable carbon isotope ratios are reported as $\delta^{13}C$ in per mill relative to the VPDB standard. Stable nitrogen isotope ratios are reported as $\delta^{15}N$ in per mill relative to the atmospheric nitrogen standard. The analytical standard deviation is 0.15 % and 0.1 % for $\delta^{15}N$ and $\delta^{13}C$, respectively.

The ash content was determined by thermogravimetry (prepAsh, Precia, Switzerland), using 0.5-1.0 g sample material. Pre-drying at 130°C was carried out to correct the dry mass and to evaporate the residual moisture. The sample was then heated to 600°C in air until no significant mass change (constant mass) could be measured (see detailed description of the method by Leifeld et al. (2011a)). The material remaining after heating is defined as the ash content of the sample.

4.2.3 Radiocarbon analyses

Radiocarbon (^{14}C) analysis was performed with accelerator mass spectrometry (AMS) at the Laboratory for the Analysis of Radiocarbon with AMS (LARA) at the University of Bern (Szidat et al., 2014). At each site, three depths were selected for radiocarbon dating, and the ^{14}C content of samples from these depths was measured for each individual core. Samples were selected after the evaluation of stable isotope and ash content depth profiles. Segments where stable isotope and ash contents clearly changed were selected for radiocarbon analysis. The ground and homogenized material was combusted, transformed into solid targets using automated graphitization equipment (AGE) (Nemec et al., 2010) and measured with the MIni CArbon DAting System MICADAS (Synal et al., 2007). Sample homogeneity and measurement reproducibility was proven by the double analysis of eigth random samples, whereas general accuracy and precision was reported earlier (Szidat et al., 2014). ^{14}C ages were calibrated using the IntCal13 data set (Reimer et al., 2013). Samples with bomb signature were dated using the Bomb13 NH1 dataset (Hua et al., 2013). Radiocarbon ages are presented for each site and selected depth are given as means (n=3) with 1 SD in cal years AD or cal years BC. Results of the individual measurements are shown in Tab. A1.5.

4.2.4 Calculation of carbon loss by the ash content and bulk density (combined method)

The integrated calculation of carbon loss of the peatland since the beginning of drainage is based on the simplified assumption that the ratio between carbon and ash content during the accumulation of peat is constant and that ash content before drainage is the same at all depths. After drainage, peat starts to oxidize and carbon is lost as CO_2 (Rogiers et al., 2008). Additionally, we assume that the ash content in the deeper parts of the profile is not affected by drainage. Ash from the oxidized peat remains at the site and accumulates in the upper layer of the profile. Differences in soil properties of bulk density, ash content and organic C content between the topsoil and undisturbed subsoil can be used to infer pre-drainage soil thickness and C stocks. The mean ash content of the deeper parts of the profiles, where samples show no enrichment of ash, in our case below 80 cm depth, of each individual core was taken as a reference value (Leifeld et al., 2011a). The C loss was calculated separately for each core.

The method of Leifeld et al. (2014) combines two previously published methods which were based on changes in bulk density (Leifeld et al., 2011b) and changes in ash content (Rogiers et al., 2008; Leifeld et al., 2011a) in peat profiles. This so-called combined method (Leifeld et al., 2014) estimates the physical primary subsidence due to the loss of pore water and peat shrinkage and estimates the chemical secondary subsidence due to the oxidative loss of organic matter.

The primary subsidence S_p (m) is calculated as follows (Leifeld et al., 2014):

$$S_P = PT_{0i} - PT_i \quad (4.1)$$

with

$$PT_{0i} = Bd_{OSi} / Bd_{OSr} \times PT_i \quad (4.2)$$

Where PT_{0i} is the pre-drainage thickness of layer i (m), Bd_{OSi} is the organic-matter density in layer i, Bd_{OSr} is organic-matter density of the reference layer (t m^{-3}), and PT_i is the thickness of layer i (m) at the time of sampling. Bd_{OS} is calculated from the soil mass of per unit soil volume minus the ash mass and the ash volume of the same soil volume, assuming a specific density of ash particles of 2.65 t m^{-3}.

The secondary subsidence S_s is calculated from the pre-drainage thickness ST_{0i} (m) attributable to organic-matter oxidation (Leifeld et al., 2014):

$$ST_{0i} = ST_i \times F_{ashi} / F_{ashr} \quad (4.3)$$

with ST_i being the thickness of layer i (m), F_{ashi} the ash concentration of layer I and F_{ashr} the ash concentration of the reference layer.

$$S_s = ST_{0i} - ST_i \quad (4.4)$$

Before drainage, any layer ST_{oi} contained the same amount of carbon per soil volume as the contemporary undisturbed reference layers ST_r in the deeper soil profile. The amount of soil carbon in any single layer C_{di} (kg m^{-2}) lost by oxidation is given as

$$C_{di} = S_s \times C_r / ST_r \quad (4.5)$$

with C_r being the soil carbon stock of the reference layer (t m^{-2}), ST_r the thickness of the reference layer (m) and S_s (m) the volumetric loss due to peat oxidation. Beside the carbon loss, total peat subsidence (m) can be calculated by the combined method. Carbon losses since the peatland was drained are displayed as kg C m^{-2}.

The NW site could not be taken as a reference for the calculation of C loss for the managed sites because it was also influenced by drainage activities in surrounding areas as indicated by higher ash contents at 10-50 cm depth. We instead used the deeper layers (samples below 80 cm depth) of the grassland sites as a reference, similar to the approach taken in previous studies (Rogiers et al., 2008; Leifeld et al., 2011a).

4.2.5 Statistical analyses

Spearman correlation analyses were used to identify the relationship between $\delta^{13}C$, $\delta^{15}N$ and C/N. Regression analysis of $\delta^{13}C$ and depth was carried out with the software R2.15.1. At each individual core, $\delta^{13}C$ values against depth were used from the uppermost sample down until $\delta^{13}C$ reached a value below -25.0 ‰.

4.3 Results and discussion

4.3.1 Stable carbon isotopes

In both grassland soils, $\delta^{13}C$ values increase from about -30.0 ‰ in the upper centimetres to about -25.0 ‰ in deeper layers (Fig. 4.2b, Fig. 4.2c). This increase in $\delta^{13}C$ values with depth indicates aerobic conditions in the peat profile, as aerobic decomposers selectively used the lighter isotope ^{12}C for respiration, whereas the heavier ^{13}C is enriched in the remaining organic material of the soil (Nadelhoffer and Fry, 1988; Ågren et al., 1996). This $\delta^{13}C$ depth pattern was also found at site NW, indicating aerobic degradation (Fig. 4.2a). In general, natural peatlands are expected to show a uniform $\delta^{13}C$ depth profile (Clymo and Bryant, 2008; Skrzypek et al., 2008) or a trend towards slightly lower values, caused by an enrichment of recalcitrant substances depleted in ^{13}C (Benner et al., 1987; Krull and Retallack, 2000; Alewell et al., 2011). The Suess effect could have contributed to the low $\delta^{13}C$ values in the uppermost layer of the near-natural site, but the further increase in $\delta^{13}C$ with depth is connected to peat material much older than the Suess effect and is very likely owing to aerobic decomposition of the peat. An increase in $\delta^{13}C$ values with depth by about 4.0 to 5.0 ‰ is typical for well-drained mineral soils (Becker-Heidmann and Scharpenseel, 1986; Nadelhoffer and Fry, 1988) and is in accordance with oxic grassland soils (Accoe et al., 2003).

In the upper layers of both grassland sites, depth profiles of $\delta^{13}C$ values are apparently compressed compared to NW (Fig. 4.2). A linear regression analysis with $\delta^{13}C$ vs. depth reveals a tendency towards steepest slopes of $\delta^{13}C$ vs. depth at GI followed by GE and NW (Tab. 4.1). However, we do not regard this pattern as a quantitative indicator. Below the inversion at -25.0 ‰, $\delta^{13}C$ values of all profiles remain more or less constant throughout the deeper profile, indicating low decomposition with limited fractionation (Clymo and Bryant, 2008).

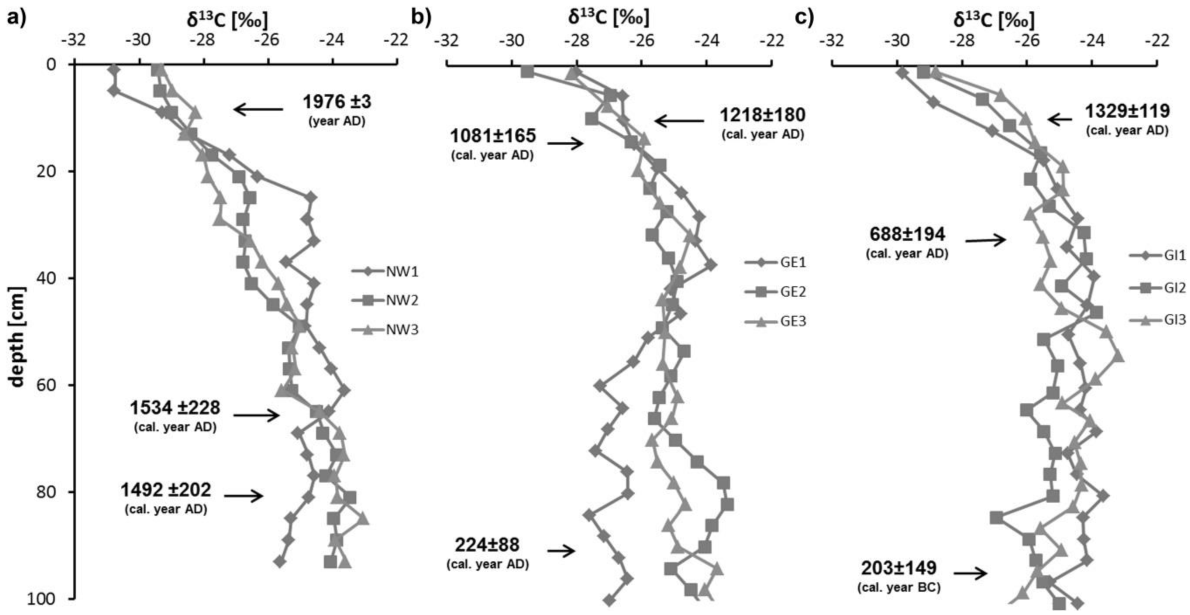

Figure 4.2: $\delta^{13}C$ depth profiles at (a) the near-natural site (NW), (b) extensively used grassland site (GE) and (c) intensively used grassland site (GI) at the Ahlen-Falkenberger peatland. Calibrated radiocarbon ages are displayed as mean calendar ages with 1 standard deviation (n=3) at their corresponding depth.

Table 4.1: Slope, depth and coefficient of determination of regression analyses between $\delta^{13}C$ and depth until a $\delta^{13}C$ value of -25.0 ‰ was reached in the depth profile. Three profiles of each site near-natural (NW), extensively managed grassland (GE) and intensively managed grassland (GI) site - from the Ahlen-Falkenberger peatland are presented. 'n' refers to number of soil segments per site and replication included in the regression.

Site/core	Depth (cm)	Slope	R^2	p	n
NW1	25.0	0.26	0.97	0.0004	7
NW2	65.0	0.07	0.92	0.0000	17
NW3	65.0	0.08	0.94	0.0000	17
GE1	23.7	0.13	0.92	0.0023	6
GE2	40.3	0.09	0.74	0.0015	10
GE3	31.7	0.11	0.92	0.0022	6
GI1	28.4	0.21	0.96	0.0008	6
GI2	31.0	0.14	0.89	0.0016	7
GI3	18.7	0.20	0.90	0.0146	5

4.3.2 Stable nitrogen isotopes

The $\delta^{15}N$ signal in peat soils is mainly driven by the following processes: vegetation input, decomposition, N deposition and fertilizer application. The $\delta^{15}N$ values of a natural bog should be constant at around 0.0 ‰ because atmospheric N is the primary source of N (Jones et al., 2010;Broder et al., 2012).

At NW the $\delta^{15}N$ values first increase and then decrease with depth (Fig. 4.3a). The inversion is located at ca. 20-40 cm depth, corresponding to $\delta^{15}N$ values of -2.0 to -4.0 ‰. At the grassland sites, stable nitrogen isotopes decrease with depth in the first 20 cm of the soil and with no further clear trend in the deeper parts of the profile. In the first few centimetres of the GE profile, $\delta^{15}N$ values are slightly positive and reach values of around -4.0 ‰ below 20 cm (Fig. 4.3b). At GI $\delta^{15}N$ values are positive in the uppermost centimetres (up to 4.0 ‰) and decrease down to -10.5 ‰ in deeper layers (Fig. 4.3c). Compared to GE $\delta^{15}N$ is more variable at GI and reaches more negative values in the deeper part of the soil profile.

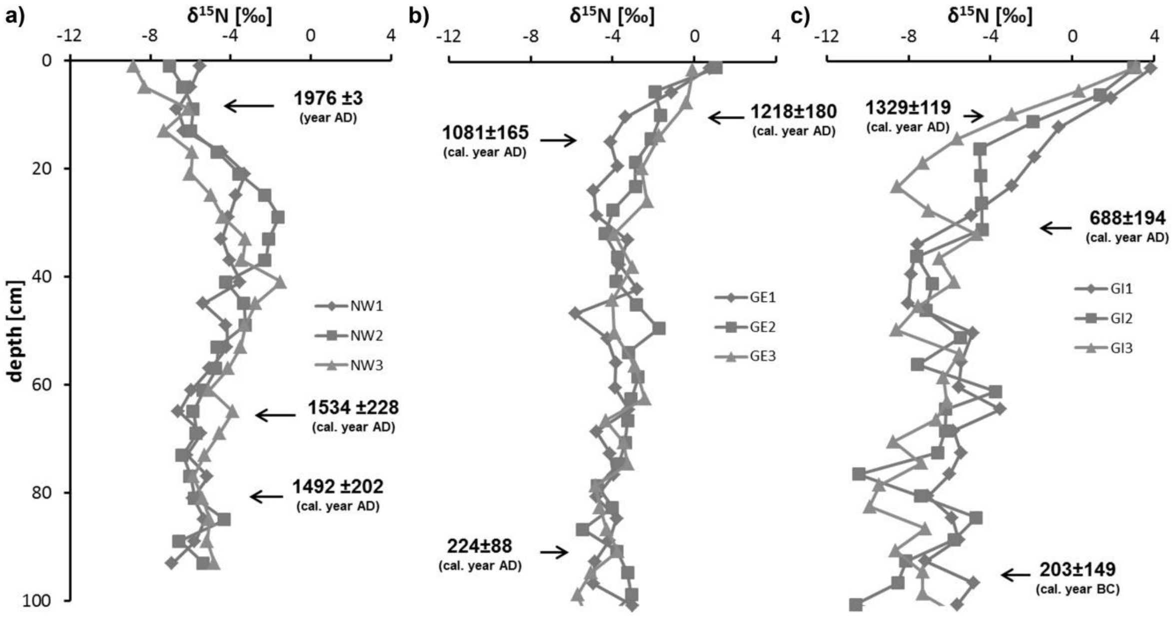

Figure 4.3: $\delta^{15}N$ depth profiles at (a) the near-natural site (NW), (b) extensively used grassland site (GE) and (c) intensively used grassland site (GI) at the Ahlen-Falkenberger peatland. Calibrated radiocarbon ages are displayed as mean calendar ages with 1 standard deviation (n=3) at their corresponding depth.

In natural peatlands, like NW, peat plant species show a wide range of $\delta^{15}N$ values from below -11.0 to above +2.0 ‰ (Asada et al., 2005b), which may influence the $\delta^{15}N$ values of the remaining peat material in the profile. The $\delta^{15}N$ depletion in the upper part of NW profiles may be assignable to the very low $\delta^{15}N$ values of the vegetation (Nordbakken et al., 2003; Bragazza et al., 2010). Sphagnum mosses are depleted in ^{15}N compared to atmospheric nitrogen and have even lower $\delta^{15}N$ values in areas affected by agricultural activities (Bragazza et al., 2005). Incubation of peat mosses has shown a ^{15}N enrichment with time resulting in an increase in $\delta^{15}N$ values with depth in the near surface (Asada et al., 2005a). Below approximately 20 cm, $\delta^{15}N$ values are less negative and in the range of nitrogen isotope values typical for mosses (Asada et al., 2005b). Human activities greatly influence $\delta^{15}N$ values in mosses beyond triggering decomposition via atmospheric N depositions. The various N sources vary in their isotopic signature (Bragazza et al., 2005). Low $\delta^{15}N$ values were reported in areas with high local ammonia emissions (from livestock during animal husbandry, manure storage and spreading) (Asman et al., 1998), owing to the very low $\delta^{15}N$ values in wet (NH_4) and dry (NH_3) deposition (Bragazza et al., 2005).

$\delta^{15}N$ depth profiles of our drained sites show a completely different depth pattern as hypothesized in our theoretical concept for drained peatlands (Fig. 4.1) and decrease rather than increase with depth (Fig. 4.3). High $\delta^{15}N$ of the topsoil in our grassland sites (Fig. 4.3) most likely indicates increased microbial activity, caused by drainage, in conjunction with effects from organic fertilizer application at GI. Decomposition is often linked to an enrichment of ^{15}N because of the preferential use of ^{14}N (Högberg, 1997; Novak et al., 1999; Kalbitz et al., 2000). Increased microbial activity in the first centimetres of the drained peatland leads to increased turnover of N, which results in an enrichment of ^{15}N (Kalbitz et al., 2000), especially in the first 2-5 centimeters. It can therefore be postulated that decomposition of peat material results in an enrichment of ^{15}N. This is one possible explanation for the higher $\delta^{15}N$ values at GE and GI as compared to NW. Atmospheric N deposition, as discussed above, could additionally influence the $\delta^{15}N$ signal in these profiles; however, we do not see any effect at site NW. Organic fertilizer may also be enriched in ^{15}N (Watzka et al., 2006), which may contribute to higher $\delta^{15}N$ values in the topsoil of GI. A study of nitrogen isotopes from mineral and organic fertilizer demonstrated that organic fertilizer has a mean $\delta^{15}N$ value of +8.5 ‰ (Bateman and Kelly, 2007). However, GE, which does not receive any fertilizer, is also enriched in^{15}N in the first centimetres of the profile. We therefore assign the (smaller) ^{15}N enrichment at GE to ongoing oxidative peat decomposition and the (stronger) ^{15}N enrichment at GI to the combined effect of peat decomposition and organic fertilizer applications.

4.3.3 Radiocarbon ages

Radiocarbon signatures from the upper peat layers (8-10 cm depth) of site NW indicate the presence of bomb carbon and organic matter fixed during the second half of the last century. This recent C accumulation of almost 1.0 kg C m^{-2} in approximately the last 50 years at NW is in accordance with the current GHG flux measurements (Beetz et al., 2013), showing that the bog has been sequestering carbon during recent years. In deeper parts (65-81 cm depth) of NW, mean peat ages range between 1328 and 1796 cal years AD. The small differences between the mean radiocarbon ages at 65 cm and 81 cm depth at NW represent an indicator for undisturbed peat. They point to an average 16 cm of peat growth in approximately 62 years.

At both grassland sites, calibrated radiocarbon ages in the upper centimetres are much higher than at NW. This finding can be taken as an indicator for peat degradation and carbon loss. Drainage-induced carbon loss starts from the top, selectively removing younger peat and exposing older peat to the surface. We found >500-year-old peat in the upper 14 centimeters at these sites.

At 14 to 19 cm depth at GE and 27 to 34 cm depth at GI, the peat is almost 1000 and 1300 years old, respectively. Peat in deeper parts of the grassland profiles shows calibrated mean ages of 165 to 325 cal years AD and 313 to 34 cal years BC at GE and GI, respectively. The higher ages in the upper parts of the profile at GI indicate higher peat and C losses compared to the GE, when similar conditions in the peat profiles before onset of drainage are assumed. In comparison to NW, peat in deeper parts of the two grassland sites is up to 1500 years older. The grassland sites have lost almost all peat that has accumulated in the last several centuries.

4.3.4 C/N ratio

At both grassland sites, C/N ratios are smaller in the upper layers of the soil profile (Fig. A1.2), indicating strong microbial transformation of the peat (Malmer and Holm, 1984; Kuhry and Vitt, 1996) and the possible influence of fertilization (GI). In most samples from NW and in deeper layers of GI and GE, C/N ratios are in the range considered typical for ombrotrophic peatlands (Kuhry and Vitt, 1996) and indicate low microbial activity.

4.3.5 Correlations between stable isotopes and soil C/N

Decomposition affects both stable $\delta^{13}C$ and $\delta^{15}N$ by an enrichment of the heavier isotopes in the remaining soil organic matter as well as decreasing C/N ratio. A linear correlation between these parameters is expected if the material is influenced by strong decomposition during peat formation or post-sedimentation (Wynn, 2007; Engel et al., 2010). However, no correlation between the above-mentioned parameters will be found in well-preserved peat (Engel et al., 2010; Jones et al., 2010).

Stable isotopes and the C/N ratio correlate in a weakly positive way (r = 0.40 to 0.60) and a weakly negative way (r = -0.41 to -0.52) at NW for $\delta^{13}C$ and $\delta^{15}N$, respectively (see Tab. 4.2), indicating that the peat is not strongly decomposed and/or that decomposition did not alter the original isotope signal (Sharma et al., 2005). Zaccone et al. (2011) also found a positive, albeit not significant correlation between $\delta^{13}C$ and C/N in a well-preserved peat bog in the Swiss Jura mountains. At our grassland sites, $\delta^{13}C$ and the C/N ratio correlate positively (r = 0.32 to 0.70), and $\delta^{15}N$ and the C/N ratio negatively (r = -0.74 to -0.85), indicating that the peat is strongly decomposed.

Table 4.2: Correlation coefficient and p value ($p<0.05$ in boldface) between $\delta^{13}C$ and C/N ratio as well as between $\delta^{15}N$ and C/N ratio for the whole profiles at the near-natural (NW), extensively managed grassland (GE) and intensively managed grassland (GI) sites at the Ahlen-Falkenberger peatland.

Site/core	$\delta^{13}C$ vs. C/N	$\delta^{15}N$ vs. C/N
NW 1	$0.40^{(0.051)}$	$-0.41^{(0.051)}$
NW 2	$0.60^{\mathbf{(0.002)}}$	$-0.52^{\mathbf{(0.010)}}$
NW 3	$0.46^{\mathbf{(0.022)}}$	$-0.49^{\mathbf{(0.016)}}$
GE 1	$0.49^{\mathbf{(0.012)}}$	$-0.81^{\mathbf{(0.000)}}$
GE 2	$0.70^{\mathbf{(0.000)}}$	$-0.85^{\mathbf{(0.000)}}$
GE 3	$0.32^{\mathbf{(0.000)}}$	$-0.74^{\mathbf{(0.002)}}$
GI 1	$0.61^{\mathbf{(0.002)}}$	$-0.78^{\mathbf{(0.000)}}$
GI 2	$0.68^{\mathbf{(0.000)}}$	$-0.75^{\mathbf{(0.000)}}$
GI 3	$0.32^{(0.109)}$	$-0.74^{\mathbf{(0.000)}}$

4.3.6 Ash content and bulk density

Ash content and bulk density are indicators of peat decomposition (Clymo, 1984). At NW, ash content is enriched between 10 and 60 cm depth at NW (Fig. 4.4a). Bulk density increases at this depth and is higher compared to deeper parts of the profiles (Fig. A1.3). A higher ash content in these depths compared to the deeper layers suggests an increase in the decomposition of the peat (Engel et al., 2010). We interpret this ash accumulation as being the result of drainage activities in the vicinity of NW during the formation of these peat layers. The peat layers with the enriched ash content at the NW site are on average between 50 and 500 years old, which corresponds to the beginning of the first land use intensification in this peatland. Above and below this depth, the ash content is small, indicating less decomposed peat. High ash contents (Fig. 4.4b, Fig. 4.4c) and bulk densities (Fig. A1.3) in the first centimetres of the profile at both grassland sites indicate peatland degradation and refer to recent and ongoing peat oxidation. In deeper layers of GE and GI, ash contents are constant and very low (Fig. 4.4) and are in the range of natural peatlands (Clymo, 1984) and also of deeper, undisturbed layers at NW.

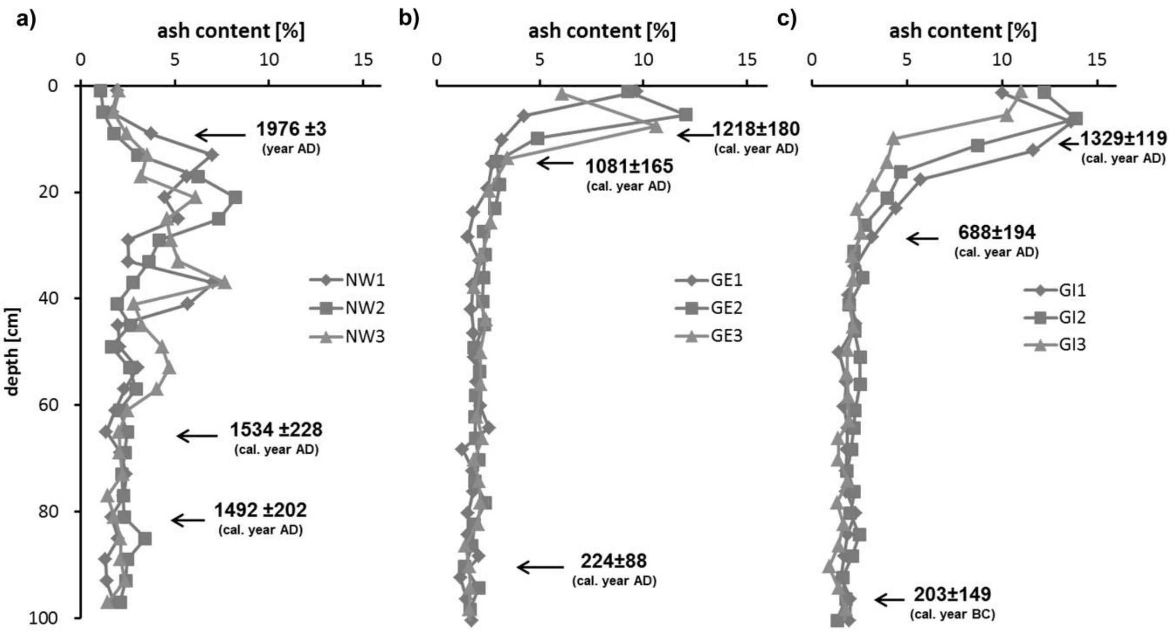

Figure 4.4: Ash content depth profiles at (a) the near-natural site (NW), (b) extensively used grassland site (GE) and (c) intensively used grassland site (GI) at the Ahlen-Falkenberger peatland. Calibrated radiocarbon ages are displayed as mean calendar ages with 1 standard deviation (n=3) at their corresponding depth.

4.3.7 Carbon loss

Carbon losses estimated by the combined method are highest at GI, intermediate at GE and lowest at NW. The mean (±SD) C losses are 11.5 (±6.3), 18.8 (±2.8) and 42.9 (±10.9) kg C m^{-2} for NW, GE and GI, respectively. The C loss at site NW may be attributed to the intensive drainage and peat extraction activities in the surrounding area in the last century, which may also have impaired the hydrology of this remaining bog. However, in recent years/decades, peat at NW has been accumulating C again (Beetz et al., 2013) and can therefore today be considered as a C sink. This is attributed to the current restoration activity within the context of the designation of a nature conservation area at this site with an accompanying increase in the water table (Beckmann and Krahn, 1991;Beller et al., 1994). The heath vegetation at NW, as is common for peat bogs in Germany, suggests a mild degradational stage (Ellenberg, 1954) with likely historical anthropogenic influences. The carbon loss of the grassland sites determined in this study is in accordance with higher measured GHG emissions at site GI than at site GE (Beetz et al., 2013). In general, the net GHG emission from extensively managed grasslands is smaller than from intensively managed grasslands, owing to a combination of smaller C exports and higher water tables (Drösler et al., 2013). The total carbon loss at these sites since the onset of drainage is comparable to drained peatlands in Switzerland under extensive management (Leifeld et al., 2011a).

4.3.8 Indicators for peatland degradation and quantification of C loss

All parameters ($\delta^{13}C$, $\delta^{15}N$, ash content, C/N ratio, bulk density and radiocarbon ages) indicate a degradation of the former bog at the Ahlen-Falkenberger peatland when managed as grassland (GE and GI). All of these parameters might be useful indicators of peatland degradation but not all can be used in a quantitative manner (Tab. 4.3).

Table 4.3: Biogeochemical parameters from the Ahlen-Falkenberger peatland profiles as indicators of peatland degradation as well as peat and carbon loss.

Parameters	Reliable indicator for peat degradation?	Quantification of C loss possible?
$\delta^{13}C$	yes	no
$\delta^{15}N$	yes	no
Ash content	yes*	yes
^{14}C age	yes	(yes)
C/N	(yes)	no
Bulk density	(yes)	(yes with ash content)
Correlation between $\delta^{13}C$, $\delta^{15}N$ and C/N	yes	no

* for bogs and assuming homogeneous atmospheric input

Stable carbon isotope depth profiles indicate degradation at all sites at the peatland. At NW in the upper 10 cm and below 65 cm depth as well as in deeper parts of the grassland sites, $\delta^{13}C$ is constant with depth indicating natural peat. Stable nitrogen isotope, ash content and C/N ratio as well as bulk density depth profiles show a higher decomposition of the peat material in the upper part at the grassland sites as well as at 20-60 cm depth at NW. The $\delta^{15}N$ signal in the peat profiles is mainly driven by decomposition (GE and GI) and fertilizer application (GI). Radiocarbon ages and $\delta^{13}C$ as well as ash content in the first centimetre of the NW depth profiles provide evidence for contemporary peat accumulation with young peat material formed in the last decades. Peat from topsoil segments of both grassland sites is much older than peat from deeper segments of the NW site. These data illustrate the consequences of peatland drainage that induces the loss of peat material which has been accumulated over the last centuries. The ash content in combination with bulk density and C content (combined method) gives reasonable estimates of C loss since the onset of drainage activities in this peatland.

Soil ash content and radiocarbon signatures have the potential to provide quantitative estimates of peatland carbon loss, whereas changes in stable isotope patterns and C/N ratios serve as qualitative indicators and support the understanding of processes and mechanisms involved.

4.4 Conclusions

Depth profiles of different biogeochemical parameters together provide a detailed insight into peatland formation and the effects of management on peat degradation. $\delta^{13}C$, $\delta^{15}N$, ash content, C/N ratio and bulk density, as well as radiocarbon ages in peat depth profiles indicate degradation of all peatlands, but to very different degrees. Peat and C loss could be quantified by the combination of ash content and bulk density and is supported by the radiocarbon ages.

(I) Increasing $\delta^{13}C$ values with depth indicate aerobic decomposition of the peat material at all sites.

(II) At the near-natural site (NW), stable carbon isotope and ash content depth profiles as well as radiocarbon dating indicate moderate degradation due to the drainage of the surrounding area in the past. Hence, also bogs considered semi-natural were impaired by anthropogenic activities. Recent organic-matter accumulation, as indicated by the ^{14}C values, indicates the rehabilitation of the peatland.

(III) With the conversion to grassland, increasing peat decomposition and fertilizer application systematically alter the $\delta^{15}N$ signature of the soil.

(IV) Based on ash accumulation calculations, the three sites lost carbon in the following order: NW<GE<GI. Higher losses under intensive management are supported by (i) higher peat ages at this site and (ii) steeper slopes of $\delta^{13}C$ depth profiles.

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CHAPTER 5

Soil carbon loss from managed peatlands along a land use gradient – a comparison of three different methods

Krüger, J. P.[1], Leifeld, J.[2], Glatzel, S.[3], and Alewell, C.[1]

[1]Environmental Geosciences, University of Basel, Bernoullistrasse 30, 4056 Basel, Switzerland

[2]Climate/Air Pollution Group, Agroscope, Reckenholzstrasse 191, 8046 Zürich, Switzerland

[3]Department of Geography and Regional Research – Geoecology, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria

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Abstract

Carbon (C) loss from managed organic soils is an important flux in the global carbon cycle. Different approaches exist to estimate greenhouse gas emissions and thus the C balance of these soils. Here we compare two methods using soil profiles and a method of greenhouse gas (GHG) flux measurements using closed chambers to quantify the net C loss from managed peatlands. We applied these methods to the well-studied peatland complex Ahlen-Falkenberger Moor near Cuxhaven in northern Germany. The peatland represents a land use gradient from near-natural wetland (NW) to extensively-used grassland (GE) (rewetted in 2003/2004) to intensively-used grassland (GI). The three methods are: (i) the so-called combined method which makes use of differences in bulk density and ash content between the upper and deeper parts of the profile (ii) the C accumulation method which uses peat accumulation rates derived from ^{14}C age-dated samples and their calculated C-stock in a certain depth and (iii) a method which gives the net ecosystem carbon balance (NECB) using closed chambers to quantify the GHG fluxes. Drainage at the Ahlen-Falkenberger Moor commenced at the beginning of the 20th century, and land use was intensified in the middle of the 20th century. For methods (i) and (ii), three peat cores down to approximately 100 cm at each site were taken in November 2012. These two profile-based methods give the C loss since the onset of drainage activities. Compared to this, the NECB represents the C balance (2007-2009) under present climate and management conditions.

According to the profile-based methods (i and ii), all three sites have lost C since the onset of drainage in the order NW<GE<GI. Calculated total C losses are, depending on the method, about 12 kg C m^{-2} for site NW, 19 to 38 kg C m^{-2} for site GE and 43 to 53 kg C m^{-2} for site GI. Based on chamber-derived GHG measurements, site NW currently accumulates C, site GE shows a neutral C balance and site GI is a C source. A comparison of these methods demonstrates that the historical C loss can be assessed by the two profile-based methods, but not by the flux measurements. By contrast, present changes in the C balance are captured by the flux measurements but not by the profile-based methods. Taken together, profile-based methods and flux measurements indicate that the C balance of these peatlands, since the beginning of drainage activities, has been changing over time.

Zusammenfassung

Kohlenstoffverluste von drainierten organischen Böden sind eine wichtige Grösse im globalen Kohlenstoffkreislauf. Es gibt verschiedene Methoden zur Bestimmung der Kohlenstoffverluste aus organischen Böden. Wir vergleichen hier zwei profilbasierte Methoden und Treibhausgasmessungen mittels Kammermessungen zur Bestimmung des Kohlenstoffverlustes aus dem Boden. Die Methoden wurden entlang eines Landnutzungsgradienten in dem Ahlen-Falkenberger Moor bei Cuxhaven, Deutschland, angewendet. Die Standorte waren ein naturnahes Moor (NW), ein extensiv genutztes Grasland (GE), sowie ein intensiv genutztes Grasland (GI). Die Kohlenstoffverlustberechnung basiert auf drei unterschiedlichen Ansätzen: (i) auf der kombinierten Methode, die Unterschiede in der Lagerungsdichte und im Aschegehalt zwischen dem Ober- und Unterboden berücksichtigt, (ii) auf der Kohlenstoffakkumulationsmethode, welche die berechneten Kohlenstoffakkumulationsraten, berechnet auf Grundlage von ^{14}C-Datierungen, zusammen mit dem Kohlenstoffvorrat in einer bestimmten Tiefe verwendet und (iii) auf einer Methode, welche die Kohlenstoffbilanz mittels Kammermessungen für die Netto Ökosystem Kohlenstoffbilanz (NECB) bestimmt. Die beiden erstgenannten Methoden (i und ii) geben den kumulierten Kohlenstoffverlust seit dem Beginn der Drainage wieder. Im Vergleich dazu repräsentiert die NECB (iii) den Kohlenstoffhaushalt unter den gegebenen und aktuellen klimatischen Bedingungen sowie der Landnutzungsart. Seit Anfang des 20. Jahrhunderts wurde das Moor drainiert und in der Mitte des 20. Jahrhunderts die Landnutzung intensiviert. Für die Analyse von verschiedenen biogeochemischen Bodenparametern wurden im November 2012 drei Bohrkerne bis etwa 100 cm Tiefe an jedem Standort entnommen.

Anhand der profilbasierten Methoden (i und ii) konnte ermittelt werden, dass seit der Drainage alle drei Standorte Kohlenstoff in der Grössenordnung $NW<GE<GI$ verloren haben. Die berechneten totalen Kohlenstoffverluste sind, je nach Methode, in der Grössenordnung von etwa 12 kg C m^{-2} für Standort NW, 19 bis 38 kg C m^{-2} für Standort GE und 43 bis 53 kg C m^{-2} für Standort GI. Die aktuellen Treibhausgasmessungen für die Jahre 2007 bis 2009 zeigen, dass NW Kohlenstoff akkumuliert, GE eine neutrale Kohlenstoffbilanz aufzeigt und GI eine Kohlenstoffquelle ist. Ein Vergleich der Methoden veranschaulicht, dass der historische Kohlenstoffverlust mittels der profilbasierten Methoden abgeschätzt werden kann, eine Information, welche nicht mit den aktuellen Treibhausgasmessungen erfasst wird. Aktuelle Veränderungen in der Kohlenstoffbilanz hingegen werden mit den Treibhausgasmessungen aufgezeigt, können aber nicht mit den profilbasierten Methoden festgestellt werden. Zusammengefasst zeigt die Kombination der Methoden, dass sich die Kohlenstoffbilanz dieser Moorböden seit dem Beginn der Drainageaktivitäten über die Zeit verändert hat.

5.1 Introduction

Carbon (C) loss from managed organic soils is an important flux in the global carbon cycle (Yu et al., 2011; Jungkunst et al., 2012). Under natural conditions, peatlands are anoxic and accumulate organic matter as peat (Clymo, 1984). Management of peatlands for agriculture or forestry requires drainage. This induces aerobic decomposition of the soil organic matter and a net C emission to the atmosphere (Maljanen et al., 2010). Over the last century, more than 50 % of the peatland area in Europe has been converted mainly to agriculture or forestry (Byrne et al., 2004). In Germany, 75 % of the greenhouse gas (GHG) emissions from soils are attributed to agricultural use (Höper, 2007), and more than half of the GHG emissions from managed peatlands originate from sites managed as grasslands (Drösler et al., 2008). Together, GHG's from organic soils contribute 5.1% to Germany's national total emissions (Drösler et al., 2013). Average C loss rates from temperate peatlands under grassland use are 0.6 kg C m^{-2} yr^{-1} for deeply drained and 0.4 kg C m^{-2} yr^{-1} for shallowly drained peatlands (IPCC, 2013a). Ranked by land use intensity, intensively-managed grasslands emit on average 2.8 kg CO_{2eq} m^{-2} yr^{-1}, extensively-managed grasslands between 0.2 and 2.0 kg CO_{2eq} m^{-2} yr^{-1} (depending on the water table), near-natural bogs are almost climate-neutral, but dry bogs emit up to 1.0 kg CO_{2eq} m^{-2} yr^{-1} (Drösler et al., 2013). The latter values include the N_2O emissions, which can contribute significantly to the GHG emission at intensively-managed sites. Different approaches exist to estimate the C balance of peatland soils. Here we compare two soil profile-based methods with each other and with greenhouse gas flux measurements by closed chambers to assess the net C loss from managed peatlands.

5.2 Material and methods

We applied the different methods to the well-studied peatland complex Ahlen-Falkenberger Moor in north-western Germany. The peatland complex represents a land use gradient (Fig. 5.1) from near-natural wetland (NW) to extensively-used grassland (GE) (which was rewetted in 2003/2004) to intensively-used grassland (GI). At both grassland sites, drainage started at the beginning of the 20th century, and land use was intensified in the middle of the 20th century. About 60 % of the remaining area is currently used as grassland, and only a small area in the centre of the bog (approx. 5 %) was never drained or cultivated and remains as a natural habitat today (Höper, 2007). Since the 1990s, the NW has been a nature conservation area. Detailed site descriptions can be found in Beetz et al. (2013) and Krüger et al. (2015b). In November 2012, three peat cores down to approximately 100 cm were taken at each site, and various biogeochemical soil parameters were analysed.

The so-called combined method (Leifeld et al., 2014) estimates the physical primary subsidence due to the loss of pore water and peat shrinkage, and the chemical secondary subsidence due to the oxidative loss of organic matter. The integrated calculation of C loss from the peatland since the beginning of drainage is based on the simplified assumptions that the ratio of C to ash content during accumulation of peat has been constant and that the ash content before drainage was the same at all depths. After drainage, peat starts to oxidise and C is lost as CO_2 while the mineral parts remain as ash in the profile. Additionally, we assume that the ash content in the permanently water-saturated subsoil is not affected by drainage and that ash from the oxidised peat remains at the site and accumulates in the respective layer. See detailed method description in Krüger et al. (2015b) and Leifeld et al. (2014).

Figure 5.1: Study sites with land use gradient from near-natural wetland site (no mowing, no fertiliser), extensively-used grassland (cut once per year, no fertiliser) and intensively-used grassland site (cut 4-5 times per year, mineral and organic fertiliser).

In a second method (C accumulation method), the C loss is calculated based on ^{14}C age-dated samples from two different layers, with the assumption of linear C accumulation rates at the NW site (Fig. 5.2). Mean linear C accumulation rates at the NW site calculated by a linear regression of the age-dated samples are 0.046 kg C m^{-2} yr^{-1} (Fig. 5.2). The radiocarbon ages in a defined depth and the cumulative C-stock (Fig. 5.3) above the ^{14}C age-dated point are used to calculate the C balance of the peat soils under grassland. The difference between the calculated cumulative C stock above the ^{14}C age-dated point at the GE and GI sites (using the C accumulation rates of the NW site) and the measured cumulative C stock (Fig. 5.3) above the ^{14}C age-dated point of the peat core at GE and GI is the C loss of the soil. In detail, the C balance is calculated by the year (in years AD/BC) of sampling minus the age-dated sample (in years AD/BC) in the depth multiplied by the calculated yearly C accumulation rates of the NW site minus the cumulative C stock (kg C m^{-2}) above the corresponding depth of the respective site.

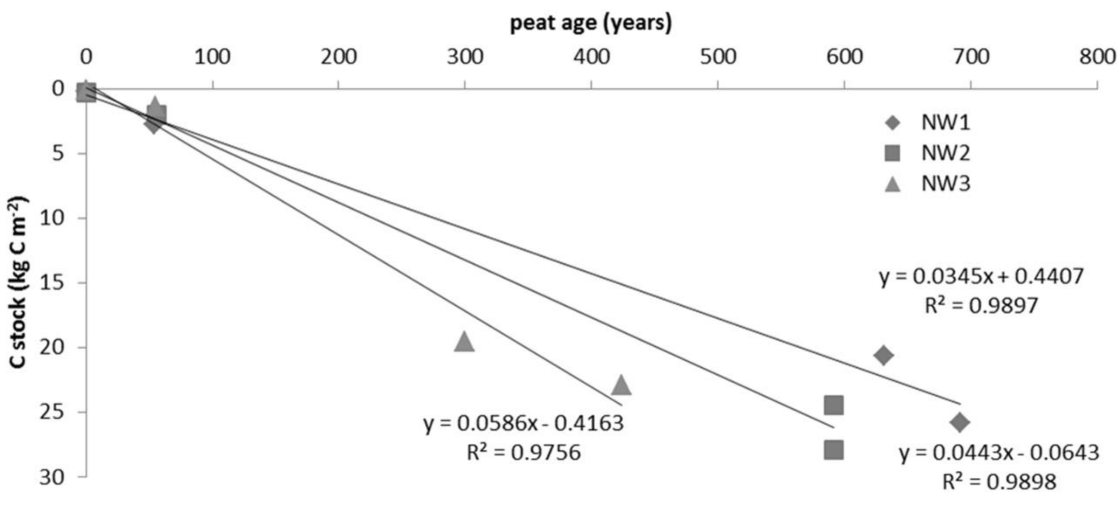

Figure 5.2: Calculated C accumulation rates by peat age vs. C stock for the near-natural wetland site.

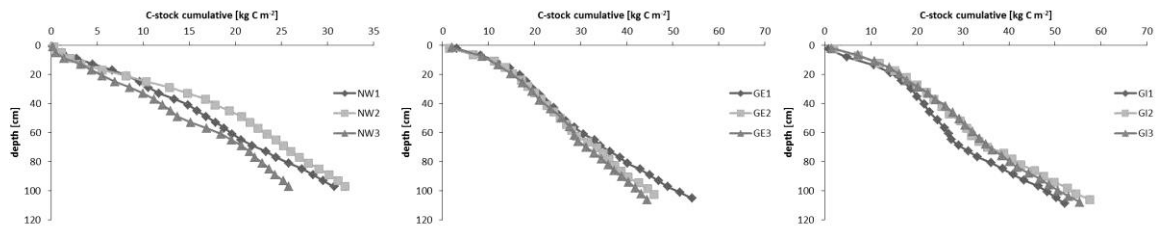

Figure 5.3: Cumulative C stock (kg C m^{-2}) of each soil core for the three sites.

These two profile-based methods give the C loss since the onset of drainage. Carbon losses are displayed as kg C m^{-2} and loss rates as kg C m^{-2} yr^{-1} by dividing the C loss by the number of years passed since the peatland drainage was intensified.

In contrast to the profile-based methods, the net ecosystem C balance (NECB) (2007-2009) represents the current C loss or gain of the soil under given climate and management conditions including the C change by harvesting and fertiliser application. The measurements were performed by Beetz et al. (2013). CO_2 fluxes were measured using closed chambers (0.78 m x 0.78 m x 0.50 m) in flow -through dynamic mode. Opaque and transparent chambers were placed in turn to obtain data on combined autotrophic and heterotrophic respiration of the ecosystem (RECO) and net ecosystem exchange (NEE), respectively. See detailed description of this method in Beetz et al. (2013).

5.3 Results and discussion

According to the profile-based methods, all three sites have lost C since the onset of drainage (Tab. 5.1). The total C loss, calculated by the two profile-based methods, is in the order NW<GE<GI. Based on the chamber-derived NECB, site NW accumulates C, site GE shows a neutral C balance and GI is still a C source in 2007 to 2009 (Beetz et al., 2013).

According to the combined method, the NW site has lost 11.5 kg C m^{-2}. According to the NECB, it is now a C sink of about 0.063 kg C m^{-2} yr^{-1} (Beetz et al., 2013) (Tab. 5.1). The calculated C loss, integrated over the period since drainage intensification, could be due to the effect of drainage activities in the surrounding area that also influenced the hydrology at the NW site (Krüger et al., 2015b). Since the 1990s, the NW site is located in a nature conservation area; this may have recovered water tables, resulting in a negative C balance (C sink) today (Beetz et al., 2013).

The GE site has lost 18.8 kg C m^{-2} according to the combined method and 38.2 kg C m^{-2} according to the C accumulation method since drainage intensification. The rewetting of the GE site is reflected in the current NECB, indicating a currently neutral C balance of the soil. However, since drainage intensification, the GE site has lost 0.313 kg C m^{-2} yr^{-1} (combined method) to 0.636 kg C m^{-2} yr^{-1} (C accumulation method) (Tab. 5.1). An increase in water table depth may have changed the C balance at this site from a C source into a C neutral status.

Table 5.1: Annual C balance in kg C m^{-2} yr^{-1} (mean with SD) calculated by three different methods along the land use gradient. Positive values indicate a C gain and negative values a C loss of the soil.

	Near-natural wetland (NW)	**Extensively-used grassland (GE)**	**Intensively-used grassland (GI)**
Combined method (Krüger et al., 2015)*	-0.191 (±0.105)	-0.313 (±0.047)	-0.716 (±0.181)
C accumulation method*	-	-0.636 (±0.026)	-0.880 (±0.074)
NECB (2007-2009) (Beetz et al., 2013)	0.063 (±0.086)	0.030 (±0.166)	-0.683 (±0.190)

*Integrated C loss since drainage intensification (60 years) with annual C losses calculated by the total C loss divided by the years.

The calculated C loss was highest at GI site (42.9 kg C m^{-2} by the combined method and 52.8 kg C m^{-2} by the C accumulation method). The current annual C emissions at this site (0.683 kg C m^{-2} yr^{-1} (NECB 2007-2009)) are in the same order of magnitude of annual C losses integrated over the whole period since drainage intensification (0.716-0.880 kg C m^{-2} yr^{-1}) (Tab. 5.1).

For both grasslands, our calculated annual C loss as revealed from the profile-based methods (Tab. 5.1), based on an assumption of 60 years of intensive drainage, is in the range of previously reported C loss rates from temperate peatlands under grassland use (IPCC, 2013a). Independent of the applied method, C loss from the GI site is the highest. Furthermore, the NW site shows the lowest C loss or even a C uptake. A higher calculated C loss at GE as revealed by the C accumulation method may be attributed to the high C accumulation rates calculated for the NW site. In future studies, estimates using the C accumulation method could be improved by using a natural site without any anthropogenic influence. Higher calculated C losses by the C accumulation method compared with the combined method at the GE site also may be due to the high radiocarbon ages of peat at this site in the deeper parts of the profile (Krüger et al., 2015b), resulting in high calculated C losses by this method. At the GI site, high radiocarbon ages in deeper parts and high ash contents in the upper part lead to high calculated C losses by both profile-based methods. The results of annual C losses at the GI site are in the same range as the calculated NECB. The three applied methods use different assumptions and give results for the two managed sites in the same range as C losses from managed peatlands in the temperate region (IPCC, 2013a).

5.4 Conclusions

The profile-based methods assess an average C balance over the last several decades or hundreds of years since the peatland drainage began, whereas GHG measurements capture short defined measurement periods of only a few years. Thus, GHG measurements present the year-to-year variation due to temperature, water table and precipitation fluctuation. Profile-based methods, however, integrate C losses during the first years of drainage activities, which are presumably higher than the average over the declining emissions in advanced years (Leifeld et al., 2012). The profile-based methods give long-term soil C changes of drained and managed peatlands.

Independent of the method, a clear distinction between the three sites with respect to their C balance can be derived. Furthermore, changes in land use alter the soil C balance of peatlands; in our case, the rewetting and the designation as a nature conservation area lead to reduced C losses or, in the recent years, to a C uptake. This change in soil C balance due to land use change can be detected by a combination of profile-based methods and flux measurements.

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CHAPTER 6

Calculating carbon changes in peat soils drained for forestry by four different profile-based methods

Krüger, J. P.[1], Alewell, C.[1], Minkkinen, K.[2], Szidat, S.[3], and Leifeld, J.[4]

[1]Environmental Geosciences, University of Basel, Bernoullistrasse 30, 4056 Basel, Switzerland

[2]Department of Forest Science, University of Helsinki, P.O. Box 27, 00014 Helsinki, Finland

[3]Department of Chemistry and Biochemistry & Oeschger Centre for Climate Change Research, University of Bern, Freiestrasse 3, 3012 Bern, Switzerland

[4]Climate/Air Pollution Group, Agroscope, Reckenholzstrasse 191, 8046 Zürich, Switzerland

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Abstract

Boreal peatlands are an important carbon (C) sink. The effect of drainage for forestry on the soil C balance in those peatlands is a controversial debate. The Lakkasuo peatland, central Finland, comprise a minerotrophic and an ombrotrophic part, both partially drained for forestry. A pair-wise comparison was conducted and four different profile-based methods were applied to calculate the C balance of those sites. The first two methods used differences in ash content (I) between the upper and lower part of the profile and (II) between the drained and natural site of the peatland, respectively. The third method (III) used radiocarbon dated samples to calculate C accumulation rates at the natural site and compared these to the current C-stocks at the drained sites. The fourth method (IV) used radiocarbon dated samples to define a 1000-year layer in the profiles for comparing the C-stocks above this layer. Stable carbon isotope depth profiles were used for a qualitative assessment of the peatland status and indicate that both undrained site are in a natural state. All four profile-based methods indicate a C loss at the minerotrophic drained site but of different magnitude (0.057 to 0.272 kg C m^{-2} yr^{-1} depending on the method). At the ombrotrophic drained site both radiocarbon methods (III and IV) indicate a C gain (0.139 to 0.179 kg C m^{-2} yr^{-1}) whereas the methods I and II suggest a C loss (0.084 to 0.270 kg C m^{-2} yr^{-1}). The comparison of profile-based methods for C balance assessment resulted in a site-specific application depending on nutrient status and presence of a natural reference site. Nevertheless, our results confirm that boreal minerotrophic drained peatlands lose more C than ombrotrophic drained peatlands.

6.1 Introduction

Boreal peatlands are an important long-term terrestrial carbon (C) sink. In their soils, they store an amount of C equivalent to almost half of the current carbon content of the atmosphere (Strack et al., 2008; Yu et al., 2011; Jungkunst et al., 2012). A substantial proportion of boreal peatlands has been drained for forestry with a total area of more than 100 000 km^2 in Fennoscandia and Russia (Minkkinen et al., 2008). In Finland, more than half of the peatlands have been drained during the 20th century, mainly for forestry use (Laine et al., 2006). Peatland drainage for agriculture usually changes a peatland from a C sink into a C source (IPCC, 2013a). However, the impact of draining boreal peatlands for forestry on the soil's C balance is discussed controversially. Several studies demonstrate that boreal peatlands drained for forestry are still C sinks, because of an increased wood, root and litter production, which compensate the increased soil respiration of the aerated peat (Minkkinen et al., 1999; Minkkinen et al., 2002; Lohila et al., 2011; Meyer et al., 2013; Ojanen et al., 2013). In contrast, other authors found net ecosystem C losses mainly caused by increased C emissions from degrading peat (Martikainen et al., 1995; Silvola et al., 1996) whereby these peatland may lose their C sink function (Minkkinen et al., 2007; Ojanen et al., 2010).

Several approaches exist to determine the soil C balance of peatlands. Simola et al. (2012) broadly divided the different approaches to determine the soil C balance of peatlands into process and inventory studies. Process studies investigate the gas exchange of the soil or the whole ecosystem (Silvola et al., 1996; Lindroth et al., 1998; Alm et al., 1999; von Arnold et al., 2005; Minkkinen et al., 2007; Lohila et al., 2011; Meyer et al., 2013; Ojanen et al., 2013; Hommeltenberg et al., 2014) while inventory studies examine the long-term changes in C-stocks (Minkkinen and Laine, 1998a; Minkkinen et al., 1999). Changes in soil C balance via inventories can be studied in two ways: (i) a study site is resampled over decades and C-stocks between present-day and historical situation are compared (Pitkänen et al., 2011; Simola et al., 2012) or (ii) peat profiles of paired undrained and drained parts of a peatland are compared (Minkkinen et al., 1999; Pitkänen et al., 2013), following a space-by-time approach.

Here we follow the second approach and study four different profile-based methods to calculate the C loss since the beginning of peatland drainage. The Lakkasuo peatland complex, central Finland, hosts both a bog and a fen ecosystem, each with adjacent drained-undrained parts. Four different profile-based methods were applied to calculate the C balance of the peatland soils: (I) a combined method with subsoil as reference, (II) a combined method with natural site as reference, (III) a C accumulation method and (IV) a cumulative C-stock comparison method. The combined methods use differences in ash content of the degraded upper part of the peatland either to the assumed natural horizons of the deeper subsoil at the same site (combined method with subsoil as reference) (Krüger et al., 2015b) or to the adjacent undisturbed site (combined method with natural site as reference). This is the first study where a natural situation, formed in the same peatland, is used as reference for the combined method. In addition, two radiocarbon methods using ^{14}C age dated samples are taken to estimate the soil C balance: The accumulation method relies on the premise of linear C accumulation rates at the natural sites. ^{14}C age dated samples at the reference site are taken to calculate the natural accumulation rates. The former C-stock at the degraded site prior to drainage is calculated with the accumulation rates of the reference sites and then compared to the measured cumulative C-stock of the degraded site. In the fourth method, the cumulative C-stock, both at the drained and natural site, above a peat layer of the same radiocarbon age was compared. The differences between the drained and natural site of the latter method give the soil C loss or gain of the drained sites relative to the undisturbed situation. As previous studies have shown that expected natural peatlands sites are affected by drainage activities of the surrounding area (Krüger et al., 2015b) $\delta^{13}C$ depth profiles were used as an indicator for a qualitative assessment of the natural status of the reference sites. In this approach, a uniform $\delta^{13}C$ depth profile indicates water-saturated conditions within a natural peatland (Alewell et al., 2011; Krüger et al., 2014; Krüger et al., 2015b).

The objectives of the present study were (I) to use $\delta^{13}C$ depth profile as a qualitative indicator for the natural status of the undrained sites, and (II) to examine the effect of peatland drainage for forestry on the soil C balance of a minerotrophic as well as an ombrotrophic peatland site by four different profile-based methods.

6.2 Material and methods

6.2.1 Study site

Peat samples were taken in the eccentric peatland complex Lakkasuo (61°48’N, 24°19’E), central Finland. The mean annual temperature is 3°C, and the mean annual precipitation is 700 mm (Minkkinen et al., 1999). The peatland complex is divided into two parts. The southern part is nutrient poor with ombrotrophic conditions and the northern part is nutrient richer with minerotrophic conditions. Approximately half of the peatland (eastern part) was drained in 1961 for forestry, using ditches with depth of 70 cm and spacing of 40 to 60 m. This spatial arrangement allows for a pair-wise comparison between an ombrotrophic natural (On) and an ombrotrophic drained (Od) as well as a minerotrophic natural (Mn) and a minerotrophic drained (Md) part. At the natural ombrotrophic part of the peatland the water table is at about 13 cm depth and at the ombrotrophic drained site at about 26 cm depth (Minkkinen et al., 1999). A greater change has been detected at the minerotrophic part of the peatland, where the water table has decreased from close to the surface at the natural site to around 35 cm depth at the drained site (Minkkinen et al., 1999). Drainage has changed the ground vegetation composition from dominating Sphagna to forest mosses (Table 6.1) (Minkkinen et al., 1999). A detailed description of the vegetation composition and other peatland characteristics is given in in Laine et al. (2004).

6.2.2 Soil sampling and analyses

In September 2013 three volumetric peat cores per site were collected in the Lakkasuo peatland complex at the four different sites. In the upper 50 cm peat samples were taken with a box sampler (8*8 cm) and in deeper parts down to approximately one meter with a Russian peat corer (Eijkelkamp, Netherlands). The peat cores were stored in plastic shells, wrapped in plastic foil and transported to the lab the same day. The cores were cut into 2 cm sections and dried at 40°C for 72 h in a drying oven. All samples were ground and homogenised in a vibrating ball mill (MM 400, Retsch, Germany). Stable carbon isotopes as well as C and N content were measured with combined mass spectrometer with a SL elemental analyser (Integra2, Sercon, UK) following standard processing techniques. Stable carbon isotope ratios are reported as $\delta^{13}C$ in [‰] relative to the V-PDB standard. The instrumental standard deviation is 0.1 % for $\delta^{13}C$. The volumetric sampling of the peat enabled the determination of the soil bulk density. The C-stocks were calculated by C content and bulk density for depth increments of each single core.

Peat ash content was determined by thermogravimetry (prepAsh, Precia, Switzerland), using 0.5-1.0 g sample material. The sample was heated to 600°C in air until no significant mass change (constant mass) could be measured (see detailed description of the method by Leifeld et al. (2011a)). The material remaining after heating is defined as the ash content of the sample.

Table 6.1: Site characteristics of the natural and drained parts of the Lakkasuo peatland in 1991 (Minkkinen et al. 1999).

	minerotrophic		ombrotrophic	
	natural (Mn)	drained (Md)	natural (On)	drained (Od)
Stand volume (m^3 ha^{-1})	0	111	5	16
Coverage Spaghna (%)	82	5	83	21
Coverage forest mosses (%)	0	58	0.4	32
Subsidence 30 years after drainage (cm)		23		-10
Water table median (cm)	2	36	13	26
Peat C store (kg C m^{-2})	70.9	68.0	77.6	79.0
Average C accumulation rate (g C m^{-2} yr^{-1})	21		26	
Bulk density (kg m^{-3})*	65	108	37	47
pH*	3.7	3.3	2.7	2.7
C (%)*	49.6	51.7	44.4	45.4
N (%)*	1.9	2.1	0.5	0.5

* 0-20 cm depth

Radiocarbon (^{14}C) content was measured with accelerator mass spectrometry (AMS) at the Laboratory for the Analysis of Radiocarbon with AMS (LARA) at the University of Bern (Szidat et al., 2014). For each site, two depths (at around 50 and 90 cm depth, see supplement) were selected for radiocarbon dating and samples at these depths were measured for each individual core. The ground and homogenised material was combusted, transformed into solid targets using an automated graphitisation equipment (AGE) (Nemec et al., 2010), and measured with the MIni CArbon DAting System MICADAS (Synal et al., 2007). ^{14}C ages were calibrated using the IntCal13 dataset (Reimer et al., 2013). Samples with bomb signature were calibrated using the Bomb13 NH1 dataset (Hua et al., 2013). Radiocarbon ages are presented for each site and selected depth as means (n=3) with 1 SD in cal. years AD or cal. years BC. Results of the individual measurements are shown in Table A1.7.

6.2.3 Methods for calculating the C balance of peatland soils

Soil C balance calculated by the combined method with subsoil as reference (combined method-subsoil) (I)

The method of Krüger et al. (2015b) combines two previously published methods which were based on changes in bulk density (Leifeld et al., 2011b) and changes in ash content (Rogiers et al., 2008; Leifeld et al., 2011a) in peat profiles. The so-called combined method (Krüger et al., 2015b) estimates the physical primary subsidence due to compaction, and the chemical secondary subsidence due to the oxidative loss of organic matter (Ewing and Vepraskas, 2006).

The integrated calculation of carbon change of the peatland since the beginning of drainage is based on the simplified assumption of a constant ratio between carbon to ash content during accumulation of peat and that ash content before drainage was the same at all depths. After drainage, the previously waterlogged peat oxidizes and carbon is lost as CO_2 (Rogiers et al., 2008). Additionally, it was assumed that ash from the oxidized peat remains in the respective horizons and accumulates in the upper layer and that the ash content in the permanent water saturated subsoil is not affected by drainage. The ash content of the deeper horizons (70-94 cm depth) of each individual core is taken as a reference value (Leifeld et al., 2011a). The carbon change was calculated separately for each core.

The chemical secondary subsidence S is calculated from the pre-drainage thickness ST_{0i} [m] (Krüger et al., 2015b):

$$ST_{0i} = ST_i \times F_{ashi} / F_{ashr} \qquad (1)$$

with ST_i the thickness of layer i [m], F_{ashi} the ash concentration of layer i, F_{ashr} the ash concentration of the reference layer.

$$S = ST_{0i} - ST_i \qquad (2)$$

Before drainage, any layer with the respective thickness ST_{oi} contained the same amount of carbon per soil volume as the contemporary undisturbed reference layers ST_r in the deeper soil profile. The amount of soil carbon in any single layer C_{di} [kg m^{-2}] lost by oxidation is given as

$$C_{di} = S \times C_r / ST_r \quad (3)$$

with C_r the soil carbon stock of the reference layer [kg m^{-2}], ST_r the thickness of the reference layer [m] and the volumetric loss due to peat oxidation S [m]. The deeper layers of the drained sites were used as a reference (Table 6.2) similar to the approach taken in previous studies (Krüger et al., 2015b; Rogiers et al., 2008).

Table 6.2: Approaches, assumptions, analyses and required reference sites of the four different profile-based methods for calculating the soil carbon balance at the Lakkasuo peatland.

	Approach	**Reference site**	**Analyses**	**Assumptions**
Method (I) [(1)] combined method – subsoil	Differences in ash content between degraded upper part and undisturbed subsoil	Subsoil+	ash content, bulk density, C%	Homogeneous ash input over time
Method (II) combined method - natural	Differences in ash content between degraded upper part and adjacent natural site	Natural site	ash content, bulk density, C%	Spatial homogeneous ash input
Method (III) [(2)] C accumulation method	Comparison of C-stock calculated by C accumulation rates and age dated sample to cumulative C-stock	Natural site*	^{14}C, bulk density, C%	Constant C accumulation rates
Method (IV) cumulative C-stock comparison method	Comparison between the cumulative C-stock of drained and natural site above a layer of the same age	Natural site	^{14}C, bulk density, C%, age depth model	Same spatial C accumulation rates

+ needs an undisturbed subsoil as a reference. Input of, for instance, sand is problematic for this method. Probably only applicable on bogs, because fens receive their nutrients and water also from surrounding mineral soils.
* could also use the C accumulation rates by comparable natural sites from the same region.
[(1)] (Krüger et al., 2015b)
[(2)] (Krüger et al., 2015a)

Soil C balance calculated by the combined method with natural site as reference (combined method-natural) (II)

The combined method with the natural site as a reference uses the same equations (1-3) above, but takes the mean values from all three cores (n=3) of the corresponding natural site as reference instead of the subsoil horizons of the drained site. Hence, the reference values of F_{ashr}, C_r and ST_r in equations 1 and 3 are mean values of the whole profile from the corresponding natural site. The C balance was calculated separately for each core at the drained sites.

Soil C balance calculated by C accumulation rates of the natural site (C accumulation method) (III)

In this method the C change of the drained sites is calculated from the mean C accumulation rates of the natural sites as inferred from ^{14}C dating (Krüger et al., 2015a). Accumulation rates of C were calculated by a linear regression of three points: two age dated samples in the catotelm and the uppermost horizon assuming as recent. The C accumulation in peatlands has been reported to be non-linear, because of decomposition in the acrotelm (Clymo, 1984; Clymo and Bryant, 2008). However, our calculated mean linear C accumulation rates of the natural parts Mn and On of the Lakkasuo peatland are quite similar to the C accumulation rates of the same peatland from Minkkinen et al. (1999) and to mean C accumulation rates of this region for bogs and fens in Finland from Turunen et al. (2002). Hence, the linear calculated C accumulation rates were used for this method. The age of samples in a defined depth as well as the corresponding C-stock above this depth was used to calculate the C balance of the peat soil. The $C_{stock\text{-}natural}$ of the drained site was calculated by the year of sampling (Age_s) minus the age in the depth (Age_d) of the drained site multiplied by the calculated yearly C accumulation rates (C_{acc}) of the natural site. The $C_{stock\text{-}natural}$ gives the expected C-stock for the drained site but under non-disturbed conditions. The cumulative C-stock (kg C m^{-2}) down to the corresponding depth ($C_{stock\text{-}drained}$) of the drained site was subtracted from $C_{stock\text{-}natural}$, whereby the difference to the expected C-stock gives the net C loss or gain from drainage ($C_{balance}$). The C-stock ($C_{stock\text{-}drained}$) above the ^{14}C dated sample in 49 cm depth at the drained sites was used for the calculation. In all cases the radiocarbon age for Age_d was taken at 49 cm depth.

$$C_{stock-natural} = (Age_s - Age_d) \times (C_{acc}) \qquad (4)$$

$$C_{balance} = C_{stock-natural} - C_{stock-drained} \qquad (5)$$

Soil C balance calculated by differences in the C-stock above a 1000-year layer (cumulative C-stock comparison) (IV)

In this method soil C change (kg C m^{-2}) is estimated by comparing the C-stocks of natural and drained sites above a layer of the same ^{14}C age (here 1000-year layer). The age-depth modelling software Bacon (Blaauw and Christen, 2011) was used to identify the depth of the 1000-year layer

(Figure A1.4). The 1000-year layer depth was calculated separately by the model for each core with two ^{14}C age dated layers. For the minerotrophic as well as the ombrotrophic sites the cumulative C-stock above the 1000-year layer was calculated. This method requires at least two dated samples at different depths in the profile, which is then inter- or extrapolated to find the 1000-year layer. The method is comparable to the method by Laine et al. (1992) who used a synchronous charcoal layer of drained and undrained parts of the same peatland to calculate the effect of drainage for forestry on the soil C stores. The difference between the mean C-stock above the 1000-year layer at the natural site (n=3) and that of the drained site (n=3) gives the C loss or C gain (kg C m^{-2}) at the drained site compared to the natural one. The 1000-year layer was used for the comparison, because this layer is represented roughly within the first meter core of the four studied sites.

All carbon changes are displayed as kg C m^{-2} and change rates as kg C m^{-2} yr^{-1} by dividing the carbon change by the number of years passed since the peatland was drained. Values of C balances are presented as means with standard error including error propagation when using the natural site as reference.

6.3 Results and discussion

6.3.1 Qualitative indicator of peatland drainage

For a preceding analysis of the natural status of the reference sites the approach of stable carbon isotope depth profiles as a qualitative indicator for peatland degradation was used (Alewell et al., 2011; Krüger et al., 2014; Krüger et al., 2015b). This was to verify if the undrained sites of the Lakkasuo peatland are without anthropogenic influence and thus suitable as reference sites for the profile-based methods.

Both, the minerotrophic and the ombrotrophic natural site, show a uniform $\delta^{13}C$ profile (Figure 6.1). Such a pattern is indicative for low decomposition rates and thus little fractionation of stable carbon isotopes (Clymo and Bryant, 2008; Alewell et al., 2011; Krüger et al., 2014). Mean $\delta^{13}C$ values at Mn are consistantly at about -29 ‰ in the upper 14 cm and represent the isotopic signature of the living vegetation. Below 14 cm, values are more or less stable at about -28 ‰. The $\delta^{13}C$ depth profile at site On shows an uniform depth pattern throughout the whole profile (mean values between -27 and -26 ‰). The differences between Mn and On resulted most likely from a different vegetation at these sites leading to different isotopic signatures (Ménot and Burns, 2001; Skrzypek et al., 2008). Thus, $\delta^{13}C$ depth profiles of the natural sites have a pattern similar to the one expected from the theoretical concept for natural peatlands (Alewell et al., 2011; Krüger et al., 2014) and are considerable suitable as reference sites.

At both of the drained sites mean $\delta^{13}C$ values increase from -30 to -26 ‰ in the upper 20 to 30 cm of the profile (Figure 6.1). Increasing $\delta^{13}C$ values with depth of up to 4-5 ‰ are a sign of aerobic decomposition of organic matter (Nadelhoffer and Fry, 1988; Alewell et al., 2011; Krüger et al., 2014). Concerning the minerotrophic drained site the age of the peat, based on the radiocarbon analyses, is much older than the drainage onset at this depth indicating that the increase in stable isotope signature is caused by aerobic decomposition and not by a vegetation change. Further down in the profile the mean δ^{13}C values at the minerotrophic drained site are higher than at the natural site possibly indicating a slight effect of drainage even in the subsoil. However, at the ombrotrophic drained site the development of a secondary (raw) humus layer in the upper 10 to 15 cm of the profile can influence the δ^{13}C signal of the soil. Nevertheless, the δ^{13}C values between 20 and 40 cm depth of the profile are much higher at the drained site, again indicating aerobic decomposition of the organic matter. Further down in the profile of the drained site (40 to 100 cm depth), mean δ^{13}C values vary only little and indicate no effect of topsoil drainage on isotopic fractionation in these still water-saturated horizon. The latter is congruent with the results from Alewell et al. (2011) and Krüger et al. (2014).

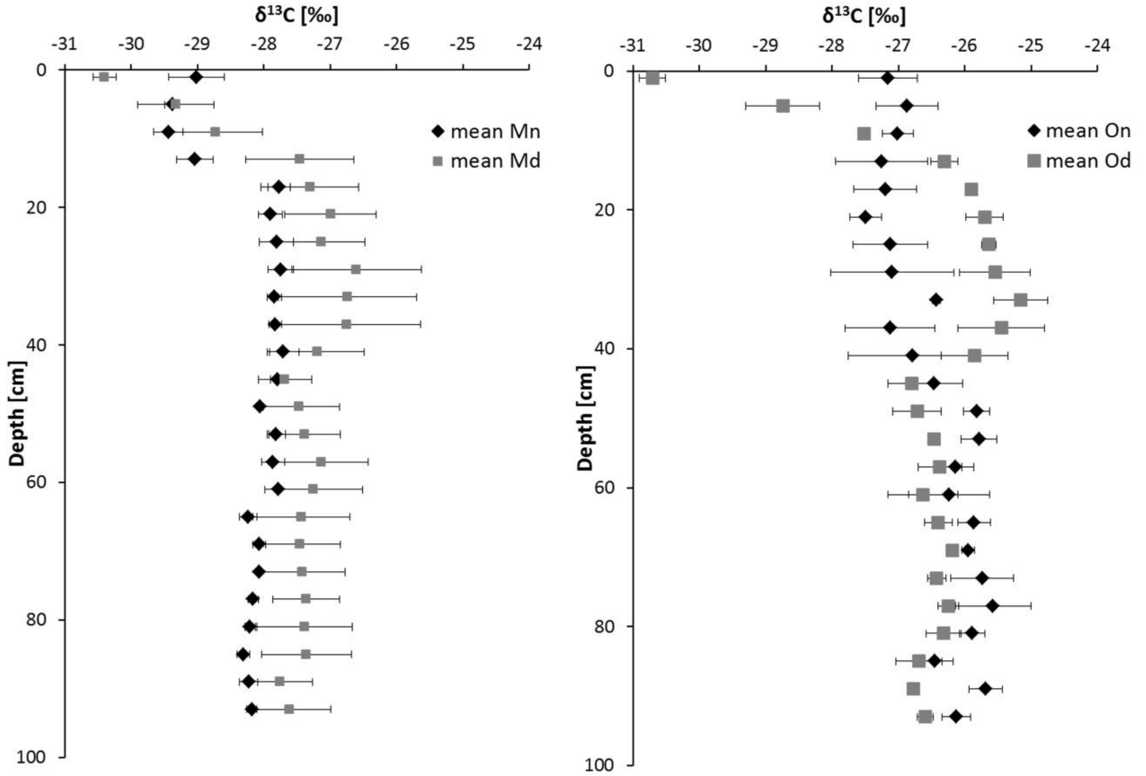

Figure 6.1: Mean (± SE) of δ^{13}C values in depth profiles (n=3) of the four study sites.

6.3.2 C-stock changes in peat soils drained for forestry

<u>Combined method-subsoil and combined method-natural (I and II)</u>

The combined methods, both with subsoil as well as with the natural site as reference, indicate a C loss at the Md as well as at the Od site (Figure 6.2). At both sites highest loss rates were calculated with the combined method taking subsoil as reference (0.272 ±0.034 kg C m^{-2} yr^{-1} for Md and 0.270 ±0.108 kg C m^{-2} yr^{-1} for Od). The combined method with the natural site as reference resulted in lower calculated C loss rates (0.140 ±0.150 kg C m^{-2} yr^{-1} for Md and 0.084 ±0.194 kg C m^{-2} yr^{-1} for Od). C balance calculations by any of the two combined methods are uncertain in these shallow drained ecosystems owing to only small differences in ash content (Figure A1.5), which result in non-significant differences in ash content between natural and drained sites. These methods are better applicable in more severely degraded peatlands with a stronger enrichment in ash. Furthermore, the combined methods might be in general more suitable for bogs, where the input of minerals is solely atmospheric. In fens, by contrast, inputs might not be exclusively atmospheric and other sources (e.g. transport with lateral groundwater flow) may influence the ash contents in minerotrophic peatlands. The influence of the ash profile by other sources than the atmosphere is displayed in the Mn profile where an ash peak is found in the first 20 cm of the profile similar to the Md profile (Figure A1.5). The enrichment of ash in an undisturbed peat profile emphasizes that application of methods I and II is, at least in fens, fraught with uncertainty (Table 6.2).

C accumulation method (III)

Our calculated mean C accumulation rates for Mn and On are 0.020 (±0.001) kg C m^{-2} yr^{-1} and 0.024 (±0.002) kg C m^{-2} yr^{-1}, respectively. The mean C accumulation rates are approximately the same as the C accumulation rates by Minkkinen et al. (1999) of the minerotrophic and ombrotrophic part of Lakkasuo peatland with 0.021 kg C m^{-2} yr^{-1} and 0.026 kg C m^{-2} yr^{-1}, respectively. Furthermore, these accumulation rates of the natural parts of the Lakkasuo peatland are very close to mean C accumulation rates for fens (0.019 kg C m^{-2} yr^{-1}) and bogs (0.029 kg C m^{-2} yr^{-1}) in Finland reported by Turunen et al. (2002). The C accumulation approach reveals C losses of 0.069 ±0.004 kg C m^{-2} yr^{-1} at Md and C gains of 0.139 ±0.019 kg C m^{-2} yr^{-1} at Od (Figure 6.2).

Cumulative C-stock comparison method (IV)

The calculated C balance from the cumulative C-stock comparison method reveals a C loss of 0.057 ±0.030 kg C m^{-2} yr^{-1} at Md and a C gain of 0.179 ±0.083 kg C m^{-2} yr^{-1} at Od (Figure 6.2). The results from the minerotrophic part are not significantly different from the rates calculated with the C accumulation approach. At the ombrotrophic site, results are also in the same range as those of the C accumulation method. The cumulative C-stock comparison method (IV) allows for determining a layer of same age. Unlike method III, the reference here is a defined by age, not by depth. Depth as a reference in peatlands can be affected by compaction and different growth rates of the peat and is therefore less appropriate as a benchmark. Therefore, method IV is considered to be the most robust in terms of estimating differences in C accumulation or loss among sites.

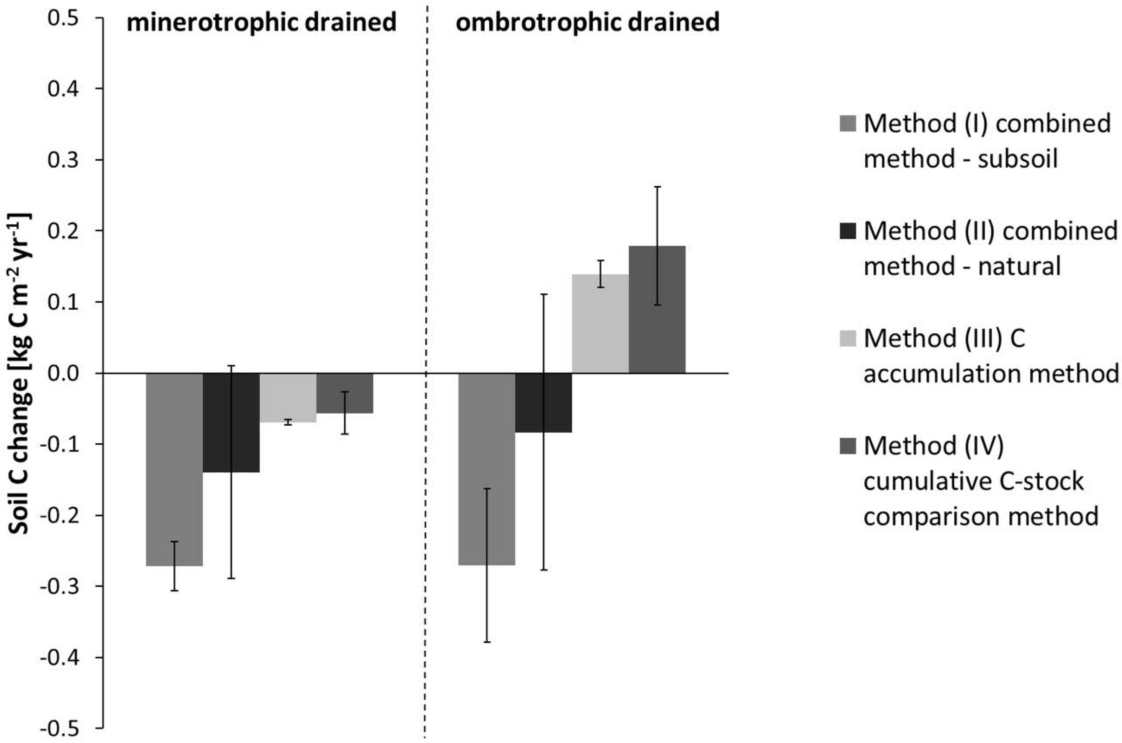

Figure 6.2: Mean (± SD) annual soil C changes (kg C m^{-2} yr^{-1}) of the drained sites at Lakkasuo peatland based on the four different profile-based methods since the onset of drainage in the year 1961 (negative values indicate C loss from the soil and positive values a C gain)

<u>Comparison of C balances to previous studies applying profile-based methods</u>

For the Lakkasuo peatland Minkkinen et al. (1999), using changes in C-stock of volumetric peat samples defined by synchronous peat layers based on charcoal and pollen analyses, reported an annual C loss of 0.060 kg C m^{-2} yr^{-1} for Md and an annual C gain of 0.070 kg C m^{-2} yr^{-1} for Od. Calculated C changes of both ^{14}C approaches (method III and method IV) at the minerotrophic drained site are right in the range of the values from Minkkinen et al. (1999). In contrary, our results using the combined methods at site Od are different to Minkkinen et al. (1999) (C loss instead of C gain). However, two other approaches from Finland, re-sampling and pairwise full peat column inventories, revealed a C loss of bogs and fens drained for forestry and of a bog drained for forestry of 0.150 kg C m^{-2} yr^{-1} (Simola et al., 2012) and 0.131 kg C m^{-2} yr^{-1} (Pitkänen et al., 2013), respectively. These results are in the range of our C losses calculated for Od by the two combined methods (0.084 kg C m^{-2} yr^{-1} and 0.270 kg C m^{-2} yr^{-1}). This shows that in general drained ombrotrophic peatlands in the boreal region does not necessarily maintain their C sink function.

<u>Influencing parameters on C balances and comparison to gas flux measurements</u>

According to our data, drainage of a nutrient-rich fen results in higher C losses or smaller C gains compared to the bog. Soil fertility plays a crucial role in modifying the impact of drainage for forestry on the greenhouse gas (GHG) balances in managed peatlands (IPCC, 2013a). The minerotrophic part of the Lakkasuo peatland showed a higher increase in the annual CO_2 emissions of the drained peat compared to the ombrotrophic site (Martikainen et al., 1995; Silvola et al., 1996). Other studies from Finland confirm the influence of the nutrient status on the soil C balance in drained peatlands (Minkkinen and Laine, 1998a; Minkkinen et al., 1999; Ojanen et al., 2013; Ojanen et al., 2014) and show higher C losses at nutrient-rich compared to nutrient-poor sites. Furthermore, at drained nutrient-poor sites root as well as moss production is higher than at drained nutrient-rich sites (Minkkinen et al., 2008), thereby providing higher organic matter inputs to soil. Additionally, soil temperature at the peat surface is lower in long-term drained peatlands compared to the natural ones which may have an additional effect on decomposition processes (Minkkinen et al., 1999). The drainage at the ombrotrophic site resulted in a small water table draw-down leading to a slight increases in the CO_2 emissions which are compensated by an increase in the primary production resulting in enhanced carbon accumulation rates after drainage. Additionally, increased litter input by trees is mixed with the mosses at nutrient-poor sites that together often forms a secondary (raw) humus layer on top of the peat (Minkkinen et al., 2008). This increased input, when not counterbalanced by a significantly increase in decomposition, favour C accumulation at the drained nutrient-poor sites (Minkkinen et al., 2008). However, lowering of the water table by 15 to 30 cm would result in a release of carbon because under these conditions the soil carbon emissions are assumed to be greater than the primary production of the forested peatland (Silvola et al., 1996). All these factors foster C accumulation in the drained bog, whereas increased decomposition at the drained fen leads to a C loss.

Net CO_2 flux rates in peatlands drained for forestry are highly variable (Silvola et al., 1996; Lohila et al., 2011; Meyer et al., 2013; Hommeltenberg et al., 2014). Several studies reported that such drained forests are still a C sink (Lohila et al., 2011) whereas others reported them to be a C source (Lindroth et al., 1998). Lohila et al. (2011) reported a C accumulation of 0.065 kg C m^{-2} yr^{-1} in a forestry drained peat soil in southern Finland as measured by eddy covariance (EC). Also with EC, Hommeltenberg et al. (2014) detected a stronger C sink in a bog drained for forestry (0.130 to 0.300 kg C m^{-2} yr^{-1}) than in a natural bog forest (0.053 to 0.073 kg C m^{-2} yr^{-1}). Furthermore, some studies determined a C balance of boreal drained peatlands close to zero (Dunn et al., 2007; Ojanen et al., 2014). The nutrient status of peatlands is an important factor to take into account for determining the C sink or source function of drained boreal peatlands for forestry (Minkkinen et al., 2007; Ojanen et al., 2010; Ojanen et al., 2013). These studies emphasize that further analysis by profile-based studies, besides flux measurements, on the C balance of drained peatlands for forestry in the boreal region are needed to determine whether and under which conditions these ecosystems function as sink or source.

The profile-based methods average over the last several decades or centuries since the onset of peatland drainage, whereas GHG flux measurements capture measurement periods of only a few years. Thus, GHG measurements present the year to year variation due to temperature, water table, precipitation fluctuation and net primary production. Furthermore, profile-based methods include C changes during the first years of drainage, which are presumably higher than the long-term average (Leifeld et al., 2012).

6.4 Conclusions

Stable carbon isotope depth profiles indicate that both undrained sites are in a natural state and that $\delta^{13}C$ becomes enriched upon drainage due to aerobic decomposition and/or vegetation change not only in the topsoil but even down to 40 cm depth. It was thus considered that the ^{13}C signature is suitable for serving as an indicator of whether a peatland is in its natural state or disturbed. With respect to the carbon budget, all four profile-based methods reveal that the drained minerotrophic peatland loses C though at different rates. However, at the ombrotrophic drained site the ^{14}C methods indicate a C gain relative to the natural situation whereas with the combined methods the site indicates a C loss. Our results confirm that in boreal regions drainage for forestry results in a higher risk of losing C when the peatland is minerotrophic. A comparison of the four applied profile-based methods revealed that both combined methods are applicable only on (strongly degraded) bogs and not on fens because fens also receive their nutrients from the groundwater. Both radiocarbon methods are applicable on both peatland types, whereas the cumulative C-stock comparison method (IV) used a layer of the same age and not depth and is therefore not affected, for instance, by compaction. However, all applied methods, except the combined method with subsoil as reference, require a natural site of the same peatland as reference. Hence, depending on the site conditions the suitable method for estimating the C balance has to be chosen. Nevertheless, considering all factors the profile-based methods are easy practicable and applicable on various drained peatland sites providing long-term changes in the soil carbon balance.

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CHAPTER 7

Conclusions and outlook

The main aims of this thesis were to use (i) stable carbon and nitrogen isotopes in depth profiles as qualitative indicators of peatland degradation, as well as to use (ii) different profile-based approaches to quantitatively calculate the soil carbon balance of degrading peatland sites. Different biogeochemical parameters in depth profiles were used to investigate peatland degradation which had occurred for different reasons. The increasing temperatures in the high northern latitudes result in accelerated permafrost thaw and in a degradation of palsa peatlands. The degradation of these ecosystems and the historical development was investigated in various subarctic palsa peatlands near Abisko, Northern Sweden (chapter 2 and chapter 3). The effect of land use intensification on stable carbon and nitrogen isotopes, the carbon balance and other biogeochemical indicators of peatland degradation were investigated in a temperate peatland near Cuxhaven, Northern Germany (chapter 4 and chapter 5). The consequence of peatland drainage for forestry use on the soil carbon balance was studied in a peatland complex with both a minerotrophic and an ombrotrophic part in the boreal Lakkasuo peatland in Central Finland (chapter 6).

7.1 Qualitative indicators of peatland degradation

This study demonstrates that the analysis of stable carbon isotopes in depth profiles is a useful tool to identify peatland degradation as well as to indicate the natural state of a peatland without anthropogenic or climatic disturbance. The depth patterns of stable carbon isotopes in palsa peatlands display the changes in decomposition processes of the peat material and indicate the current palsa degradation by permafrost thaw and the historical permafrost aggradation (chapter 2). The projected increase in temperature in the high northern latitudes (IPCC, 2013b) will further increase the active layer thickness and decrease most likely the area suitable for palsa peatlands. Although it is unsolved if the climate feedback of palsa degradation on the carbon balance is positive or negative, the results of the $\delta^{13}C$ depth profiles in palsa peatlands have a great potential for indicating paleoecological changes in these peatlands and to support the understanding of future changes in permafrost peatlands.

The $\delta^{13}C$ depth profiles indicate historical degradation of the peat even though the current situation presents a (near-) natural peatland (chapter 4). This could be used as a proxy for degraded peatlands because dry peatlands influenced by historic drainage activities are supposed to be carbon sources. Moreover, the usefulness of $\delta^{13}C$ depth patterns as indicators of peatland degradation from the subarctic and the temperate region were validated by other indicators of peat decomposition (C/N ratio and ash content) and peat degradation (carbon loss) (chapter 2 and chapter 4).

The assumed natural status of the minerotrophic and the ombrotrophic part in the Lakkasuo peatland in Central Finland was confirmed by the stable carbon isotope depth profiles with a uniform depth pattern (chapter 6). In contrast, both adjacent drained sites show increasing values of stable isotopes in the depth profiles indicating aerobic decomposition of the peat.

With reference to stable nitrogen isotopes as indicators of peatland degradation, the influence of other sources on the isotopic signal needs to be considered when interpreting the data of intensively used peatland sites (chapter 4). Nevertheless, the stable nitrogen isotope depth profiles in palsa peatlands could be used as indicators for changes in decomposition processes, and, when relating to the C/N ratio, as indicators of soil perturbation (chapter 3).

To sum up, the $\delta^{13}C$ depth patterns are a powerful tool to indicate the degradation/natural status of a peatland independently of peatland type, climate region and degradation causes. In accordance with other biogeochemical soil parameters the $\delta^{13}C$ depth profiles serve as qualitative indicators of peatland degradation. The $\delta^{15}N$ depth patterns can provide further qualitative information on involved processes and indicate soil perturbation when relating to the C/N ratio.

7.2 Quantitative indicators of peatland degradation

The carbon balance calculations of degraded peatlands by different profile-based methods demonstrated that these methods give valuable results regarding the evaluation of long-term soil carbon balance. Impacts of the former management are indicated by the $\delta^{13}C$ depth patterns and the long-term carbon loss (chapter 4). Nevertheless, a clear distinction between the three sites regarding the carbon balance by the profile-based methods can be derived through increasing carbon loss parallel to increasing land use intensity (chapter 5). This highlights the great impact of land use management on the carbon balance of agricultural used peatlands (IPCC, 2013a). A change from intensive used sites to a more climate-friendly land use management, such as extensification and raising the water table, will significantly reduce the greenhouse gas emissions from drained peatlands. In Germany, for instance, the estimated reduction potential of greenhouse gas emissions from drained peatlands by those changes is considerable proportion of about 75 % of the current emissions (Freibauer et al., 2009).

The results of all applied methods in the Lakkasuo peatland in Central Finland confirm that in boreal regions drainage for forestry increases the risk for losing carbon when the peatland is minerotrophic (chapter 6). The comparison of four different profile-based methods has revealed that the radiocarbon method determining the carbon stock above the same age of the peat at the natural and drained site (method IV in chapter 6) appears to be the best method for estimating the carbon balance of degraded peatlands because it provides a distinct age value as the absolute reference.

Even though the single measurements of radiocarbon signatures are expensive, the applied profile-based methods are overall less time-consuming and cost-intensive than the flux measurements and provide nonetheless quantitative results. The profile-based methods average over the last several decades or centuries since the onset of peatland drainage, whereas chamber and eddy covariance measurements capture measurement periods of only a few years and present the year to year variation due to temperature, water table depth, precipitation changes and net primary production.

To sum up, both profile-based approaches of soil ash content and radiocarbon signatures have the potential to provide quantitative estimations of peatland carbon losses integrated over long time periods. They deliver complementary results to the flux measurements in terms of total and long-term carbon losses of the degraded peatland.

7.3 Outlook

During this PhD project several methods for qualitative and quantitative indicators of peatland degradation were developed and evaluated. However, the results of the thesis also open a variety of new questions and potential future research studies regarding peatland degradation.

Stable isotope depth profiles could be compared to other indicators of changes in peatland hydrology or peatland decomposition like testate amoeba, peat humification and macrofossils. A study by Alewell et al. (in prep.) investigates stable isotope depth profiles, peat humification degree and macroscopic plant remains in two peatlands in the Black Forest, Southern Germany to differentiate between growing and degrading peatland sites. Moreover, $\delta^{13}C$ depth profiles can detect degraded peatland sites which are not obviously influenced by drainage activities or which have been affected by past drainage activities, as these sites are also losing carbon to the atmosphere (Drösler et al., 2013). Furthermore, the application of the profile-based methods will give estimations of quantitative carbon loss or gain of these sites.

The approach by changes in macroscopic plant remains and in testate amoeba composition could also be applied to the palsa peatlands in Northern Sweden for paleohydrological reconstruction and detecting permafrost aggradation. This paleoecological study is investigating the long-term changes during the Holocene in these palsa peatlands and will give further insights into palsa development. A higher resolution of soil sampling (<2 cm) in depth profiles of the palsa peatlands may be necessary because of the low peat accumulation rates in these ecosystems and therefore an alteration of the ecosystem within a few centimeters of the depth profile. Furthermore, radiocarbon dating of the samples in the depth profiles where drastic changes are observed will give quantitative carbon balance estimations of the different phases of palsa development and palsa degradation. This will give further insights into the question whether degrading palsa peatlands are carbon sinks or carbon sources and/or on which rates they are accumulating carbon during the different phases.

Furthermore, the parameters influencing the $\delta^{13}C$ and $\delta^{15}N$ signal in peatland soils, such as the isotopic signature of the vegetation and the effect of water table depth, presented, for instance, by Loisel et al. (2009), could be used in combination with the results of macroscopic plant remains for paleohydrological studies of peatlands.

One further interesting topic is to determine the differences in organic matter quality of various degraded peatlands, analysed by ^{13}C nuclear magnetic resonance (NMR) which is in preparation (Leifeld et al., in prep.). Organic matter decomposition is may be an important factor controlling peat decomposition rates and with this carbon losses of degraded peatlands (Leifeld et al., 2012). A change in organic matter quality is also expected to occur in the depth profiles of the hummocks from the palsa peatlands, with a drastic change in the peat material when lifted up by permafrost.

To address the question whether boreal peatlands drained for forestry are carbon sinks or carbon sources, the influencing factors on the carbon balance, such as nutrient status, drainage depth and organic matter input, could be investigated in more detail, as these factors seems to be the most important ones determining the soil carbon balance of these peatlands.

For a comprehensive comparison of the carbon balance calculations of degraded peatlands in Germany, the profile-based methods could be applied on other sites from the joint research project 'organic soils' (our results of the Ahlenfalkenberger Moor near Cuxhaven, Northern Germany, were compared to the chamber measurements by Beetz et al. 2013 in chapter 5) and could be compared to the performed flux measurements. To test if assumed natural peatlands have been affected by (historic) degradation the $\delta^{13}C$ depth profiles can be applied for a qualitative assessment. The sites include land uses and hydrological conditions of representative peatlands in Northern and Southern Germany and will give an overview of the long-term emission factors of drained peatlands in Germany. This allows a comparison of contemporary carbon budgets with long-term carbon balances for managed peatlands. Finally, the profile-based data could be used to improve carbon balance calculations of degraded peatlands on a landscape scale and to assess long-term carbon balances of degraded peatlands under certain land use management for upcoming decades.

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Appendix

Appendix 1: Supplementary materials of the publications

Appendix 1.1 Supplementary materials of chapter 2

The following tables are the supplementary materials of the chapter 2 (Krüger, J. P., Leifeld, J., and Alewell, C.: Degradation changes stable carbon isotope depth profiles in palsa peatlands, Biogeosciences 11: 3369-3380) of the thesis.

Table A1.1: $\delta^{13}C$, C and N content of hummocks at the three palsa peatlands

site	depth [cm]	$\delta^{13}C$ [‰]	C [%]	N [%]	C/N ratio
SDhu1	1.3	-26.51	47.53	1.34	30.50
	3.8	-26.88	49.22	1.46	28.85
	6.3	-26.66	49.45	1.50	28.21
	8.8	-27.31	42.42	1.64	22.21
	11.3	-27.55	43.26	2.04	18.15
	13.8	-28.68	9.42	0.42	19.27
SDhu2	1.3	-26.02	45.26	0.84	46.27
	3.8	-26.19	48.92	1.04	40.17
	6.3	-25.11	47.20	0.96	41.96
	8.8	-27.35	51.17	1.40	31.30
	11.4	-26.32	50.84	1.32	32.91
	13.9	-26.27	51.11	1.43	30.62
	16.4	-25.91	50.28	1.49	29.03
	18.9	-25.95	49.86	1.76	24.33
	21.5	-26.79	48.85	2.29	18.27
	24.0	-27.77	40.18	2.05	16.85
	26.5	-26.78	34.44	1.60	18.48
	29.1	-27.47	24.85	1.41	15.15
	31.6	-27.10	39.04	2.32	14.42
	34.1	-27.70	45.98	2.79	14.14
	36.6	-27.62	48.03	2.98	13.84
	39.2	-27.36	49.36	3.05	13.89
	41.7	-26.95	43.85	2.21	17.05
	44.2	-26.32	43.71	1.66	22.60
	46.7	-26.43	42.08	1.81	19.89
SDhu3	1.1	-26.82	47.57	1.08	37.83
	3.3	-27.09	50.25	0.92	46.67

	5.5	-24.79	46.07	0.56	71.12
	7.7	-25.13	45.99	0.53	73.79
	9.9	-25.32	46.50	0.64	62.62
	12.1	-25.61	46.79	0.67	59.47
	14.4	-25.34	48.22	0.97	42.75
	16.6	-25.19	47.37	0.83	48.94
	18.8	-25.88	48.05	1.03	40.16
	21.0	-26.47	49.77	1.46	29.30
	23.2	-26.28	48.62	1.29	32.35
	25.4	-25.50	47.76	1.64	25.03
	27.6	-25.80	48.49	2.17	19.12
	29.8	-26.70	50.47	2.03	21.35
	32.0	-27.29	50.61	1.93	22.48
	34.2	-27.75	51.09	1.82	24.01
	36.4	-28.16	49.80	1.73	24.75
	38.6	-27.27	47.14	2.26	17.92
	40.9	-27.48	39.83	1.98	17.24
	43.1	-27.55	41.31	2.13	16.60
	45.3	-28.00	30.90	1.68	15.75
	47.5	-27.73	28.06	1.60	15.04
	49.7	-27.90	22.73	1.37	14.22
SFhu1	1.0	-27.52	46.04	0.95	41.55
	3.1	-27.28	46.74	0.85	47.39
	5.1	-27.52	48.93	1.00	42.07
	7.2	-26.61	46.21	0.89	44.59
	9.3	-26.41	46.93	1.19	33.89
	11.3	-26.08	47.37	1.37	29.58
	13.4	-25.71	47.22	1.45	28.00
	15.4	-25.88	47.22	1.39	29.22
	17.5	-25.90	46.72	1.21	32.98
	19.5	-25.38	47.72	1.38	29.63
	21.6	-25.83	47.02	1.93	20.91
	23.7	-25.62	44.24	1.72	22.00
	25.7	-26.45	48.31	1.87	22.16
	27.8	-25.47	44.60	1.66	23.11
	29.8	-26.41	43.51	1.80	20.78
	31.9	-24.67	45.45	1.23	31.68
	33.9	-25.09	45.60	1.21	32.38
	36.0	-26.97	46.12	2.30	17.23
	38.0	-26.59	48.23	2.21	18.72
	40.1	-26.33	49.35	1.78	23.72
	42.2	-27.23	50.91	1.36	32.20
	44.2	-27.48	49.41	1.69	25.06
	46.3	-27.45	46.27	2.10	18.85
	48.3	-27.44	48.60	2.40	17.35
	50.4	-27.62	47.95	2.43	16.95

	52.4	-28.84	45.23	2.15	18.07
SFhu2	1.0	-26.83	45.06	0.87	44.43
	3.0	-26.39	44.60	0.95	40.35
	5.0	-25.41	44.54	0.72	53.19
	7.0	-25.63	45.17	0.78	49.76
	9.0	-25.04	45.32	0.80	48.48
	11.0	-24.07	43.91	0.56	67.74
	13.0	-25.95	48.15	1.43	28.81
	15.0	-26.26	49.56	1.66	25.56
	17.0	-25.91	47.87	1.73	23.74
	19.0	-26.69	44.27	2.08	18.25
	21.0	-26.52	40.60	2.17	16.05
	23.0	-26.87	45.71	2.11	18.61
	25.0	-27.71	40.27	2.02	17.06
	27.0	-27.43	38.42	1.93	17.10
	29.0	-27.45	37.85	2.07	15.65
	31.0	-28.09	44.17	2.02	18.74
	33.0	-27.49	42.24	2.33	15.56
	35.0	-27.56	44.66	2.25	17.02
	37.0	-28.04	46.15	2.15	18.39
	39.0	-27.92	46.43	1.87	21.33
	41.0	-27.60	47.01	1.76	22.87
	43.0	-27.92	46.55	1.51	26.41
	45.0	-27.40	47.48	1.42	28.75
	47.0	-26.43	46.55	1.75	22.78
	49.0	-26.13	46.33	1.64	24.29
SFhu3	1.4	-27.94	45.50	0.58	67.34
	4.1	-27.92	48.19	0.96	43.07
	6.9	-27.15	48.36	0.96	43.40
	9.6	-26.12	45.51	0.61	63.86
	12.4	-25.68	44.44	0.49	77.51
	15.1	-25.75	48.49	1.03	40.36
	17.9	-26.97	50.10	1.02	42.19
	20.6	-26.87	50.63	0.95	45.52
	23.4	-26.63	47.46	1.06	38.30
	26.1	-26.85	47.42	1.24	32.85
	28.9	-27.00	48.15	1.43	28.86
	31.6	-27.11	47.69	1.91	21.40
	34.4	-27.10	48.35	1.59	26.01
	37.1	-27.53	46.91	1.78	22.57
	39.9	-27.65	51.46	1.51	29.16
	42.6	-27.23	49.20	1.89	22.35
	45.4	-26.95	46.02	1.06	37.40
	48.1	-27.21	47.76	1.50	27.26
	50.9	-27.57	48.47	1.21	34.37
	53.6	-28.17	54.47	1.48	31.59

TThu1	1.6	-27.15	45.87	1.14	34.37
	4.9	-27.12	46.29	0.83	47.63
	8.2	-25.76	45.54	0.74	52.96
	11.4	-25.95	45.72	0.63	62.59
	14.7	-26.14	49.14	1.15	36.69
	18.0	-25.82	47.59	0.80	50.85
	21.2	-25.62	47.79	1.13	36.28
	24.5	-25.26	46.72	1.04	38.66
	27.8	-26.11	47.75	1.34	30.49
	31.0	-25.77	45.99	1.12	35.14
	34.3	-24.62	44.97	0.77	49.90
	37.6	-24.96	45.26	0.79	49.43
	40.8	-26.35	46.36	0.98	40.75
	44.1	-26.48	47.36	1.04	39.07
	47.4	-26.62	47.60	1.15	35.57
TThu2	1.1	-28.93	48.57	1.23	33.86
	3.3	-28.27	48.15	0.95	43.46
	5.6	-27.99	48.32	0.84	49.08
	7.8	-27.49	46.76	0.70	57.63
	10.0	-27.43	47.09	0.91	44.42
	12.3	-27.51	48.43	0.99	42.13
	14.5	-26.81	48.20	0.90	45.93
	16.7	-26.76	46.82	0.81	49.72
	18.9	-26.50	49.46	1.23	34.43
	21.2	-26.93	50.85	1.37	31.74
	23.4	-26.38	48.49	1.08	38.50
	25.6	-25.68	45.22	0.52	73.97
	27.8	-25.02	44.80	0.44	87.93
	30.1	-25.17	44.20	0.42	90.76
	32.3	-25.50	44.10	0.39	96.43
	34.5	-26.12	44.43	0.46	82.46
	36.8	-25.69	44.23	0.51	74.34
	39.0	-26.30	45.24	0.74	52.51
	41.2	-24.62	45.12	0.87	44.30
	43.4	-25.30	45.67	0.75	52.14
	45.7	-25.27	45.89	0.80	49.24
	47.9	-25.50	45.61	0.72	54.16
TThu3	1.5	-27.29	47.04	1.31	30.86
	4.5	-27.40	47.83	1.00	40.98
	7.5	-27.12	41.94	0.66	54.10
	10.5	-27.69	50.04	1.09	39.55
	13.5	-26.93	48.01	0.90	45.50
	16.5	-26.47	48.99	1.38	30.40
	19.5	-25.82	47.02	1.03	39.23
	22.5	-25.57	44.94	0.77	50.22
	25.5	-27.19	49.88	1.54	27.78

	28.5	-27.14	49.05	1.27	33.16
	31.5	-26.91	49.61	1.36	31.26
	34.5	-27.47	47.39	1.09	37.19
	37.5	-26.99	48.21	1.03	40.28
	40.5	-26.87	48.08	0.99	41.59
	43.5	-26.77	47.07	0.91	44.15
	46.5	-26.78	47.64	0.95	42.80

Table A1.2: $\delta^{13}C$, C and N content of degraded hummocks at the three palsa peatlands

site	depth [cm]	$\delta^{13}C$ [‰]	C [%]	N [%]	C/N ratio
SDhud1	1.0	-27.08	47.89	1.88	21.81
	3.0	-27.15	47.96	1.95	21.09
	5.0	-27.04	46.37	1.91	20.78
	7.0	-27.33	44.63	1.92	19.90
	9.0	-26.96	44.94	1.92	20.03
	11.0	-27.22	43.12	2.05	18.02
	13.0	-27.68	41.37	2.25	15.74
	15.0	-28.22	39.62	2.42	14.01
	17.0	-28.40	40.07	2.61	13.16
	19.0	-28.44	40.43	2.67	12.98
	21.0	-28.50	39.44	2.65	12.76
	23.0	-28.65	38.89	2.62	12.71
	25.0	-28.64	39.00	2.66	12.60
	27.0	-28.40	39.13	2.63	12.77
	29.0	-28.34	40.41	2.72	12.74
	31.0	-28.39	42.57	2.73	13.39
	33.0	-28.39	47.59	2.63	15.52
	35.0	-28.44	51.16	2.53	17.34
	37.0	-28.69	52.59	2.70	16.68
	39.0	-29.00	51.64	2.92	15.17
	41.0	-28.92	50.73	2.74	15.90
	43.0	n.d.	51.52	2.84	15.54
	45.0	-28.65	52.38	2.76	16.26
	47.0	-29.11	50.88	2.96	14.74
	49.0	-28.32	49.67	2.86	14.91
	51.0	n.d.	52.91	2.34	19.39
	53.0	-28.40	50.99	2.89	15.12
	55.0	-27.48	50.50	3.01	14.39
	57.0	-27.35	50.00	2.89	14.82
	59.0	-28.27	25.26	1.42	15.23
	61.0	-28.72	10.06	0.53	16.25
SDhud2	1.0	-26.02	48.60	1.17	35.72
	5.0	-25.90	46.96	0.91	44.18
	9.0	-24.88	45.57	0.48	80.65
	13.0	-24.98	46.79	0.90	44.38

	17.0	-26.38	49.99	1.46	29.35
	21.0	-26.84	49.97	1.35	31.70
	25.0	-26.56	48.99	1.30	32.30
	29.0	-26.09	46.18	1.00	39.44
	33.0	-26.46	47.20	1.12	36.16
	37.0	-26.35	46.35	1.74	22.88
	41.0	-26.78	47.28	2.31	17.53
	45.0	-26.80	46.72	2.37	16.87
SDhud3	1.0	-27.25	47.62	1.34	30.56
	3.0	-27.64	49.22	1.51	27.93
	5.0	-27.55	49.74	1.56	27.29
	7.0	-27.75	50.47	1.57	27.59
	9.0	-27.64	50.52	1.58	27.34
	11.0	-27.63	50.11	1.35	31.83
	13.0	-26.94	47.15	1.84	21.99
	15.0	-26.78	45.96	2.37	16.63
	17.0	-27.16	45.99	2.65	14.91
	19.0	-27.13	45.94	2.50	15.75
	21.0	-27.11	47.49	2.55	15.95
	25.0	-27.11	47.00	2.64	15.25
	27.0	-27.15	48.02	2.44	16.85
	29.0	-27.43	47.55	2.57	15.89
	31.0	-27.37	46.57	2.41	16.59
	33.0	-27.55	46.32	2.34	17.00
	35.0	-27.76	43.35	2.24	16.60
	37.0	-27.79	42.10	2.07	17.48
	39.0	-27.74	40.91	2.06	17.00
	41.0	-27.88	29.85	1.50	17.04
	43.0	-27.67	17.55	0.86	17.49
	45.0	-28.08	12.06	0.56	18.33
	47.0	-27.33	10.99	0.49	19.32
SFhud1	1.0	-28.56	47.77	1.61	25.40
	5.0	-27.24	49.66	1.72	24.82
	9.0	-26.81	50.42	1.60	27.07
	13.0	-27.38	43.67	2.10	17.81
	17.0	-27.16	45.88	2.01	19.61
	21.0	-27.31	45.95	2.07	19.07
	25.0	-26.98	44.86	1.84	20.95
	29.0	-26.63	43.48	1.80	20.74
	33.0	-25.62	45.00	1.55	24.90
	37.0	-25.87	45.08	1.69	22.85
	41.0	-25.52	44.63	1.58	24.24
	45.0	-25.13	45.52	1.85	21.11
SFhud2	1.0	-27.91	45.23	1.43	27.10
	5.0	-26.45	45.22	1.49	25.97
	9.0	-26.76	46.79	1.67	24.01

	13.0	-27.02	47.95	1.72	23.88
	17.0	-26.68	47.15	1.31	30.80
	21.0	-26.31	46.74	1.47	27.30
	25.0	-26.21	46.68	1.50	26.62
	29.0	-25.27	46.16	1.12	35.33
	37.0	-27.69	45.90	1.57	25.14
	43.0	-27.85	45.31	1.62	23.92
SFhud3	1.0	-25.61	43.59	0.98	38.33
	3.0	-25.26	42.69	0.68	53.56
	5.0	-26.15	44.90	0.96	40.26
	7.0	-26.43	46.15	0.84	47.08
	9.0	-26.16	47.40	0.96	42.54
	11.0	-24.78	46.22	0.81	48.66
	13.0	-24.51	45.28	0.82	47.26
	15.0	-25.66	46.98	1.48	27.23
	17.0	-26.22	47.07	2.01	20.09
	19.0	-25.72	45.29	1.69	23.03
	21.0	-25.42	43.47	1.57	23.72
	25.0	-25.80	45.26	2.01	19.31
	29.0	-26.10	46.55	2.05	19.47
	33.0	-26.20	46.50	1.96	20.30
	37.0	-26.07	48.94	1.94	21.63
	41.0	-26.76	47.52	2.21	18.47
	45.0	-26.55	47.66	1.85	22.10
	49.0	-26.59	47.65	1.72	23.78
TThud1	1.0	-26.56	47.24	1.26	32.12
	5.0	-26.11	46.42	0.99	40.06
	9.0	-26.18	47.51	1.12	36.23
	13.0	-26.17	47.33	1.18	34.48
	17.0	-24.96	46.40	1.08	36.94
	21.0	-25.01	44.07	0.63	60.17
	25.0	-24.61	43.96	0.53	71.36
	29.0	-26.81	46.19	1.09	36.32
	33.0	-25.83	45.48	0.69	56.57
	37.0	-25.96	45.25	0.64	60.81
	41.0	-26.87	46.08	0.61	64.67
	45.0	-26.75	46.44	0.67	59.11
	49.0	-26.42	45.30	0.70	55.57
TThud2	1.0	-27.12	44.71	0.99	38.72
	3.0	-26.09	41.41	0.93	38.14
	5.0	-25.04	43.84	0.68	55.39
	7.0	-25.62	44.97	1.09	35.30
	9.0	-26.20	45.37	1.33	29.31
	11.0	-24.83	42.28	0.67	54.05
	13.0	-24.95	42.68	0.58	63.20
	15.0	-24.96	43.23	0.60	62.07

	17.0	-25.24	44.83	0.69	55.93
	19.0	-26.39	45.44	0.95	40.83
	21.0	-25.82	45.03	0.79	49.12
	23.0	-26.53	44.90	0.81	47.30
	25.0	-27.24	44.70	0.91	42.09
	27.0	-26.73	45.34	0.92	42.13
	29.0	-26.38	45.85	0.94	41.67
	31.0	-25.54	45.37	0.80	48.65
	33.0	-26.32	46.44	0.81	48.96
	35.0	-26.48	46.12	1.07	36.88
	37.0	-26.59	44.64	0.82	46.92
	39.0	-27.16	45.34	0.75	51.71
	41.0	-26.81	44.19	0.73	51.57
	43.0	-25.27	44.30	0.58	65.08
	45.0	-25.50	44.37	0.67	56.37
	47.0	-26.09	45.40	0.75	51.68
	49.0	-27.06	47.55	1.17	34.72
TThud3	1.0	-26.59	46.50	1.27	31.28
	3.0	-26.65	47.57	1.31	31.17
	5.0	-26.86	48.65	1.47	28.37
	7.0	-27.03	49.31	1.51	28.04
	9.0	-26.80	48.84	1.63	25.77
	11.0	-26.97	48.51	1.36	30.59
	13.0	-27.20	48.92	1.27	32.99
	15.0	-27.15	47.99	1.27	32.45
	17.0	-27.17	48.82	1.41	29.75
	19.0	-27.13	47.39	1.69	24.04
	21.0	-27.28	49.07	1.85	22.70
	23.0	-27.14	49.65	2.55	16.70
	25.0	-27.06	50.74	1.96	22.21
	27.0	-26.85	50.24	2.21	19.53
	29.0	-26.80	49.37	2.11	20.11
	31.0	-26.77	48.77	2.20	19.02
	33.0	-27.12	49.69	2.04	20.92
	35.0	-27.14	49.80	1.57	27.27
	37.0	-27.06	50.23	1.67	25.85
	39.0	-27.03	49.50	1.79	23.73
	41.0	-26.87	49.41	1.39	30.39
	43.0	-26.70	49.87	1.22	34.95
	45.0	-27.08	50.07	1.27	33.79

Table A1.3: $\delta^{13}C$, C and N content of hollows at the three palsa peatlands

site	depth [cm]	$\delta^{13}C$ [‰]	C [%]	N [%]	C/N ratio
SDho1	2.0	-25.73	44.43	0.86	44.08
	6.0	-26.21	43.71	0.86	43.67
	10.0	-27.19	43.84	0.76	49.20
	14.0	-27.14	44.00	0.66	56.80
	18.0	-27.18	45.70	1.02	38.50
	22.0	-26.51	44.41	0.95	39.94
	26.0	-26.43	46.29	1.43	27.77
	30.0	-26.48	45.71	1.55	25.34
	34.0	-25.61	47.63	1.72	23.79
SDho2	2.0	-25.27	43.81	0.69	54.80
	6.0	-26.21	43.04	0.49	75.83
	10.0	-25.85	42.88	0.39	94.61
	14.0	-25.80	43.31	0.49	76.01
	18.0	-26.51	45.18	0.53	72.61
	22.0	-27.33	45.20	0.79	49.07
	34.0	-26.51	46.12	1.13	35.13
	38.0	-26.22	46.34	1.42	28.08
SDho3	2.0	-26.83	43.94	0.66	57.13
	6.0	-27.20	44.26	0.61	62.64
	10.0	-26.98	43.55	0.64	58.20
	14.0	-27.42	43.89	0.67	56.23
	18.0	-27.27	44.11	0.82	46.01
	22.0	-26.69	44.43	0.75	51.02
	26.0	-26.07	44.01	0.61	62.21
	34.0	-23.74	44.09	0.40	94.37
	38.0	-23.55	44.56	0.47	81.80
SFho1	1.0	-24.06	43.67	1.95	19.20
	3.0	-24.64	42.67	1.91	19.13
	5.0	-24.91	43.56	2.03	18.36
	7.0	-24.91	44.76	2.21	17.36
	9.0	-25.29	48.96	2.01	20.84
	11.0	-24.49	46.83	2.11	19.03
	15.0	-23.82	45.84	1.33	29.59
	19.0	-25.76	45.31	1.52	25.55
	23.0	-25.08	46.22	1.63	24.33
	25.0	-25.49	48.58	2.42	17.25
	27.0	-24.95	46.20	1.58	25.04
	29.0	-24.93	45.09	1.55	24.93
	31.0	-24.68	45.30	1.49	26.10
	33.0	-23.97	45.00	1.17	32.99
SFho2	1.0	-23.22	45.15	1.09	35.68
	5.0	-26.75	42.52	1.13	32.38
	9.0	-28.43	43.10	1.71	21.57
	13.0	-27.76	44.64	1.66	23.11

	17.0	-27.88	44.98	1.81	21.33
	21.0	-27.53	45.64	2.23	17.53
	25.0	-28.12	45.08	2.36	16.39
	29.0	-27.45	44.28	2.35	16.15
	33.0	-27.53	39.90	1.99	17.22
SFho3	1.0	-27.36	43.89	1.10	34.27
	3.0	-27.79	44.36	1.32	28.71
	5.0	-28.07	44.64	1.27	30.25
	7.0	-28.29	44.66	1.28	29.80
	9.0	-28.37	44.52	1.32	28.99
	11.0	-28.42	43.85	1.22	30.81
	13.0	-28.31	44.02	1.35	28.04
	15.0	-28.20	44.98	1.44	26.79
	17.0	-28.11	44.97	1.55	24.83
	19.0	-27.84	44.99	1.42	27.21
	23.0	-27.17	46.76	1.14	35.33
	25.0	-27.29	45.94	1.07	36.76
	27.0	-26.15	47.32	1.17	34.61
	29.0	-26.24	46.74	1.26	31.79
	31.0	-27.40	49.77	1.75	24.37
	35.0	-26.76	49.02	2.14	19.63
	37.0	-26.01	46.57	2.17	18.43
	39.0	-25.26	44.83	2.20	17.46
	41.0	-25.53	44.97	2.36	16.37
	43.0	-25.94	46.47	2.08	19.15
	45.0	-26.06	46.96	1.95	20.61
TTho1	2.0	-25.62	43.07	0.57	65.00
	6.0	-26.33	42.66	0.39	93.86
	10.0	-26.72	43.27	0.59	62.37
	14.0	-26.72	42.90	0.56	66.27
	18.0	-27.20	43.08	0.53	69.65
	22.0	-26.74	42.67	0.44	82.40
	26.0	-26.65	43.08	0.44	84.89
TTho2	2.0	-26.33	43.13	0.59	62.86
	6.0	-26.26	43.59	0.49	75.73
	10.0	-25.99	42.38	0.47	77.94
	14.0	-25.88	43.54	0.48	77.29
	18.0	-25.99	43.57	0.60	62.22
	22.0	-26.16	43.90	0.51	73.27
TTho3	2.0	-26.32	43.36	0.38	96.96
	6.0	-27.37	42.99	0.35	104.28
	10.0	-26.55	43.94	0.32	116.04
	14.0	-25.27	43.86	0.26	144.10
	18.0	-25.70	42.95	0.26	143.99
	22.0	-25.90	42.68	0.23	162.51
	26.0	-26.65	44.59	0.37	104.02

Table A1.4: $\delta^{13}C$, C and N content of degraded hollows at the three palsa peatlands

site	depth [cm]	$\delta^{13}C$ [‰]	C [%]	N [%]	C/N ratio
SDhod1	1.0	-24.33	43.33	1.50	24.81
	3.0	-24.51	43.97	1.41	26.75
	5.0	-24.49	43.21	1.34	27.61
	7.0	-24.74	43.51	1.37	27.25
	9.0	-25.74	43.21	1.34	27.75
	11.0	-26.62	43.20	1.33	27.82
	13.0	-27.49	44.94	1.84	20.98
	15.0	-28.83	46.96	1.60	25.09
	17.0	-28.36	47.07	1.15	35.06
	19.0	-27.99	46.64	1.17	34.20
	21.0	-26.70	47.64	1.07	38.01
	23.0	-27.28	48.77	1.24	33.71
	25.0	-27.30	47.96	1.21	34.08
	27.0	-27.56	48.94	1.27	33.10
	29.0	-27.04	47.81	1.21	33.90
	31.0	-27.05	47.95	1.34	30.80
	33.0	-27.35	48.77	1.66	25.25
	35.0	n.d.	48.22	1.74	23.77
	37.0	n.d.	51.33	1.90	23.13
	39.0	-27.76	50.11	2.18	19.70
	41.0	-28.11	48.63	2.15	19.41
	43.0	-28.22	44.95	2.33	16.53
	45.0	-28.22	44.99	2.33	16.53
	47.0	-28.14	44.47	2.19	17.42
	49.0	-28.42	43.92	2.44	15.46
	51.0	-28.50	43.37	2.45	15.18
	53.0	-28.49	44.21	2.58	14.68
SDhod2	1.0	-25.20	43.41	0.69	53.87
	3.0	-25.25	43.52	0.66	56.22
	5.0	-25.33	42.36	0.65	56.07
	7.0	-24.97	42.64	0.67	54.97
	9.0	-24.72	42.96	0.96	38.40
	11.0	-25.03	43.65	1.04	36.01
	13.0	-26.40	46.00	1.09	36.04
	15.0	-28.16	50.15	1.13	38.00
	17.0	-28.15	48.38	1.34	31.07
	19.0	-27.78	50.19	1.38	31.21
	21.0	-26.95	49.75	1.08	39.40
	23.0	-26.85	48.89	0.94	44.41
	25.0	-27.02	49.28	1.05	40.16
	27.0	-26.97	49.78	1.18	36.27
	29.0	-26.66	49.62	1.18	36.13
	31.0	-25.95	47.17	1.07	37.73
	33.0	-26.91	49.36	1.29	32.82

	35.0	-27.01	49.09	1.24	34.07
	37.0	-27.50	49.61	1.20	35.35
	39.0	-28.62	49.99	0.95	45.26
SDhod3	1.0	-28.32	47.00	1.32	30.44
	3.0	-28.47	46.70	1.26	31.73
	5.0	-28.05	45.38	1.33	29.32
	7.0	-28.14	46.13	1.45	27.33
	9.0	-27.10	46.13	1.91	20.67
	11.0	-26.85	46.18	2.41	16.40
	13.0	-27.07	44.67	2.53	15.14
	15.0	-27.24	43.20	2.76	13.44
	17.0	-26.95	43.55	2.90	12.89
	19.0	-27.07	43.56	2.91	12.84
	21.0	-27.27	44.09	2.95	12.81
	23.0	-27.11	45.94	2.81	14.04
	25.0	-27.02	46.55	2.59	15.43
	27.0	-27.27	45.65	2.45	15.99
	29.0	-27.43	43.39	2.19	16.97
	31.0	-27.54	42.50	2.13	17.08
	33.0	-28.07	41.01	2.01	17.48
	35.0	-28.09	37.58	1.88	17.14
	37.0	-28.09	32.37	1.64	16.90
	39.0	-28.25	25.29	1.31	16.60
	41.0	-28.20	20.20	1.04	16.68
	43.0	-28.40	17.11	0.87	16.84
	45.0	-28.23	21.09	1.10	16.40
SFhod1	1.0	-26.33	42.03	0.96	37.38
	5.0	-25.77	41.97	1.11	32.48
	9.0	-27.08	45.32	1.34	28.92
	13.0	-26.10	45.68	1.30	30.10
	17.0	-25.03	46.33	1.83	21.74
	21.0	-26.46	36.62	1.64	19.16
	25.0	-27.53	20.88	1.25	14.28
	29.0	-28.10	12.19	0.73	14.36
	33.0	-27.71	5.16	0.34	13.11
	37.0	-27.36	4.71	0.31	13.11
SFhod2	1.0	-27.71	44.11	1.15	32.84
	5.0	-28.33	43.71	1.35	27.74
	9.0	-27.42	44.89	1.52	25.26
	13.0	-26.97	49.45	2.01	21.10
	17.0	-26.79	50.58	1.80	24.11
	21.0	-26.49	47.28	1.57	25.91
	25.0	-26.70	46.95	1.39	29.01
	29.0	-26.18	46.52	1.23	32.56
	37.0	-26.01	44.44	1.13	33.76
SFhod3	1.0	-28.32	45.40	1.50	25.98

	3.0	-28.11	45.87	1.43	27.42
	5.0	-28.23	46.39	1.38	28.91
	7.0	-28.32	46.58	1.38	29.03
	9.0	-27.93	46.34	1.33	29.87
	11.0	-27.62	47.46	1.43	28.54
	13.0	-27.28	45.81	1.71	22.96
	15.0	-26.58	44.39	0.95	40.12
	17.0	-26.54	44.11	0.99	38.29
	19.0	-26.72	44.74	1.05	36.54
	21.0	-26.88	44.53	1.08	35.23
	23.0	-26.66	44.54	1.22	31.43
	25.0	-26.55	45.46	1.40	27.83
	27.0	-26.26	45.43	1.51	25.76
	29.0	-26.25	45.72	1.52	25.79
	31.0	-25.96	44.56	1.37	27.90
	33.0	-25.81	45.16	1.44	26.98
	35.0	-26.08	44.86	1.36	28.25
	37.0	-25.76	44.32	1.29	29.46
	39.0	-26.80	48.65	1.77	23.56
TThod1	2.0	-24.10	43.26	1.09	33.94
	6.0	-28.33	53.48	0.95	48.47
	10.0	-27.69	48.68	1.31	31.88
	14.0	-26.95	46.12	0.90	44.11
	18.0	-26.76	47.20	0.75	53.70
	22.0	-27.38	47.61	0.81	50.70
	30.0	-25.99	45.15	0.74	52.62
	38.0	-25.89	46.71	1.42	28.29
	42.0	-25.79	45.95	1.54	25.52
TThod2	2.0	-21.29	43.08	1.42	26.04
	6.0	-22.23	42.51	1.37	26.70
	10.0	-23.19	41.94	1.04	34.64
	14.0	-24.12	42.81	1.09	33.56
	18.0	-25.75	43.53	1.44	25.89
	22.0	-25.24	44.48	1.55	24.53
	26.0	-26.57	47.24	1.43	28.33
	30.0	-26.83	45.86	1.08	36.34
	34.0	-26.71	46.76	1.06	37.81
	38.0	-27.05	47.38	1.10	36.79
	42.0	-26.85	46.13	0.80	49.19
	46.0	-26.80	46.36	0.85	46.68
TThod3	2.0	-22.79	42.75	0.96	38.28
	6.0	-23.12	41.86	0.67	53.41
	10.0	-24.14	42.34	0.76	48.01
	14.0	-24.85	42.97	0.81	45.40
	18.0	-25.06	43.94	0.90	41.98
	22.0	-26.73	47.28	1.08	37.41

26.0	-26.33	46.03	0.93	42.55
30.0	-28.44	47.25	1.08	37.40
34.0	-28.89	50.15	1.26	34.25
38.0	-28.21	49.89	1.24	34.59
42.0	-27.21	49.28	1.32	32.03
46.0	-26.95	49.01	1.35	31.02

Appendix 1.2 Supplementary materials of chapter 4

The following are the supplementary materials of the chapter 4 (Krüger, J. P., Leifeld, J., Glatzel, S., Szidat, S., and Alewell, C.: Biogeochemical indicators of peatland degradation – a case study of a temperate bog in northern Germany, Biogeosciences 12: 2861-2871) of the thesis.

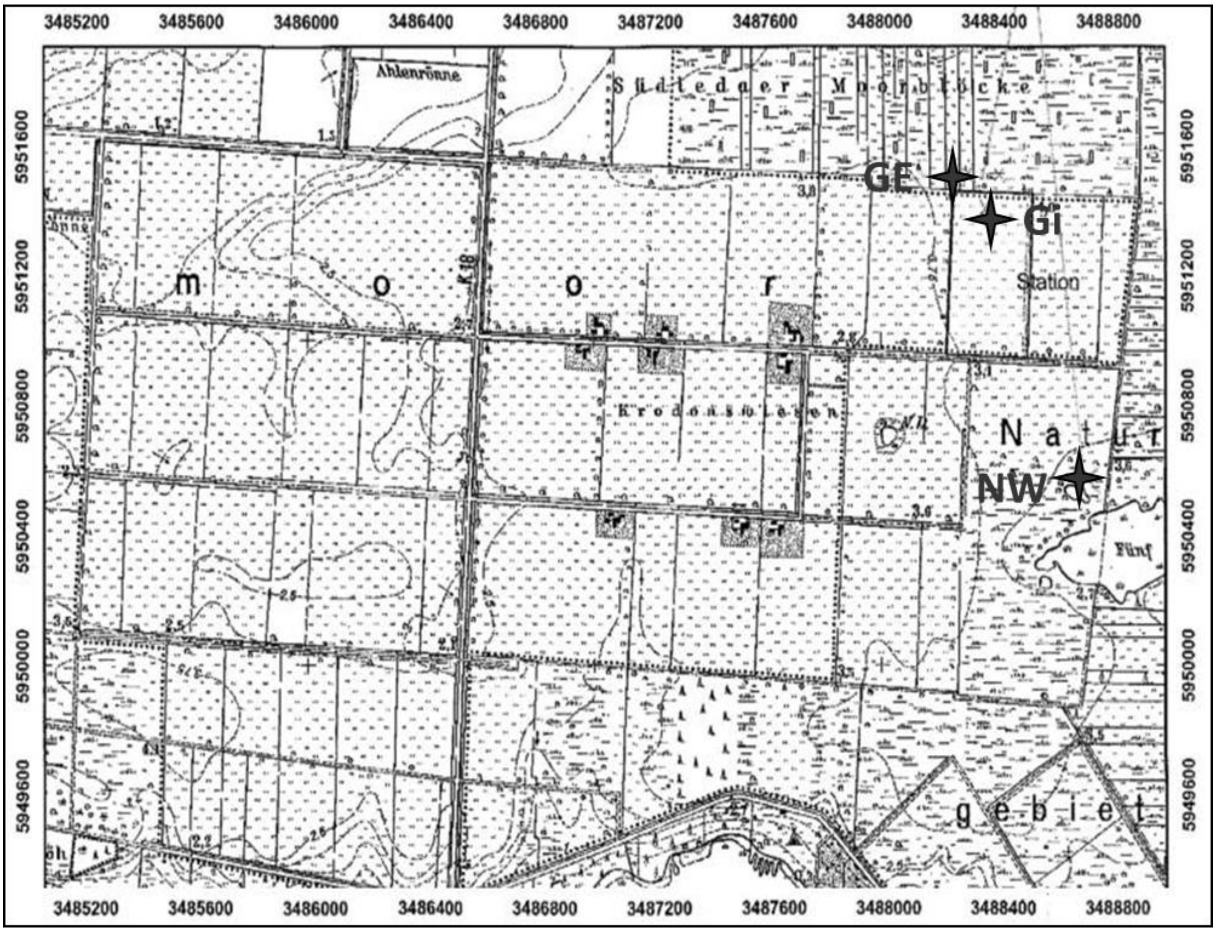


Figure A1.1: Study sites at the Ahlen-Falkenberger peatland with the near-natural site (NW), the extensive used grassland site (GE) and the intensive used grassland site (GI).

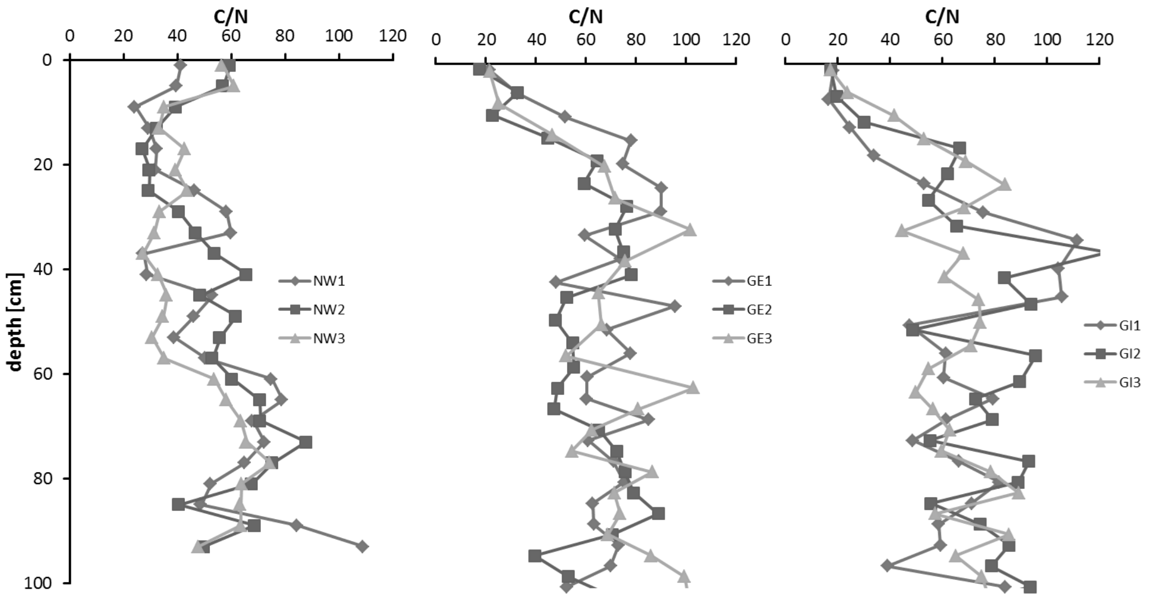


Figure A1.2: C/N ratio depth profiles at the near-natural site (NW), extensive used grassland site (GE) and intensive used grassland site (GI) at the Ahlen-Falkenberger peatland.

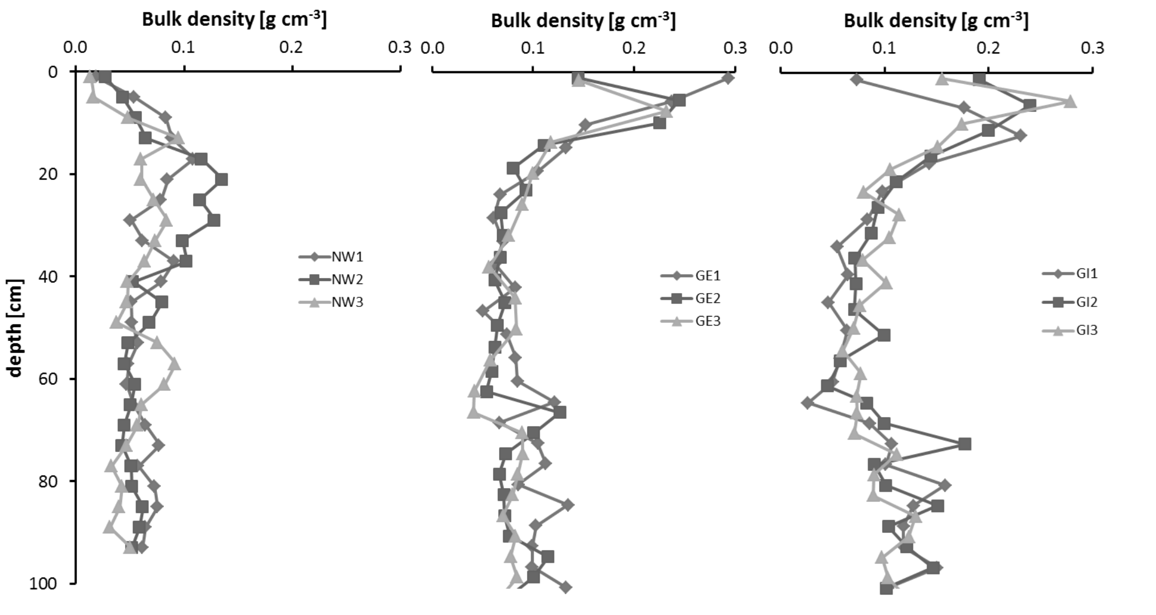


Figure A1.3: Bulk density depth profiles at the near-natural site (NW), extensive used grassland site (GE) and intensive used grassland site (GI) at the Ahlen-Falkenberger peatland.

Table A1.5: ^{14}C age dating of peat layers from each site, near-natural (NW), extensive managed grassland (GE) and intensive managed grassland (GI) site, from the Ahlen-Falkenberger peatland. Uncertainties of F14C values represent one sigma. For calibrated ages, the lower and upper boundary is given with 95% confidence. Calibrated ages are displayed as years AD/BC.

Lab number	Site/core	Depth [cm]	F14C	F14C uncertainty	Calibrated ages (years AD/BC) Upper	Calibrated ages (years AD/BC) Lower
BE 1723.1.1	NW1	9.0	1.1655	0.0026	1958 AD	1990 AD
BE 1724.1.1	NW1	65.0	0.9361	0.0020	1330 AD	1434 AD
BE 1725.1.1	NW1	81.0	0.9177	0.0020	1274 AD	1381 AD
BE 1726.1.1	NW2	9.0	1.0840	0.0023	1956 AD	2002 AD
BE 1727.1.1	NW2	65.0	0.9418	0.0021	1409 AD	1438 AD
BE 1728.1.1	NW2	81.0	0.9418	0.0021	1415 AD	1446 AD
BE 1729.1.1	NW3	9.0	1.1391	0.0024	1957 AD	1992 AD
BE 1730.1.1	NW3	65.0	0.9782	0.0021	1665 AD	1927 AD
BE 1731.1.1	NW3	81.0	0.9692	0.0021	1641 AD	1797 AD
BE 1732.1.1	GE1	10.2	0.8895	0.0020	1030 AD	1155 AD
BE 1733.1.1	GE1	14.7	0.8769	0.0020	907 AD	1023 AD
BE 1734.1.1	GE1	88.0	0.7957	0.0018	129 AD	233 AD
BE 1735.1.1	GE2	9.8	0.9393	0.0020	1409 AD	1440 AD
BE 1736.1.1	GE2	14.2	0.9115	0.0020	1253 AD	1285 AD
BE 1737.1.2	GE2	86.0	0.8085	0.0018	257 AD	393 AD
BE 1738.1.2	GE3	13.6	0.8970	0.0020	1053 AD	1219 AD
BE 1739.1.1	GE3	19.6	0.8805	0.0020	988 AD	1028 AD
BE 1740.1.1	GE3	102.0	0.7949	0.0019	93 AD	236 AD
BE 1741.1.1	GI1	12.2	0.9460	0.0021	1426 AD	1459 AD
BE 1742.1.1	GI1	33.8	0.8655	0.0019	775 AD	953 AD
BE 1743.1.2	GI1	96.0	0.7628	0.0017	356 BC	171 BC
BE 1744.1.1	GI2	11.2	0.9233	0.0020	1287 AD	1392 AD
BE 1745.1.1	GI2	31.0	0.8212	0.0018	422 AD	537 AD
BE 1746.1.1	GI2	92.0	0.7548	0.0017	394 BC	231 BC
BE 1747.1.1	GI3	9.9	0.9002	0.0020	1161 AD	1248 AD
BE 1748.1.2	GI3	27.5	0.8525	0.0019	671 AD	770 AD
BE 1749.1.1	GI3	86.0	0.7771	0.0017	90 BC	26 AD

Table A1.6: $\delta^{13}C$, $\delta^{15}N$, ash content, carbon content, nitrogen content, C/N ratio and bulk density (BD) of the three sites at the Ahlen-Falkenberger peatland, northern Germany.

Site/Core	Depth [cm]	$\delta^{15}N$ [‰]	$\delta^{13}C$ [‰]	N [%]	C [%]	C/N ratio	BD [g cm^{-3}]	Ash [%]
NW1	1.0	-5.50	-30.75	1.27	44.79	41.22	0.02	1.95
	5.0	-5.96	-30.76	1.36	45.93	39.50	0.05	1.67
	9.0	-6.66	-29.27	2.29	47.35	24.16	0.08	3.73
	13.0	-6.29	-28.51	1.96	49.23	29.24	0.09	6.99
	17.0	-4.40	-27.18	1.74	47.98	32.20	0.11	5.65
	21.0	-3.27	-26.31	1.72	46.78	31.72	0.09	4.46
	25.0	-3.72	-24.65	1.13	44.99	46.50	0.08	5.18
	29.0	-4.08	-24.78	0.92	45.75	58.16	0.05	2.51
	33.0	-4.43	-24.55	0.88	45.37	59.91	0.06	2.53
	37.0	-4.03	-25.43	1.99	46.78	27.35	0.09	7.05
	41.0	-3.49	-24.54	1.91	47.07	28.68	0.08	5.71
	45.0	-5.35	-24.77	1.03	46.56	52.97	0.05	1.99
	49.0	-4.19	-24.83	1.18	46.86	46.19	0.05	2.04
	53.0	-4.17	-24.39	1.40	46.52	38.71	0.06	3.02
	57.0	-5.01	-24.02	1.08	46.65	50.43	0.05	2.31
	61.0	-5.94	-23.63	0.71	45.85	74.90	0.05	1.84
	65.0	-6.57	-24.10	0.68	46.15	78.91	0.05	1.36
	69.0	-5.44	-25.06	0.82	47.56	67.94	0.06	2.12
	73.0	-6.16	-24.76	0.75	46.79	72.28	0.08	2.41
	77.0	-5.13	-24.55	0.84	46.92	64.91	0.06	2.28
	81.0	-5.86	-24.73	1.05	47.42	52.42	0.07	1.63
	85.0	-5.29	-25.29	1.16	48.32	48.70	0.08	2.00
	89.0	-5.76	-25.36	0.64	46.45	84.44	0.06	1.31
	93.0	-6.88	-25.60	0.49	45.50	108.99	0.06	1.37
NW2	1.0	-7.01	-29.41	0.93	47.37	59.49	0.03	1.05
	5.0	-6.35	-29.34	0.94	45.94	56.93	0.04	1.19
	9.0	-5.85	-28.98	1.33	44.84	39.27	0.06	1.78
	13.0	-5.96	-28.39	1.65	45.66	32.27	0.06	3.02

	17.0	-4.63	-27.72	2.13	49.13	26.85	0.12	6.24
	21.0	-3.57	-26.89	1.88	47.50	29.51	0.14	8.23
	25.0	-2.26	-26.55	1.93	48.42	29.25	0.11	7.35
	29.0	-1.59	-26.76	1.41	49.03	40.42	0.13	4.17
	33.0	-2.08	-26.70	1.23	49.02	46.55	0.10	3.63
	37.0	-2.26	-26.77	1.06	48.81	53.85	0.10	2.79
	41.0	-4.23	-26.50	0.85	47.80	65.63	0.05	1.92
	45.0	-3.32	-25.83	1.16	48.16	48.38	0.08	2.64
	49.0	-3.24	-25.02	0.92	48.69	61.66	0.07	1.64
	53.0	-4.63	-25.35	0.99	47.50	55.71	0.05	2.59
	57.0	-4.70	-25.33	1.04	47.25	52.99	0.04	2.94
	61.0	-5.33	-25.25	0.90	46.63	60.33	0.05	2.05
	65.0	-5.86	-24.49	0.77	46.48	70.60	0.05	2.47
	69.0	-5.68	-24.28	0.76	46.35	70.71	0.04	2.34
	73.0	-6.37	-23.86	0.61	45.58	87.71	0.04	2.17
	77.0	-5.99	-24.20	0.72	46.52	75.27	0.05	2.26
	81.0	-5.77	-23.44	0.79	45.78	67.55	0.05	2.31
	85.0	-4.27	-23.96	1.35	46.90	40.60	0.06	3.43
	89.0	-6.54	-23.86	0.78	45.73	68.66	0.06	2.47
	93.0	-5.35	-24.06	1.10	46.95	49.66	0.05	2.39
NW3	1.0	-8.81	-29.28	0.97	47.08	56.58	0.01	2.04
	5.0	-8.25	-28.95	0.90	46.86	60.94	0.02	1.75
	9.0	-6.09	-28.24	1.58	47.63	35.09	0.05	2.42
	13.0	-7.29	-28.57	1.70	48.05	33.04	0.10	3.53
	17.0	-5.89	-28.00	1.29	47.28	42.64	0.06	3.20
	21.0	-5.99	-27.86	1.43	48.16	39.23	0.06	6.10
	25.0	-4.96	-27.46	1.27	47.63	43.71	0.07	4.58
	29.0	-4.38	-27.49	1.69	48.50	33.42	0.08	4.79
	33.0	-3.24	-26.54	1.78	48.13	31.45	0.07	5.19
	37.0	-3.41	-26.17	2.04	47.31	27.09	0.06	7.69
	41.0	-1.48	-25.67	1.69	47.50	32.75	0.05	2.84

	45.0	-2.73	-25.41	1.52	46.98	35.98	0.05	3.24
	49.0	-3.27	-25.01	1.58	46.71	34.57	0.04	4.32
	53.0	-3.48	-25.25	1.81	47.28	30.48	0.08	4.70
	57.0	-4.10	-25.14	1.56	46.92	34.99	0.09	4.05
	61.0	-5.05	-25.56	1.04	47.89	53.59	0.08	2.48
	65.0	-3.86	-24.39	0.93	46.65	58.23	0.06	2.03
	69.0	-4.53	-23.76	0.86	46.98	63.49	0.06	2.07
	73.0	-5.28	-23.63	0.82	46.34	65.62	0.05	2.22
	77.0	-5.86	-23.93	0.72	46.16	74.34	0.03	1.42
	81.0	-5.39	-23.84	0.85	46.54	63.84	0.04	1.78
	85.0	-5.04	-23.03	0.85	46.18	63.42	0.04	2.11
	89.0	-5.16	-23.91	0.86	46.82	63.51	0.03	2.11
	93.0	-4.81	-23.58	1.15	47.04	47.74	0.05	2.35
GE1	1.1	0.77	-28.02	2.52	45.88	21.25	0.29	9.67
	5.7	-1.12	-26.59	1.76	48.98	32.48	0.24	4.23
	10.2	-3.35	-26.56	1.12	49.80	51.76	0.15	3.14
	14.7	-4.11	-26.23	0.71	47.51	78.02	0.13	2.69
	19.2	-3.76	-25.52	0.74	47.42	74.72	0.10	2.47
	23.7	-4.93	-24.77	0.60	46.38	90.17	0.07	1.79
	28.3	-4.79	-24.22	0.60	46.17	90.11	0.06	1.52
	32.8	-3.26	-24.35	0.93	47.49	59.52	0.07	2.06
	37.3	-3.65	-23.86	0.74	46.65	73.76	0.06	1.75
	41.8	-2.78	-25.11	1.19	49.05	48.08	0.08	1.67
	46.3	-5.82	-24.79	0.57	46.69	95.58	0.05	1.78
	50.9	-4.24	-25.81	0.83	48.69	68.33	0.07	1.83
	55.4	-3.84	-26.24	0.73	48.58	77.88	0.08	1.93
	59.9	-3.87	-27.28	0.98	51.07	60.52	0.08	2.12
	64.0	-3.21	-26.58	0.95	49.09	60.24	0.12	2.54
	68.0	-4.80	-27.04	0.65	47.29	85.15	0.07	1.24
	72.0	-4.13	-27.41	0.95	49.58	60.85	0.10	1.75
	76.0	-3.95	-26.43	0.80	48.89	71.12	0.11	1.77

	80.0	-4.78	-26.43	0.74	47.98	75.34	0.09	1.52
	84.0	-3.79	-27.60	0.96	51.46	62.76	0.13	1.52
	88.0	-4.17	-27.15	0.92	49.78	63.16	0.10	2.05
	92.0	-4.86	-26.70	0.78	49.06	73.11	0.10	1.15
	96.0	-4.91	-26.43	0.82	48.97	69.89	0.10	1.43
	100.0	-3.03	-26.98	1.14	51.08	52.38	0.13	1.69
	104.0	-2.57	-27.60	1.11	51.25	53.84	0.13	1.67
GE2	1.1	1.07	-29.51	3.01	45.27	17.56	0.14	9.27
	5.5	-1.92	-26.97	1.74	48.82	32.64	0.24	12.06
	9.8	-1.64	-27.54	2.40	46.61	22.69	0.23	4.88
	14.2	-2.10	-26.31	1.24	47.92	44.90	0.11	2.90
	18.5	-2.88	-25.44	0.85	47.12	64.61	0.08	3.06
	22.9	-2.89	-25.76	0.94	47.68	59.24	0.09	2.81
	27.3	-3.96	-25.23	0.72	47.18	76.35	0.07	2.28
	31.6	-4.37	-25.68	0.77	47.59	71.74	0.07	2.34
	36.0	-3.75	-25.17	0.74	47.41	74.97	0.07	2.26
	40.3	-3.83	-24.91	0.70	47.10	78.13	0.06	2.23
	44.7	-2.82	-25.06	1.09	49.02	52.28	0.07	2.30
	49.1	-1.74	-25.36	1.20	49.41	47.93	0.06	1.82
	53.4	-3.23	-24.69	1.04	48.52	54.62	0.06	2.07
	58.0	-2.75	-25.10	1.03	48.57	55.10	0.06	1.88
	62.0	-3.09	-25.46	1.17	48.70	48.69	0.05	1.85
	66.0	-3.26	-25.62	1.22	49.41	47.23	0.13	1.88
	70.0	-3.37	-24.97	0.86	47.85	65.11	0.10	2.06
	74.0	-3.69	-24.29	0.76	47.21	72.31	0.07	1.84
	78.0	-4.72	-23.49	0.72	46.76	75.70	0.07	2.36
	82.0	-4.00	-23.37	0.69	46.69	79.12	0.07	1.81
	86.0	-5.45	-23.84	0.61	46.81	89.01	0.07	1.70
	90.0	-3.78	-24.07	0.78	47.48	70.70	0.08	1.36
	94.0	-3.27	-25.11	1.48	50.10	39.48	0.11	2.03
	98.0	-3.08	-24.49	1.07	48.89	53.05	0.10	1.61

	102.0	-4.12	-24.03	0.78	47.82	71.18	0.07	1.50
GE3	1.5	-0.08	-28.16	2.52	46.78	21.61	0.15	6.05
	7.6	-0.38	-27.04	2.18	46.96	25.14	0.23	10.62
	13.6	-1.72	-25.91	1.19	47.68	46.60	0.12	3.43
	19.6	-2.57	-26.12	0.81	46.92	67.36	0.10	2.53
	25.7	-2.31	-25.43	0.76	46.60	71.66	0.09	2.63
	31.7	-3.93	-24.50	0.52	45.80	101.94	0.08	2.16
	37.8	-3.03	-24.82	0.72	46.48	75.65	0.06	1.83
	43.8	-4.01	-25.36	0.87	48.48	64.98	0.08	2.40
	49.8	-3.90	-25.28	0.84	47.98	66.28	0.08	2.10
	55.9	-2.89	-25.35	1.08	48.39	52.19	0.06	2.13
	61.9	-2.43	-24.89	0.50	43.94	103.12	0.04	1.94
	66.0	-4.33	-25.07	0.69	47.61	80.92	0.04	2.21
	70.0	-3.45	-25.68	0.90	47.92	62.37	0.09	1.81
	74.0	-3.25	-25.51	1.04	48.33	54.41	0.09	2.03
	78.0	-4.82	-25.00	0.63	46.47	86.53	0.08	2.14
	82.0	-4.62	-24.66	0.76	46.73	71.40	0.08	1.99
	86.0	-4.29	-25.17	0.75	47.54	73.72	0.07	1.40
	90.0	-3.73	-24.89	0.81	47.63	68.76	0.08	1.58
	94.0	-5.05	-23.68	0.63	46.58	86.15	0.08	1.63
	98.0	-5.69	-24.05	0.55	46.70	99.37	0.08	1.57
	102.0	-5.28	-23.59	0.53	46.25	101.06	0.07	1.63
	106.0	-4.98	-23.94	0.54	46.49	100.52	0.07	1.22
GI1	1.4	3.84	-29.83	2.76	43.38	18.32	0.07	10.01
	6.8	1.88	-28.88	2.92	41.36	16.54	0.18	13.64
	12.2	-0.65	-27.05	2.21	46.70	24.67	0.23	11.65
	17.6	-1.83	-25.49	1.61	46.57	33.80	0.14	5.73
	23.0	-2.95	-25.07	0.99	45.17	53.07	0.10	4.42
	28.4	-4.94	-24.45	0.71	45.88	75.51	0.08	3.18
	33.8	-7.58	-24.76	0.47	45.09	111.63	0.05	2.27
	39.2	-7.87	-23.93	0.51	45.61	104.40	0.06	1.94

	44.6	-8.02	-24.14	0.50	45.68	105.69	0.05	2.31
	50.0	-4.87	-24.73	1.22	49.69	47.45	0.06	1.43
	55.4	-5.41	-24.36	0.93	48.96	61.39	0.06	1.81
	60.0	-5.54	-24.20	0.94	48.89	60.48	0.05	1.68
	64.0	-3.50	-24.38	0.70	47.51	79.33	0.03	1.88
	68.0	-5.79	-23.86	0.91	47.99	61.46	0.09	1.85
	72.0	-5.44	-24.75	1.19	49.66	48.67	0.11	1.79
	76.0	-5.99	-24.47	0.86	48.80	66.37	0.10	1.81
	80.0	-7.06	-23.65	0.67	47.22	81.79	0.16	2.29
	84.0	-5.87	-24.28	0.79	48.11	71.11	0.13	1.88
	88.0	-5.55	-24.26	0.98	49.23	58.60	0.12	1.72
	92.0	-7.17	-24.15	0.95	49.24	59.32	0.12	1.55
	96.0	-4.80	-25.31	1.52	51.67	39.08	0.15	2.01
	100.0	-5.61	-24.44	0.66	47.67	83.95	0.10	1.97
	104.0	-5.85	-25.30	0.83	49.06	68.52	0.10	2.02
	108.0	-5.46	-25.24	0.88	49.33	65.37	0.09	2.03
GI2	1.2	3.01	-29.18	2.80	41.98	17.50	0.19	12.21
	6.2	1.35	-27.37	2.63	44.32	19.67	0.24	13.88
	11.2	-1.90	-26.52	1.80	46.38	30.03	0.20	8.72
	16.1	-4.51	-25.58	0.81	46.11	66.71	0.14	4.68
	21.1	-4.49	-25.89	0.89	47.01	61.91	0.11	3.98
	26.0	-4.42	-25.33	1.02	47.87	54.69	0.09	2.80
	31.0	-4.40	-24.25	0.86	47.96	65.41	0.09	2.23
	36.0	-7.60	-24.18	0.44	46.04	123.10	0.07	2.69
	40.9	-6.83	-24.93	0.67	47.67	83.58	0.07	1.97
	45.9	-7.15	-23.86	0.58	46.32	93.74	0.07	2.26
	50.8	-5.46	-25.48	1.20	50.01	48.72	0.10	2.54
	55.8	-7.54	-25.06	0.58	47.18	95.58	0.06	2.53
	60.8	-3.73	-25.21	0.61	46.53	89.60	0.05	2.28
	64.0	-6.18	-26.02	0.78	48.50	72.57	0.08	2.20
	68.0	-6.19	-25.48	0.70	47.19	79.15	0.10	2.08

	72.0	-6.56	-25.14	1.04	49.51	55.22	0.18	1.85
	76.0	-10.44	-25.29	0.56	47.26	93.00	0.09	2.24
	80.0	-7.42	-25.21	0.63	47.88	88.96	0.10	2.01
	84.0	-4.70	-26.95	1.06	50.12	55.68	0.15	2.49
	88.0	-5.75	-25.94	0.76	48.82	74.45	0.10	2.12
	92.0	-8.12	-25.73	0.64	47.19	85.46	0.12	1.62
	96.0	-8.52	-25.51	0.67	47.77	78.76	0.15	1.79
	100.0	-10.59	-25.02	0.58	47.41	93.66	0.10	1.34
	104.0	-6.74	-27.38	0.92	50.09	63.28	0.15	1.88
GI3	1.1	3.11	-28.81	2.97	43.92	17.25	0.16	11.02
	5.5	0.32	-26.79	2.27	46.32	23.79	0.28	10.24
	9.9	-2.95	-26.03	1.33	47.55	41.61	0.17	4.29
	14.3	-5.63	-25.76	1.06	48.04	53.06	0.15	3.95
	18.7	-7.30	-24.90	0.78	45.99	69.05	0.11	3.23
	23.1	-8.54	-24.88	0.65	46.53	83.94	0.08	2.39
	27.5	-7.02	-25.90	0.82	48.13	68.49	0.11	2.60
	31.9	-4.65	-25.50	1.27	48.59	44.60	0.10	2.12
	36.3	-6.51	-25.27	0.81	47.06	67.95	0.08	2.18
	40.7	-5.76	-25.58	0.92	47.99	60.78	0.10	1.96
	45.1	-7.52	-24.93	0.74	47.18	73.92	0.08	2.18
	49.5	-8.58	-23.55	0.72	46.12	74.45	0.07	1.88
	53.9	-5.50	-23.19	0.76	45.92	70.92	0.06	1.86
	58.3	-6.30	-23.89	1.01	47.33	54.62	0.08	1.92
	62.7	-6.12	-24.91	1.14	48.66	49.81	0.07	1.97
	66.0	-6.65	-24.06	0.98	47.34	56.41	0.07	1.39
	70.0	-8.74	-24.54	0.87	46.86	62.76	0.07	1.40
	74.0	-7.38	-24.35	0.92	47.17	59.74	0.11	1.89
	78.0	-9.42	-24.33	0.69	46.48	78.57	0.09	1.34
	82.0	-9.91	-24.58	0.60	45.97	89.07	0.09	1.67
	86.0	-7.17	-25.58	0.99	48.69	57.26	0.13	1.42
	90.0	-8.65	-24.94	0.67	49.32	85.52	0.12	0.92

94.0	-7.31	-25.68	0.89	49.79	65.10	0.10	1.42
98.0	-7.30	-26.13	0.74	47.63	75.14	0.10	1.80
102.0	-5.58	-26.92	0.72	48.17	77.79	0.12	1.61
106.0	-4.71	-26.65	0.99	50.05	58.68	0.12	1.87

Appendix 1.3 Supplementary materials of chapter 6

The presented tables and figures are the supplementary materials of chapter 6 (Krüger, J. P., Alewell, C., Minkkinen, K., Szidat, S., and Leifeld, J.: Calculating carbon changes in peat soils drained for forestry with four different profile-based methods, under review in Forest Ecology and Management)

Table A1.7: ^{14}C age dated samples of the four study sites at the Lakkasuo peatland. Uncertainties of F14C values represent one sigma. For calibrated ages, the lower and upper boundary is given with 95% confidence. Calibrated ages are displayed as years AD/BC.

BE-No. of sample	Site/core	depth (cm)	F14C value	F14C Uncertainty	Lower Cal age (1σ)	Upper Cal age (1σ)
2410.1.1	Md 1	49	0.8396	0.0018	632 AD	655 AD
2411.1.1	Md 1	89	0.7782	0.0018	42 BC	3 AD
2412.1.1	Md 2	49	0.8374	0.0019	617 AD	646 AD
2413.1.1	Md 2	89	0.7578	0.0017	362 BC	214 BC
2414.1.1	Md 3	49	0.8362	0.0019	610 AD	641 AD
2415.1.1	Md 3	89	0.7765	0.0017	49 BC	0
2416.1.1	Mn 1	49	0.8845	0.0019	1019 AD	1113 AD
2417.1.1	Mn 1	89	0.8126	0.0018	353 AD	407 AD
2418.1.1	Mn 2	49	0.9068	0.0020	1225 AD	1264 AD
2419.1.1	Mn 2	89	0.8076	0.0018	260 AD	380 AD
2420.1.1	Mn 3	49	0.9020	0.0020	1194 AD	1249 AD
2421.1.1	Mn 3	89	0.8124	0.0018	351 AD	404 AD
2422.1.1	Od 1	49	0.9848	0.0022	1685 AD	1927 AD
2423.1.1	Od 1	89	0.8883	0.0020	1031 AD	1148 AD
2424.1.1	Od 2	49	0.9567	0.0022	1474 AD	1619 AD
2425.1.1	Od 2	89	0.8910	0.0020	1044 AD	1153 AD
2426.1.1	Od 3	49	0.9633	0.0021	1524 AD	1644 AD
2427.1.1	Od 3	89	0.8742	0.0019	903 AD	993 AD
2428.1.1	On 1	49	0.9997	0.0022	1899 AD	1958 AD
2429.1.1	On 1	85	0.9174	0.0020	1279 AD	1292 AD
2430.1.1	On 2	49	1.0047	0.0021	1956 AD	1957 AD
2431.1.1	On 2	89	0.9180	0.0020	1280 AD	1295 AD
2432.1.1	On 3	45	1.0005	0.0021	1956 AD	1957 AD
2433.1.1	On 3	89	0.9118	0.0020	1266 AD	1278 AD

Table A1.8: Mean $\delta^{13}C$, mean bulk density (BD) and mean ash content with standard error (SE) of the four study sites of the Lakkasuo peatland in Finland.

Site	Depth [cm]	$\delta^{13}C$ [‰] mean	$\delta^{13}C$ [‰] SE	BD [g cm^{-3}] mean	BD [g cm^{-3}] SE	Ash content [%] mean	Ash content [%] SE
Mn	1	-29.01	0.42	0.01	0.00	1.48	1.48
	5	-29.38	0.11	0.02	0.00	9.64	2.70
	9	-29.44	0.22	0.02	0.00	15.29	6.32
	13	-29.04	0.28	0.04	0.01	14.01	1.60
	17	-27.77	0.17	0.04	0.01	9.89	1.59
	21	-27.90	0.18	0.05	0.01	9.96	1.40
	25	-27.81	0.26	0.08	0.02	6.62	1.11
	29	-27.74	0.20	0.08	0.02	6.48	1.54
	33	-27.84	0.11	0.11	0.01	4.34	0.68
	37	-27.83	0.10	0.11	0.01	3.53	0.24
	41	-27.71	0.24	0.09	0.01	3.39	0.25
	45	-27.80	0.11	0.08	0.01	3.10	0.19
	49	-28.05	0.04	0.07	0.00	2.95	0.26
	53	-27.81	0.14	0.05	0.01	3.95	0.57
	57	-27.86	0.17	0.07	0.01	3.05	0.20
	61	-27.78	0.03	0.06	0.01	3.20	0.33
	65	-28.23	0.13	0.08	0.01	3.38	0.09
	69	-28.06	0.09	0.08	0.01	3.03	0.02
	73	-28.07	0.04	0.09	0.01	2.82	0.08
	77	-28.16	0.08	0.08	0.01	2.89	0.11
	81	-28.21	0.08	0.09	0.00	2.81	0.12
	85	-28.31	0.09	0.09	0.01	2.87	0.10
	89	-28.23	0.14	0.09	0.00	2.95	0.11
	93	-28.18	0.08	0.08	0.00	2.99	0.21
Md	1	-30.40	0.17	0.02	0.00	2.54	0.58
	5	-29.32	0.57	0.06	0.01	2.12	0.63
	9	-28.73	0.71	0.05	0.01	3.03	0.81
	13	-27.46	0.82	0.13	0.02	15.46	4.72
	17	-27.31	0.73	0.20	0.01	6.39	2.79
	21	-26.99	0.69	0.13	0.02	2.72	0.29
	25	-27.13	0.66	0.11	0.00	2.83	0.04
	29	-26.61	0.97	0.10	0.01	2.39	0.11
	33	-26.74	1.04	0.08	0.00	2.20	0.39
	37	-26.75	1.11	0.08	0.00	2.66	0.14
	41	-27.20	0.71	0.09	0.01	2.83	0.34
	45	-27.68	0.40	0.09	0.00	2.66	0.02
	49	-27.47	0.62	0.08	0.01	2.59	0.08
	53	-27.39	0.53	0.08	0.01	2.58	0.14
	57	-27.13	0.71	0.09	0.02	2.29	0.07
	61	-27.25	0.74	0.10	0.01	2.35	0.07
	65	-27.44	0.73	0.10	0.00	2.38	0.13
	69	-27.46	0.61	0.09	0.01	2.18	0.34

	73	-27.43	0.64	0.09	0.01	2.59	0.03
	77	-27.36	0.50	0.10	0.01	2.56	0.21
	81	-27.38	0.72	0.10	0.02	2.77	0.19
	85	-27.36	0.68	0.09	0.02	2.78	0.03
	89	-27.76	0.49	0.10	0.01	2.45	0.17
	93	-27.61	0.63	0.11	0.01	2.83	0.32
On	1	-27.16	0.44	0.01	0.00	1.62	0.64
	5	-26.88	0.47	0.02	0.00	1.84	0.41
	9	-27.01	0.24	0.03	0.01	0.95	0.49
	13	-27.25	0.69	0.02	0.00	1.09	0.59
	17	-27.20	0.48	0.03	0.00	0.81	0.40
	21	-27.50	0.24	0.03	0.00	0.95	0.45
	25	-27.12	0.56	0.04	0.01	1.77	0.20
	29	-27.09	0.93	0.04	0.00	2.48	0.52
	33	-26.42	0.06	0.04	0.00	1.89	0.43
	37	-27.12	0.68	0.04	0.01	2.17	0.26
	41	-26.78	0.98	0.04	0.00	1.34	0.48
	45	-26.46	0.43	0.05	0.01	2.16	0.38
	49	-25.82	0.20	0.05	0.01	1.92	0.51
	53	-25.78	0.27	0.06	0.01	1.19	0.30
	57	-26.14	0.27	0.07	0.00	1.53	0.33
	61	-26.23	0.61	0.07	0.00	1.27	0.84
	65	-25.86	0.24	0.07	0.01	0.95	0.14
	69	-25.95	0.09	0.07	0.02	0.98	0.46
	73	-25.74	0.47	0.09	0.01	0.25	0.14
	77	-25.57	0.57	0.07	0.00	0.46	0.24
	81	-25.89	0.20	0.07	0.01	0.52	0.26
	85	-26.45	0.27	0.07	0.00	0.74	0.38
	89	-25.69	0.25	0.06	0.00	0.82	0.44
	93	-26.13	0.21	0.06	0.01	0.90	0.38
Od	1	-30.71	0.20	0.03	0.01	1.97	0.14
	5	-28.74	0.56	0.06	0.02	2.48	0.69
	9	-27.52	0.06	0.09	0.02	2.24	0.29
	13	-26.31	0.20	0.07	0.00	2.16	0.14
	17	-25.90	0.04	0.07	0.00	1.61	0.18
	21	-25.70	0.28	0.07	0.00	1.48	0.10
	25	-25.64	0.11	0.07	0.00	1.09	0.20
	29	-25.55	0.54	0.06	0.01	1.11	0.28
	33	-25.16	0.41	0.06	0.01	0.72	0.37
	37	-25.45	0.65	0.07	0.01	1.03	0.30
	41	-25.85	0.51	0.09	0.02	1.20	0.05
	45	-26.80	0.35	0.08	0.00	0.67	0.37
	49	-26.72	0.37	0.09	0.01	1.13	0.51
	53	-26.47	0.08	0.07	0.01	1.03	0.41
	57	-26.38	0.33	0.09	0.01	0.94	0.31
	61	-26.63	0.53	0.08	0.01	1.44	1.21

65	-26.40	0.21	0.08	0.01	0.51	0.26
69	-26.19	0.04	0.08	0.01	0.62	0.31
73	-26.43	0.14	0.08	0.01	1.03	0.05
77	-26.25	0.15	0.09	0.00	0.74	0.05
81	-26.32	0.26	0.07	0.01	1.02	0.20
85	-26.69	0.34	0.08	0.01	0.88	0.14
89	-26.78	0.02	0.08	0.01	0.90	0.06
93	-26.59	0.12	0.07	0.01	0.93	0.14

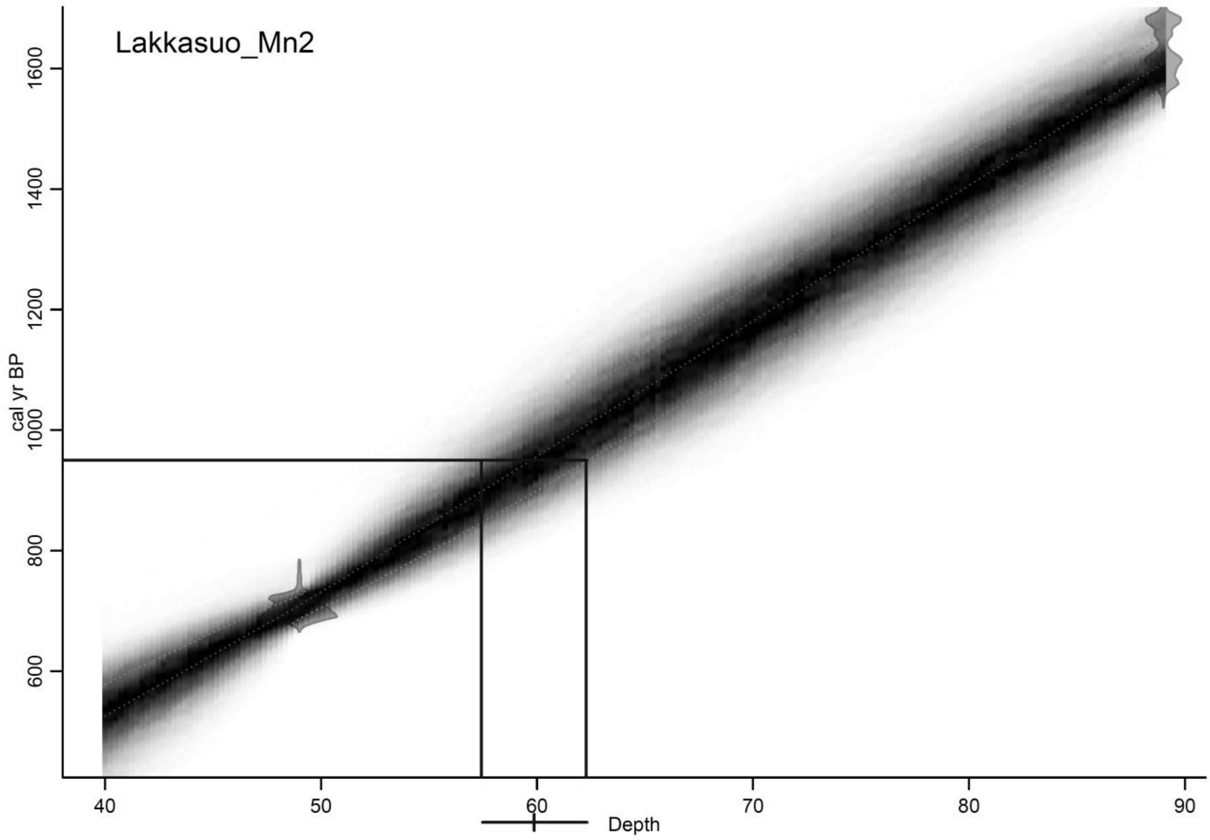


Figure A1.4: Determination of the depth of the 1000-year layer (in cm) for the core Mn 2 as an example using the age–depth modelling software Bacon (Blaauw and Christen, 2011). The year 950 BP corresponds to the calendar year 1000 AD. The dotted red and the white lines indicate the mean modelled age and the 1s uncertainties, respectively.

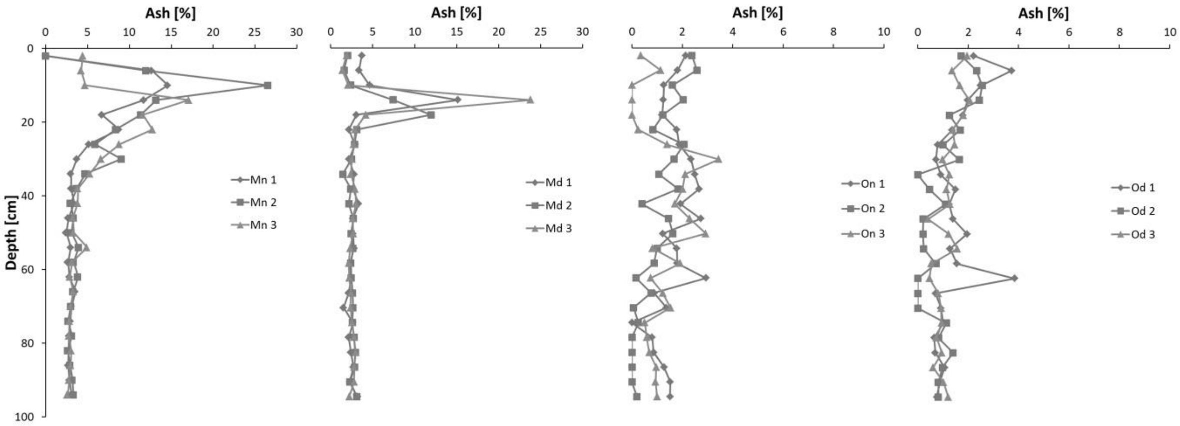


Figure A1.5: Ash content depth profiles of the four different sites at the Lakkasuo peatland with three replicates per site.

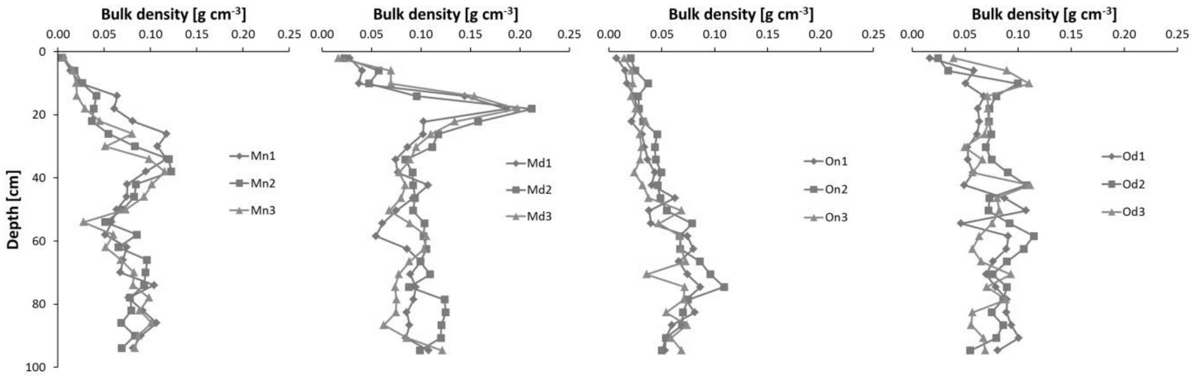


Figure A1.6: Bulk density depth profiles of the four different sites at the Lakkasuo peatland with three replicates per site.

Appendix 2: Results from further study sites of the project

Material and methods

In July 2012 peat cores were collected in the peatland called Breitlohmisse, Northern Black Forest, Germany at four different sites (figure 1.2). The sites represent different degradation status of the peat bog complex. At the Rotmeer Moor, Southern Black Forest, Germany three different sites along a moisture gradient were sampled (figure 1.2). Furthermore, at the Ursee Moor, Southern Black Forest three different sites were sampled (figure 1.2). In May 2013 at the Degerö-Stormyr, Sweden one natural site, one natural dry site and one site close to a drainage channel were sampled (figure 1.2). In October 2012 samples from the subarctic peatland Kattajokken, Northern Sweden, hummocks and hollows were taken (figure 1.2). Each of the sites are represented by three peat cores (n=3). Peat samples were taken with a russian peat corer (Eijkelkamp, Netherlands) down to the approximately one meter. The peat cores were embedded in plastic shells, wrapped with plastic foil and transported directly to the lab. There cores were cut into 2 cm sections and dried at 40°C for 72 h in a drying oven. All samples were ground and homogenised in a vibrating ball mill (MM 400, Retsch, Germany).

For the samples from the Breitlohmisse, Northern Black Forest, stable carbon and nitrogen isotope as well as C and N content analyses were accomplished using a continuous flow isotope ratio mass spectrometer (DELTAplusXP, 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. Samples from the Rotmeer Moor and Ursee Moor, Southern Black Forest, Germany, from Degerö-Stormyr, Sweden and from Kattajokken, Northern Sweden were analysed on stable carbon isotopes and nitrogen as well as C and N content with a combined mass spectrometer with a SL elemental analyser (Integra2, Sercon, UK) following standard processing techniques. The C/N ratio represents the atomic relationship between carbon and nitrogen content of the bulk peat material. Stable isotope ratios are reported as $\delta^{13}C$ values [‰] relative to V-PDB. Stable nitrogen isotope ratios are reported as $\delta^{15}N$ in [‰] relative to the atmospheric nitrogen standard.

Radiocarbon (^{14}C) content was measured with accelerator mass spectrometry (AMS) at the Laboratory of for the Analysis of Radiocarbon with AMS (LARA) at the University of Bern (Szidat et al., 2014). For each site samples were selected for radiocarbon dating after evaluating the stable isotope depth profiles. The ground and homogenised material was combusted, transformed into solid targets using an automated graphitisation equipment (AGE) (Nemec et al., 2010), and measured with the MIni CArbon DAting System MICADAS (Synal et al., 2007). 14C ages were calibrated using the IntCal13 dataset (Reimer et al., 2013). Samples with bomb signature were dated using the Bomb13 NH1 dataset (Hua et al., 2013).

Appendix 2.1: Black Forest, Germany

<u>Breitlohmisse, Northern Black Forest</u>

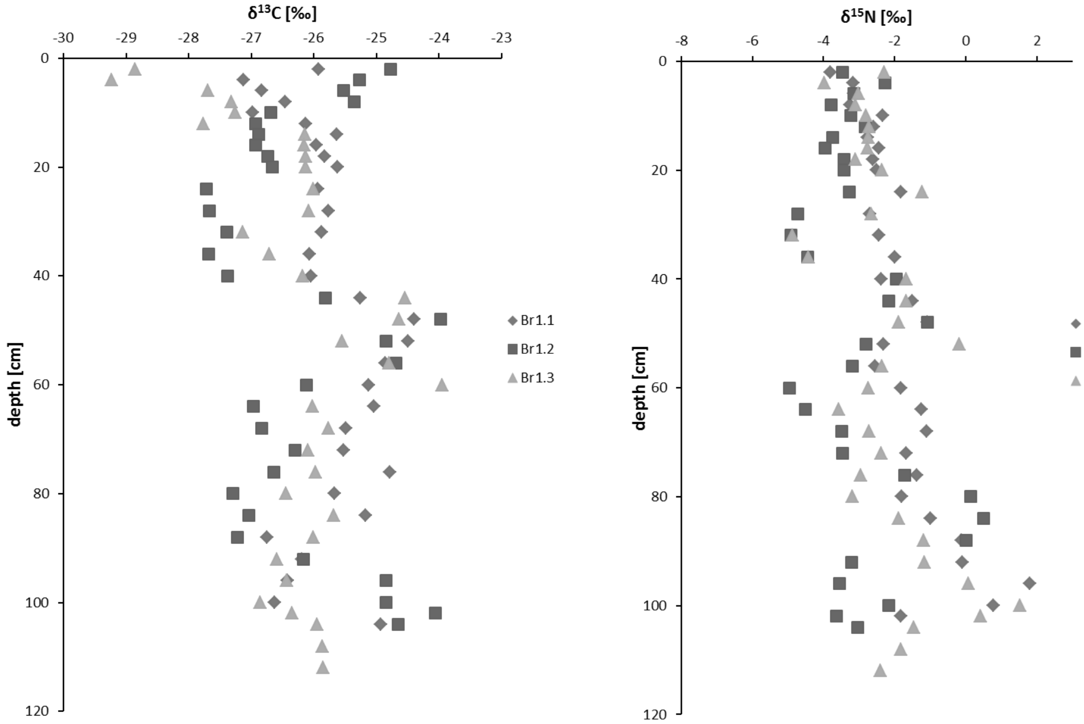


Figure A2.1: Stable carbon and stable nitrogen isotope depth profiles of the site 1 at the Breitlohmisse, Northern Black Forest, Germany.

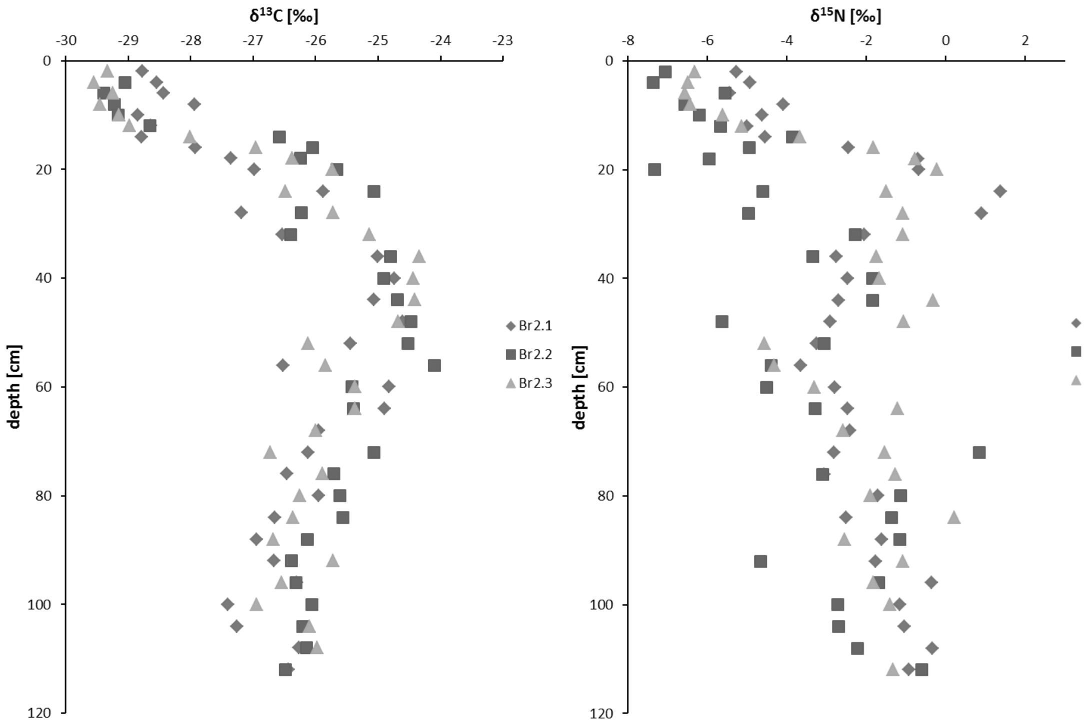


Figure A2.2: Stable carbon and stable nitrogen isotope depth profiles of the site 2 at the Breitlohmisse, Northern Black Forest, Germany.

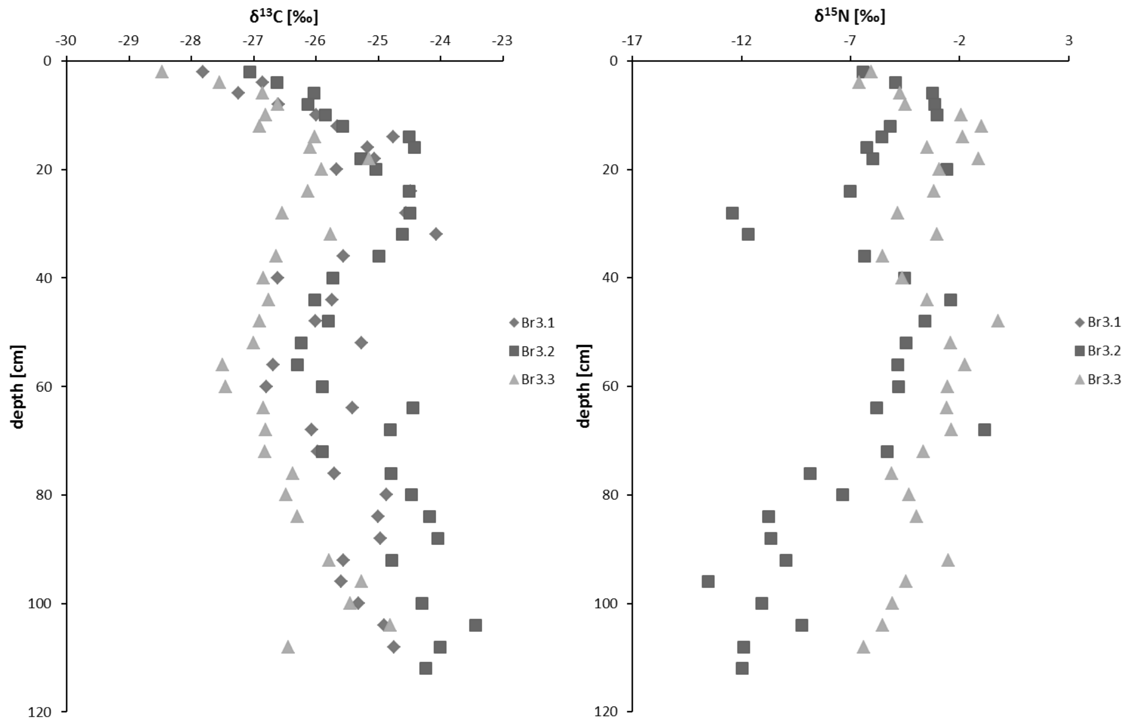


Figure A2.3: Stable carbon and stable nitrogen isotope depth profiles of the site 3 at the Breitlohmisse, Northern Black Forest, Germany.

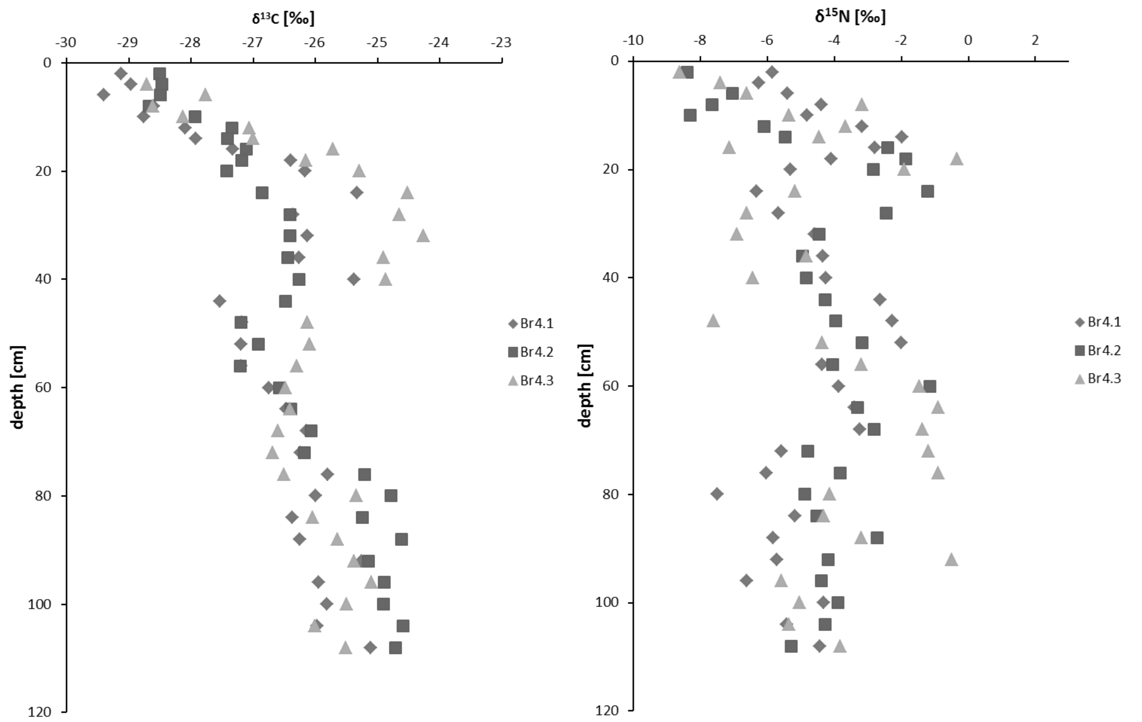


Figure A2.4: Stable carbon and stable nitrogen isotope depth profiles of the site 4 at the Breitlohmisse, Northern Black Forest, Germany.

<u>Rotmeer Moor, Southern Black Forest</u>

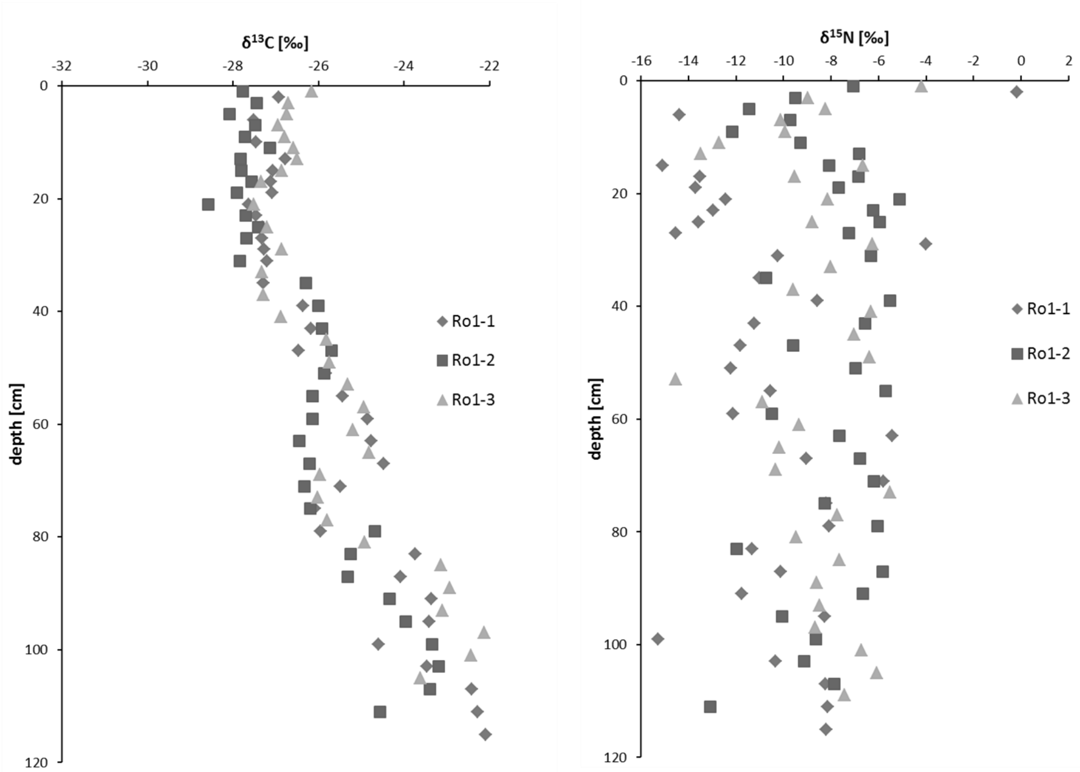


Figure A2.5: Stable carbon and stable nitrogen isotope depth profiles of the site 1 at the Rotmeer Moor, Southern Black Forest, Germany.

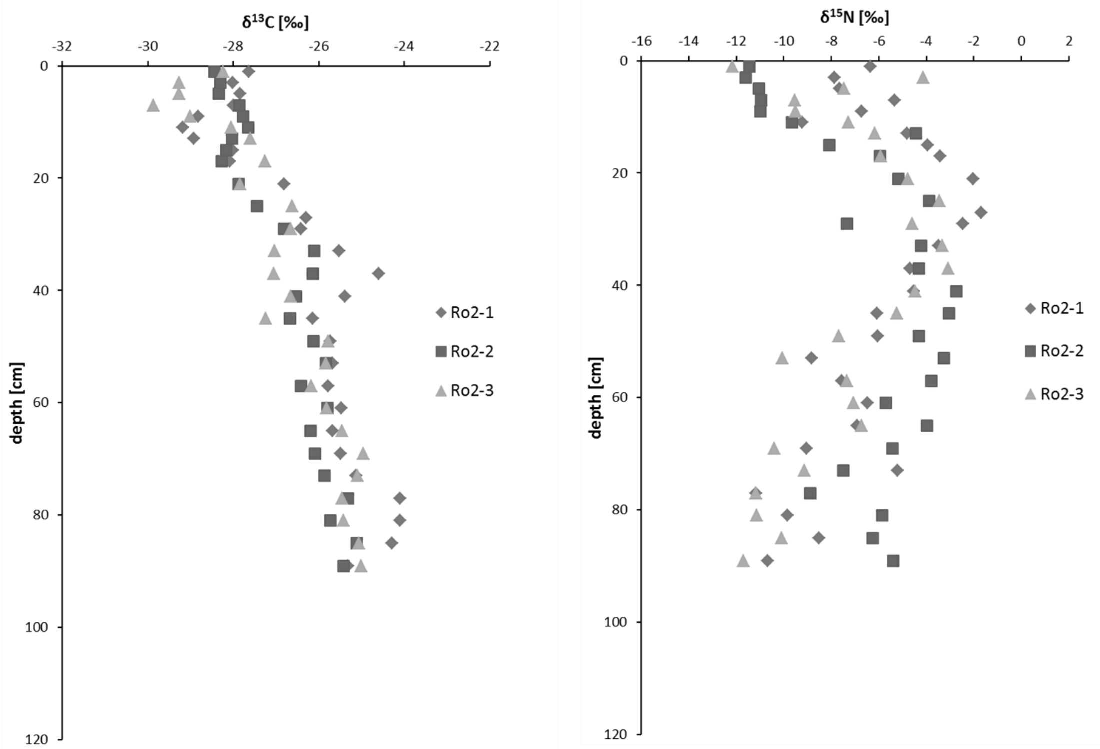


Figure A2.6: Stable carbon and stable nitrogen isotope depth profiles of the site 2 at the Rotmeer Moor, Southern Black Forest, Germany.

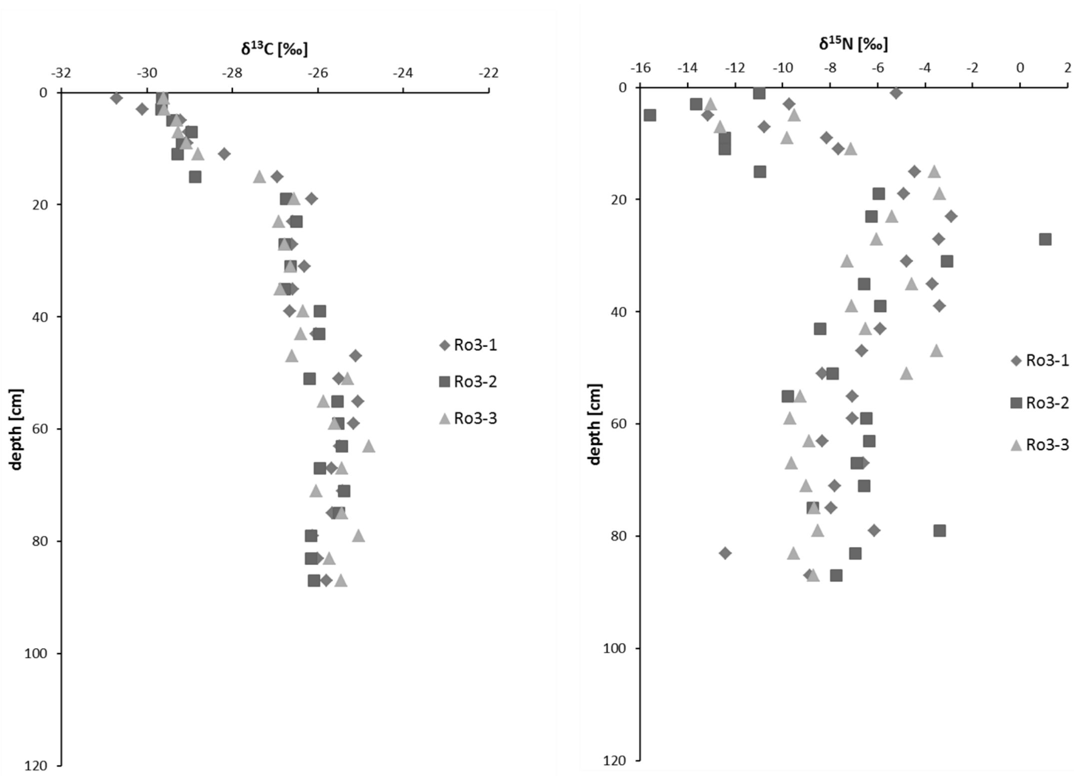


Figure A2.7: Stable carbon and stable nitrogen isotope depth profiles of the site 3 at the Rotmeer Moor, Southern Black Forest, Germany.

Ursee Moor, Southern Black Forest

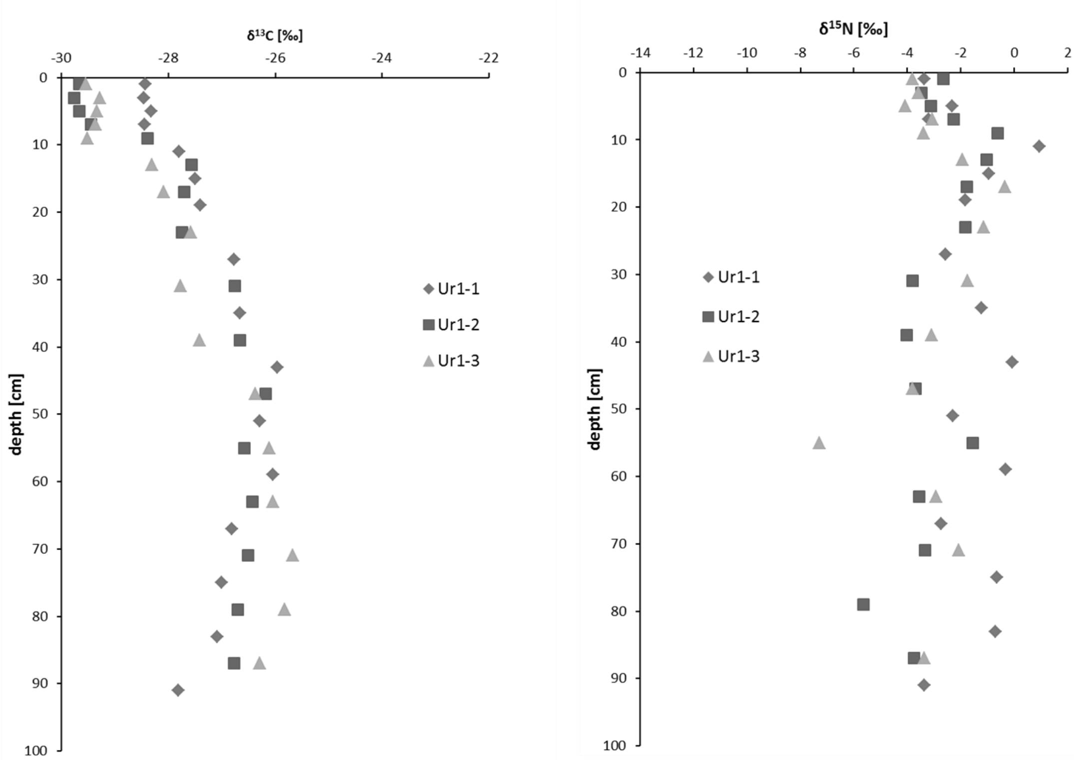


Figure A2.8: Stable carbon and stable nitrogen isotope depth profiles of the site 1 at the Ursee Moor, Southern Black Forest, Germany.

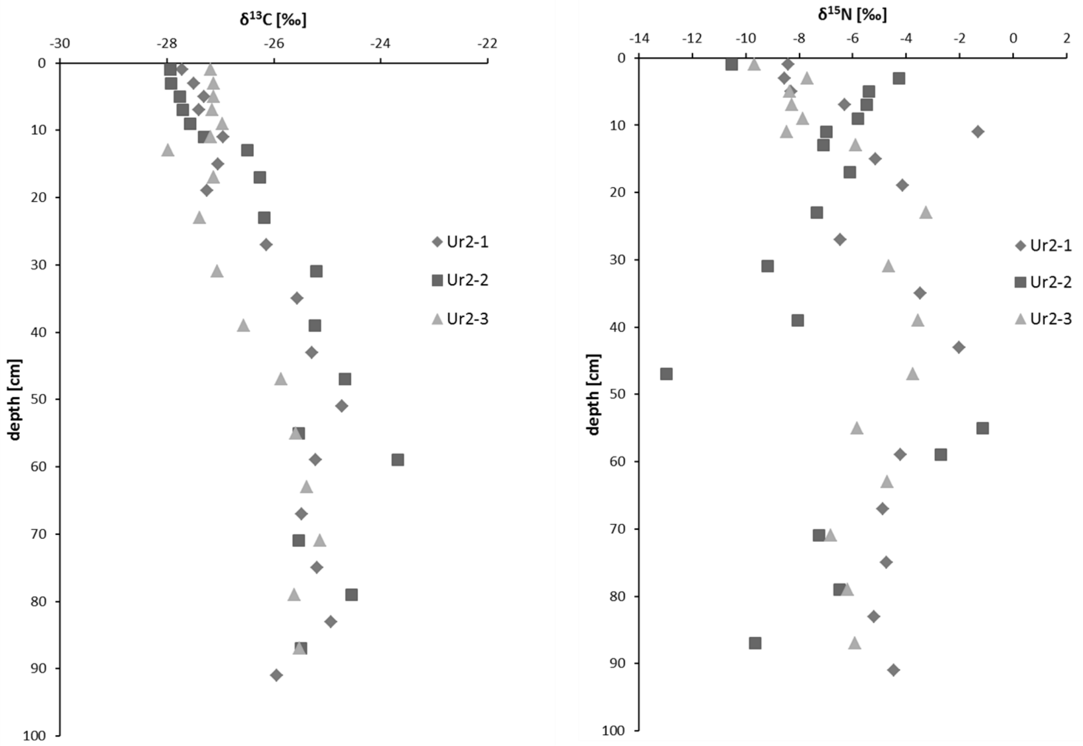


Figure A2.9: Stable carbon and stable nitrogen isotope depth profiles of the site 2 at the Ursee Moor, Southern Black Forest, Germany.

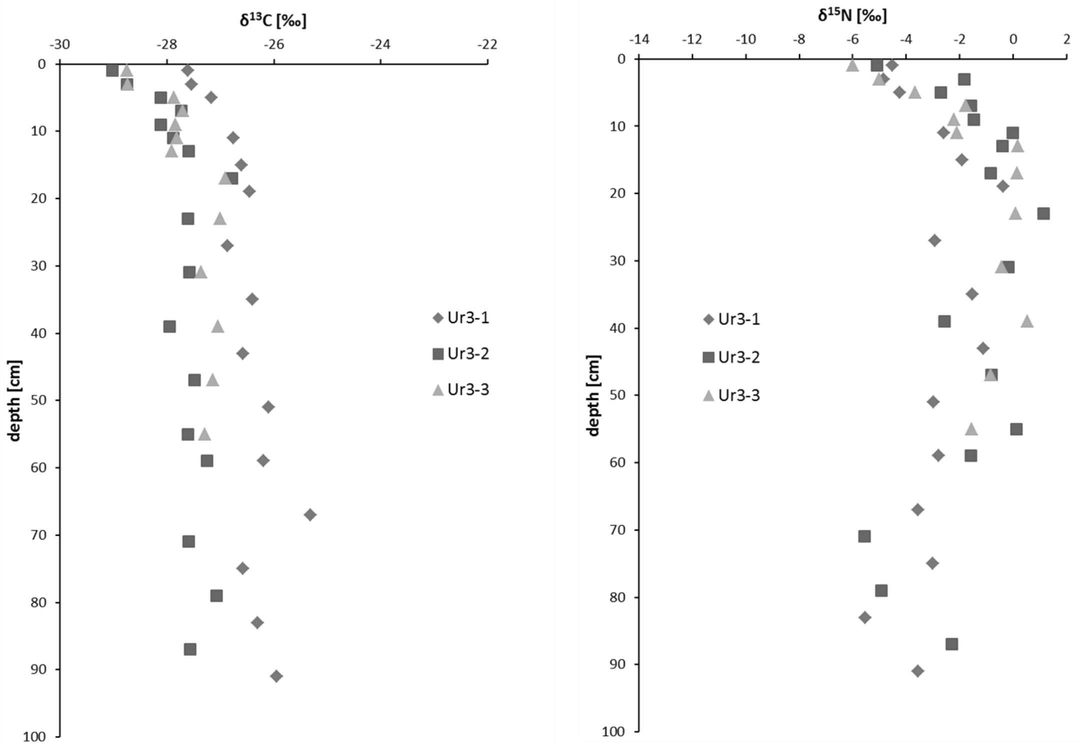


Figure A2.10: Stable carbon and stable nitrogen isotope depth profiles of the site 3 at the Ursee Moor, Southern Black Forest, Germany.

Radiocarbon data from the three study sites in the Black Forest

Table A2.1: ^{14}C age dated samples of the study sites Breitlohmisse (Br), Rotmeer Moor (Ro) and Ursee Moor (Ur) in the Black Forest, Germany. Uncertainties of F14C values represent one sigma.

BE nr.	sample label	extracted depth (cm)	$F^{14}C$	+- (%)	+- ($F^{14}C$)	age (y)	+-(y)	$\delta^{13}C$ (‰)
4497.1.1	Ro2.1 14-16	20	1.2243	0.26	0.0031	-1'626	21	-28.9
4498.1.1	Ro2.1 46-48	52	0.9324	0.28	0.0026	562	22	-31.9
4499.1.1	Ro2.1 66-68	72	0.9122	0.27	0.0025	739	22	-26.3
4500.1.1	Ro2.2 14-16	20	1.1396	0.26	0.0029	-1'050	21	-27.7
4501.1.1	Ro2.2 46-48	52	0.9767	0.27	0.0026	189	21	-27.1
4502.1.1	Ro2.2 66-68	72	0.9321	0.27	0.0025	565	22	-25.5
4503.1.1	Ro3.2 10-12	12	1.0890	0.26	0.0029	-685	21	-29.9
4504.1.1	Ro3.2 22-24	24	1.0170	0.26	0.0027	-135	21	-25.5
4505.1.1	Ro3.2 66-68	68	0.9112	0.27	0.0025	747	22	-25.7
4506.1.1	Br1.1 32	32	0.9948	0.27	0.0026	42	21	-24.8
4507.1.1	Br1.1 48	48	0.9994	0.26	0.0026	5	21	-24.0
4508.1.1	Br1.1 100	100	0.8965	0.27	0.0024	878	22	-27.9
4509.1.1	Br1.2 32	32	1.0048	0.27	0.0027	-38	21	-27.6
4510.1.1	Br1.2 48	48	0.9959	0.27	0.0026	33	21	-23.1
4511.1.1	Br1.2 100	100	0.8794	0.27	0.0024	1'032	22	-25.0
4512.1.1	Br2.2 36	36	0.9786	0.27	0.0026	174	21	-25.6
4513.1.1	Br2.2 52	52	0.9889	0.27	0.0026	90	21	-25.9
4514.1.1	Br2.2 100	100	0.8894	0.27	0.0024	942	22	-25.5
4515.1.1	Ur2.2 22	24	1.1695	0.26	0.0030	-1'258	21	-26.7
4516.1.1	Ur3.2 22	24	0.9888	0.27	0.0026	90	21	-27.4

Appendix 2.2: Degerö-Stormyr, Sweden

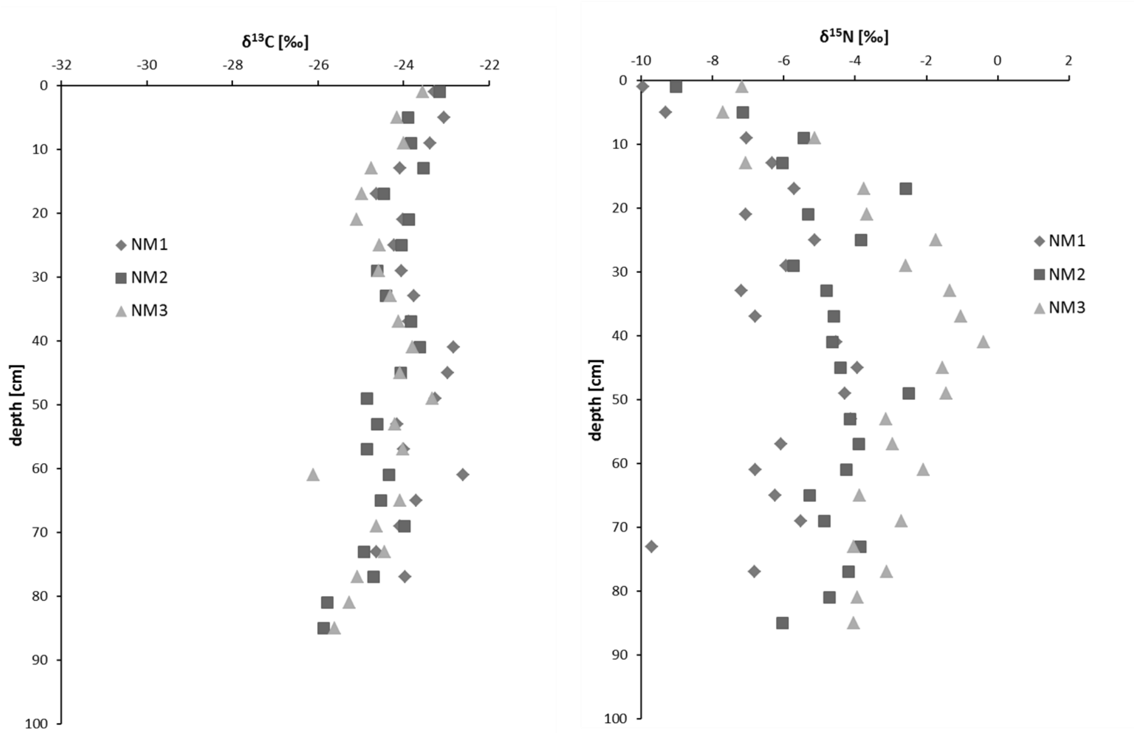


Figure A2.11: Stable carbon and stable nitrogen isotope depth profiles of natural mire (NM) site at the Degerö-Stormyr peatland, Sweden.

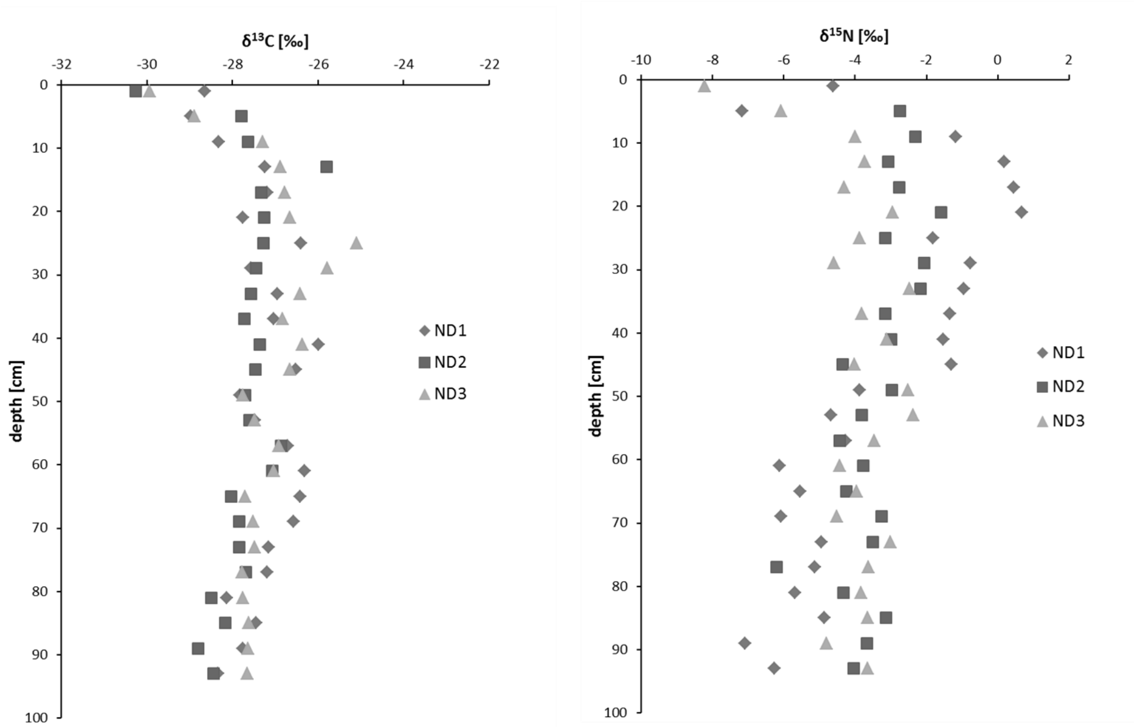
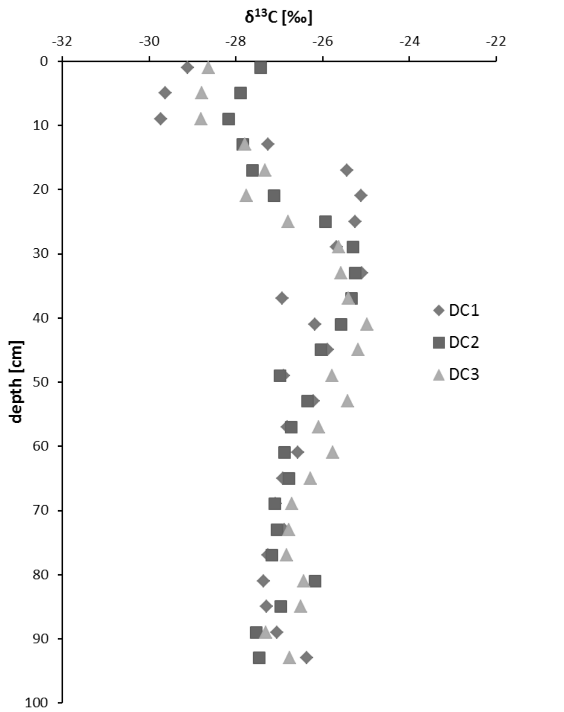


Figure A2.12: Stable carbon and stable nitrogen isotope depth profiles of natural dry (ND) site at the Degerö-Stormyr peatland, Sweden.



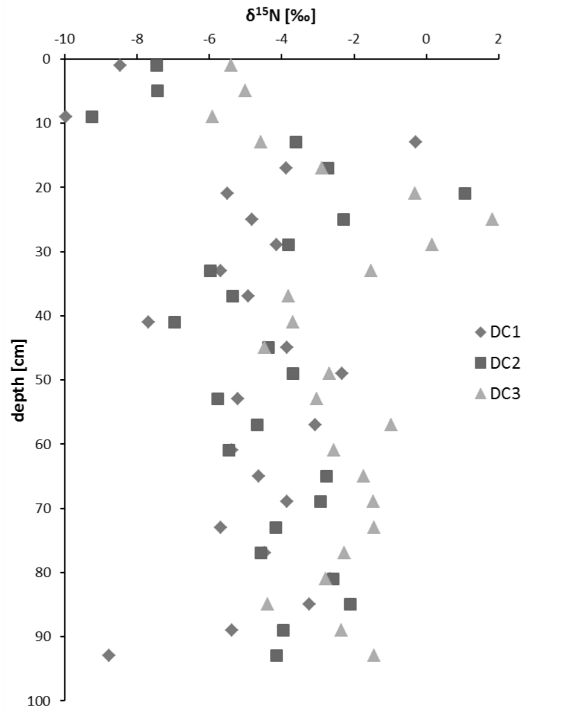
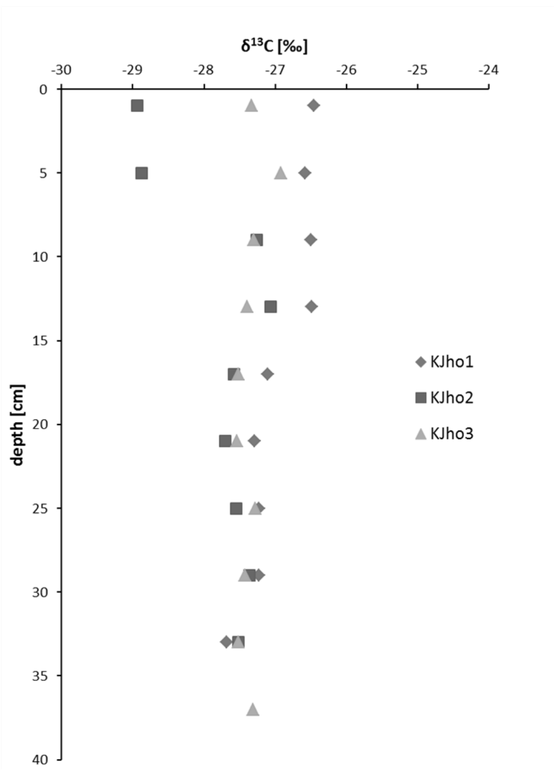


Figure A2.13: Stable carbon and stable nitrogen isotope depth profiles of drainage channel (DC) site at the Degerö-Stormyr peatland, Sweden.

Appendix 2.3: Kattajokken, Sweden



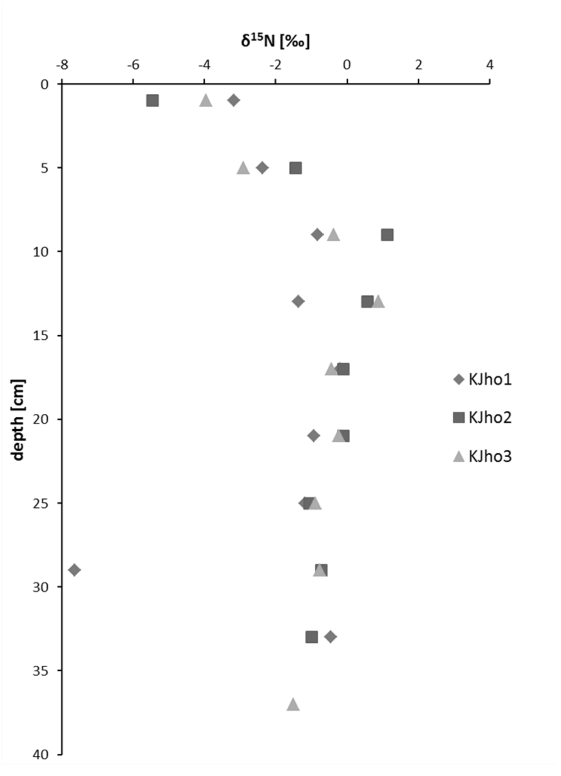


Figure A2.14: Stable carbon and stable nitrogen isotope depth profiles of the hollows at the Kattajokken peatland near Abisko, Sweden.

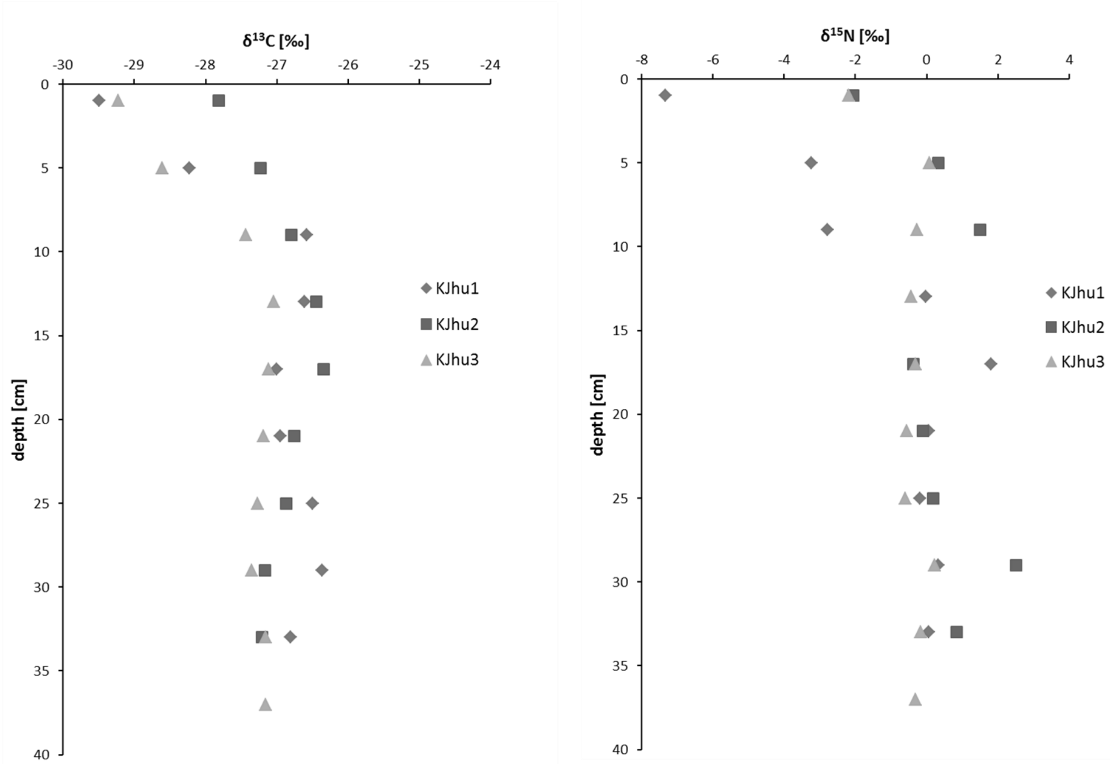


Figure A2.15: Stable carbon and stable nitrogen isotope depth profiles of the hummocks at the Kattajokken peatland near Abisko, Sweden.