Impacts of peatland drainage on soil properties

A study of drainage effects on boreal peatlands in northern Sweden

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Swedish University of Agricultural Sciences, SLU
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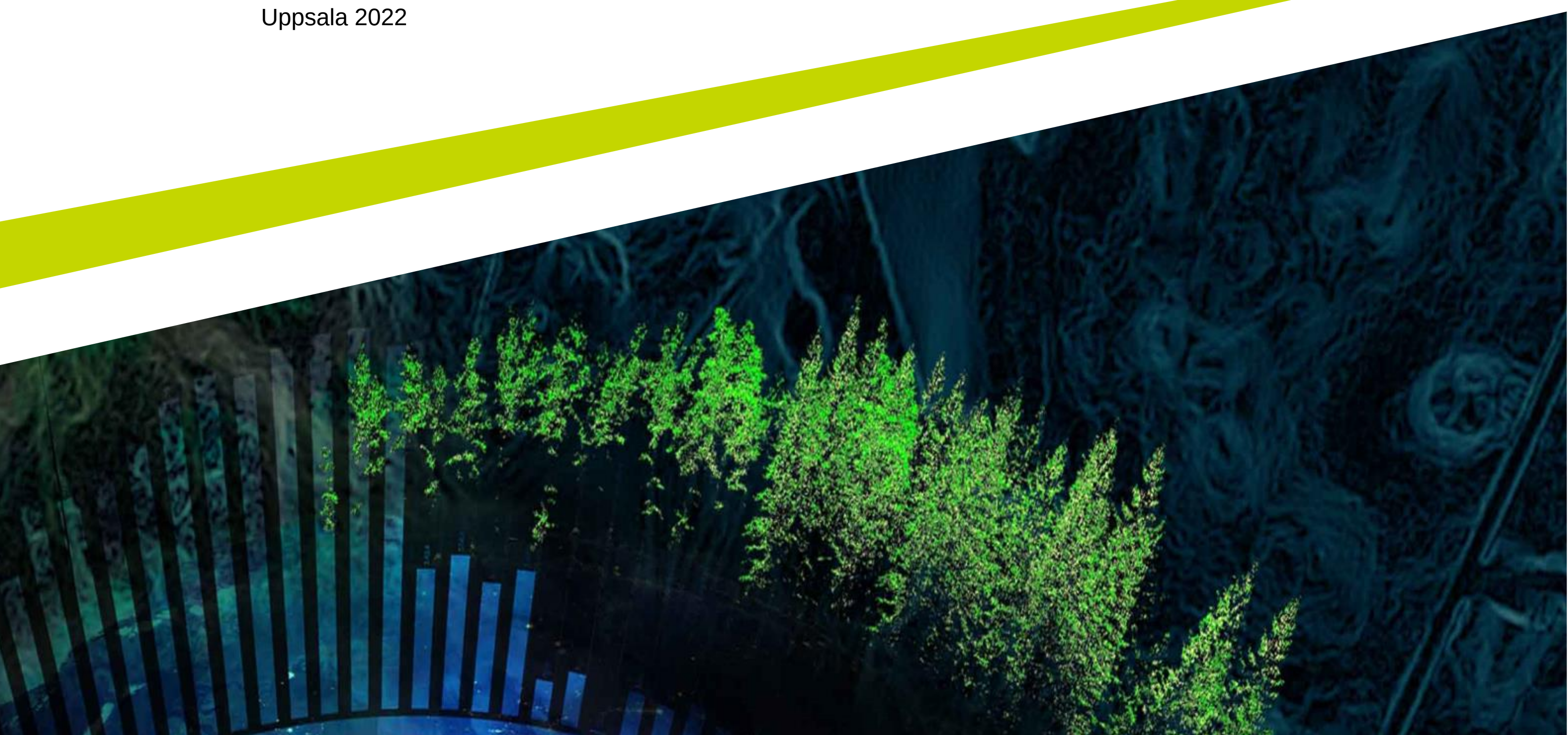

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A study of drainage effects on boreal peatlands in northern Sweden

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Abstract

Peatlands cover approximately 3% of the terrestrial surface on Earth and perform several important ecosystem functions, such as carbon storage and water retention. During the late 19th and early 20th centuries, approximately 2 million hectares of peatlands in Sweden were drained to manage the land for forestry and agriculture. Peatland drainage has since become a more regulated practice, and several projects are underway to rewet drained peatlands to restore their important ecosystem functions. Though the rewetting of peatlands restores the saturated conditions, the effects of drainage on the chemical and physical properties of peat can potentially still have an impact on biogeochemical processes following restoration. The aim of this thesis is therefore to investigate the intermediate drainage period to identify its effects on several key peat properties.

This project utilized data collected in 2020 from three drained and four natural peatlands in northern Sweden. Peat cores were collected to a depth of 50 cm, and the studied variables were dry bulk density, organic matter content, C:N ratio, carbon content, nitrogen content, $\delta^{13}C$, and $\delta^{15}N$. Groundwater data recorded in 2021 was also included from four of the seven peatlands.

The organic matter content and dry bulk density showed the most significant difference between the natural and drained peatlands. In both cases, these differences were primarily at 10-20 cm depth, where the drained peatlands had a higher bulk density and lower organic matter content than the natural. These patterns are indicative of drainage effects, as it enables greater compaction of the soil and increased decomposition rates. The C:N ratio, carbon content, nitrogen content, $\delta^{13}C$, and $\delta^{15}N$ did not show a statistically significant difference between the natural and drained peatlands.

The impact on dry bulk density has implications for peatland water retention and the loss of organic matter may affect carbon storage abilities. Impacts on carbon and nitrogen dynamics were less clear and warrant further study. As peatland rewetting initiatives are implemented, it is important to further our understanding of drainage impacts on peatlands in order to carry out successful and effective restoration projects.

Keywords: boreal peatlands, bulk density**,** carbon, greenhouse gas, isotopes, nitrogen, organic matter, peatlands, peatland drainage, peatland restoration

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1. Introduction

1.1 Background

Peatlands cover 3% of Earth's terrestrial surface and store 600 Pg C, making them a significant carbon sink (Vasander and Drösler, 2008; Yu et al., 2011; Loisel et al., 2021). Globally, approximately 80% of peatlands are found in the boreal region and they have been reported to contain 10-30% of the global soil carbon stock (Joosten and Clark, 2002). Drainage of boreal peatlands was a common practice in the previous century, a period during which >50% of European peatlands were drained for the purposes of agriculture or forestry (Jukaine and Laiho, 1995; Laiho et al., 1998; Byrne et al., 2004; Krüger et al., 2015). This has serious implications for the carbon cycle and drained peatlands globally account for approximately 2 Gt CO_2 emissions each year (Günther et al., 2020).

Peatland drainage impacts several properties and processes of the ecosystem and has been found to convert peatlands from carbon sinks to sources (Mayer et al., 2013; Loisel et al., 2021), cause biodiversity loss (Minayeva et al., 2017), and impair ecosystem function (Kimmel and Mander, 2010). Due to these adverse effects and the contemporary understanding of peatlands as an important tool in combating climate change, there are global and national efforts to rewet and restore drained peatlands.

In Sweden, peatlands cover 10 million hectares, representing approximately one-quarter of the national land area. Drainage became a significant practice in the late 19th century, and it has been estimated that up to 2 million hectares of peatlands have been drained since (Holmen, 1964; Hånell, 2009). Due to the increased understanding of the importance of peatlands, permits are now required for drainage and the practice is prohibited in some parts of the country (Skogsstyrelsen, 2022). Furthermore, peatland restoration projects have been implemented as a strategy for carbon mitigation and environmental protection (Byrne et al., 2004; Hånell, 2009).

Peat forms over centuries of anoxic conditions, and its alteration has complex effects, depending on factors such as decomposition, vegetation, and climate. Several physical and chemical variables can be used as indicators of peat degradation and help evaluate drainage impacts on the important biogeochemical processes that occur in peatlands (Krüger et al., 2015). As restoration efforts are implemented in many parts of the world, it is important to understand the changes occurring in the intermediary drainage step in order to carry out the most effective and beneficial restoration possible.

1.2 Peat definitions and formation

Peat soils are unique in their formation as they develop in the anoxic conditions created in bogs, fens, and some wetlands. Strict classification varies across the globe, but the Swedish definition requires a >30 cm thick layer of peat in order for an ecosystem to be considered a peatland (Naturvårdsverket, 2011). The limited oxygen availability inhibits organic matter decomposition, creating peat that consists of partially decomposed materials (Clymo, 1984). Peatlands are largely divided into two categories – bogs and fens, both of which are common in boreal regions. The primary difference is that bogs receive their water from precipitation only, whereas fens are also supplied with mineral-rich groundwater. Bogs also tend to be more acidic and dominated by *Sphagnum* mosses with some shrubs and sedges (Turetsky et al., 2014). Fens on the other hand can be classified as poor (low mineral content and acidic) or rich (higher mineral content and a more neutral pH) and tend to have higher plant diversity, nutrient content, and primary productivity (Turetsky et al., 2014; Loisel et al., 2021).

As peat accumulates it forms two functionally distinct layers – the upper acrotelm (living) and the lower catotelm (dead). The boundary between the two is generally determined by the depth of the peat that is permanently water-saturated and has also been estimated as the top 10-50 cm. The deeper catotelm usually represents most of the peat mass, is predominantly anaerobic, and only supports very low rates of decomposition (Clymo, 1984). The acrotelm, on the other hand, is exposed to varying degrees of saturation and therefore more aerobic than the catotelm, and hosts microorganisms and bacteria that aid in the peat-forming process (Ingram, 1977). As such, the acrotelm is the site of many of the key biogeochemical processes associated with peatlands.

1.3 The physical and chemical attributes of peat

1.3.1 Peatlands and the carbon cycle

Peatlands are widely recognized for their role in the carbon cycle, as the carbon stored in organic matter (such as mosses, leaf litter, or vascular plants) is stored in the peat, rather than being released as carbon dioxide (CO_2) in the decomposition process (Nilsson et al., 2008; Ojanen et al., 2013). Though peatlands serve as a net sink for CO_2, they have the potential to serve as a source of methane (CH_4), which is 27-30 times more potent as a greenhouse gas (over 100 years) when compared to CO_2 (Waddington and Roulet, 2000; Ojanen et al., 2013; Kotsyurbenko et al., 2019; Forster et al., 2021). Methane in peatlands is produced through the development of anaerobic microbial communities that decompose the organic matter through fermentation. In turn, these fermentation products sustain CH_4 production through methanogenesis. The net balance between carbon storage in peat and CH_4 emission in pristine peatlands is a widely researched and discussed topic and the environmental processes controlling peatland CH_4 flux are complex. Therefore, many of the mechanisms controlling the overall carbon balance in peatlands are not fully understood (Turetsky et al., 2014).

1.3.2 Nutrient dynamics

The nutrient dynamics of peatlands may vary depending on their pH, landscape drainage patterns, water source, and regional climate. In general, boreal peatlands tend to be nutrient-poor and have a higher carbon to nitrogen (C:N) ratio, as the carbon is stored in the ecosystem whereas nitrogen may be cycled or used by microorganisms and vegetation (Krüger et al., 2015). Peatlands also tend to be phosphorus limited, as the only inputs are groundwater (in the case of fens), and potential atmospheric deposition (Wang et al., 2015).

1.3.3 Physical attributes

Another key characteristic of peat is its physical structure. Due to the material's high water content and structure, peat usually contains large pore spaces and is difficult to compact (Sinclair et al., 2020). This enables peat to store large volumes of water and supports the growth of non-vascular plants, such as *Sphagnum* mosses, that rely on passive capillary transport for water uptake (Noble et al., 2017).

1.4 The peatland ecosystem

Peatlands provide several ecosystem services in addition to their function as carbon stores. Firstly, peatland ecosystems host unique biology and are important for biodiversity. The peatland ecosystem is highly heterogeneous and supports several endemic and specialized species. Though the total number of species tends to be low, the composition of organisms is unique and can contribute to regional biodiversity (Minayeva et al., 2017; Alsila et al., 2021). As previously mentioned, *Sphagnum* mosses are the dominant vegetation in boreal peatlands. These species are not only adapted to the peatland environment, but they also aid in creating it. Their high water holding capacity contributes to the waterlogged conditions, their slow decomposition rate enables peat formation, and their cellular processes aid in acidifying their environment, preventing competition from vascular plants (Rydin et al., 2006; Rice 2009; Bengtsson et al., 2017).

Furthermore, peatlands serve important functions for water quality and storage (Martin-Ortega et al., 2014). The physical structure of the acrotelm and water retention by *Sphagnum* mosses both allow for high volumes of water storage (Rochefort and Lode, 2006; Rydin et al., 2006). These processes also aid in naturally filtering water, a quality which may be lost with peatland drainage (Laine et al., 2006). Research has also found increased leaching of nutrients with drainage, which has implications both for water quality and terrestrial productivity (Laiho et al., 1998; Martin-Ortega et al., 2014; Ritson et al., 2016).

1.5 Consequences of drainage

1.5.1 Impacts on carbon processes

As previously stated, drainage impacts several facets of the peatland ecosystem. One of the most acknowledged processes is the impact on the carbon cycle. The increased soil aeration that comes with drainage enables aerobic decomposition, a process through which organic C is mineralized and CO_2 is released (Loisel et al., 2021). The overall carbon balance of peatlands is therefore altered, as it goes from a site of anaerobic decomposition and low mineralization rates and CO_2 release (and CH_4 production) to aerobic decomposition, which releases only CO_2. Previous research has found that northern peatlands emit approximately 36 Tg CH_4-C annually (Zhuang et al., 2006; Turetsky et al., 2014), while drained peatlands globally account for approximately 2000 Tg CO_2 emissions each year (Günther et al., 2020). The carbon balance on the landscape scale will largely depend on temperature, vegetation, soil pH, and water table depth (Abdalla et al., 2016). The impact of natural and drained peatlands on global carbon emissions is therefore dependent on the balance of these processes, and a widely studied and debated topic (e.g., Ojanen et al., 2014; Turestsky et al., 2014).

The analysis of stable carbon isotopes is another valuable tool for the study of carbon dynamics as it can be used to trace carbon forms and processes in the profile. The most abundant isotopes of carbon are ^{12}C and ^{13}C, and their ratio ($\delta^{13}C$) in peatlands is largely the result of plant fractionation and decomposition. Previous studies (e.g., Alewell et al., 2011) have found that $\delta^{13}C$ tends to be uniform with depth in natural peatlands, as the low rates of decomposition result in little fractionation. In more aerobic conditions, decomposers preferentially use ^{12}C, which has been found to increase $\delta^{13}C$ with depth, as ^{13}C remains in the organic material (Alewell et al., 2011; Krüger et al., 2015).

1.5.2 Nitrogen

In addition to the alteration of carbon biogeochemistry, drainage has implications for the nutrient dynamics of peatlands as well. Increased microbial activity after drainage has been found to increase mineralization rates, which makes the nutrients more mobile and potentially prone to leaching (Laiho et al., 1998). The shift in vegetation following drainage will also impact nutrients, as trees take over and become a nutrient sink (Holmen, 1964). For nitrogen (N), microbial fixation is generally the greatest source of N for the peatland ecosystem which allows for accumulation. The impacts of drainage on the nitrogen dynamics are largely dependent on if a peatland is rich or poor in nutrients. Previous studies have found that drainage of nutrient-rich sites can increase N_2O emissions, especially if the water table is deeper than 30 cm (Minkkinen et al., 2020).

Additionally, isotopic analysis of ^{14}N and ^{15}N is used in research for understanding decomposition processes in peatland soils. As with carbon, the lighter isotope is preferentially lost in decomposition, generally resulting in higher $\delta^{15}N$ at sites with more decomposition (Krüger et al., 2015).

1.5.3 Physical properties

In addition to the biogeochemical impacts, the physical attributes of peatlands also stand to be impacted by drainage. As previously mentioned, the bulk density of peatlands tends to be very low, allowing for water-filled pore spaces. Previous studies have found an increase in compaction following drainage, as it disrupts peat structure and causes physical collapse (Laine et al., 2006). These effects can be exacerbated by the use of heavy machinery that is sometimes associated with forestry or agricultural practices or even the colonization of trees and heavier vegetation (Laine et al., 2006; Sinclair et al., 2012). Peat compaction consequently alters the water retention and hydraulic conductivity (Price and Schloutzhauer, 1999; Laine et al., 2006).

1.6 Aim

The aim of this project is to better understand the impact of drainage on key physical and biogeochemical properties of peat in Swedish boreal peatlands. The selected sites are located in Kulbäcksliden, Västerbotten County where four of the sites are pristine and three have been drained in the past 100 years. In order to assess peat degradation and drainage impacts, we studied dry bulk density, organic matter content, C:N ratio, carbon and nitrogen content, $\delta^{13}C$ and $\delta^{15}N$. Based on the findings in previous research, drainage could affect several of these properties. Within the drained sites, the increased oxygen availability is expected to increase productivity and decomposition rates, contributing to a loss of organic matter and decreased C:N ratio. Due to the limited fractionation occurring under anaerobic conditions, $\delta^{13}C$ and $\delta^{15}N$ patterns are likely to be more uniform in the natural peatlands than in the drained peatlands. Drainage has also been found to affect the physical peatland structure, and a greater bulk density is therefore expected at the drained sites.

2. Methods

2.1 Site description

This project utilized already available data that was collected from seven peatland sites in Västerbotten County in the summer of 2020. All sites are located in Vindeln Municipality, where four are natural and the remaining three were drained in the early 20th century. The natural peatlands and one of the drained belong to the Kulbäcksliden Experimental Forest, while the other two drained sites are located within the Trollberget Experimental Area. All sites fall within the northern fen region that covers most of northern Sweden (Norstedt et al., 2021). The climate of the area is classified as cold temperate humid, with a mean average temperature of +1.2° C (ICOS Sweden).

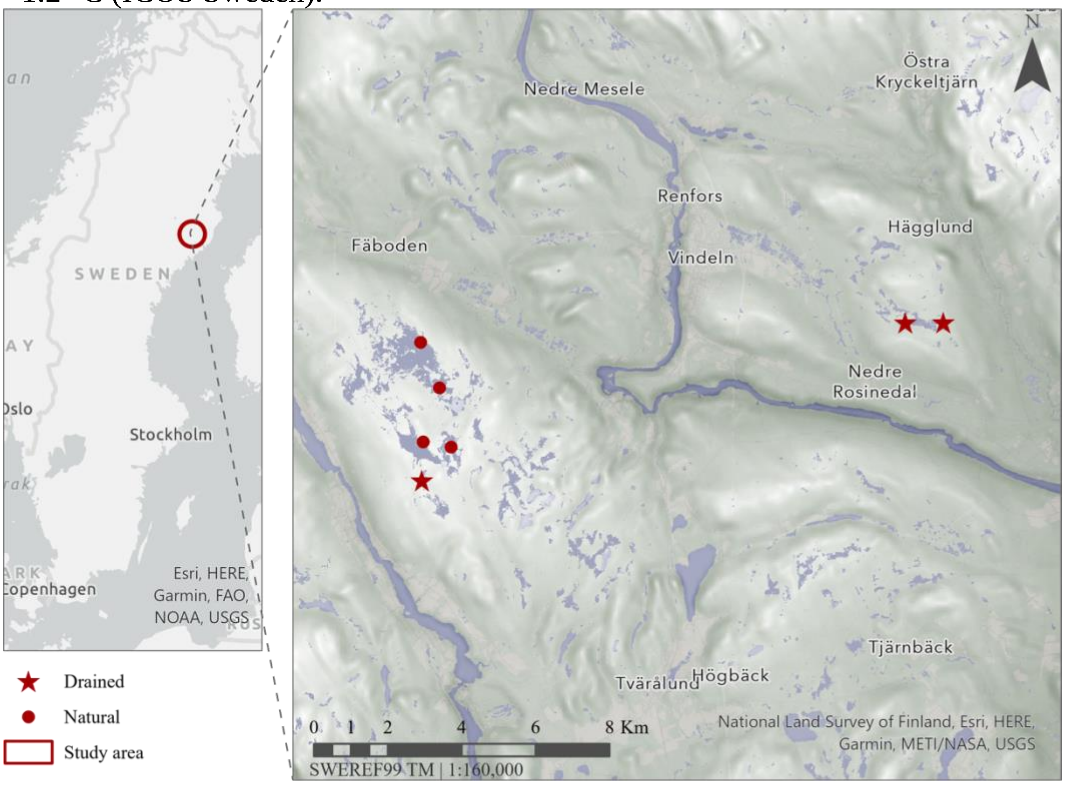

Figure 1. *Map of the study area in Vindeln municipality, located at approximately 64.20° N. Map was created in ArcGIS Pro (ESRI).*

The sites at Kulbäcksliden include the natural sites Degerö, Stormyran, Hålmyran, Hälsingfors Stormyran and the drained Hälsingfors open forested site. Most research in the area has been at the Degerö mire, which is a nutrient-poor fen and considered a good representation of many mires at this latitude (ICOS Sweden). Peat accumulation in the area started almost 6,000 years ago and the average peat depth is estimated to approximately 3-4 m (Nilsson et al., 2008; SLU, 2017).

Trollberget was drained for forestry in the early 1920s and is now classified as a forested mire, with a moderately sparse growth of Scots pine and smaller deciduous trees. The nutrient availability of the site is low, and the ditches have been poorly maintained, resulting in low productivity of the forest (Skogssällskapet, 2020; Casselgård, 2020).

2.2 Laboratory analyses

Three peat cores were collected using a 15 cm diameter soil corer at each site. Since the acrotelm is the site of greatest biological activity, the cores were taken to a depth of 50 cm. Each peat core was divided into 2 cm thick discs, giving 25 samples per peat core. Samples were analyzed for organic matter content, bulk density, carbon and nitrogen content, and isotopes.

Samples were first dried to measure dry bulk density, i.e., the weight of soil per unit volume of soil. Dry bulk density was calculated as the mass of dry soil per sample, divided by the volume of each 2 cm thick disc, as determined in the calculation below.

$$Dry\ BD = \frac{(M_{both}\ (g) - M_{Cont}\ (g))}{V\ (cm^3)}$$

Where,
M_{both} is the mass of the container and the dried soil samples, and
M_{Cont} is the mass of the container in which the sample is held, and
V is the volume of the dried sample.

Subsamples were then ground up and used for measuring organic matter content, through a test of loss on ignition (LOI). Samples of ~1 g were placed in ceramic cups, dried overnight at 105° C, and then cooled in a desiccator to prevent moisture absorption. They were then weighed and heated in a muffled furnace at 550° C for 6 hours. This method gives a measure of the organic content of the samples, as the organic matter is burned off during combustion, while heat-resistant minerals remain. Percent organic matter was calculated according to the calculation below.

$$\%OM = \left(\frac{M_1 - M_2}{M_1 - M_C}\right) \times 100$$

Where,
M_1 is the mass of the crucible and the sample before combustion, and
M_2 is the mass of the crucible and the sample following combustion, and
M_C is the mass of the crucible.

Prior to carbon and nitrogen analyses, the samples were ground up, dried at 70° C for 18 hours, and then cooled in a desiccator. Samples were then weighed into small aluminium containers. Elemental analysis was used to determine the mass fraction of carbon and nitrogen in the samples, and isotopic ratios were calculated through mass spectrometry. These analyses were carried out using instrumentation from Thermo Fischer Scientific and performed by analysts at the Stable Isotope and Biogeochemical Analyses laboratories at the Department of Forest Ecology and Management at SLU Umeå.

In addition to peat cores, groundwater data was recorded each hour June-November in 2021. This data was collected at three of the natural sites (Stormyran, Hålmyran and Hälsingfors Stormyran) and one of the drained sites (Hälsingfors open forested site). The areas of Trollberget used in this study were rewetted in November 2020 and groundwater data from those sites was subsequently not included in this study (Skogssällskapet, 2020).

2.3 Statistical analyses

Statistical analyses were based on the average value for the three samples at each site. A principal components analysis including the variables organic matter content, dry bulk density, depth, C:N ratio, %C in organic matter, %N in organic matter, $\delta^{13}C$, and $\delta^{15}N$ was performed to get an initial overview of the data. The variables were also tested for normality of distribution, using histograms and QQ-plots, and the data did not require transformation. As samples were collected at several depths at each peatland, the two predictor variables were the depth of the sample and category (natural or drained). For this reason, a linear mixed-effects model was chosen to perform statistical analysis, as it allowed us to investigate the differences between natural and drained peatlands, while also accounting for the effect of depth. Additionally, a function of continuous correlation structure (corCAR1) was included to account for the correlation between samples at each depth within the core. The model was executed using the R function lme in the package *nlme* and performed according to the formula on the following page (Pinheiro et al., 2000; Pinheiro et al., 2022).

$$Y_{ijk} = \mu + \alpha_i + b_j + \alpha b_{ij} + C_k + e_{ijk}$$

Where,
Y_{ijk} is the variable (e.g., organic matter content) at a given depth (i) at a peatland in the category (j) at the peatland site (k),
μ is the overall mean,
αi and bj are the fixed effects of depth and category,
αb_{ij} is the interactive effect of depth and category,
C_k is the random effect of the peatland (k), and
e_{ijk} is random error.

As both depth and category (drained or natural) constitute independent variables, the interactive effect of both was used as the value determining statistical significance ($p<0.05$).

An ANOVA test was used to determine whether there was a significant difference between drained and natural peatlands for each variable. A subsequent post-hoc test (least-squares means) was performed on the variables that showed statistical significance in the interactive effect of the linear mixed effects model. The post-hoc test was used to identify the depths at which these differences were present. All statistical analyses were performed in RStudio version 1.4.1717 and plots were created using the package ggplot2 (R Core Team, 2022; Wickham, 2016).

3. Results

3.1 Overview

In the resulting principal components analysis (PCA), PC1 was found to explain 52.9% of the variance, and PC2 explained 23.4%, and a scree plot showed that most variance was explained by the first three principal components (see the figure in Appendix 1). The samples from drained peatlands were found to have a greater spread across both PC1 and PC2, whereas this spread was less severe in natural samples. Dry bulk density had the greatest influence on PC1 (0.456), whereas mean depth was the most influential variable on PC2 (-0.589), as seen in Figure 2.

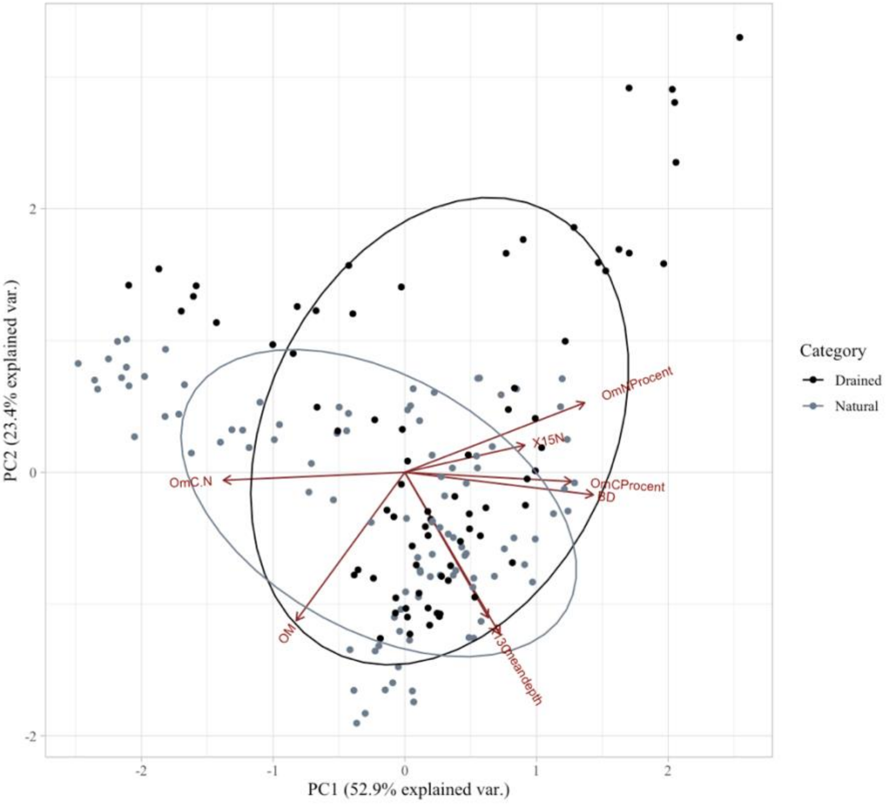

Figure 2 *The principal components analysis shows groups of similar samples and visualizes the sampling points in different colors based on category (natural peatland samples in gray and drained are in black). The variables included and their weighting on principal components is indicated by the arrows in red.*

3.2 Groundwater depth

Groundwater loggers recorded levels throughout the summer season in 2021, from the sites Stormyran, Hålmyran, Hälsingfors Stormyran, and Hälsingfors open forested (Figure 3). The data from the natural sites are all averages of the multiple loggers at each site (three at Stormyran and two at Hålmyran and Hälsingfors Stormyran). The one drained site with groundwater data (Hälsingfors open forested site) is the representation of one logger. The groundwater levels at Hälsingfors open forested site are notably lower than at the natural sites, with a mean depth of 43 cm, while the mean depth at the natural sites was 17 cm. All four peatlands exhibit similar patterns in groundwater level fluctuations, notably all increasing at the end of July. From the end of September through the beginning of October, Hälsingfors open forested site showed greater variation than the natural sites, ranging from 45 to 28 cm in two days. During the same period, Stormyran showed the greatest variation of the natural sites, going from 21 to 13 cm.

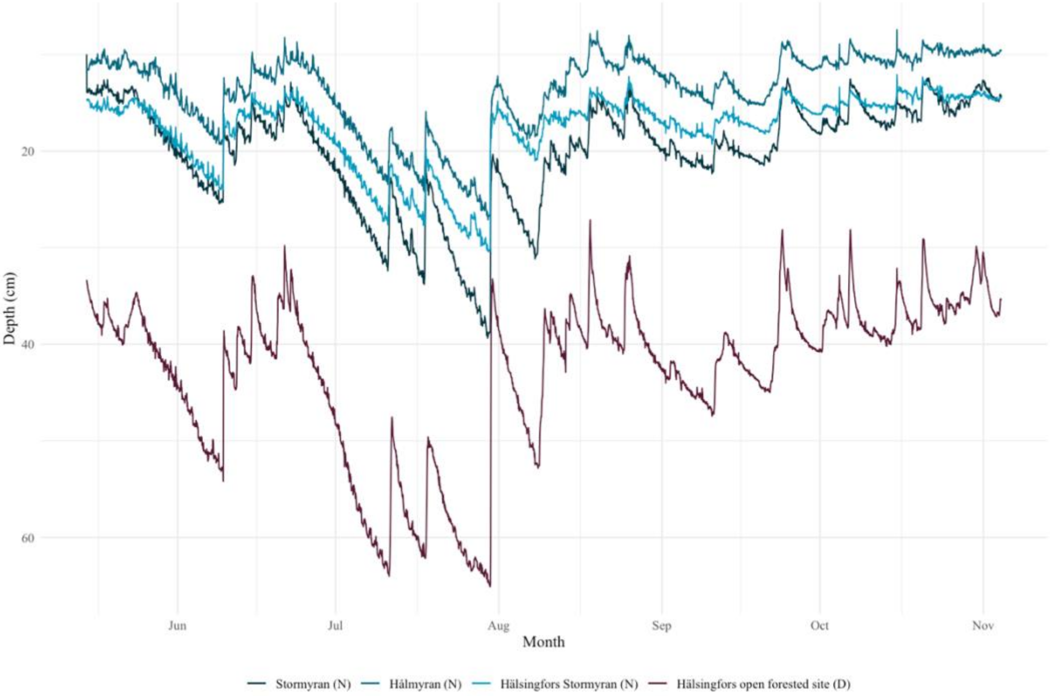

Figure 3 *Time series of groundwater levels (in cm) recorded in June-November 2021 from three of the natural sites and one of the drained. Each natural site had 2-3 loggers while the drained site (Hälsingfors open forested site) only had one logger.*

3.3 Organic matter content

Organic matter content (%OM) ranged from 77 to 98% in drained sites and from 92 to 98% in natural peatlands. These patterns in %OM were most divergent in the top 15 cm, where both Hälsingfors open forested site and Trollberget decreased in organic matter content with the lowest values of 77 and 88%, respectively (Figure 4). Organic matter increased when deeper than 15 cm, and at the bottom of the profiles, organic matter content was within the range of 97-99% for all seven sites.

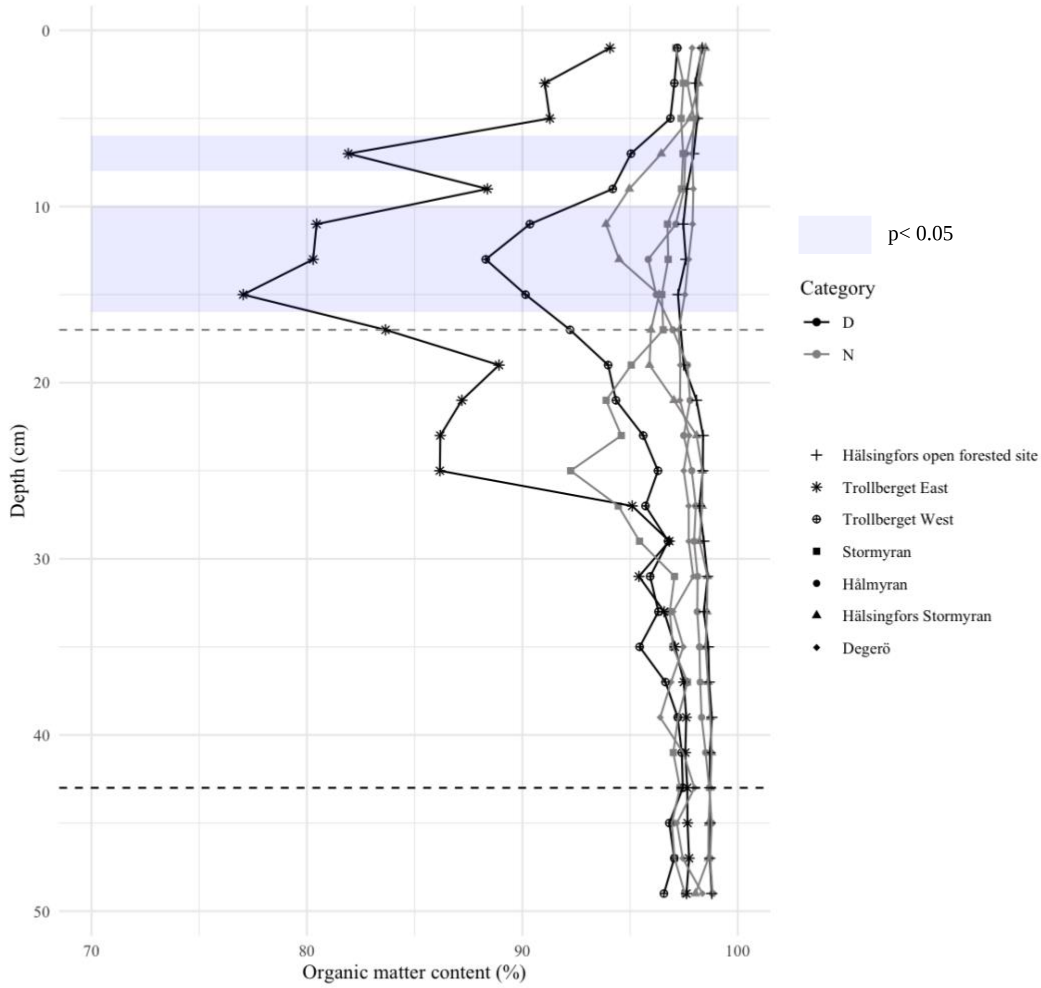

Figure 4 *Organic matter content (%) measurements to a peat depth of 50 cm, where the natural peatlands and their mean groundwater level are shown in grey and the drained in black. The blue box indicates the depth at which a statistically significant difference between organic matter content in drained and natural peatlands was found.*

The mixed-effects model results showed a statistically significant relationship between organic matter content and the interactive effect of depth and category(p=0.027), as seen in Table 1. As labeled in Figure 4, the subsequent post-hoc t-test showed significant differences between natural and drained at 6-8 cm and 10-16 cm depth.

Table 1. *ANOVA p-values of the relationship between each variable and depth and category (natural or drained). The interactive effect refers to the model results that account for the effect of both depth and category.*

	%OM	**BD**	**OMC:N**	**%OMC**	**%OMN**	**$\delta^{15}N$**	**$\delta^{13}C$**
Depth	0.011	<0.0001	<0.0001	0.001	<0.0001	0.001	0.000
Category	0.217	0.932	0.313	0.186	0.430	0.495	0.313
Interactive effect	0.027	0.017	0.519	0.259	0.080	0.734	0.608

3.4 Dry bulk density

Dry bulk density values increased with depth in the top 15-20 cm in all sampling locations (Figure 5). Values ranged from 0.01– 0.17 g/cm^3 throughout the entire depth with the samples from Trollberget East (drained) showing the most drastic increase in the top 15 cm of the core. Both sites from Trollberget showed an increasing dry bulk density in the top 15 cm, which then decreased slightly with depth. Hälsingfors Stormyran (natural) showed a similar pattern as Trollberget West, whereas the other natural sites increased in bulk density deeper in the profile.

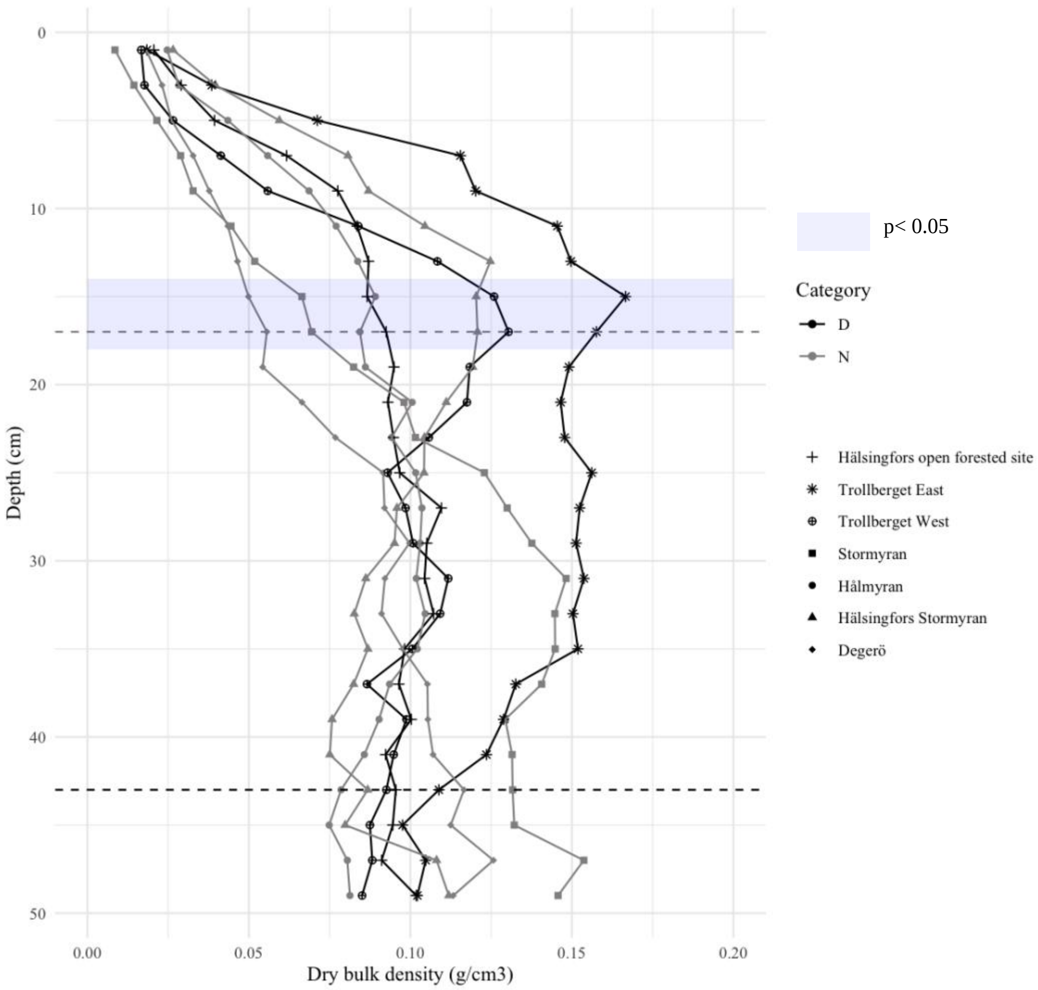

Figure 5 *Bulk density values (g/cm³) in natural and drained peatlands to a depth of 50 cm, where the natural peatlands and their mean groundwater level are shown in grey and the drained in black. The blue box indicates the depth at which a statistically significant difference between the dry bulk density values in drained and natural peatlands was found.*

The ANOVA results showed a statistically significant relationship between dry bulk density, depth, and category ($p=0.017$), as seen in Table 1. The post-hoc results test showed that this difference between natural and drained peatlands was significant in the 14-16 ($p=0.043$) and 16-18 ($p=0.045$) depth categories.

3.5 C:N ratio

Natural peatlands showed a greater C:N ratio in the top 10 cm of the profile, with the Degerö and Stormyran, sites increasing to a maximum of 112.1 (Figure 6). Both Hålmyran and Hälsingfors Stormyran demonstrated decreasing C:N ratio in the top 15 cm, going from >80 at the top to <40 at 15 cm depth. Below 15 cm depth, the C:N ratio in natural peatlands ranged from 26.7 to 57.2.

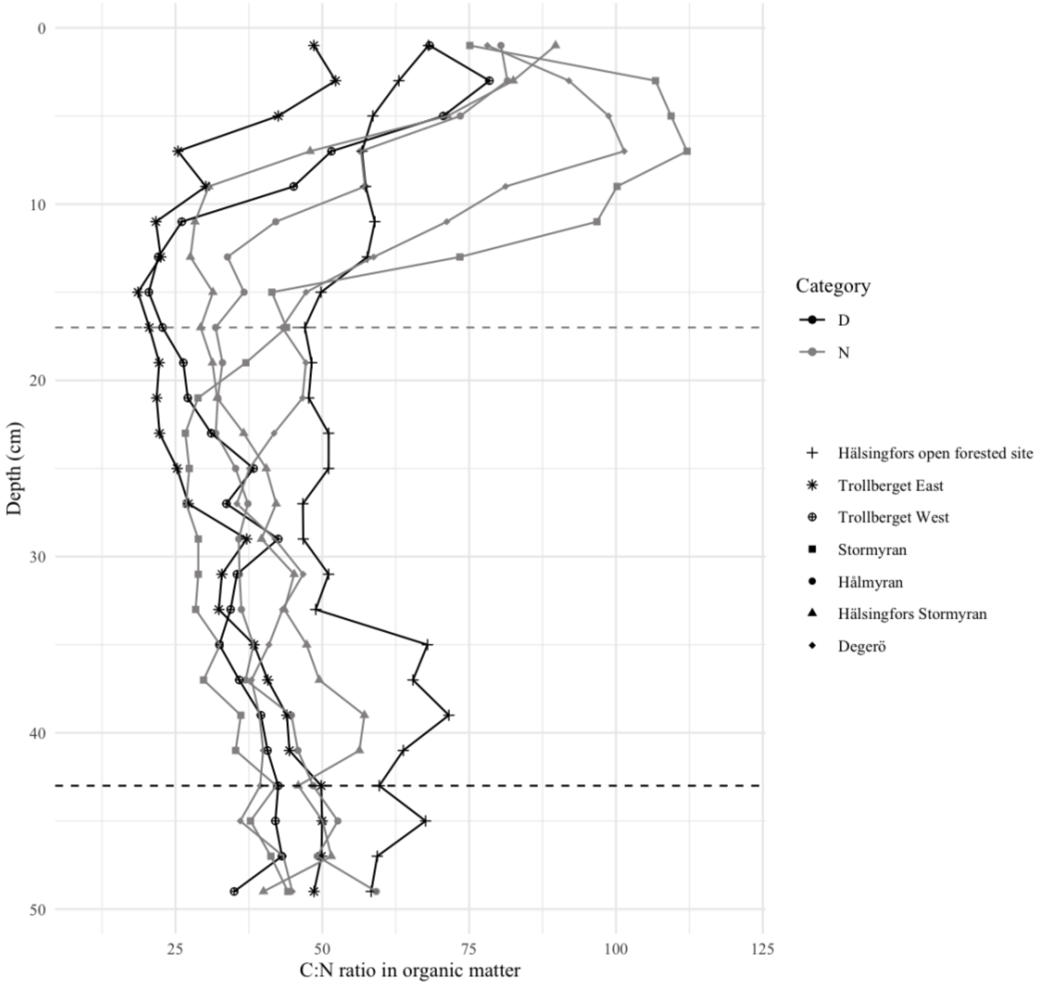

Figure 6 *Ratio of carbon to nitrogen (C:N) in the peat organic matter to a depth of 50 cm in drained and natural peatlands. The natural peatlands and their mean groundwater level are shown in grey and the drained in black.*

The C:N ratio in drained peatlands ranged from 20.5 to 78.4 with both sites at Trollberget showing decreasing values in the top 10 cm. The Hälsingfors open forested site showed a more uniform C:N ratio with depth, ranging between 46.7 and 71.6 throughout the entire profile. There was no significant difference in the C:N ratio at natural and drained peatlands when considering the entire peat column (Table 1).

3.6 Carbon and nitrogen content in organic matter

Total carbon in organic matter ranged between 49.1–61.9%, with the greatest percentage measured at the depth of 39 cm at Trollberget E (Figure 7). Carbon content in natural peatlands generally increased slightly with depth, with a minimum of 49.1% and a maximum of 59%. The corresponding range for drained peatlands was 49.9–61.9% and both Trollberget West and Hälsingfors open forested site demonstrated rather uniform patterns, between 49.9–57% throughout the 50 cm profile. Trollberget East had a more variable pattern of the three drained peatlands, e.g., ranging between 55.2 and 61.3% at the depth of 25–27 cm. A closer examination of the raw data reveals that the source of this variation is primarily from one of the three peat cores collected and thus may be skewing the average (see the figure in Appendix 2).

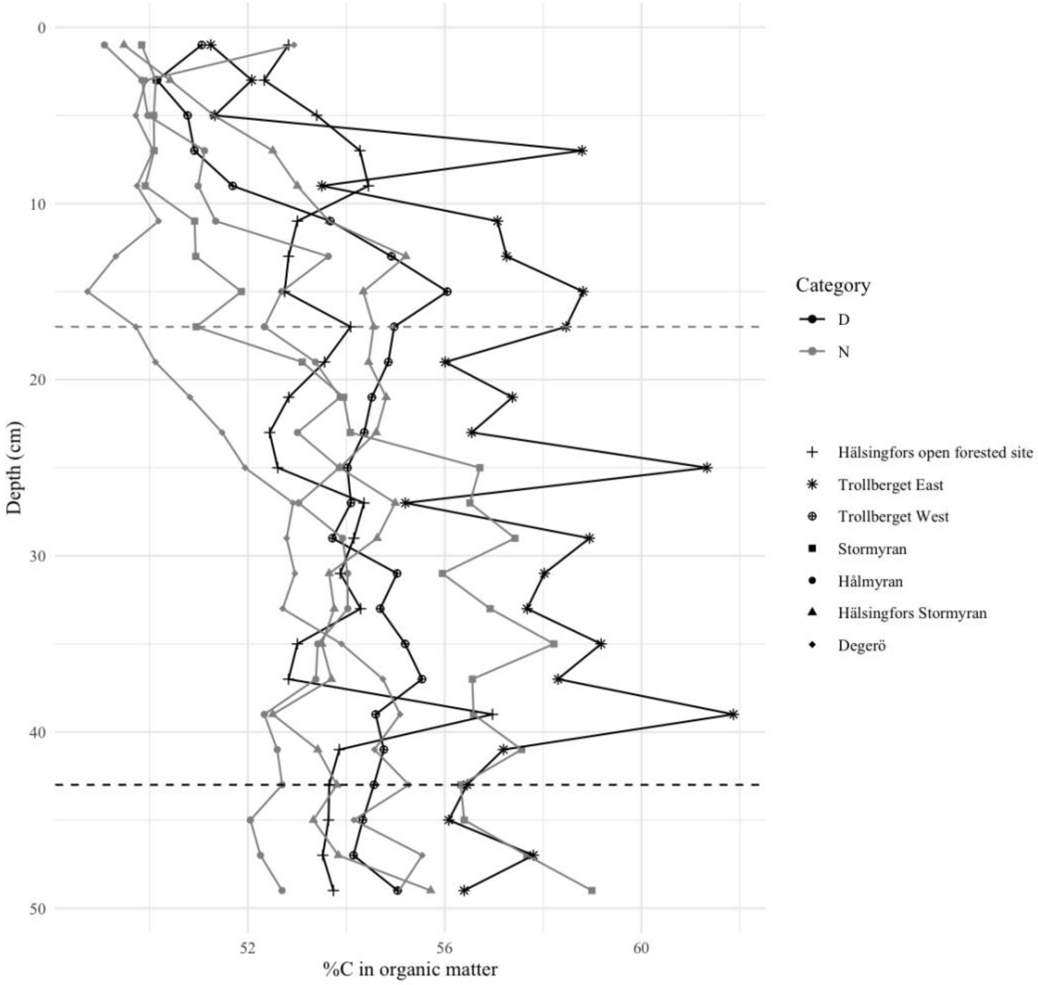

Figure 7 *Percent carbon (C) content in peat organic matter in the top 50 cm of the peat profiles. The natural peatlands and their mean groundwater level are shown in grey and the drained in black.*

Nitrogen content ranged from 0.64 to 3.16%, with the highest concentration measured at 15 cm depth at Trollberget East (Figure 8). Both sites at Trollberget increased in concentration in the top 15 cm, whereas Hälsingfors open forested site displayed a more uniform concentration with depth, ranging between 0.78–1.15%. The concentrations in natural peatlands were 0.45–2%, with the highest values recorded below 10 cm depth.

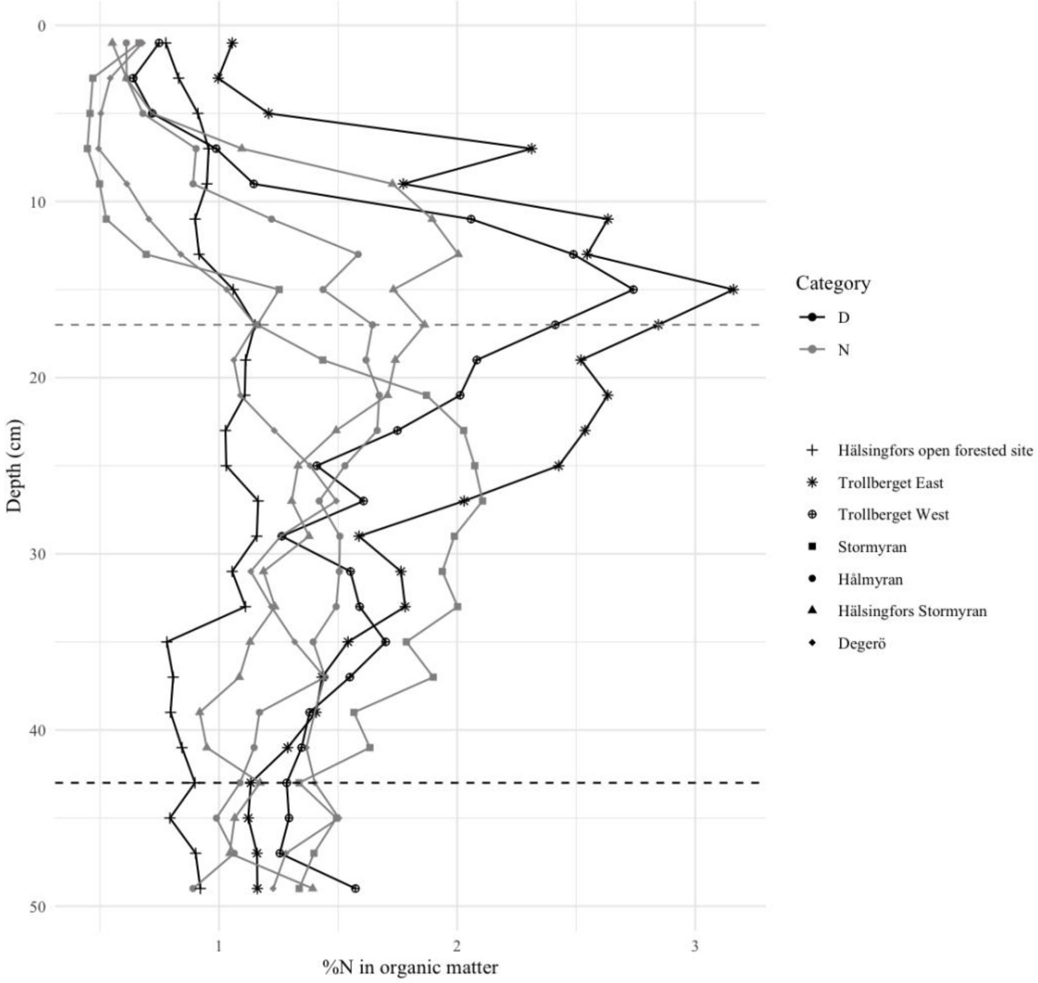

Figure 8 *Percent nitrogen (N) content in peat organic matter in the top 50 cm of the peat profiles. The natural peatlands and their mean groundwater level are shown in grey and the drained in black.*

The ANOVA test of carbon and nitrogen concentrations showed that both variables were influenced by depth ($p<0.05$) but there was no relationship between concentrations and category (Table 1).

3.7 Isotopic analysis of δ^{13}C and δ^{15}N

The isotopic signature of δ^{13}C in organic matter with depth showed slightly increasing values with depth for both drained and natural peatlands (Figure 9). Values ranged between -30.2 to -24.5‰ δ^{13}C, with the lowest values in the top 10 cm of the peat profile. The highest value was measured at 39 cm depth at Hälsingfors Stormyran, though this pattern is largely dictated by one of the three cores taken at that location (see the figure in Appendix 3).

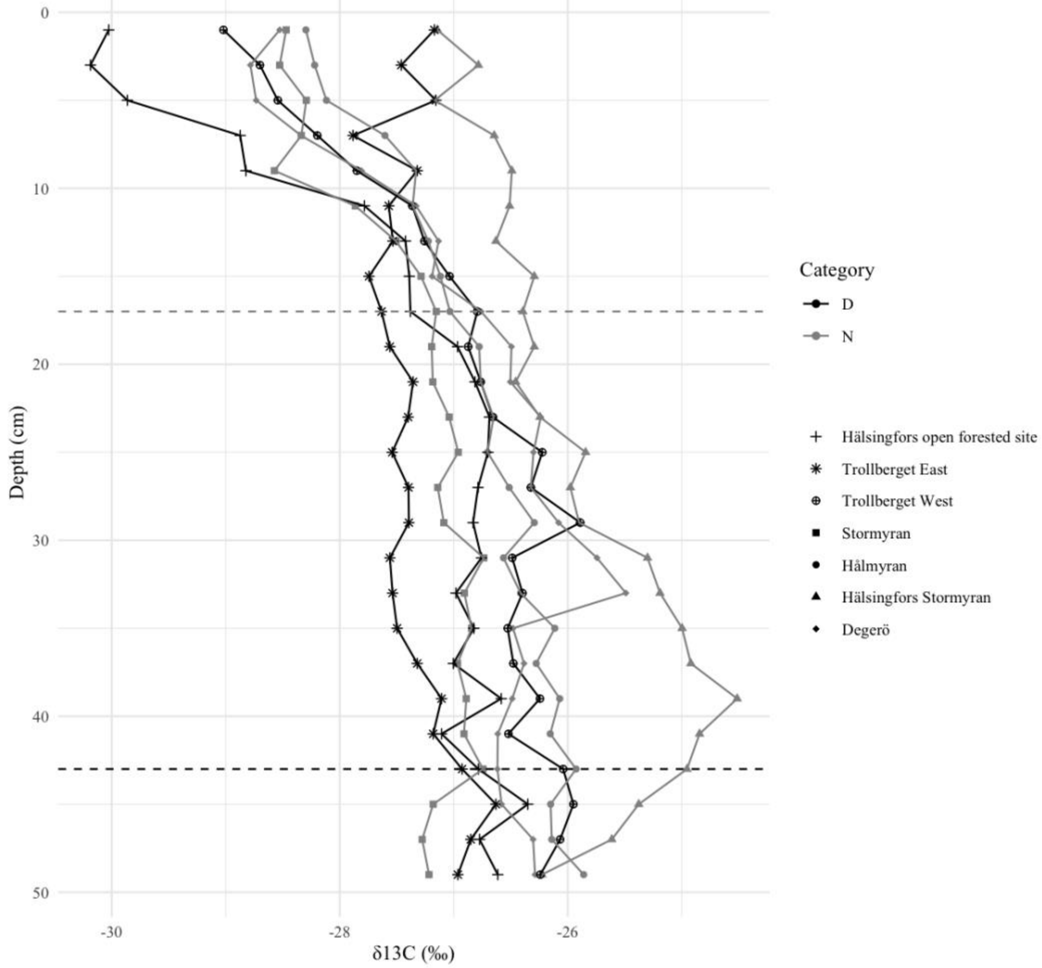

Figure 9 *Ratio of the stable isotopes ^{13}C to ^{12}C in peat organic matter in the top 50 cm of the peat profiles. The natural peatlands and their mean groundwater level are shown in grey and the drained in black.*

As seen in Figure 10, the values of $\delta^{15}N$ ranged from -6.29 to 2.26‰, with the most visible differences in the top 15 cm in the drained peatlands. Samples from Hälsingfors open forested site demonstrated the most significant increase in $\delta^{15}N$, going from -6.30 to 1.13‰. Apart from Hälsingfors open forested site, the drained peatlands at Trollberget exhibited a curving pattern with increasing $\delta^{15}N$ in the top 15 cm, followed by a slight decrease to a depth of 35 cm. Natural peatlands showed a more uniform pattern, with slightly increasing or uniform values with depth, ranging from a minimum of -4.12 to a maximum of 1.33‰ in the top 50 cm.

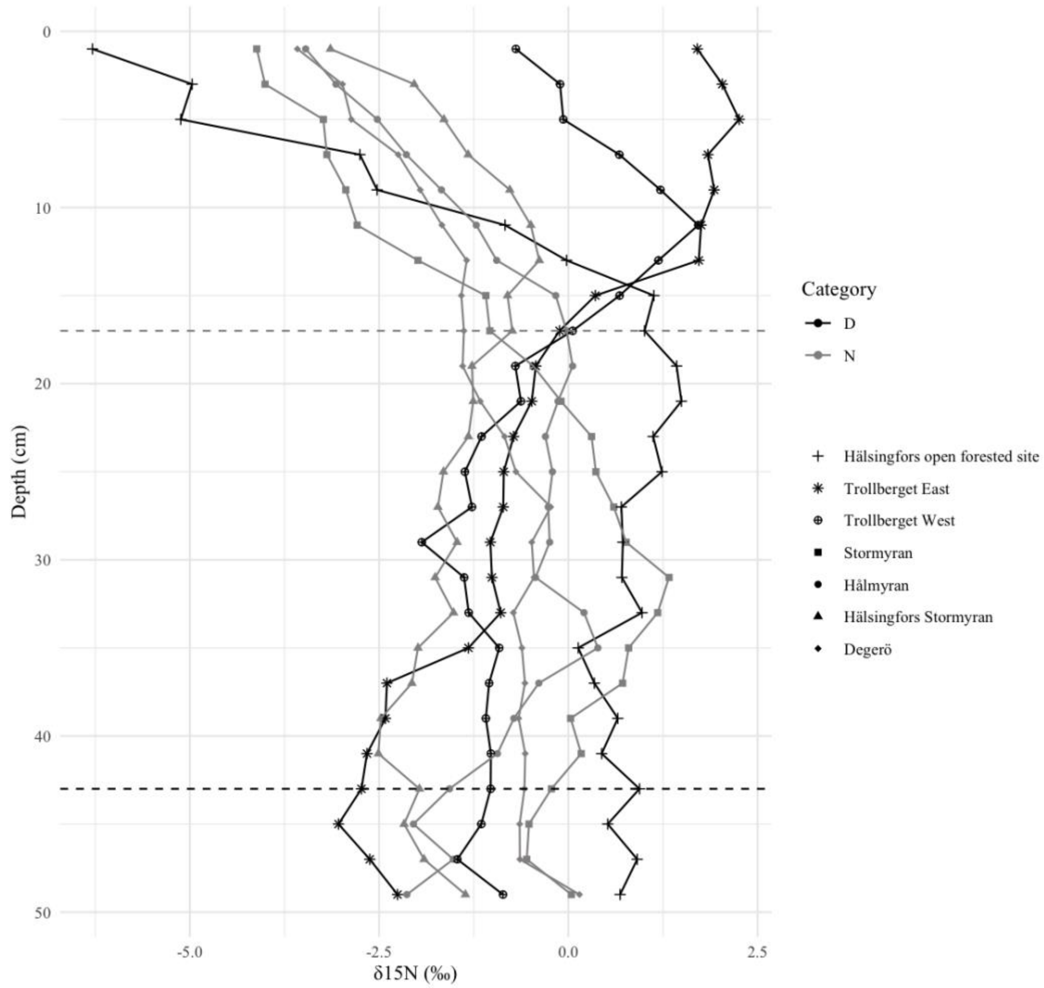

Figure 10 *Ratio of the stable isotopes ^{15}N to ^{14}N in peat organic matter in the top 50 cm of the peat profiles. The natural peatlands and their mean groundwater level are shown in grey and the drained in black.*

4. Discussion

4.1 Overview

The variables that showed a statistically significant difference between the two categories were organic matter content (p=0.027) and dry bulk density (p=0.017), which were the variables with the greatest impact on the principal components analysis. Across multiple variables, primarily in organic matter content, bulk density, and nitrogen content, the drained Hälsingfors open forested site exhibited patterns more similar to the natural sites rather than the other two drained sites. Some of these differences may be attributed to vegetation differences at the sites, the distance between the sampling locations and drainage ditch, or a potentially lesser drainage effect at this site.

It is also important to note the impact of age on the peat cores. As these samples have not been dated, it is difficult to discern whether the different patterns between cores are due to depth, drainage status, or age. Potential compaction of the peat at the drained sites could further exacerbate this issue, as it shifts the relationship between the age of the sample and the depth at which it is located. For this reason, dated samples would improve our understanding of peatland properties and is a step recommended for future research.

4.2 Groundwater depth

Groundwater recordings showed an average difference of 26 cm in depth between the natural and the drained peatlands. An important consideration regarding the groundwater levels is the lack of additional data from drained peatlands. Hälsingfors open forested site only had one logger, and 2021 data was not available from the sites at Trollberget, since they were both restored in the fall of 2020. The average groundwater depth for drained peatlands is therefore one mire and not an ideal representation of all the sites studied. Additionally, the groundwater data was collected in 2021, the year after the peat samples were collected. Though the patterns may differ from year to year, the relative relationship among the sites should prevail. Additionally, the peat characteristics studied are the result of centuries of peat formation during which the hydrological regime may have undergone shifts on a year-by-year basis. In reviewing these results, it is important to consider that this data only represents a snapshot of the hydrological patterns at the sites and was included for a better understanding of the difference in groundwater levels at the drained and natural sites.

4.3 Organic matter content

The greatest difference in organic matter content was observed in the top 20 cm of the profile, where concentrations were generally lower in drained peatlands. This pattern is likely explained by the greater degree of oxygen availability in drained peatlands, resulting in a higher rate of decomposition (Chapin et al., 2011). Below 20 cm these differences were less, as the peat is more likely to be saturated at greater depth, despite the drainage status. Notably, the Hälsingfors open forested site (D) exhibited a pattern more similar to the natural peatlands, with values only ranging between 96–99%. A closer study of the three individual peat cores at the site reveals that two of them showed a similar pattern with depth as the drained sites at Trollberget, though at a smaller scale (as seen in the figure in Appendix 4). The lowest concentration of organic matter at Hälsingfors open forested site was recorded at 15 cm as approximately 96%, while the other drained sites had a %OM of 77 and 90% at the same depth.

4.4 Dry bulk density

The most notable difference in dry bulk density between drained and natural peatlands was at 13–17 cm depth, close to the water table position of the natural peatlands. Higher densities in the drained peatlands can likely be attributed to drainage, as the removal of water can cause pore structure collapse and peat compaction (Laiho et al., 1999; Krüger et al., 2015; Liu et al., 2019). Other studies have reported similar results, for example, Krüger et al., (2015) found increasing bulk density in the top –60 cm in a drained temperate bog, and Casselgård (2020) reported greater bulk density in the same drained boreal peatlands as our study at 5–15 cm depth. As with organic matter content, the Hälsingfors open forested site displayed a pattern more similar to that of the natural peatlands. However, the individual cores at the site increased in bulk density in this depth range, although at lesser increments than the other drained sites, which could be indicative of a smaller drainage effect.

4.5 Carbon and nitrogen dynamics in organic matter

Patterns in C:N ratio were not statistically different but visually distinct above 15 cm depth, where especially two of the natural peatlands showed higher ratios than the drained. Below 15 cm depth, all peatlands showed more similar C:N ratios. The C:N ratio was expected to be more different between the natural and drained peatlands, as previous studies have found that increased decomposition rates would lead to a greater degree of carbon mineralizing to CO_2, resulting in a lower C:N ratio (Krüger et al., 2015). Though peatland drainage also can cause a loss of N through the increase in N_2O emissions, these effects are primarily significant in more nutrient-rich peatlands and therefore not expected to be relevant at these sites (Martikainen., 1993; Minkkinen et al., 2020). The quality of organic matter substrates may also impact the C:N ratio and the difference between the categories. A lower C:N ratio can be indicative of greater productivity at the drained sites, where oxygen availability can support a transition to more vascular plants that can decompose easier than *Sphagnum* (Luan et al., 2019). However, in comparison to non-peatland soils, the C:N ratios in both categories are significantly higher. For example, forest O-horizons have been found to have a ratio of 30–40 (Brady and Weil 2008) whereas the natural peatlands surpassed 100 near the surface which is indicative of a low degree of decomposition (Krüger et al., 2015).

Carbon content in organic matter was not significantly different between the natural and drained peatlands, and all sites showed a slight increase in concentrations with depth. The notably shifting pattern at Trollberget East can be largely attributed to one core (Appendix 2). Potential loss of carbon in drained peatlands would therefore not be attributed to altered dynamics in organic matter, but rather to the decomposition of organic matter in the more aerobic environment. The large-scale impact of drainage on peatland carbon is widely researched, and some studies have reported a net loss of carbon through CO_2 production in aerobic decomposition and peat degradation (e.g., Martikainen et al., 1995; Simola et al., 2012), whereas others have found that the increase in woody biomass and litter production can compensate for this loss (Ojanen et al., 2013; Krüger et al., 2016).

Nitrogen content in organic matter was not statistically different between the natural and drained peatlands but showed some difference in the top 15 cm where the drained had more N than natural. Previous studies have also reported more nitrogen in peatland soil where there is a greater degree of decomposition (Laiho et al., 1999; Casselgård, 2020), which could explain the pattern in the drained peatlands, where concentrations are higher at the top and decrease with depth. The lower percentages in natural peatlands also relate to their higher C:N ratio, as this can limit microbial processes, requiring organisms to scavenge the soil for nutrients rather than obtaining it from other inputs (Brady and Weil 2008). Similar to the bulk density and organic matter content, the Hälsingfors open forested site was the site closest aligned with the natural peatlands, which could be another indicator of a lesser drainage effect at this site.

4.6 Isotopic analysis of $\delta^{13}C$ and $\delta^{15}N$

The results did not indicate significant differences in $\delta^{13}C$ between the natural and drained peatlands. At all sites $\delta^{13}C$ generally increased slightly with depth. Due to the preferential use of ^{12}C in decomposition, a higher $\delta^{13}C$ would be expected near the surface and in the drained peatlands (Krüger et al., 2015). The $\delta^{13}C$ increase observed in these peatlands was very small but contradicted the expectation of greater $\delta^{13}C$ in areas of more decomposition. Previous research into the isotopic composition of carbon in peatlands has demonstrated varied results. A study by Krüger et al. (2015) also found that $\delta^{13}C$ increased 4–5‰ with depth in peatland soils, however, this was at sites with high aerobic composition and good drainage. Another study by Alewell et al. (2011) discovered that natural peatlands in boreal latitudes had a more uniform $\delta^{13}C$ pattern with depth, as the overall low decomposition rates would not lead to much fractionation. Though multiple forcings are possibly at play, the applicability and evaluation of these theories on the results herein are limited due to the differences in environmental conditions and study design. Considering the small scale at which microbial decomposition occurs, the effects of fractionation may not be detectable in the bulk samples collected for this project. The greater impacts on $\delta^{13}C$ could potentially be attributed to the source material of decomposition instead, where the activity and presence of certain decomposing organisms will depend on what kind of plant or moss material is being broken down.

Considering the $\delta^{15}N$, there were no significant differences between the categories, though drained peatlands showed a more cohesive pattern whereas the drained showed more variation. Vegetation differences potentially play a significant role here, as nitrogen-fixing *Sphagnum* mosses are dominant in natural peatlands, whereas the drained sites would potentially have a greater proportion of vascular plants. As plants preferentially use ^{14}N, the expectation would be of greater $\delta^{15}N$ near the surface of the drained profiles, which was evident at Trollberget but not at the Hälsingfors open forested site. As with $\delta^{13}C$, decomposition has been found to contribute to an enrichment of the heavier isotope (Krüger et al., 2015) though this pattern was not evident in our samples.

5. Conclusion

Across all variables, the strongest drainage effect was observed in the top 15–20 cm. Statistically, this difference was only significant in organic matter content and dry bulk density, where the drained peatlands showed lower organic matter content and higher dry bulk density in the top 20 cm. These findings corresponded with expectations, as peatland drainage has been found to increase peat compaction and the rate of organic matter decomposition.

The other variables did not indicate statistically significant differences, though some showed visibly distinct patterns. For example, the C:N ratio at two of the natural sites showed a ratio of around 100 in the top 15 cm of the profile, while the other peatlands were <75 at the same depth. The higher C:N ratio at Stormyran and Degerö could be indicative of lower decomposition rates than the other natural sites, or a reflection of the litter quality at the sites. The carbon content was not distinctly different between the categories, indicating a small drainage effect on carbon concentrations in organic matter. Nitrogen did show a greater difference, as the drained sites had higher nitrogen concentrations in the top 15 cm, a pattern which has also been found in previous research (e.g., Casselgård, 2020).

Neither measure of isotopic composition indicated a significant drainage effect. Previous studies have reported enrichment of the heavier isotope in areas of greater decomposition, as the lighter is preferentially used in the process (Alewell et al., 2011; Krüger et al., 2015). The two drained sites at Trollberget did show greater $\delta^{15}N$ at the depth where decomposition is expected, however, this pattern did not apply at the remaining drained site. Previous research has also found a more uniform $\delta^{13}C$ with depth in areas with low decomposition, which could be the reason for the low variation in $\delta^{13}C$ across the sites.

The practice of drainage is no longer as prevalent as it once was, and peatland restoration projects have been implemented across the country to improve the conditions of previously drained peatlands. In the period between 2010 and 2021 state funds have enabled the restoration of 5729.01 ha of Swedish peatlands, frequently through clogging existing ditches (Öberg, 2018). Further research is required to improve our understanding of peatlands that remain drained and to inform restoration projects. Firstly, based on our study, it would be recommended for future studies to date the peat samples to better understand the relationship between sample age and drainage status. Furthermore, including vegetation surveys in studies would also be beneficial to get a more comprehensive view of the effect of drainage on nutrient dynamics and the peatland ecosystem. The efficacy of restoration projects is contingent upon the biogeochemical processes of peatlands and understanding the impacts of decades of drainage on peat properties is therefore vital to ensure successful outcomes.

References

Abdalla, M., Hastings, A., Truu, J., Espenberg, M., Mander, Ü., & Smith, P. (2016). Emissions of methane from northern peatlands: A review of management impacts and implications for future management options. *Ecology and Evolution*, *6*(19), 7080–7102. https://doi.org/10.1002/ece3.2469

Alewell, C., Giesler, R., Klaminder, J., Leifeld, J., & Rollog, M. (2011). Stable carbon isotopes as indicators for environmental change in palsa peats. *Biogeosciences*, *8*(7), 1769–1778. https://doi.org/10.5194/bg-8-1769-2011

Alsila, T., Elo, M., Hakkari, T., & Kotiaho, J. S. (2021). Effects of habitat restoration on peatland bird communities. *Restoration Ecology*, *29*(1). https://doi.org/10.1111/rec.13304

Bengtsson, F., Granath, G., & Rydin, H. (2016). Photosynthesis, growth, and decay traits in Sphagnum – a multispecies comparison. Ecology and Evolution, 6(10), 3325–3341. https://doi.org/10.1002/ece3.2119

Brady, Nye C., and Weil, Ray R. (2008) *The nature and properties of soils*. 14th edition. US: Pearson

Byrne, K. A., Chojnicki, B., Christensen, T. R., Drosler, M., Frolking, S., Lindroth, A., Mailhammer, J., Malmer, N., Selin, P., Turunen, J., Valentini, R., & Zetterberg, L. (n.d.). *EU Peatlands: Current Carbon Stocks and Trace Gas Fluxes*. 60.

Casselgård, M. (2020.). *Effects of 100 years of drainage on peat properties in a drained peatland forests in northern Sweden*. 41.

Chapin, F. S., Matson, P. A., & Vitousek, P. M. (2011). *Principles of Terrestrial Ecosystem Ecology*. Springer New York. https://doi.org/10.1007/978-1-4419-9504-9

Clymo, R. S. (1984). The Limits to Peat Bog Growth. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, Jan. 30, 1984, Vol. 303, No. 1117

Esri Inc. (2021). ArcGIS Pro (Version 2.9.3). Esri Inc. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte,V., P. Zhai,A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud,Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi:10.1017/9781009157896.009.

Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebsch, F., & Couwenberg, J. (2020). Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nature Communications*, *11*(1), 1644. https://doi.org/10.1038/s41467-020-15499-z

Holmen H. (1964). Forest ecological studies on drained peat land in the province of Uppland, Sweden: Skogsekologiska studier på dikad torvmark i Uppland. Diss. Uppsala University. Primo database (2019-12-10)

Hånell, B. (2009). Möjligheterna till höjning av skogsproduktionen i Sverige genom dikesrensning, dikning och gödsling av torvmarker. In: Fahlvik, N, Johansson, U, Nilsson, U (2009), Skogsskötsel för ökad tillväxt. Faktaunderlag till MINT-utredningen. Bilaga 4. SLU, Rapport pp.17-28. ISBN : 9789186197438

ICOS Sweden (n.d.). Degerö. Retrieved April 29, 2022, from https://www.icos-sweden.se/degero#clim

Ingram, H. A. P. (1978). Soil layers in mires: Function and Terminology *Journal of Soil Science*, *29*(2), 224–227. https://doi.org/10.1111/j.1365-2389.1978.tb02053.x

Joosten H. & Clarke D. (2002). Wise use of mires and peatlands background and principles including a framework for decision-making. Intl Mire Conserv Group, Intl Peat Soc, Vapaudenkatu.

Jukaine, Vasander, H., & Laiho, R. (1995). Long-Term Effects of Water Level Drawdown on the Vegetation of Drained Pine Mires in Southern Finland. *The Journal of Applied Ecology*, *32*(4), 785. https://doi.org/10.2307/2404818

Kimmel, K., & Mander, Ü. (2010). Ecosystem services of peatlands: Implications for restoration. *Progress in Physical Geography: Earth and Environment*, *34*(4), 491–514. https://doi.org/10.1177/0309133310365595

Kotsyurbenko, O. R., Glagolev, M. V., Merkel, A. Y., Sabrekov, A. F., & Terentieva, I. E. (2019). Methanogenesis in Soils, Wetlands, and Peat. In A. J. M. Stams & D. Z. Sousa (Eds.), *Biogenesis of Hydrocarbons* (pp. 211–228). Springer International Publishing. https://doi.org/10.1007/978-3-319-78108-2_9

Krüger, J. P., Alewell, C., Minkkinen, K., Szidat, S., & Leifeld, J. (2016). Calculating carbon changes in peat soils drained for forestry with four different profile-based methods. *Forest Ecology and Management*, *381*, 29–36. https://doi.org/10.1016/j.foreco.2016.09.006

Krüger, J. P., Leifeld, J., Glatzel, S., Szidat, S., & Alewell, C. (2015). Biogeochemical indicators of peatland degradation – a case study of a temperate bog in northern Germany. *Biogeosciences*, *12*(10), 2861–2871. https://doi.org/10.5194/bg-12-2861-2015

Laiho, R., Sallantaus, T., & Laine, J. (1998). *The effect of forestry drainage on vertical distributions of major plant nutrients in peat soils*. 13.

Laine J., Laiho R., Minkkinen K. & Vasander H. (2006). Forestry and boreal peatlands. In: Wieder K. & Vitt D. H. (eds.), *Boreal peatland ecosystems*. Ecological Studies, Boreal Peatland Ecosystem, pp. 331-357.

Liu, H., & Lennartz, B. (2019). Hydraulic properties of peat soils along a bulk density gradient-A meta study. *Hydrological Processes*, *33*(1), 101–114. https://doi.org/10.1002/hyp.13314

Loisel, J., Gallego-Sala, A. V., Amesbury, M. J., Magnan, G., Anshari, G., Beilman, D. W., Benavides, J. C., Blewett, J., Camill, P., Charman, D. J., Chawchai, S., Hedgpeth, A., Kleinen, T., Korhola, A., Large, D., Mansilla, C. A., Müller, J., van Bellen, S., West, J. B., … Wu, J. (2021). Expert assessment of future vulnerability of the global peatland carbon sink. *Nature Climate Change*, *11*(1), 70–77. https://doi.org/10.1038/s41558-020-00944-0

Luan, J., Wu, J., Liu, S., Roulet, N., & Wang, M. (2019). Soil nitrogen determines greenhouse gas emissions from northern peatlands under concurrent warming and vegetation shifting. Communications Biology, 2(1), 132. https://doi.org/10.1038/s42003-019-0370-1

Martí, M., Juottonen, H., Robroek, B. J. M., Yrjälä, K., Danielsson, Å., Lindgren, P.-E., & Svensson, B. H. (2015). Nitrogen and methanogen community composition within and among three Sphagnum dominated peatlands in Scandinavia. *Soil Biology and Biochemistry*, *81*, 204–211. https://doi.org/10.1016/j.soilbio.2014.11.016

Martin-Ortega, J. (2014). Valuing water quality improvements from peatland restoration_ Evidence and challenges. *Ecosystem Services*, 10.

Martikainen, P. J., Nykänen, H., Crill, P., & Silvola, J. (1993). Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. *Nature*, *366*(6450), 51–53. https://doi.org/10.1038/366051a0

Minayeva, T. Yu., Bragg, O. M., & Sirin, A. A. (2017). Towards ecosystem-based restoration of peatland biodiversity. *Mires and Peat*, *19*, 1–36. https://doi.org/10.19189/MaP.2013.OMB.150

Minkkinen, K., Ojanen, P., Koskinen, M., & Penttilä, T. (2020). Nitrous oxide emissions of undrained, forestry-drained, and rewetted boreal peatlands. *Forest Ecology and Management*, *478*, 118494. https://doi.org/10.1016/j.foreco.2020.118494

Naturvårdsverket (2011). Öppna mossar och kärr. Vägledning för svenska naturtyper i habitatdirektivets bilaga 1. https://www.naturvardsverket.se/contentassets/314d0c514b614f52901c298a9c6bec97/vl-7140-oppnamossarochkarr.pdf

Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P., & Lindroth, A. (2008). Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire - a significant sink after accounting for all C-fluxes: Contemporary Carbon Accumulation. *Global Change Biology*, *14*(10), 2317–2332. https://doi.org/10.1111/j.1365-2486.2008.01654.x

Noble, A., Palmer, S. M., Glaves, D. J., Crowle, A., & Holden, J. (2017). Impacts of peat bulk density, ash deposition and rainwater chemistry on establishment of peatland mosses. *Plant and Soil*, *419*(1–2), 41–52. https://doi.org/10.1007/s11104-017-3325-7

Norstedt, G., et al. (2021). From Haymaking to Wood Production: Past Use of Mires in Northern Sweden Affect Current Ecosystem Services and Function. RuralLandscapes: Society,Environment,History, 8(1): 2, 1–15. DOI: https://doi.org/10.16993/rl.70

Ojanen, P., Lehtonen, A., Heikkinen, J., Penttilä, T., & Minkkinen, K. (2014). Soil CO2 balance and its uncertainty in forestry-drained peatlands in Finland. *Forest Ecology and Management*, *325*, 60–73. https://doi.org/10.1016/j.foreco.2014.03.049

Ojanen, P., Minkkinen, K., & Penttilä, T. (2013). The current greenhouse gas impact of forestry-drained boreal peatlands. *Forest Ecology and Management*, *289*, 201–208. https://doi.org/10.1016/j.foreco.2012.10.008

Pinheiro, J.C., and Bates, D.M. (2000) "Mixed-Effects Models in S and S-PLUS", Springer, esp. pp. 236, 243.

Pinheiro J, Bates D, R Core Team (2022). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-157, https://CRAN.R-project.org/package=nlme.

R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/.

Rice, S. K. (2009). Mosses (Bryophytes). In Encyclopedia of Inland Waters (pp. 88–96). Elsevier. https://doi.org/10.1016/B978-012370626-3.00219-2

Ritson, J. P., Bell, M., Brazier, R. E., Grand-Clement, E., Graham, N. J. D., Freeman, C., Smith, D., Templeton, M. R., & Clark, J. M. (2016). Managing peatland vegetation for drinking water treatment. *Scientific Reports*, *6*(1), 36751. https://doi.org/10.1038/srep36751

Rochefort, L., and Lode, E. (2006). Restoration of degraded boreal peatlands. In: Wieder K. & Vitt D. H. (eds.), Boreal peatland ecosystems. Ecological Studies, Boreal Peatland Ecosystem, pp. 331-357.

Rydin, H., Gunnarsson, U., Sundberg, S. (2006). The role of *Sphagnum* in peatland development and persistence. In: Wieder K. & Vitt D. H. (eds.), *Boreal peatland ecosystems*. Ecological Studies, Boreal Peatland Ecosystem, pp. 331-357.

Simola, H., Pitkänen, A., & Turunen, J. (2012). Carbon loss in drained forestry peatlands in Finland, estimated by re-sampling peatlands surveyed in the 1980s. European Journal of Soil Science, 63(6), 798–807. https://doi.org/10.1111/j.1365-2389.2012.01499.x

Sinclair, A. L., Graham, L. L. B., Putra, E. I., Saharjo, B. H., Applegate, G., Grover, S. P., & Cochrane, M. A. (2020). Effects of distance from canal and degradation history on peat bulk density in a degraded tropical peatland. *Science of The Total Environment*, *699*, 134199. https://doi.org/10.1016/j.scitotenv.2019.134199

Skogsstyrelsen (2022) Olika typer av dikning. Retrieved June 18, 2022, from https://www.skogsstyrelsen.se/bruka-skog/dikning/dikning/

Skogssällskapet (2020) Ny forskning ska visa hur skog på torvmark kan göra bäst klimatnytta. Retrieved April 18, 2022, from https://www.skogssallskapet.se/kunskapsbank/artiklar/2020-10-27-ny-forskning-ska-visa-hur-skog-pa-torvmark-kan-gora-bast-klimatnytta.html

SLU (2017) Research at the Degerö mire. Retrieved April 29, 2022, from https://www.slu.se/en/departments/field-based-forest-research/experimental-forests/vindeln-experimental-forests/degero_stormyr/

Price, J. S., & Schlotzhauer, S. M. (1999). Importance of shrinkage and compression in determining water storage changes in peat: The case of a mined peatland. Hydrological Processes, 13(16), 2591–2601. https://doi.org/10.1002/(SICI)1099-1085(199911)13:16<2591::AID-HYP933>3.0.CO;2-E

Thermo Fisher scientific, EA-IRMS. Elemental Analyzer - Isotope Ratio Mass Spectrometry [product] https://www.thermofisher.com/order/catalog/product/11206175#/1120617

Turetsky, M. R., Kotowska, A., Bubier, J., Dise, N. B., Crill, P., Hornibrook, E. R. C., Minkkinen, K., Moore, T. R., Myers-Smith, I. H., Nykänen, H., Olefeldt, D., Rinne, J., Saarnio, S., Shurpali, N., Tuittila, E.-S., Waddington, J. M., White, J. R., Wickland, K. P., & Wilmking, M. (2014). A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands. *Global Change Biology*, *20*(7), 2183–2197. https://doi.org/10.1111/gcb.12580

Vasander, H., Drösler, M. (2008). Executive Summary for Policymakers. In: Strack M (ed), *Peatlands and Climate Change*. International Peat Society, pp. 9-10.

Waddington, J. M., & Roulet, N. T. (2000). Carbon balance of a boreal patterned peatland. *Global Change Biology*, *6*(1), 87–97. https://doi.org/10.1046/j.1365-2486.2000.00283.x

Wang, M., Moore, T. R., Talbot, J., & Riley, J. L. (2015). The stoichiometry of carbon and nutrients in peat formation: C and nutrients in peat. Global Biogeochemical Cycles, 29(2), 113–121. https://doi.org/10.1002/2014GB005000

Wickham H (2016). ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York. ISBN 978-3-319-24277-4, https://ggplot2.tidyverse.org.

Wieder, R. K. (2006). Primary Production in Boreal Peatlands. In: Wieder K. & Vitt D. H. (eds.), *Boreal peatland ecosystems*. Ecological Studies, Boreal Peatland Ecosystem, pp. 145-159.

Yu, Z., Beilman, D. W., Frolking, S., MacDonald, G. M., Roulet, N. T., Camill, P., & Charman, D. J. (2011). Peatlands and Their Role in the Global Carbon Cycle. *Eos, Transactions American Geophysical Union*, *92*(12), 97–98. https://doi.org/10.1029/2011EO120001

Zhuang, Q., Melillo, J. M., Sarofim, M. C., Kicklighter, D. W., McGuire, A. D., Felzer, B. S., Sokolov, A., Prinn, R. G., Steudler, P. A., & Hu, S. (2006). CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. *Geophysical Research Letters*, *33*(17), L17403. https://doi.org/10.1029/2006GL026972

Öberg H. (2018). Hydrologisk restaurering av torvmarker. Sveriges Miljömål, Naturvårdsverket. Retrieved May 16, 2022, from: https://www.sverigesmiljomal.se/miljomalen/myllrande-vatmarker/hydrologisk-restaurering-av-torvmarker/

Popular science summary

Peatlands are wetland ecosystems where the limited oxygen availability prevents decomposition, resulting in the formation of partially decayed organic materials, i.e., peat. The accumulation of peat makes peatlands a persistent and efficient carbon sink. Though peatlands are now considered an important tool in climate change mitigation, they were frequently drained to make way for agriculture and forestry in the 19^{th}-20^{th} century. Drainage lowers the water table of peatlands, resulting in greater oxygen availability, altered microbial processes, and structural changes within the peat. Though many peatlands are currently being restored, the changes brought by drainage can still impact the function and processes of the peatland ecosystem. The aim of this thesis is therefore to study the drainage impacts on key chemical and physical indicators, by comparing natural and drained peatlands in northern Sweden.

The chosen properties were dry bulk density, percent organic matter (OM), carbon to nitrogen (C:N) ratio, carbon content, nitrogen content, and stable isotope analyses of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). At each peatland, samples were collected to a depth of 50cm, and groundwater data was also recorded at four of the seven sites.

Dry bulk density is a useful measure of how densely material is packed in the soil and was found to be higher in the drained peatlands. This is indicative of the compaction associated with water table drawdown. Organic matter content was found to be lower near the surface of the drained sites, which may also indicate peat degradation due to the greater oxygen availability at the drained sites. The C:N ratio, carbon content, and nitrogen content did not show statistically significant differences, though differing patterns were most visible in the top 20 cm, where oxygen availability would be the most different between the sites. $\delta^{13}C$ and $\delta^{15}N$ are isotopic indicators and were not statistically significant between the categories. Decomposition processes, vegetation differences, and microbial processes can affect these variables and warrant further study.

Most significant differences were found in the top 20-30 cm, indicating that the increased oxygen availability does affect peat chemical and physical properties and subsequently the biogeochemical processes. As drained peatlands are rewet with the aim to restore carbon storage capacities and ecosystem functions, it is important to evaluate the potentially long-lasting effects on drainage.

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Appendix 1

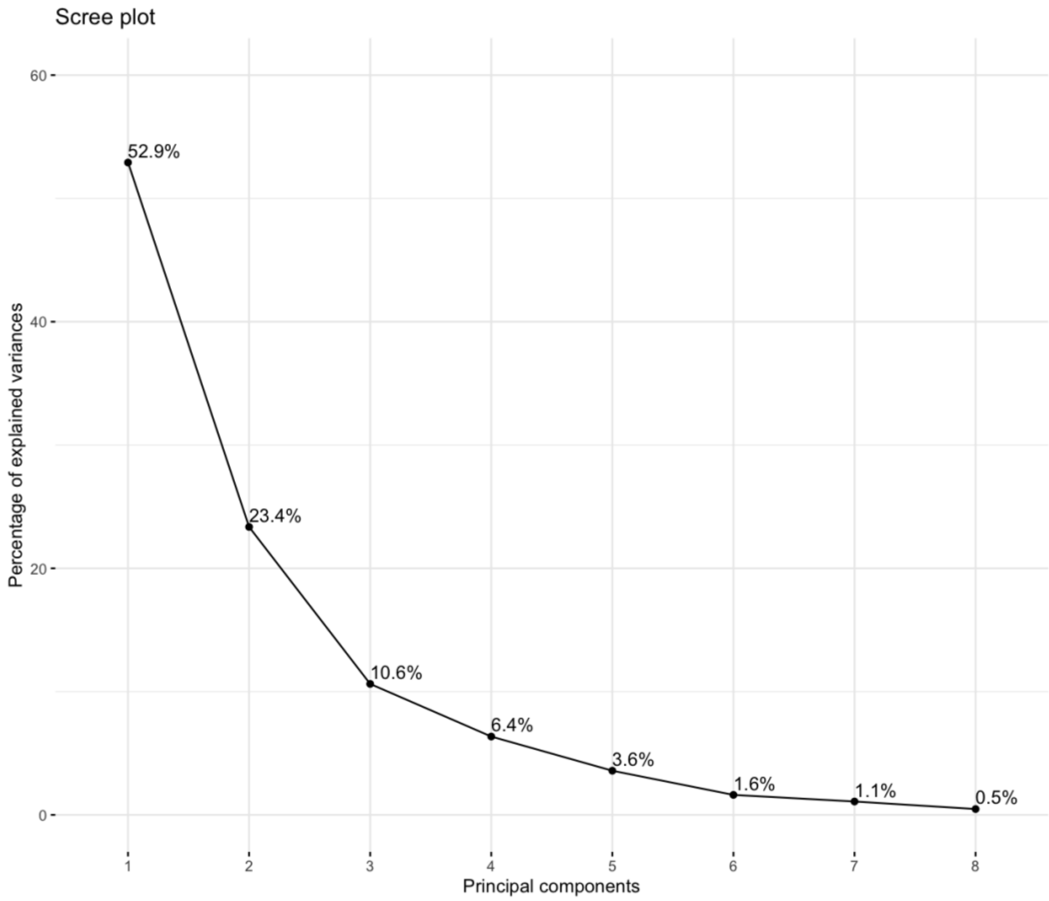

Figure 11 *Scree plot illustrating the influence of each principal component of the PCA.*

Appendix 2

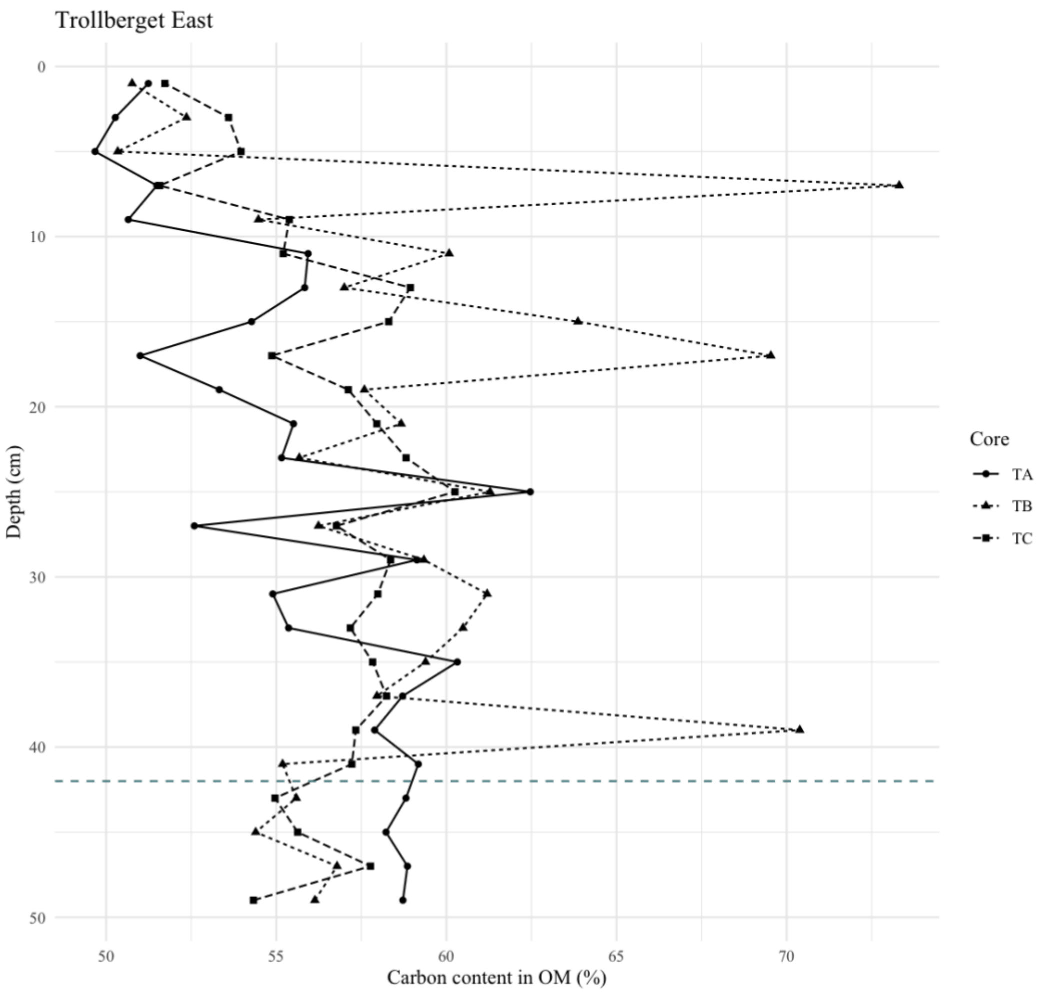

Figure 12 *Carbon concentrations of the three individual cores at Trollberget East (drained peatland site).*

Appendix 3

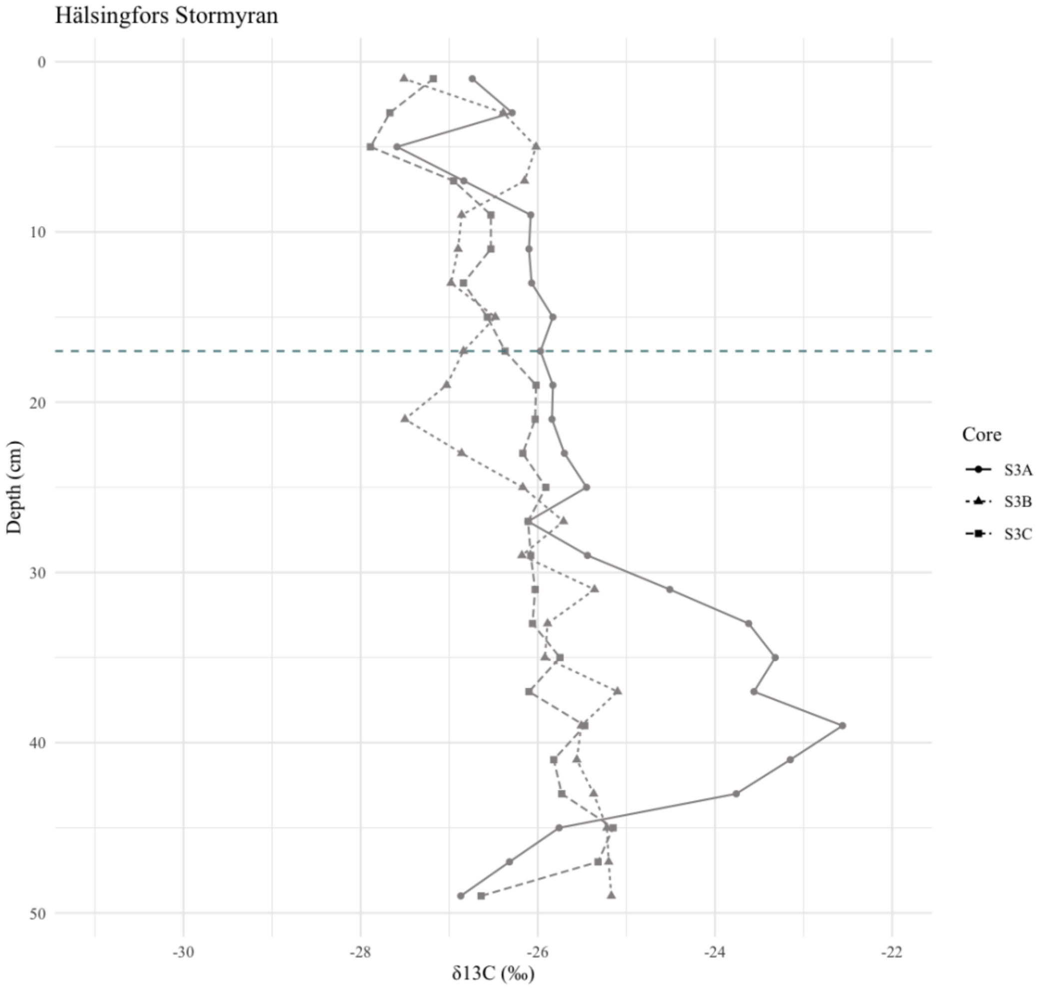

Figure 13 *$\delta^{13}C$ patterns of the three cores from Hälsingfors Stormyran (drained peatland site).*

Appendix 4

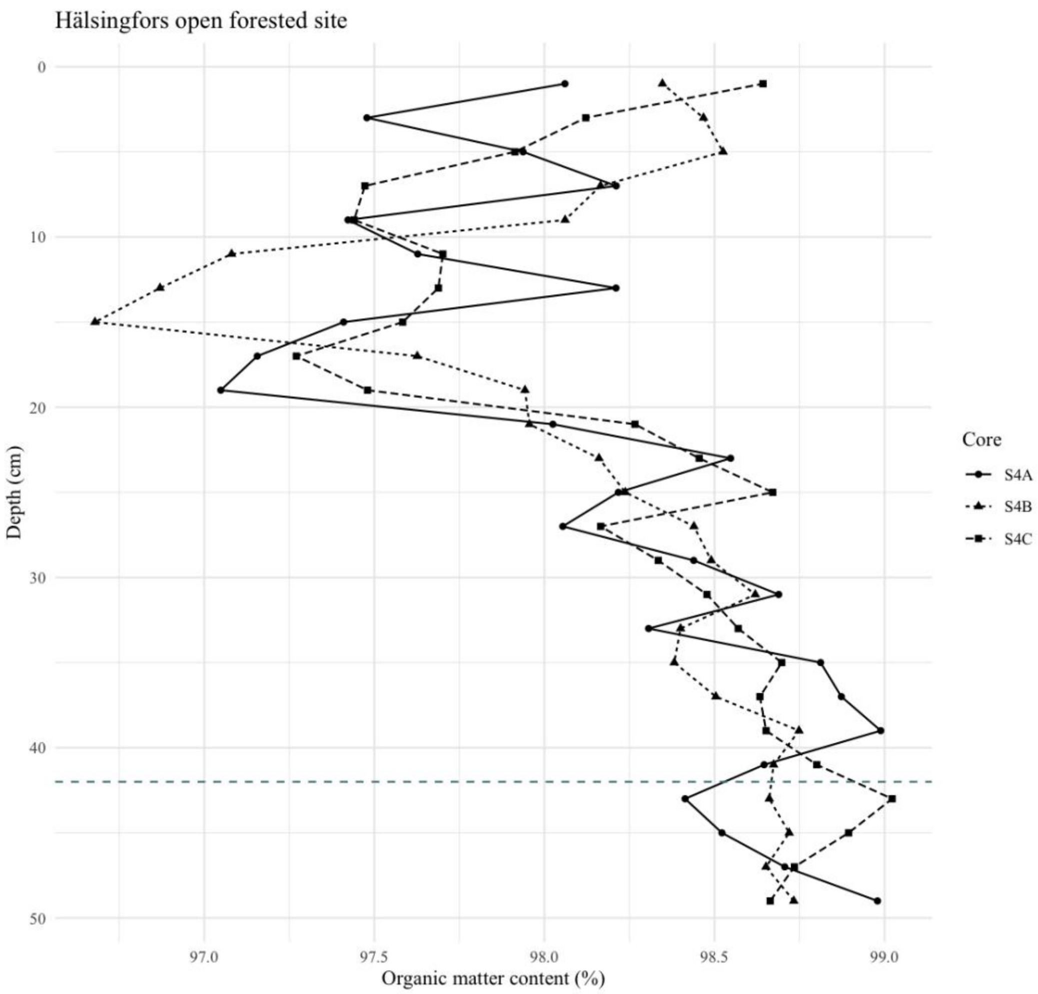

Figure 14 *Organic matter content of the three cores taken at the drained Hälsingfors open forested site.*

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