Biogeochemistry and Peat Properties of Restored Peatlands

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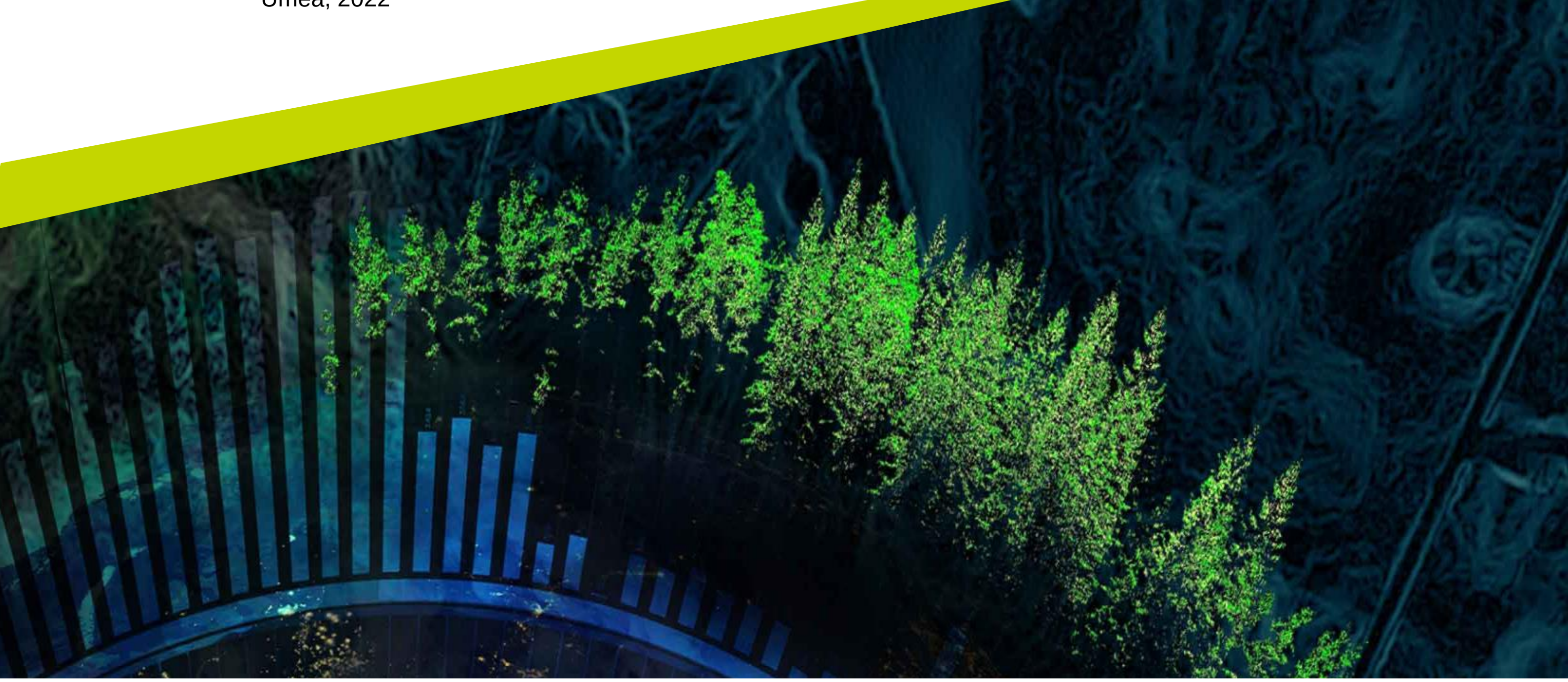

Biogeochemistry and Peat Properties of Restored Peatlands

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Abstract

Globally, peatlands comprise the most important soil organic carbon pool storing approximately one third of all terrestrial soil carbon. Drainage can turn peatlands to net sources of carbon dioxide. Peatlands have historically been drained to increase the productivity of agriculture and forestry. To mitigate the undesired effects of peatland drainage the interest in peatland restoration is growing on a global level. However, peatland restoration does not only have beneficial effects since it can cause increased methane production and mercury methylation.

The overall aim of this study was to investigate the differences in peat properties between natural and restored peatlands. Peat cores were sampled from restored peatlands and adjacent natural control mires. The bulk density, organic matter content, C content, N content, C/N ratio, $\delta^{13}C$ and $\delta^{15}N$ in the cores were then analysed. The results indicated that there were statistically significant differences at certain depths between the natural and restored peatlands for these properties. At these depths the restored peatlands had higher bulk density, C content, N content, and $\delta^{15}N$, while the natural cores had higher organic matter content, C/N ratios and $\delta^{13}C$. Except for $\delta^{13}C$ this is how these properties are expected to be affected following drainage.

Overall, these results indicate that the soil properties at the restored peatlands have changed during the time they were drained and are different from the soil conditions at natural pristine mires. This could make the impact on biogeochemical processes challenging to predict following restoration. Therefore, more research on how these changed soil properties affect the outcome of peatland restoration projects is needed.

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Keywords: Drainage, bulk density, Nitrogen, Carbon, stable isotopes

Sammanfattning

Torvmarker utgör globalt en av de viktigaste kolsänkorna och lagrar en tredjedel av allt markbundet kol. Dränering kan göra att torvmarker istället blir kolkällor till atmosfären. Torvmarker har historiskt dränerats för att öka produktiviteten för jordbruk och skogsbruk. För att motverka effekterna av dränering växer intresset för att återställa torvmarker globalt. Men återställning av torvmarker har inte bara gynnsamma effekter då det kan öka metanproduktionen och kvicksilvermetylering.

Målet med den här studien var att undersöka skillnader i torvegenskaper mellan naturliga och återställda torvmarker. Torvkärnor hämtades från återställda torvmarker samt närliggande naturliga torvmarker. Bulkdensiteten, det organiska innehållet, kolhalten, kvävehalten, C/N kvot, $\delta^{13}C$ och $\delta^{15}N$ i kärnorna undersöktes. Resultatet indikerade att det fanns statistiska skillnader mellan de återställda och naturliga myrarna vid vissa djup för de här torvegenskaperna. Vid dessa djup hade de återställda torvmarkerna högre bulkdensitet, kolhalt, kvävehalt och $\delta^{15}N$, medan de naturliga myrarna hade högre organiskt innehåll, C/N kvot och $\delta^{13}C$. Förutom för $\delta^{13}C$ är detta hur dessa egenskaper förväntas påverkas efter dränering.

Resultaten indikerade att markegenskaperna vid de återställda torvmarkerna har ändrats under tiden de var dränerade och är annorlunda från markegenskaperna för naturliga myrar. Detta kan göra att det är utmanande att förutse hur de biogeokemiska processerna påverkas av torvmarkers återställning. Det finns ett behov av mer forskning på hur dessa förändrade torvegenskaper påverkar resultatet av återställning av torvmarker.

Nyckelord: Dränering, bulkdensiteten, kol, kväve, stabila isotoper

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Abbreviations

ANOVA	Analysis of variance
BD	Bulk density
OM	Organic matter
PCA	Principal component analysis
SLU	Swedish University of Agricultural Sciences

1. Introduction

Natural peatlands have a net cooling effect on the climate (IUCN, 2021). Drainage lowers the water table and can turn peatlands from net sinks to net sources of carbon dioxide **(**Karki et al., 2016; Günther et al., 2020)**.** Drained peatlands also cause nutrient leakage and can reduce the quality of drinking water as it becomes polluted with organic carbon and pollutants that were historically absorbed by the peat (IUCN, 2021). For these reasons there is a great interest in restoring peatlands in Sweden and other EU countries (Tenning, 2015; Andersen et al., 2017). The main goal with wetland restoration projects is to recover the main functions of undisturbed wetlands. This is achieved by raising the water table to levels similar to the level's characteristic of the original wetlands (Tenning, 2015; Casselgård, 2020)**.**

However, wetland restoration can also result in undesired impacts and potential environmental threats such as increased methane production and microbial formation of methyl-mercury (Lai, 2009; Eklöf, 2021). We currently have a solid scientific knowledge on the fundamentals of methane and mercury biogeochemistry at peatlands. However, a century or more of drained conditions could have drastically changed the physical and chemical soil properties at the restored peatlands in relation to natural wetlands (Hånell, 2009; Kruger et al., 2015). Thus, even if drained peatlands are rewetted it is very likely that these differences in the chemical and physical properties will remain between natural undisturbed peatlands and the restored peatlands (Kreyling et al., 2021). This renders the impact of restoration on biogeochemical processes such as methane production and mercury methylation difficult to predict.

This study is written under the umbrella of more extensive project at the Swedish University of Agricultural Sciences (SLU), Umeå, which has the aim of identifying properties of rewetted wetlands that are critical for methane production and mercury methylation. Understanding these biological systems is urgently needed for developing models and strategies to minimize the undesired effects of peatland restoration. The outcome of the SLU project will be a set of easily identified wetland soil characteristics that will tell whether or not a specific wetland will turn into a hot-spot for methane emissions or mercury net methylation following restoration

The SLU project will study the top 50 cm of restored peatland soils. This upper part of the peat profiles will be tested for several things including its chemical and physical properties, vertical distribution of methane producing and mercury methylating microbial communities, the total amount of Hg in the peat profiles, and methane production. Measurements from adjacent natural peatlands will be used as references to these results.

This study focuses on characterizing some of the physical and chemical properties of the peatlands, and how they have been affected by the restoration. This is important since these properties affect the distribution of the methane producing and mercury methylating microbial communities at the peatlands. These communities affect the production of methane and mercury methylation (Zhou et al., 2017; Putkinen et al., 2018; Eklöf, 2021**).** More specifically when comparing natural and restored peatlands I have focused on the following peat properties: bulk density, organic matter content, C-content, N-content, C/N ratio, $\delta^{13}C$ and $\delta^{15}N$. The questions this study intended to answer were:

- How do the physical and chemical peat properties change with depth along the peat profiles for the natural and restored peatlands?
- What are the differences in physical and chemical peat properties between a restored (previously drained) vs. a natural peatland? Have ~ 10 years of restored conditions returned the peatlands to their original state?

1.1 Peat

Peat consists of the remains of dead organic material and is formed when the rate of organic matter (OM) deposition in the soil exceeds the rate of decay. This occurs under water-saturated conditions when the anaerobic conditions prevent most of the decomposition of organic material thus forming peat (Minkkinen & Laine 1998; Rydin et al., 2015). However, there is some decay in the buried peat trough anaerobic processes releasing some carbon in the form of carbon dioxide and methane (Strack et al., 2016;2017. Natural peat grows slowly at an average rate of 0-3mm/year. Quite different plant material can be involved in peat formation including woody parts, leaves, roots, rhizomes, and bryophytes (Rydin et al., 2015). In the northern hemisphere *sphagnum* moss dominate the vegetation at peatlands (Amesbury et al., 2015). According to most definitions peat has at least 30 % (dry mass) of OM (Jungkunst et al., 2012), but *sphagnum* peat typically has OM contents of at least 80–90% (Rydin et al., 2015).

1.2 Peatland

Peatlands have been estimated to globally have an area of 4 million km^2, approximately 3% of the earth's terrestrial surface area (Maltby & Proctor, 1996;

Rydin et al., 2015). Peatland is terrain where the soil consists of peat (Minkkinen, 1999). A minimum depth of peat soil is required for a site to be classified as a peatland: in Sweden the limit is a peat depth of more than 30 cm (Hånell, 2006). Peat soils can have a thickness from 0.3m to more than 15m (Agus et al., 2011; Rydin et al., 2015). Peatlands are usually found in regions with humid climate and favourable geomorphological features, including its position in the landscape (Rydin et al., 2015; Finlayson et al., 2016). Peatlands are for example often formed in local topographical depressions (Householder E & Page, 2021). Peat will never accumulate where there is surface erosion, as the plant debris is washed away rather than accumulating (Xintu, 2009). These conditions can be found all over the world from the tropics to the Arctic (Rydin et al., 2015). The greatest concentration of the world's peatlands occurs in the humid climates of the boreal northern hemisphere (Tfaily et al., 2014). For example, the Swedish land area consists of 6 million hectares of peatlands which corresponds to about 13% of the total land area (Hånell 2009).

1.2.1 Peatland: Mire, fens and bogs

A mire is a term for a wet terrain dominated by living peat forming plants. In one sense it is a broader concept than peatlands since peat accumulation can occur on sites that have not accumulated the required depth of peat to be classified as a peatland (Rydin et al., 2015). Mires and peatlands are commonly classified on the basis of its water source that governs its water and nutrient chemistry. Fens are minerotrophic and thus receive their nutrients primally trough mineral rich groundwater. This input typically results in high mineral concentrations and a more basic pH in these mires (Rydin et al., 2015). Bogs are mires with the surface above the surrounding terrain or otherwise isolated from laterally moving mineral-rich soil waters. They receive all their nutrients and minerals from precipitation. Bogs are thus nutrient poor and acidic. The vegetation in fens is dominated by grasses and grass like plants like sedges if nutrient regime allows for it. Under more nutrient poor conditions *Sphagnum* mosses dominate. In bogs the vegetation is dominated by the growth of *sphagnum* and heats (Rydin et al., 2015).

1.3 Greenhouse gases

Peatlands affect the carbon cycle and the emissions of greenhouse gases on a global scale. They notably affect the balance of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Globally, peatlands comprise the most important soil organic carbon pool storing more than 600 Pg of carbon, this is one third of all terrestrial soil carbon (Minkkinen, 1999; Tfaily et al., 2014). In fact, peatlands store more carbon than all vegetation found in the world combined.

Natural peatlands act as net atmospheric sinks of CO_2 and display negligible N_2O emissions (Karki et al., 2016; Liimatainen et al., 2018). They can even act as a net sink for N_2O (Liimatainen et al., 2018). However natural peatlands are a net atmospheric source for CH_4 (Karki et al., 2016).

1.4 Drainage and restoration

1.4.1 Drainage

Peatlands have historically been drained for several reasons. Spatially most of the drainage have been done to eliminate anaerobic conditions to increase the soil productivity for agriculture and forestry. But peatlands have also been drained for other reasons including to stabilize the substrate for road construction and for increasing the capacity of soil to support heavy machinery for industrial activities like peat and petroleum extraction (Landry & Rochefort 2012). In boreal Europe most peatlands have been drained to increase forestry production (Krüger, 2016). The technique of draining peatlands to improve forest growth has a long history and was already a well-known practise during the middle of the 19^{th} century. The aim of the drainage is to adjust the water content in peatlands to ensure sufficient aeration for tree roots. This is achieved by lowering the water table by digging drainage ditches (Laine et al., 2006). This practise was the greatest after 1950 when mechanized techniques replaced manual ditching, it peaked in the 1960s to 1970s and largely ended after the 1980s (Nieminen et al., 2021). Due to this ditching only a minor fraction of the original wetlands remains in Europe, around 15 million hectares of the northern peatlands have been drained for forestry. More than 90% of this area is found in Scandinavia and Russia (Laine et al., 2006).

In total between 1.5-2 million hectares of peatland have been drained in Sweden (Hånell, 2006). In Sweden the forest drainage was most intense between 1920-1940 as it became a way to decrease the unemployment during the depression (Holmen 1964). A second peak in ditching occurred in the 1980s because of new ditching techniques. Since 1986 forest owners must seek permission and pay for ditching (Hånell, 2009). Due to these environmental restrictions and low productivity of these soils the interest in ditching is today very low in Sweden (Hånell, 2009; Maswar et al., 2021).

Drainage lowers the water table in the peatlands causing aerobic peat mineralization. This can turn the peatlands to net sources of CO_2 and N_2O (Karki et al., 2016; Slowinski et al., 2016; Liimatainen et al., 2018; Leifeld, 2018). Drained peatlands emit ca. 2 Gt of CO_2 each year, contributing to 5% of all anthropogenic GHG emissions (Günther et al., 2020). However, drainage can also reduce the CH_4 emissions from peatlands (Karki et al., 2016). Methane has a 25 times greater global warming potential than CO_2 over a 100-year scale (Lai, 2009)**.** When rewetting drained peatlands there thus is a trade-off between increased CH_4 emissions and decreased CO_2 emissions. Drainage also affects the vegetation that grows on the peatlands. Long lasting water table decrease and increased shading by tree stands increases the forest species on the peatlands (e.g. *Vaccinium myrtillus, Vaccinium vitisidaea*) and decreases the peat forming *Sphagnums* and sedges (Nykänen et al., 2018, Casselgård, 2020)**.**

1.4.2 Restoration

Because the ecosystem services peatlands provide**,** they are becoming increasingly valued at the global level and interests in restoring peatlands is growing. Between 1993 and 2015 the EU-LIFE nature programme invested 167.6 M euro in 80 projects. The projects aimed to restore 913 km^2 of peatland habitats in European countries (Andersen et al., 2017). Peatland restoration can play a key part in increasing biodiversity, decreasing the net release of CO_2 to the atmosphere, improving groundwater quality and decreasing eutrophication (Andersen et al., 2017; Casselgård, 2020).

Restoration of peatlands typically involve rewetting the system by blocking drainage ditches, restoring the hydrological regime, and facilitating the return of peat-forming vegetation. Flooding these environments decreases the rate of peat decomposition by physically impeding the transport of oxygen required for oxic respiration in the soil and it also creates habitat for wildlife (Knox et al., 2015). However, raising the water table can also lead to increased methane production and mercury methylation.

Between 2010-2021 ca 5739, 01 ha of peatlands have been hydrologically restored in Sweden (Öberg, 2021). Most of these peatlands have been within the project *Life to Ad(d)mire* which was an EU-LIFE funded project. During the project (2010-2015) 35 peatlands were restored in 7 counties (Jämtland, Västernorrland, Dalarna, Jönköping, Östergötland, Kronberg and Skåne). In practice, the restorations were achieved by filling the ditches so that the peatlands were no longer being drained. Excavators were used to fill in thousands of meters of ditches. In total 2930 ha of peatlands were restored in these counties during the project (Tenning, 2015).

1.5 Drainage impact on peat properties

1.5.1 Bulk Density

Peat has a very low mineral content and therefore is much less dense than other soil materials and most of its volume is occupied by water when wet. Bulk density (BD) values of peat soils generally range between 0.03 and 0.3 g/cm^3. Under more extreme conditions the BD of peat can be between <0.01 and >0.4 (Agus et al., 2011). Vertically the BD of peat typically increases downwards because increasing decomposition results in a loss of strength in the organic matrix, which leads to compaction as more mass accumulates above it (Minkkinen & Laine 1998; Hansson et al., 2013). The botanical composition of peat also affects its BD. Peat with vegetation dominated by grasses and sedges is usually denser than *sphagnum* peat and residues of wood-forming vegetation also raises the BD (Minkkinen & Laine 1998). Climatic and hydrological conditions can thus affect the BD by influencing the type of vegetation that grows on it. Following drainage and the drawdown of the water-level, plant structures collapse and the peat surface subsidies quickly. The surface peat layers are consequently compacted into a smaller volume, and the peat density is increased. Later on, the accelerated rate of organic decomposition and compacts the peat at drained mires. If trees start colonizing the peatland following drainage the pressure of growing tree stands also further compacts the peat. The degree of decomposition in peat correlates positively with BD (Minkkinen & Laine 1998).

The BD is closely related to many other physical properties such as hydrological conductivity, total pore space, water content and water retention properties (Minkkinen & Laine 1998). Higher BD typically means that the peat contains less water at saturation and has a lower hydrological conductivity (Laine et al., 2006).

1.5.2 Organic matter

Peat is partially decomposed organic material and thus consist of high amounts of OM. There is no general agreement on how to define peat using OM content; the minimum percentage of OM required has ranged from 20% to 80% (Rydin et al., 2015). In Sweden the peat typically has organic content of 90–98% (Sohlenius et al., 2013). The mineral content in peat is derived primally from peat forming plants but it may also have been introduced by flooding or been deposited from the atmosphere. The mineral content of peat strongly affects its BD since the particle density of it is almost twice that of OM (Minkkinen & Laine 1998). Drainage will cause a lower water table in the peatland will expose the organic material to oxygen increasing peat decomposition and the OM in the peat will decrease (Krüger et al., 2015).

1.5.3 Carbon and nitrogen content

The carbon content (C%) is the mass of carbon per unit dry weight of soil. The carbon content in peat soils typically range from 18-60% (Agus et al., 2011), primarily driven by the OM-content. The nitrogen content (N%) is the mass of nitrogen per unit weight of dry soil. The nitrogen content in peat soils typically range from 0.3-4% (Tfaily et al., 2014). The nitrogen content in peat can vary depending on the surface vegetation. Peat that is developed from sedges and reeds usually have 2-4 times higher nitrogen content than peat formed by *Sphagnum* mosses (Tfaily et al., 2014). The peat carbon content can also vary depending on the botanical composition, *Sphagnum* peat has significantly lower carbon content than other peat types (Chambers et al., 2010). During decomposition the organic C and N content increase and since deeper peat is typically more decomposed compared to shallow peat increasing C and N content is expected with depth (Damman, 1998, Leifeld et al., 2020: Tfaily et al., 2014).

Following drainage, the carbon content and nitrogen content of peat typically increases. During the decomposition, the carbon compounds in the peat are consumed but there is no inert mineral material to increase in relative concentration, so the remaining material relatively increases in carbon even as C is lost (Minkkinen, 1999; Tfaily et al., 2014). Nitrogen content increases during decomposition when the nitrogen is immobilized in microbial biomass as soil microbes accumulate nutrients from decomposition products and the surrounding soil. Also, some of the substrate is converted to fluvic and humic compounds that have high N content (Tfaily et al., 2014).

1.5.4 C/N ratio

Soil C/N ratios in intact peat varies over a wide range due to differences in vegetation, site condition, the respective soil layer, and atmospheric N deposition. C/N ratios of organic soils formed by peat accumulation are much higher than those of mineral soils. A study of northern peatlands revealed a median C/N ratio of 49 (Leifeld et al., 2020). The C/N ratio indicate the degree of decomposition of the peat material. Peat that is only slightly decomposed has larger C/N ratios reflecting the former plant material. During decomposition the ratio becomes smaller owing to a preferential loss of C over N during microbial decomposition, as well as by external N inputs to topsoils from atmospheric deposition (Krüger et al., 2015; Leifeld, 2018). Deeper and older peat is more decomposed than surface peat, thus decreasing C/N ratios are expected with depth (Leifeld et al., 2020). After drainage the C/N ratio of the remaining organic material is thus also expected to decline (Leifeld, 2018).

1.5.5 Carbon and Nitrogen isotopes

There are two stable carbon isotopes: ^{12}C and ^{13}C. The substrates that make up and form the peat has a specific range of $\delta^{13}C$ values. It is the water table level and surface vegetation composition that control what $\delta^{13}C$ a peat site has. Peatlands with more vascular plants growing are typically depleted in ^{13}C compared to peatlands with more *Sphagnum* (Nykänen et al., 2018). In peat-forming C3 plants the $\delta^{13}C$ values is in the range between -33 and -24 ‰, Loisel et al., (2010) found that the average $\delta^{13}C$ values for *sphagnum* was -26.5 ‰. There are two stable nitrogen isotopes: ^{14}N and ^{15}N. The $\delta^{15}N$ values at natural peatlands are assumed to scatter around 0 ‰ since atmospheric nitrogen is the primary source of nitrogen in these ecosystems. However, plant species in peatlands can vary in their δ ^{15}N signature from -11.3 ‰ to +2.7 ‰, this can influence the $\delta^{15}N$ values of the remaining peat material (Krüger, 2016).

Previous studies on peat have shown that in undrained peatlands the $\delta^{13}C$ and $\delta^{15}N$ values of the substrates is mostly preserved due to the anaerobic conditions. The $\delta^{13}C$ and $\delta^{15}N$ values thus have a uniform or only slightly increasing trend with depth in these peatlands (Alewell et al., 2011; Krüger et al., 2015). Following drainage or drier conditions, the water table in peatlands decreases enabling aerobic conditions. Under aerobic conditions, the original $\delta^{13}C$ or $\delta^{15}N$ values change because the decomposers prefer the lighter isotopes. Thus, according to this theory, the original $\delta^{13}C$ and $\delta^{15}N$ values are expected to increase with depth after drainage because of the increased decomposition rates (Alewell et al., 2011; Krüger et al., 2015).

2. Material and Method

2.1 Site description

Peat cores were sampled from six restored peatlands in Västernorrland and Jämtland, table 1. These two regions were chosen to get results from peatlands with different nutrient status and pH. All the sampled peatlands were restored within the EU "Life to ad(d)mire" project between 2010 and 2015 (Tenning, 2015). Peatlands restored within the "Life to ad(d)mire" project were chosen for this project since it is important that the peatlands have been restored with the same method and for the same amount of time when comparing the effect of the restoration. Unfortunately, there is a lack of available information about the drainage history of these restored peatlands, for example when they were first drained or if there have been ditch-cleaning at the sites**.** It is however known that none of these peatlands were drained for peat extraction or agriculture (Länsstyrelsen Jämtland län 2012; Harning, 2013; Länsstyrelsen Jämtland län, 2018a-b; Länsstyrelsen Västernorrland län, 2018a-c). For all restored peatland sites, cores were also sampled from an adjacent natural peatland. The natural peatlands were peatlands that never had been drained and that were located as closely as possible to their restored peatland. The occurrence of an adjacent natural peatland was thus a requirement when these six restored peatlands were chosen from the peatlands that had been restored. Another reason why these restored peatlands were chosen was that they were located close to roads and relatively close to each other, this made it possible to finish the sampling within the timeframe of the project.

Table 1. The locations, abbreviations, and coordinates of the sampled peatlands

County	Peatland	Abbreviations for the cores from the natural peatlands	Abbreviations for the cores from the restored peatlands	Coordinates
Jämtland	Ånnsjön N	ANN 1-3	ANR 1-3	Natural: 63,3142; 12,5292 Restored: 63,3168; 12,5297
	Ånnsjön S	ANN 4-6	ANR 4-6	Natural: 63,3118; 12,5266 Restored: 63,3165; 12,5289
	Öjsjömyrarna	OMN 1-3	OMR 1-3	Natural: 63,4587; 15,1062 Restored: 63,4533; 15,0940
Västernorrland	Mossaträsk	MTN 1-3	MTR 1-3	Natural: 63,8227; 17,3073 Restored: 63,8221; 17,3178
	Stensjöflon	SFN 1-3	SFR 1-3	Natural: 63,2515; 16,4828 Restored: 63,2545; 16,4719
	Sör-Lappmyran	SLN 1-3	SLR 1-3	Natural: 62,8852; 17,5829 Restored: 62,8796; 17,5692

When describing the peatlands the Swedish environmental protection agency's (Naturvårdsverket) classifications of peatlands will be used (Naturvårdsverket, 2010; Naturvårdsverket, 2011). The peatlands located in Jämtland were Ånnsjön N, Ånnsjön S and Öjsjömyrarna, table 1. Ånnsjön is a large peatland complex dominated by fens (Länsstyrelsen Jämtland, 2018a). Ånnsjön mire is a large peatland complex, dominated by blanket bogs (1430 ha) (Länsstyrelsen Jämtland, 2008a). This mire was therefore sampled at two different ends of the former drainage system, which is denoted as two separate mires in the following study: Ånnsjön North (N) and Ånnsjön South (S). Both restored sites were paired with respective adjacent reference mire, i.e., natural mires that were never drained or restored. Blanket bogs are open mires with ombrotrophic conditions. In these types of mires vegetation that normally is associated with fens can be found (Länsstyrelsen Jämtland, 2011). The drainage ditches at Ånnsjön were constructed more than 100 years ago by the people living close to the peatland to reduce the ice fog from it (Harning, 2013).

Öjsjömyrarna mostly consists of alkaline fens (244 ha) and transition mires and quaking bogs (76.3 ha). The peatlands have a rich vegetation of grasses and sedges (Länsstyrelsen Jämtland, 2018b). Alkaline fens are wetlands mostly consisting of peat producing small sedge and brown moss communities developed on permanently waterlogged soils (Länsstyrelsen Jämtland, 2018b). Transition mires and quaking bogs refer to peatlands with vegetation that is transitional between that of an acid bog and an alkaline fen (Länsstyrelsen Jämtland, 2018b). The first drainage ditches at Öjsjömyrarna were constructed at the start of the 20th century (Länsstyrelsen Jämtlands län, 2012).

The mires located in Västernorrland were Mossaträsk, Stensjöflon and Sör-Lappmyran, table 1. Mossaträsk is the largest peatland in Västernorrland. The peatland is dominated by aapa mire complexes (549 ha) (Länsstyrelsen Västernorrland, 2018c). The northern aapa mire complexes are characterized by patterned fens with flarks (wet surfaces) and bog zone margins with *sphagnum* moss cover (Kolari et al., 2021). Stensjöflon is one of the biggest mire complexes in Västernorrland and is dominated by aapa mire complexes (470 ha) (Länsstyrelsen Västernorrland, 2018a). Sör-Lappmyran is located on a high plateau and consists of transition mires and quaking bogs (35 ha). (Länsstyrelsen Västernorrland, 2018b).

2.2 Field measurements

Three peat cores were sampled at every restored and natural peatland in July-August 2021. When sampling we tried to take the peat cores approximately five meters from the blocked drainage ditches, this was however not always possible for practical reasons. The peat cores were sampled using a using a stainless-steel circular soil corer and PVC pipes (radius 7.53 cm). The soil corer was used to pre-drill a hole in the peat and the PVC pipe was then inserted into that hole. The PVC pipe containing the peat was lifted out from the hole to get an intact peat core, figure 1. The peat cores were taken from the uppermost 50 cm of the peatlands. After sampling the peat cores were stored in a freezer room at –20 ° C. While still frozen, the peat cores were then sliced into 25 discs with a target thickness of 2 cm. After slicing the weight and thickness of all discs were measured. From this data the volume of all the discs were calculated. The discs were then sliced into three pieces so that they could be used for several types of analyses, figure 1. The largest of these three pieces will be referred to as a half-disc in this report.

Figure 1. An intact peat core and some sliced samples.

2.3 Laboratory work and calculations

2.3.1 Density

The half discs were placed in individual aluminium trays and dried at 60 °C for approximately four days until constant weight was reached in the samples. They were then placed in a desiccator cabinet to cool down without adsorbing any moisture or particle contamination. Lastly, the half discs were weighted to determine their dry weight. With these results the dry weight (DW) of all the half discs were calculated, equation 1. The BD (g/cm^3) of the full disc could then be calculated based on their volume and dry matter, equation 2.

Equation 1. $DW\ (\%) = \frac{DW_{HD}(g)}{WW_{HD}(g)}$

Equation 2. $BD\ \left(\frac{g}{cm^3}\right) = \frac{WW_{FD} * DW\ (\%)}{V_{FD}}$

Where:
DW_{HD} is the dry half disc weight (g)
WW_{HD} is the wet half disc weight (g)
WW_{FD} is the wet full disc weight (g)
V_{FD} is the full disc volume (cm^3)

2.3.2 Organic matter

The OM was determined using loss of ignition (LOI). Firstly, the half discs were homogenized and placed into crucibles with a known weight. The crucibles containing the peat were then weighed on a digital scale. After that the crucibles were burned in a muffle furnace at 500 °C for 4 hours. The trays were removed from the furnace when it had cooled down to approximately 100 °C and then put into a desiccator cabinet to avoid the samples adsorbing moisture from the air. The burned crucibles were then weighted, and their ash content calculated with equation 3. Lastly, the OM content was calculated from the ash content, equation 4.

Equation 3. $Ash\ content\ (\%) = \left(\frac{m_{1\,(g)}}{m_2(g)}\right) * 100$

Equation 4. $Organic\ matter\ (\%) \ = \ 100 - \ Ash\ content\ (\%)$

Where:
m_1 is the mass of peat before burning (g)
m_2 is the mass of peat after burning (g)

2.3.3 Chemical analysis: C (%), N (%), δ^{13}C (‰) and δ^{15}N (‰)

The samples had to be prepared for the chemical analysis. Firstly, a representative amount of the dried half discs was put into an IKA tube mill where it was grinded to a fine powder using a disposable grinding chamber (IKA MT 40.100). The grinded powder was then transferred to a test tube and dried at 70 ˚C to remove moisture and reach a constant weight (~16 hours). Lastly, the powder was transferred to small tin cups and weighted with a target weight of 5 mg (±0.5 mg) using a six decimal micro-scale (Mettler Toledo). After the preparation, the samples were analysed for C and N nitrogen content (%) as well as δ^{13}C and δ^{15}N values (‰) on an Elemental Analyzer/Isotope Ratio Mass Spectrometry system (Thermo Fisher Scientific) by the Stable Isotope Laboratory the department of Forest Ecology and Management, SLU, Umeå.

2.4 Data analysis

The ωC (%), ωN (%) and their C/N ratio were multiplied by the OM (%) to calculate their amount in the OM for all depths. The $_{OM}$C (%), $_{OM}$N (%), and their $_{OM}$C/N ratio were used for the ANOVA, Post hoc, Spearman correlations and depth graphs. For the principal component analysis (PCA), the original ωC (%), ωN (%) and their C/N ratios were used.

2.4.1 Principal component analysis

A principal component analysis (PCA) was made using RStudio (RStudio Team, 2021) to explore correlation patterns among the natural and restored peatlands. With the results from the PCA a biplot was created using ggbiplot (v0.55; Vu, 2011) package in Rstudio. A biplot overlays the score plot and loadings plot from the PCA in a single graph. The biplot gives a visual representation of how the different peat properties are related and of how similar the two categories (natural and restored) are.

2.4.2 ANOVA and Post hoc

An analysis of variance (ANOVA) and post hoc tests were done using RStudio (RStudio Team, 2021) to observe if there were any statistically significant differences between the natural and the restored peatlands. The ANOVA was done at every site to test for differences between the natural and restored peatlands. Before utilizing ANOVA, the residuals for the data were tested for normality using QQ-plots and histograms.

Firstly, linear mixed effects models (LMES) of all peat properties for the restored and natural peatlands were created and fitted in RStudio using the nlme package (v3.1-153; Pinheiro et al., 2021). The ANOVA was then done on the produced models**.** The ANOVA gave results with p-values indicating if there were statistically significant differences between the different depth categories (0-2, 2-4, 4-6 cm etc), categories (natural and restored) and the interaction effect between the depth categories and categories, respectively. If the interaction effect ((depth category * category (Natural and restored)) was statistically significant ($p<0.05$), there is empirical evidence that there are differences between the natural and restored peatlands at different depths in the profile.

To determine at which depths these differences existed, a post hoc test was done on the peat properties that generated significant p-values for the interaction effect at each site. This was done with the emmeans package (v1.7.2; Lenth, 2022) in Rstudio, which is a tool for post hoc comparisons after fitting a model. The package was used for pairwise comparisons (t-test) of the natural and restored fitted models for the peatlands at every 2cm (0-2, 2-4, 4-6 cm etc). The results from this gave p-values indicating if there was a statistically significant difference between the restored and natural peatland at any of the depth categories.

2.4.3 Depth profiles and spearman correlation

At all paired peatlands the data from the three cores from the natural peatland and three cores from the restored peatland were plotted against depth for all investigated peat properties. The spearman correlation coefficients of the different peat properties against depth were also calculated using RStudio (RStudio Team, 2021). In this paper spearman correlations of ±>0.7 are defined as very strong relationships, ±0.4-0.69 as strong relationships, ±0.3-0.39 as moderate relationship and ±0.2-0.29 as weak relationships. The statistical significance (p-values) of all spearman correlations was also calculated. If the p-values were >0.05, the correlations were considered as non-significant.

2.4.4 Total surface carbon and nitrogen content

The total amount of carbon and nitrogen (kg/m^2) in the sampled cores were also calculated. This was done by calculating the peat mass at every depth with equation 5 and then taking the sum of all these peat masses. After that the total carbon and nitrogen content (g) at every depth was calculated with the principal from equation 6. The sum of these weights was then calculated to get the total carbon and nitrogen content (g) in the cores. These weights were then converted to kg/m^2.

The total nitrogen and carbon (natural and restored) were then plotted in bar charts for each paired peatland. A paired t-test was then done on the total surface C and N to observe if there were any statistically significant differences between the natural and restored peatlands. The paired t-test was done using real statics resource pack in Microsoft Excel (Zaiontz, 2021).

Equation 5: $peat\ mass\ (g) = V(cm^3)\ * BD\left(\frac{g}{cm^3}\right)$

Equation 6: $Total\ surface\ C\ conetent\ (g) = \frac{peat\ mass\ (g) * \omega C\ (\%)}{100}$

3. Results

3.1 Correlation structure among the investigated variables

The correlations among all the peat properties were investigated using a PCA Most of the variance (75.1%) was explained by the first two principal components, PC1 explained 57.4% and PC2 17.7%. All variables (peat properties) had long vectors which were approximately the same length, figure 2. Thus, all variables (peat properties) had approximately the same amount of effect on the PCA.

The ωN (%), ωC (%), BD (g/cm^3) and $\delta^{15}N$ (‰) were grouped together on the positive side of PC1 and they all had low angles to PC1. The C/N ratio was found at approximately a 180° angle from this group at the negative side of the PC1 axle. These variables thus had the largest effect on the PC1 axle. From the biplot one can conclude that the ωN (%), ωC (%), BD (g/cm^3) and $\delta^{15}N$ were positively correlated to each other and negatively correlated to the C/N ratio (strong correlation) and OM (moderate correlation). The $\delta^{13}C$ (‰) was found at the negative side of the PC2 axle at approximately a 90° angle from the group with ωN (%), ωC (%), BD (g/cm^3) and $\delta^{15}N$ (‰) as well as the C/N ratio. The $\delta^{13}C$ (‰) thus had a very low angle to PC2 and the largest effect on that PC. The position of the ^{13}C (‰) variable indicated that it had no or very low correlations to the ωN (%), ωC (%), BD (g/cm^3), $\delta^{15}N$ (‰) and C/N variables. The depth and OM variables had ca. 45° angles from PC1 and PC2, they thus affected both components but not as strongly as the other variables. The OM content variable is positioned at approximately a 90° angle from the depth variable and is thus the only parameter were the biplot doesn’t indicate a correlation with depth

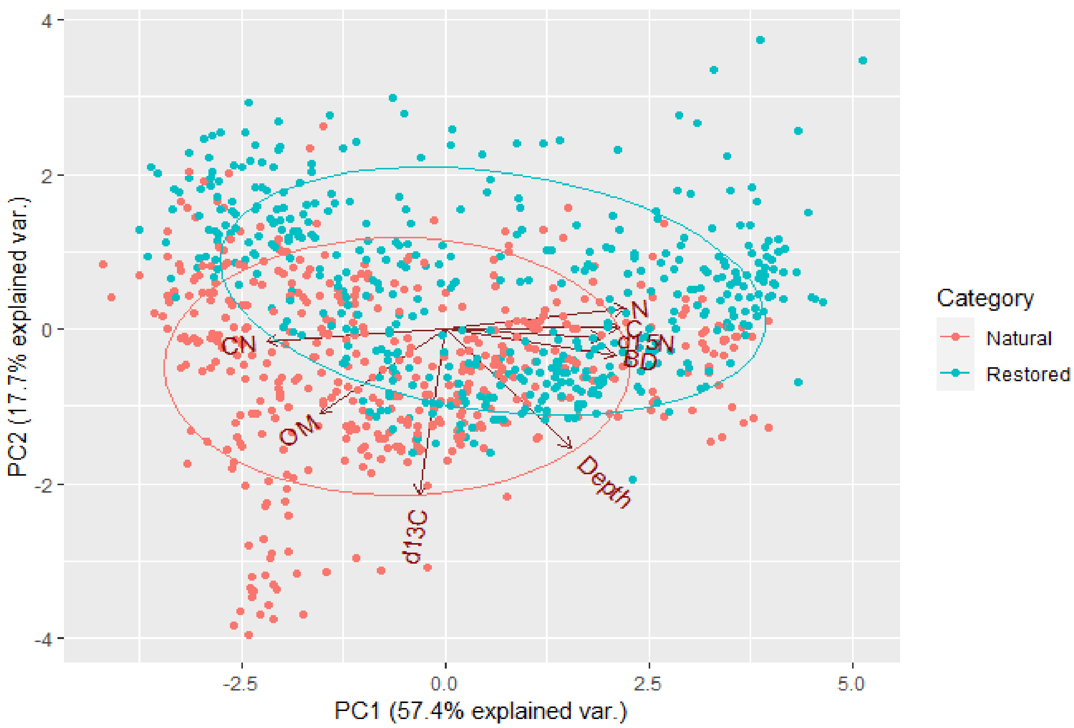

Figure 2. The biplot with the results from the PCA analysis.

3.2 Total surface carbon and nitrogen content

The total surface C content was higher at the restored peatlands compared to their natural reference peatlands at all sites, figure 3. The results from the t-test indicated that there was a statistically significant difference for the total surface C content between the natural and restored sites, figure 3. The restored Ånnsjön S peatland had the highest total surface C content (31.31 kg/m^2) and the natural Stensjöflon peatland had the lowest total surface C content (11.67 kg/m^2).

The total surface N content was higher at the restored peatlands compared to their natural reference peatlands at five of the six paired peatlands, figure 3. At Öjsjömyrarna the total surface N content was higher at the natural peatland (0.87 kg/m^2) compared to the restored peatland (0.84 kg/m^2), figure 3. However, the t-test indicated that there was no statistically significant difference for the total surface N content between the restored and natural sites, figure 3. The restored Ånnsjön S peatland had the highest total surface N content (1.22 kg/m^2) and the natural Stensjöflon peatland had the lowest total surface N content (0.14 kg/m^2).

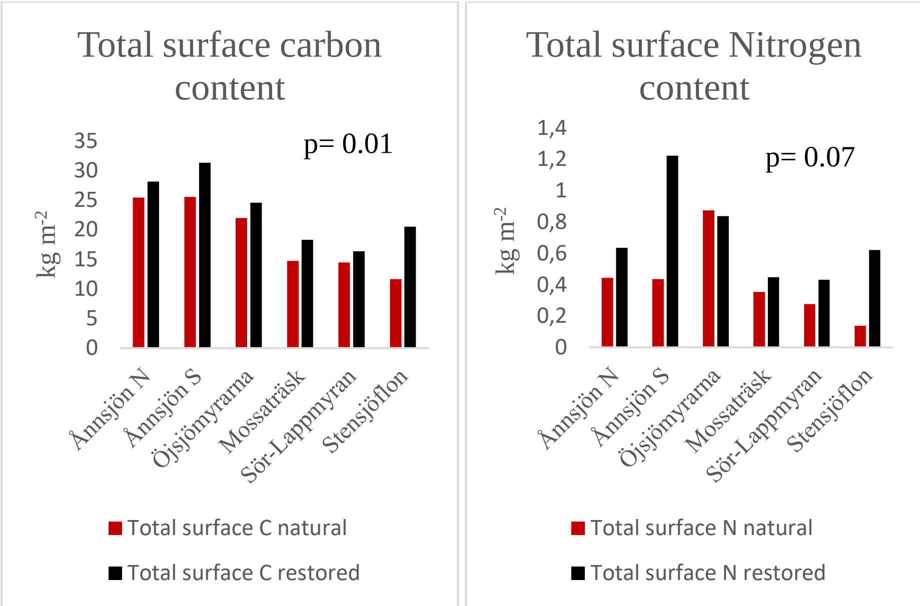

Figure 3. The total surface C and N content (0-50 cm) at the peatland sites. The p-values from the t-test indicating if there are any statistically significant differences on the total surface C and N content between the restored and natural peatlands, are also displayed in the graph.

3.3 Differences between the natural and restored peatlands

The results from ANOVA indicated that there was a statistically significant difference in the interaction effect for at least one of the peat properties at four of the six paired peatlands, table 2. If the interaction effect between category (natural and restored) and depth categories is significant that means that there will be differences between the categories at different depths. The post hoc test was thus done on the peat properties that had significant interaction effects, table 2 and 3.

Table 2. The result from ANOVA showing the p-values for the interaction effect. Green =p<0.05, grey = n.s. The post hoc test was then done on all parameters with p<0.05

	BD	OM	$_{OM}$C	$_{OM}$N	$_{OM}$C/N	δ^{13}C	δ^{15}N
Årnsjön N	0.01 *	0.8 n.s	0.2 n.s	0.2 n.s	0.4 n.s	0.002 **	0.03*
Årnsjön S	0.005 **	0.8 n.s	0.003 **	0.001**	0.0004 ***	0.3 n.s	0.003 **
Öjsjömyrarna	0.07 n.s	0.9 n.s	0.2 n.s	0.6 n.s	0.5 n.s	0.4 n.s	0.8 n.s
Mossaträsk	N.A	0.07 n.s	0.8 n.s	0.9 n.s	0.5 n.s	0.3 n.s	0.1 n.s
Stensjöflon	<0.0001 ****	0.003 **	0.0001 ****	0.0001 ****	0.003 **	0.03 *	<0.0001 ****
Sör-Lappmyran	0.008 **	0.4 n.s	0.09 n.s	0.3 n.s	0.4 n.s	0.5 n.s	0.06 n.s

** p < 0.05, ** p < 0.01, *** p < 0.001, **** p < 0.0001, n.s. = not significant*

Table 3. The results from the post hoc test showing at what depths there was a statistically significant difference between the natural and restored peatlands. These results are also expressed in figure 4-17

	BD	OM	$_{OM}$C	$_{OM}$N	$_{OM}$C/N	δ^{13}C	δ^{15}N
Årnsjön N	22–24 cm	-	-	-	-	0-18 cm	20-26 cm
Årnsjön S	24-26, 28-38 and 44-46 cm	-	30-32, 34-36 and 40-46 cm	20-50 cm	26-40 and 44-50 cm	-	No
Öjsjömyrarna	-	-	-	-	-	-	-
Mossaträsk	-	-	-	-	-	-	-
Stensjöflon	30–50 cm	8–10, 16-18, 22-26, and 28-50 cm	38-50 cm	22-50 cm	8-50 cm	30-50 cm	22-50 cm
Sör-Lappmyran	40–50 cm	-	-	-	-	-	-

The post hoc results for Årnsjön N indicated that there were statistically significant differences at certain depths between the category's (natural and restored) for the BD as well as the δ^{15}N and and δ^{13}C values table 3. The BD and δ^{15}N (‰) values were significantly higher at the restored peatland, while the δ^{13}C (‰) values were higher at the natural peatland at these depths, table 3. The statistically differences were found at similar depths for the BD (g/cm^3) and δ^{15}N (‰), table 3. For the BD (g/cm^3) the statistically significant differences were only found at a depth range of 2 cm (22-24 cm) and for the δ^{15}N values only at a depth range of 6 cm (20-26 cm).

For the $\delta^{13}C$ values the differences are found at lower depths and a larger depth range (0-18 cm), table 3.

At Ånnsjön S the post hoc test indicated that there were statistically significant differences between the category's (natural and restored) for the BD, $_{OM}C$ content, $_{OM}N$ content and the C/N ratio, table 3. The BD, $_{OM}C$ content and $_{OM}N$ content were significantly higher at the restored peatland, while the C/N ratio was higher at the natural peatland at these depths. The results indicated differences over large depth ranges for these peat properties between the natural and restored peatland. For example, differences in $_{OM}N$ at 20-50 cm depth, table 3. The post hoc results indicate that the BD (g/cm^3), $_{OM}C$ content, $_{OM}N$ content and the $_{OM}C/N$ ratio had their differences at similar depths at Ånnsjön S, table 3. The ANOVA results indicated that there would be differences between the categories at certain depths for ^{15}N at Ånnsjön S, table 2. However, the results from the post hoc test had p-values >0.05 at all depths, table 3. However, the p-values were very close to being <0.05 at 46-50 cm, 46-48 cm p =0.05 and at 48-50 cm p = 0.05.

At Stensjöflon the post hoc test indicated statistically significant differences at certain depths between the categories (natural and restored) for all the investigated peat properties, table 3. The BD, organic matter content, $_{OM}N$ content and $\delta^{15}N$ values were significantly higher at the restored peatland, while the OM content, C/N ratio and $\delta^{13}C$ were higher at the natural peatland at these depths. These statistical differences were observed over large depth ranges. For example, the results indicated differences in $_{OM}C/N$ at 8-50 cm depths, table 3. However, there is some variation in at what depths the post hoc test indicates statistical differences at for the peat properties. For the OM and $_{OM}C/N$, the statistically significant differences between the categories (natural and restored) appear at depths from 8 down to 50 cm. The other peat properties do not have any statistically significant differences at these shallower depths. However, all peat properties have statistically significant differences at higher depths (30-50 cm), table 3.

Sör-Lappmyran was the only paired peatland where the post hoc test only was done on one peat property (BD) after the ANOVA, table 2. The post hoc test indicated that for the BD (g/cm^3) there were statistically significant differences between the category's (natural and restored) at 40-50 cm depth, table 3. The restored peatland had significantly higher BD at this depth.

The samples from the two categories' (natural and restored) were not separated into two clear clusters in the biplot, figure 2. There is a clear overlap of the two clusters with most of the samples being located close to the origin. However, there exists a bit of separations between the two categories in the biplot. Along the PC2 axle the restored samples had more positive values while the natural samples had more negative values. Along the PC1 axle the majority of the restored samples had more positive values while the natural samples have more negative values.

However, at the negative PC1 values there also was a large cluster with restored samples with more positive PC2 values, figure 2.

3.4 Depth profiles for the peat properties

In the depth profiles, it is visible how the peat properties change with depth at the different paired peatlands, figure 4-17. Table 4 and 5 show the correlation between the investigated peat properties and depth (0-50 cm) at the peatlands. The post hoc tests indicated statistical differences at certain depths between the natural and restored peatlands for several of the investigated peat properties. In the depth profiles it is visible that the cores from the restored peatlands had higher BD, $_{OM}N$ content, $_{OM}C$ content and $\delta^{13}C$ values and that the cores from the natural peatlands have lower OM content, C/N ratio and $\delta^{15}N$ values at these depths, figure 4-17.

Table 4. The spearman correlation coefficients of the peat properties against depth for the Jämtland peatlands

	Ånnsjön N natural	Ånnsjön N restored	Ånnsjön S natural	Ånnsjön S restored	Öjsjömyrarna natural	Öjsjömyrarna restored
BD vs depth	0.43 ***	0.6 ****	0.48 ***	0.71 ****	0.78 ****	0.92 ****
OM vs depth	0.42 ***	0.43 ***	0.15 n.s	-0.3 **	-0.57 ****	-0.81 ****
$_{OM}C$ vs depth	0.45 ****	0.25 *	0.59	0.78 ****	0.8 ****	0.89 ****
$_{OM}N$ vs depth	-0.15 n.s	-0.05 ns	0.24 *	0.55 ****	0.82 ****	0.88 ****
$_{OM}C/N$ vs depth	0.23 *	0.07 ns	-0.21 n.s	-0.51 ****	-0.82 ****	-0.85 ****
$\delta^{13}C$ vs depth	0.3 **	0.71 ****	-0.12 n.s	0 n.s	0.48 ****	0.11 n.s
$\delta^{15}N$ vs depth	0.04 ns	0.25 *	-0.17 n.s	0.39 ****	0.6 ****	0.85 ****

1 0.75 0.5 0.25 0 -0.25 -0.5 -0.75 -1

** p < 0.05, ** p < 0.01, *** p < 0.001, **** p < 0.0001, n.s. = not significant*

Table 5. The spearman correlation coefficients of the peat properties against depth for the Västernorrland peatlands

	Mossaträsk natural	Mossaträsk restored	Stensjöflon natural	Stensjöflon restored	Sörl-Lappmyran natural	Sör-Lappmyran restored
BD vs depth	N.A	0.85 ****	0.76 ****	0.88 ****	0.9 ****	0.37 **
OM vs depth	-0.52 ****	-0.58 ****	0.3 ***	-0.63 ****	-0.37 ***	-0.47 ****
$_{OM}C$ vs depth	0.8 ****	0.83 ****	0.17 n.s	0.87 ****	0.55 ****	0.82 ****
$_{OM}N$ vs depth	0.77 ****	0.88 ****	-0.07 n.s	0.9 ****	0.6 ****	0.82 ****
$_{OM}C/N$ vs depth	-0.77 ****	-0.87 ****	0.11 n.s	-0.87 ****	-0.59 ****	-0.81 ****
$\delta^{13}C$ vs depth	0.1 n.s	0.44 ****	0.81 ****	0.38 ****	0.73 ****	0.74 ****
$\delta^{15}N$ vs depth	0.8 ****	0.71 ****	0.29 *	0.95 ****	0.82 ****	-0.47 **

1 0.75 0.5 0.25 0 -0.25 -0.5 -0.75 -1 *

*p < 0.05, ** p < 0.01, *** p < 0.001, **** p < 0.0001, n.s. = not significant*

3.4.1 Depth profiles: Bulk density

The cores from the natural and restored peatlands had Bulk densities ranging from 0.011 to 0.2 g/cm^3, figure 4 and 5. The spearman correlation indicated increasing BD with depth (0-50 cm) at all peatlands, table 4 and 5. This trend with increasing bulk densities with depth was also observed in the depth profiles, figure 4 and 5. A majority of the cores from the restored and natural peatlands had their highest observed bulk densities at the bottom or close to the bottom of the depth profile. However, at Ånnsjön S and Ånnsjön N the trend with increasing bulk densities with depth were the strongest until 20-25 cm depth. After that depth, the bulk density appeared to have more of a decreasing trend with depth at these paired peatlands, figure 5.

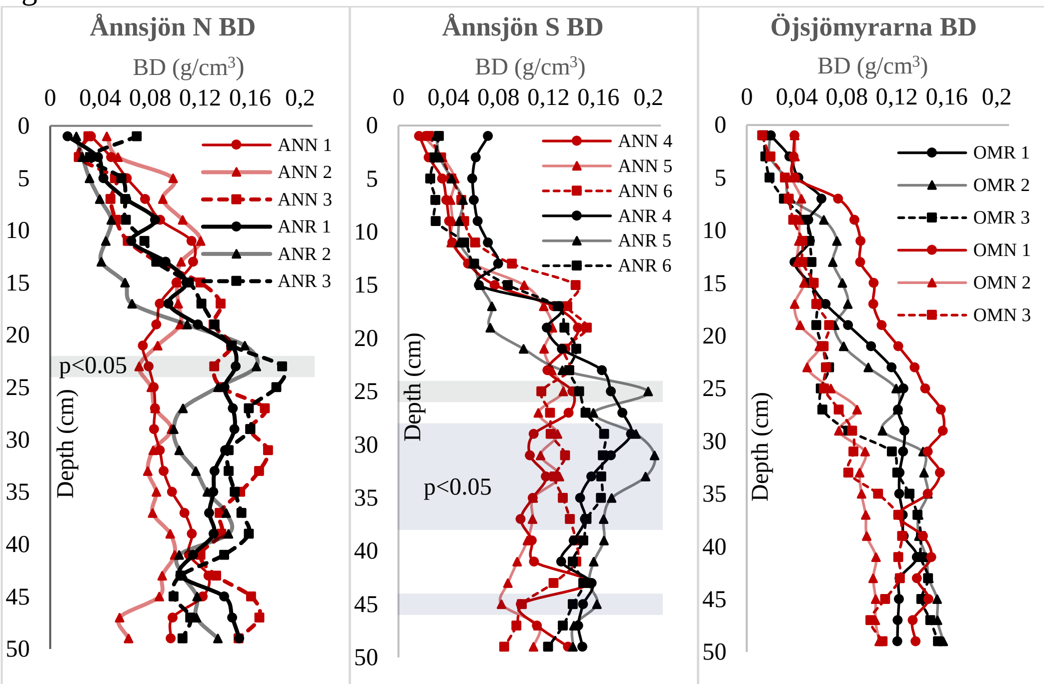

Figure 4. The BD (g/cm^3) across the profiles at the Jämtland peatlands. At Mossaträsk natural the BD (g/cm^3) was plotted with only two cores since the results from the third core was lost. Red (N) = the cores from the

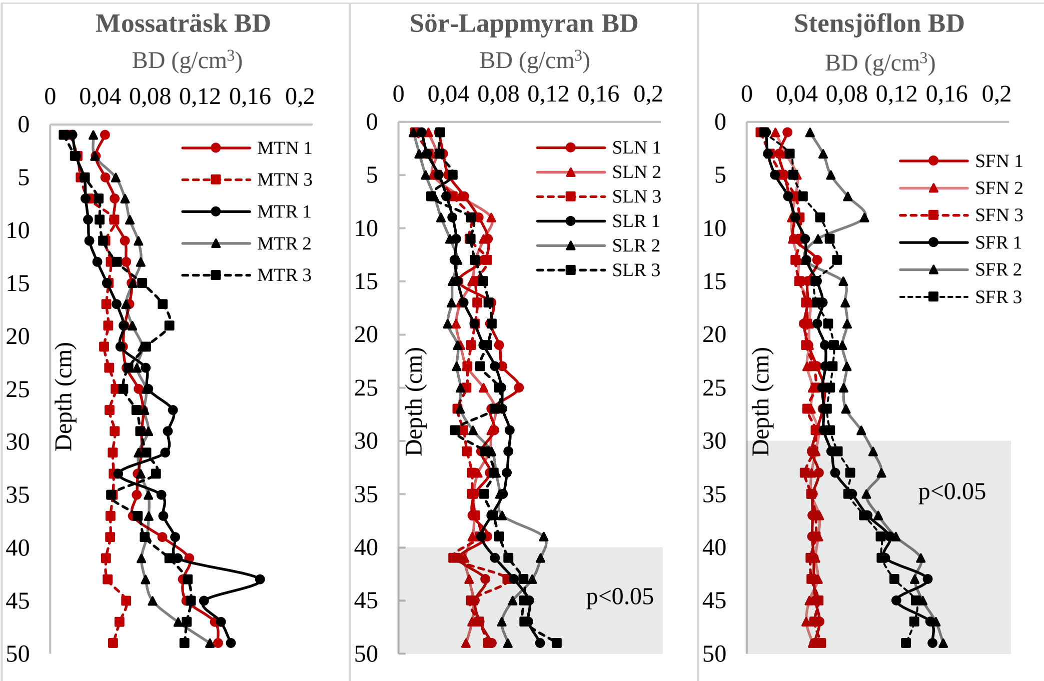

Figure 5. The BD (g/cm^3) across the profiles at the Västernorrland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands

3.4.2 Depth profiles: Organic matter content

The cores from the natural and restored peatlands had OM content ranging from 80.37 to 99.92 %, figure 6 and 7. The spearman correlation was negative (moderate-very strong) at eight of the twelve peatlands indicating decreasing OM content with depth, table 4 and 5. However, at Ånnsjön N natural, Ånnsjön N restored and Stensjöflon natural all had moderately positive correlations with for OM content against depth, table 4 and 5. In the graphs it appears like the OM content stays rather uniform or have a slightly decreasing trend with depth at most peatlands, figure 6 and 7. However, at Ånnsjön N and Ånnsjön S, and Sör-Lappmyran there are negative peaks in the OM content for some of the cores. In the depth profiles at Ånnsjön N (20-24 cm), Ånnsjön S (22-28 cm) and Sörlappsmyrarna (42-50 cm) the cores from the restored peatland appeared to have lower OM compared to the cores from the natural peatland, figure 6 and 7. However, the ANOVA did not indicate a significant interaction effect at these paired peatlands, table 2.

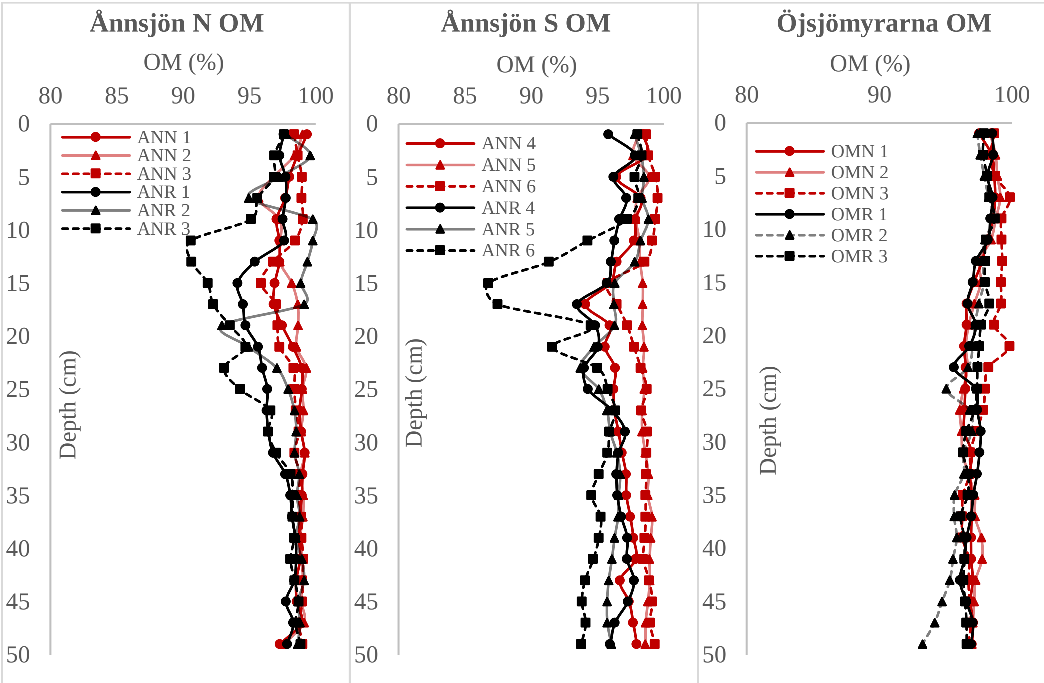

Figure 6. The OM content across the proifles at the Jämtland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland.

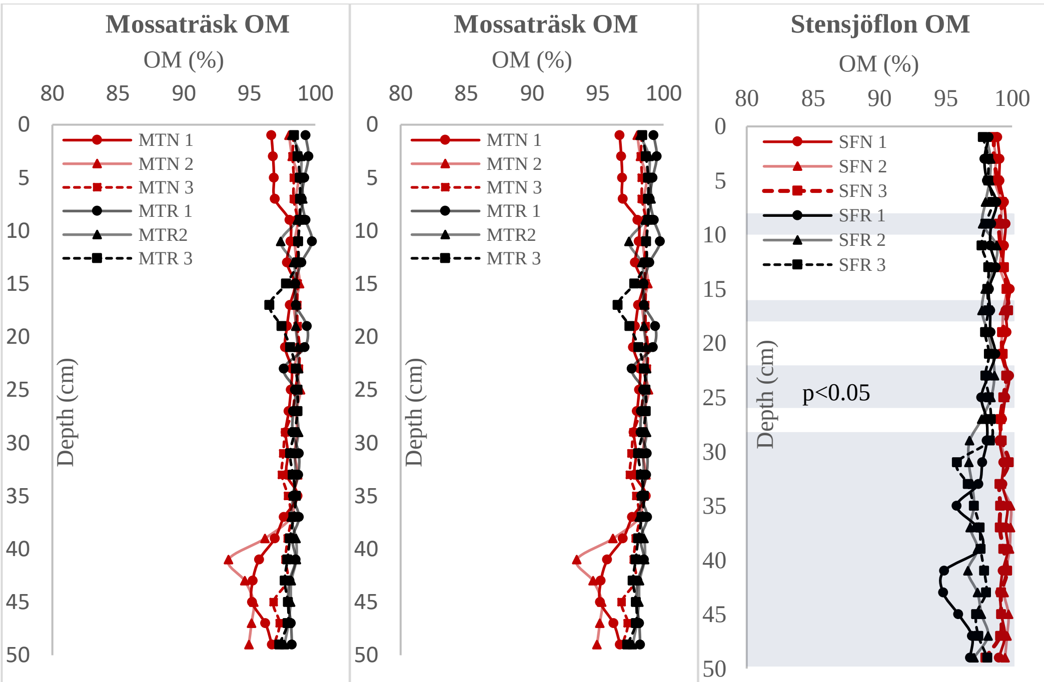

Figure 7. The OM content across the proifles at the Jämtland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

3.4.3 Depth profiles: Carbon content

The cores from the natural and restored peatlands had a $_{OM}C$ content ranging from 43.02 to 66.63 %, figure 8 and 9. The spearman correlation of $_{OM}C$ content against depth were positive (moderate-very strong) at ten of the twelve peatlands, table 4 and 5. This trend with increasing $_{OM}C$ content with depth was also observed in the depth profiles, figure 8 and 9. In the depth profiles at Öjsjömyrarna (32-50 cm) and Sör-Lappmyran (44-50 cm) the cores from the restored peatland appeared to have higher $_{OM}C$ content than the cores from the natural peatland, figure 8 and 9. However, the ANOVA did not indicate a significant interaction effect for the $_{OM}C$ content at these paired peatlands, table 2.

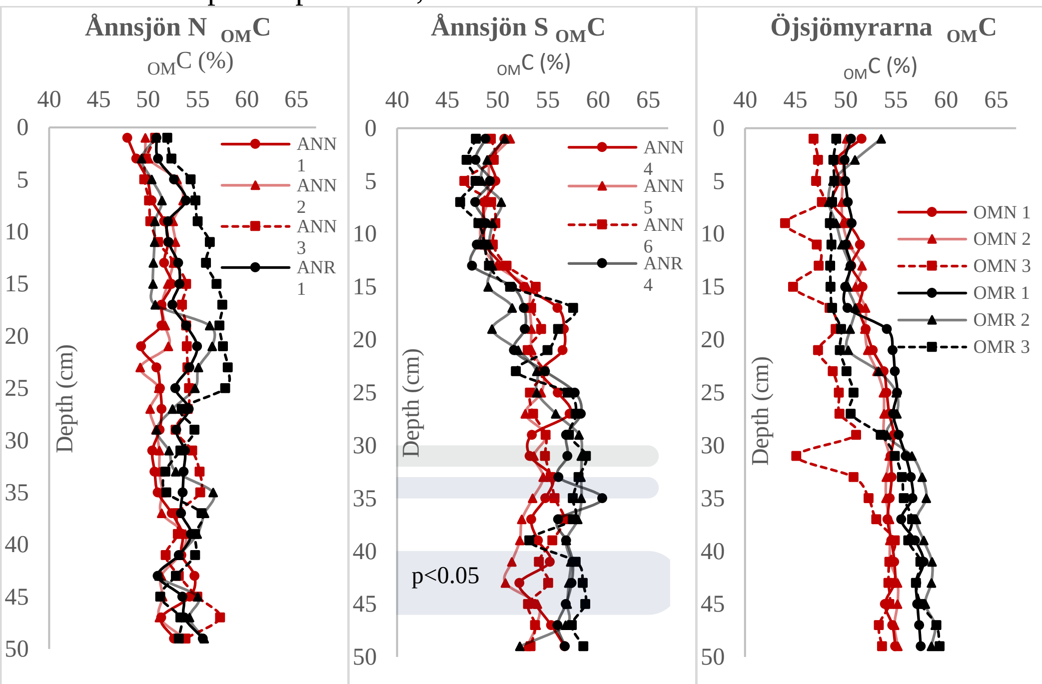

Figure 8. The $_{OM}C$ content across the profiles at the Jämtland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

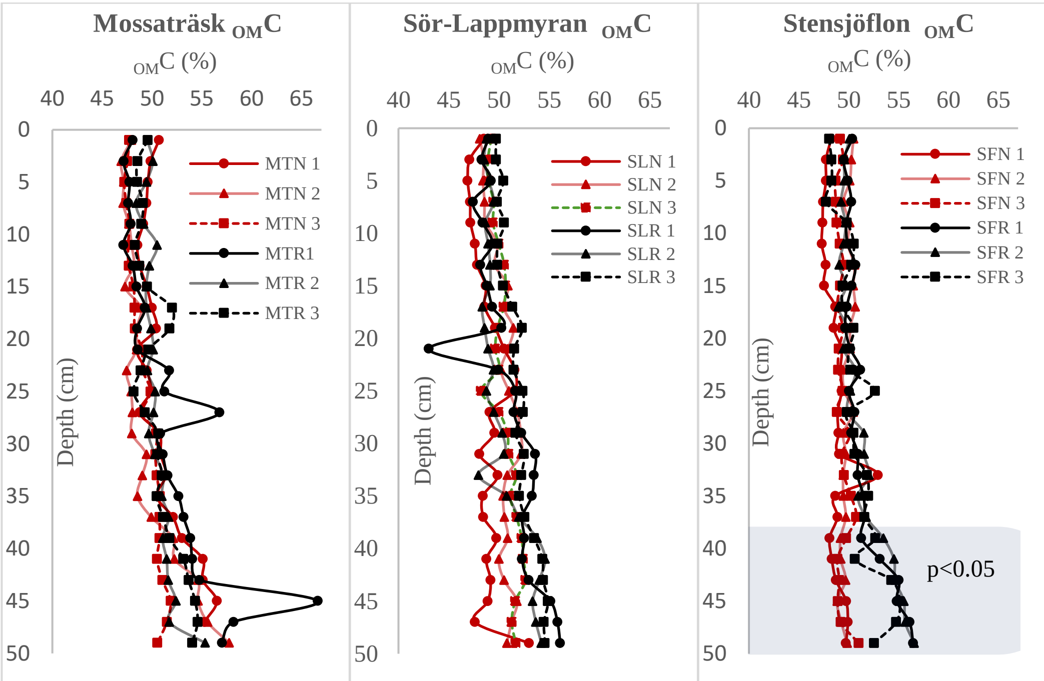

Figure 9. The $_{OM}C$ content across the profiles at the Västernorrland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

3.4.4 Depth profiles: Nitrogen content

The cores from the natural and restored peatlands had $_{OM}N$ content ranging from 0.36 to 3.07 %, figure 10 and 11. The spearman correlation of the $_{OM}N$ content against depth was positive (moderate-very strong) at eight of the twelve peatland, table 4 and 5. At the other peatlands the correlation was non significant or weakly positive, table 4 and 5. This trend with increasing $_{OM}N$ content with depth was also observed in the depth profiles. However, at Ånnsjön S, the cores from the natural peatland and restored peatlands have a increasing trend until ca. 15-20 cm depth, below that depth these cores apperared to have decreasing $_{OM}N$ content with depth , figure 10 and 11. The post hoc tests indicated a statistically significant difference in the $_{OM}N$ content between the natural and restored peatlands at Ånnsjön S and Stensjöflon, table 3. In the depth profiles at Ånnsjön N (18-26 cm) the cores from the restored peatland also appeared to have higher $_{OM}N$ content compared to the cores from the natural peatland. In contrast, at Öjsjömyrarna (37-41 cm) the cores from the natural peatland had higher $_{OM}N$ content compared to the cores from the restored peatland, figure 10-11. However, the ANOVA did not indicate a significant interaction effect for the $_{OM}N$ content at these paired peatlands, table 2.

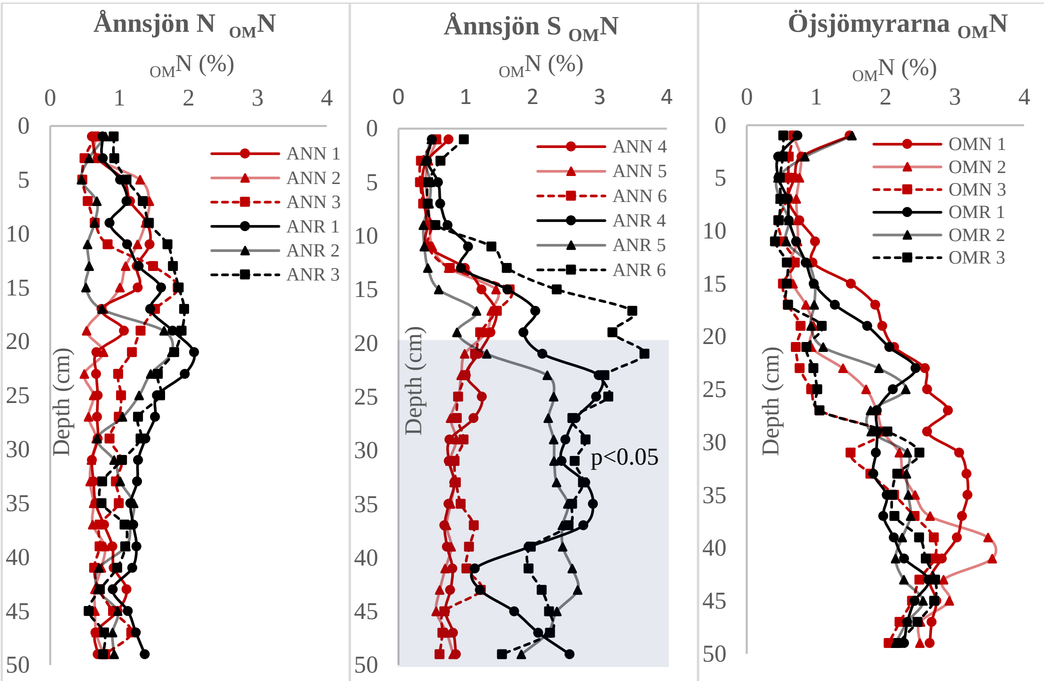

Figure 10. The $_{OM}$N content across the profiles at the Jämtland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

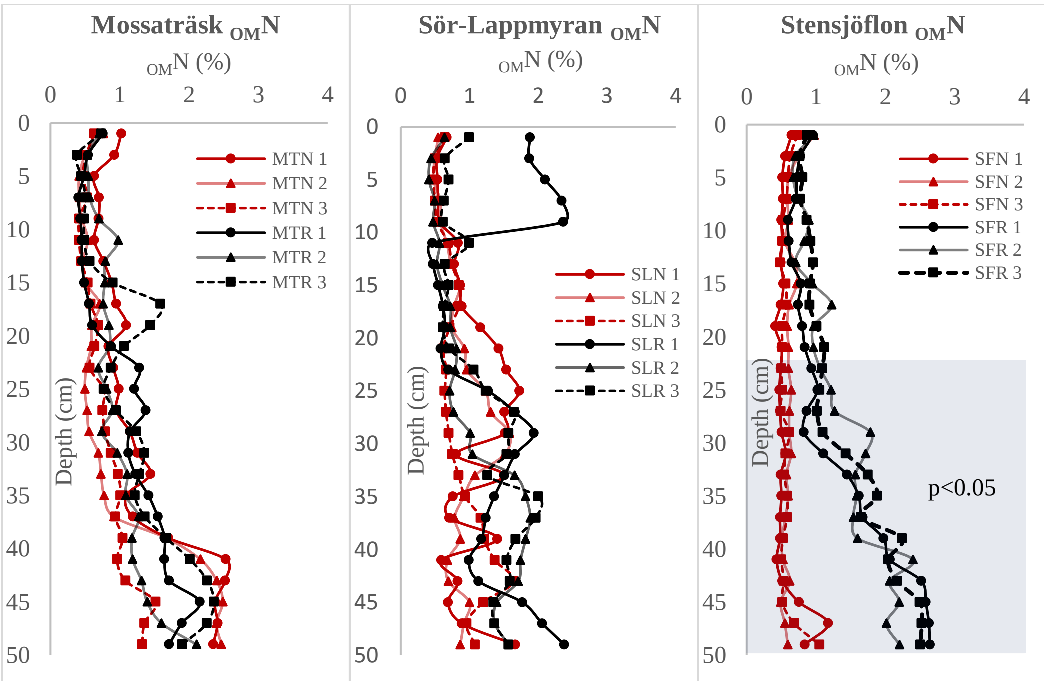

Figure 11. The $_{OM}$N content across the profiles at the Västernorrland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands

3.4.5 Depth profiles: C/N ratio

The cores from the natural and restored peatlands had $_{OM}$C/N ratios ranging from 15.0 to 146, figure 12 and 13. The spearman correlation of the C/N ratio against depth was negative at 8 of the 12 peatlands, table 4 and 5. At the other peatlands the correlation was non significant expect or weakly positive, table 4 and 5.. This trend with decreasing C/N rations with depth was also observed in the depth profiles. In the graphs the $_{OM}$C/N ratio appeared to increase in the top 5 cm at most peatlands, figure 12 and 13. A majority of the cores from the restored and natural peatlad have their lowest C/N ratios at the bottom or close to the bottom of the depth profile. However, at Ånnsjön S the cores from the natural and restored peatlands appered to have a decreasing trend with depth from 5-15 cm depth. Below that depth the cores appeared to have a trend with uniform or slighly increasing C/N ratios with depth, figure 12 and 13. The post hoc tests indicated a statistically significant difference in the $_{OM}$C/N ratio between the natural and restored peatlands at Ånnsjön S and Stensjöflon, table 3. In the depth profiles at Ånnsjön N (20-26 cm) the cores from the restored peatland also had lower $_{OM}$C/N ratios compared to the cores from the natural peatland, figure 12 and 13. However, the ANOVA did not indicate a significant interaction effect for the $_{OM}$C/N ratio at this paired peatland, table 2.

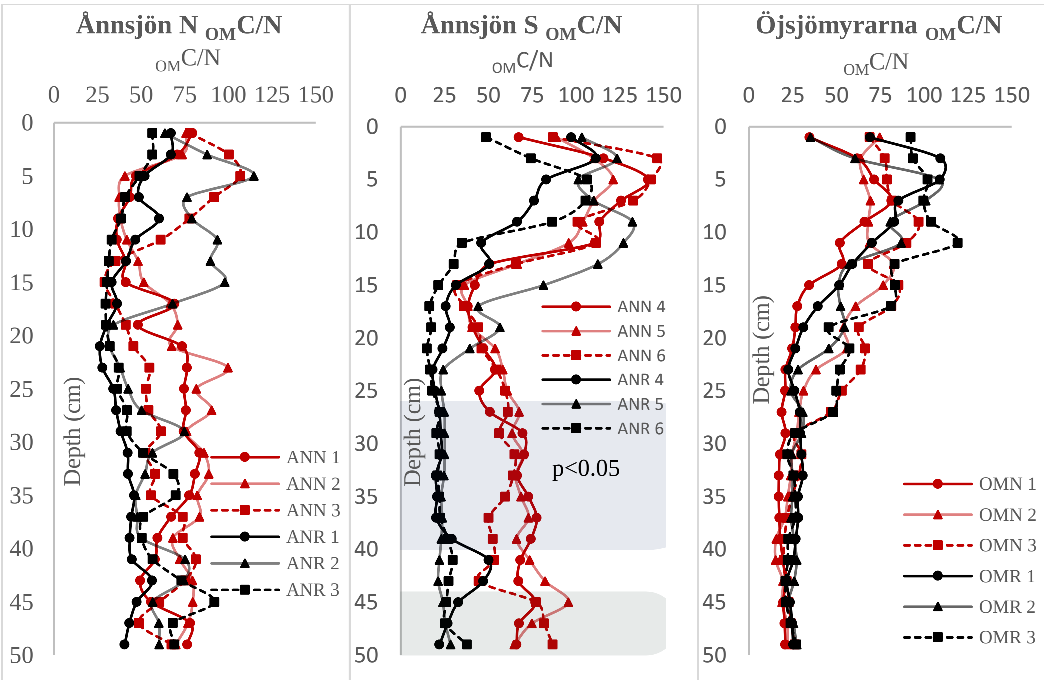

Figure 12. The $_{OM}$C/N ratio across the profiles at the Jämtland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

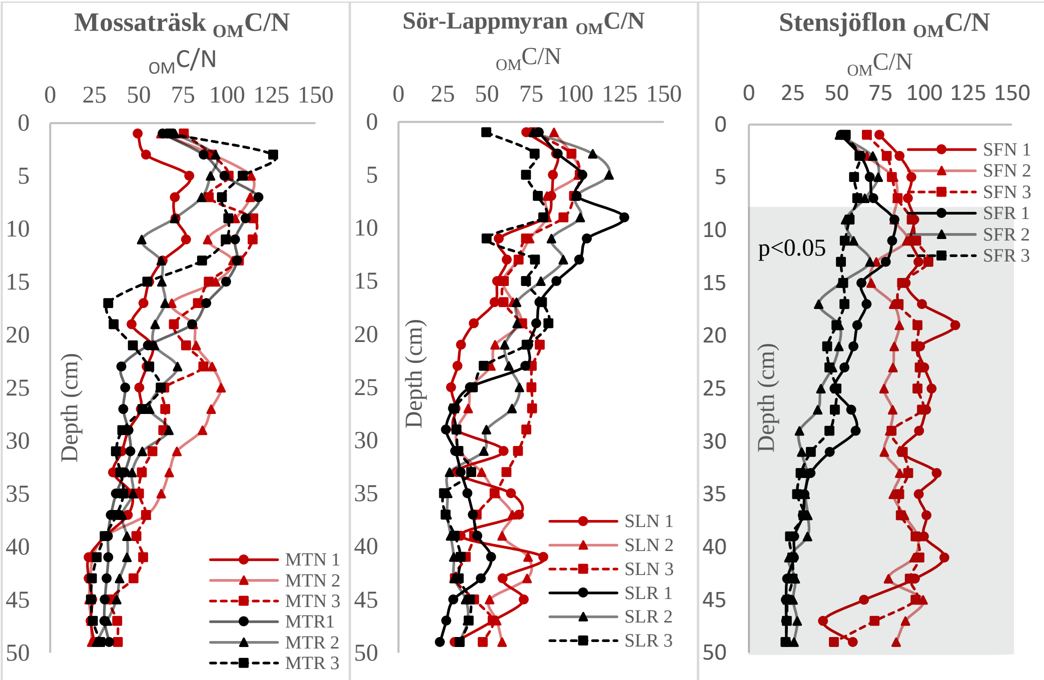

Figure 13. The $_{OM}C/N$ ratio across the profiles at the Västernorrland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

3.4.6 Depth profiles: Stable carbon isotopes

The cores from the natural and restored peatland had $\delta^{13}C$ values ranging from -29.6 to -22.46 ‰, figure 14 and 15. The spearman correlation of $\delta^{13}C$ against depth was positive at eight of the twelve peatlands. At the other peatlands, this correlation was non-significant, table 4 and 5. This trend with mostly increasing $\delta^{13}C$ with depth was also observed in the depth profiles. From the graphs the $\delta^{13}C$ (‰) appeared to be either increasing with depth or stay relativly uniform with depth at the peatlands, figure 14 and 15. The post hoc tests indicated a statistically significant difference in the $\delta^{13}C$ values between the natural and restored peatlands at Ånnsjön N and Stensjöflon, table 3. At Ånnsjön S (4-12, 16-20 and 28-46 cm) and Öjsjömyrarna (24-50 cm) the cores from the natural peatland also had higher $\delta^{13}C$ values compared to the cores from the restored peatland, figure 14 and 15. However, the ANOVA did not indicate a significant interaction effect for the $\delta^{13}C$ values at these paired peatlands, table 2.

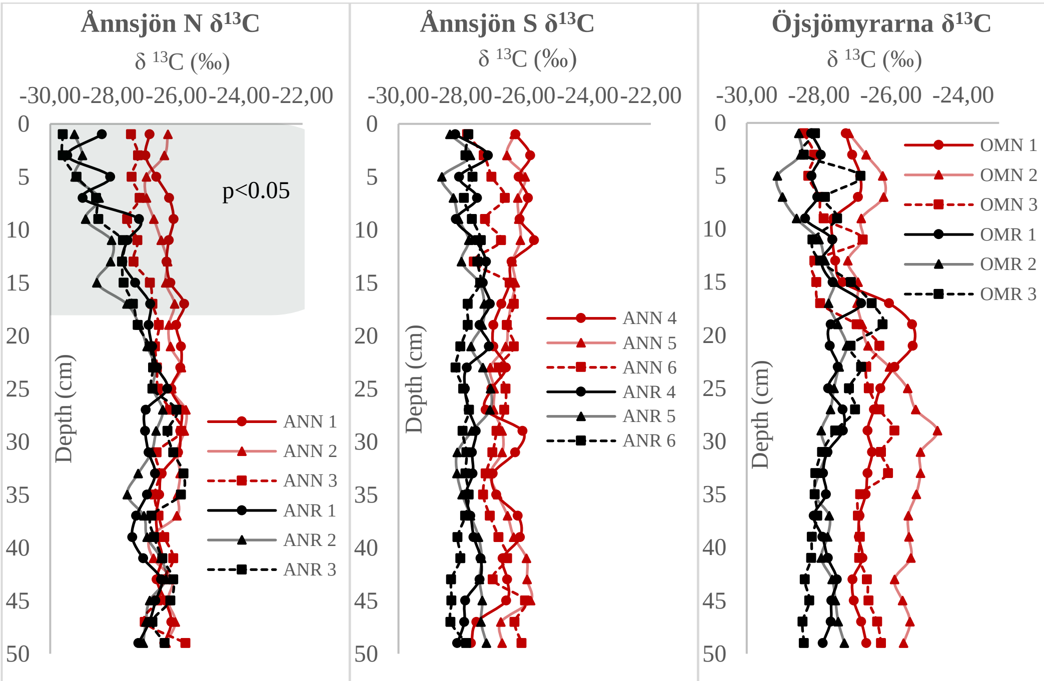

Figure 14. The $\delta^{13}C$ values across the profiles at the Jämtland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

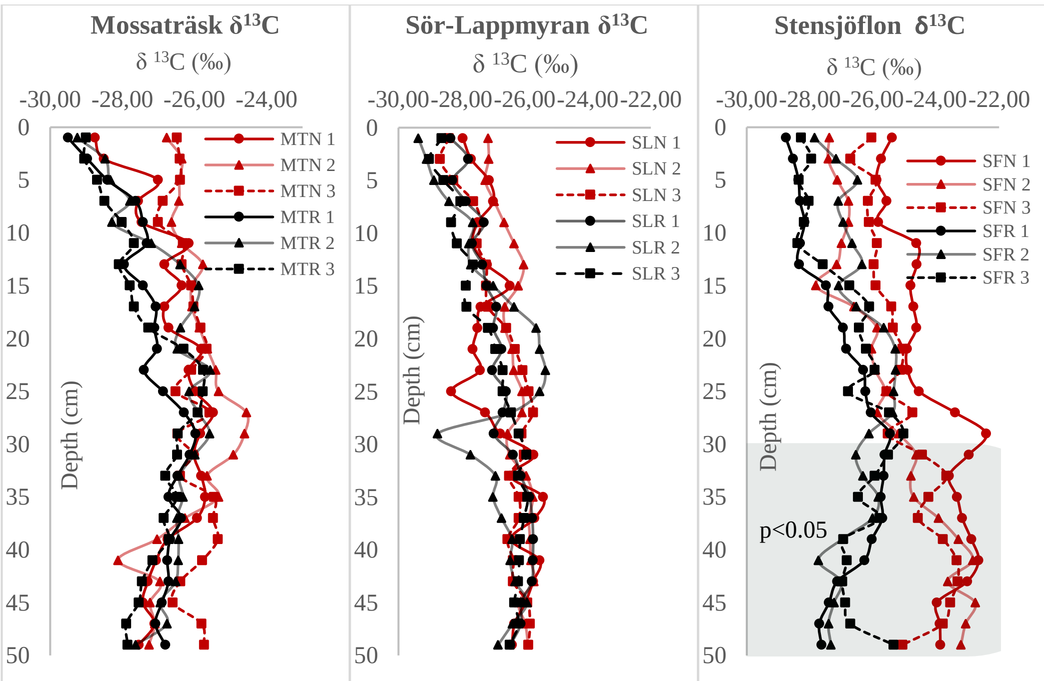

Figure 15. The $\delta^{13}C$ values across the profiles at the Västernorrland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands

3.4.7 Depth profiles: Stable nitrogen isotopes

The cores from the natural and restored peatlands had $\delta^{15}N$ (‰) values ranging from -6.21 to -3.88, figure 16 and 17. The spearman correlation of $\delta^{15}N$ against depth was postive (moderate-very strong) at seven of the twelve peatlands. At the other peatlands this correlation was non significant or weakly positive, table 4 and5. This trend with increasing or uniform $\delta^{15}N$ (‰) with depth was also observed in the depth profiles, figure 16 and 17. A majority of the cores from the restored and natural peatlands have their higest $\delta^{15}N$ values at the bottom or close to the bottom of the depth profile. However, at Årnsjön S the cores from the natural peatland appeared to have a trend with decreasing $\delta^{15}N$ values below ca 15-20 cm depth, figure 16 and 17. The post hoc test indicated a statistically significant differences in the $\delta^{15}N$ (‰) between the natural and restored peatlands at Årnsjön N and Stensjöflon, table 3. In the depth profiles at Årnsjön S (14-18 and 46-50 cm), Mossaträsk (28-32 cm) and Sör-Lappmyran (14-18 cm) the three cores from the restored peatland also appeared to have higher $\delta^{15}N$ (‰) compared to the cores from the natural peatland, figure 16 and 17. However, the ANOVA did not indicate that there was a statistically significant interaction effect for the $\delta^{15}N$ (‰) at Mossaträsk and Sör-Lappmyran, table 2. For Årnsjön S the ANOVA gave significant results for the interaction effect but no differences at any depths were found when the post hoc test was done, table 2 and 3.

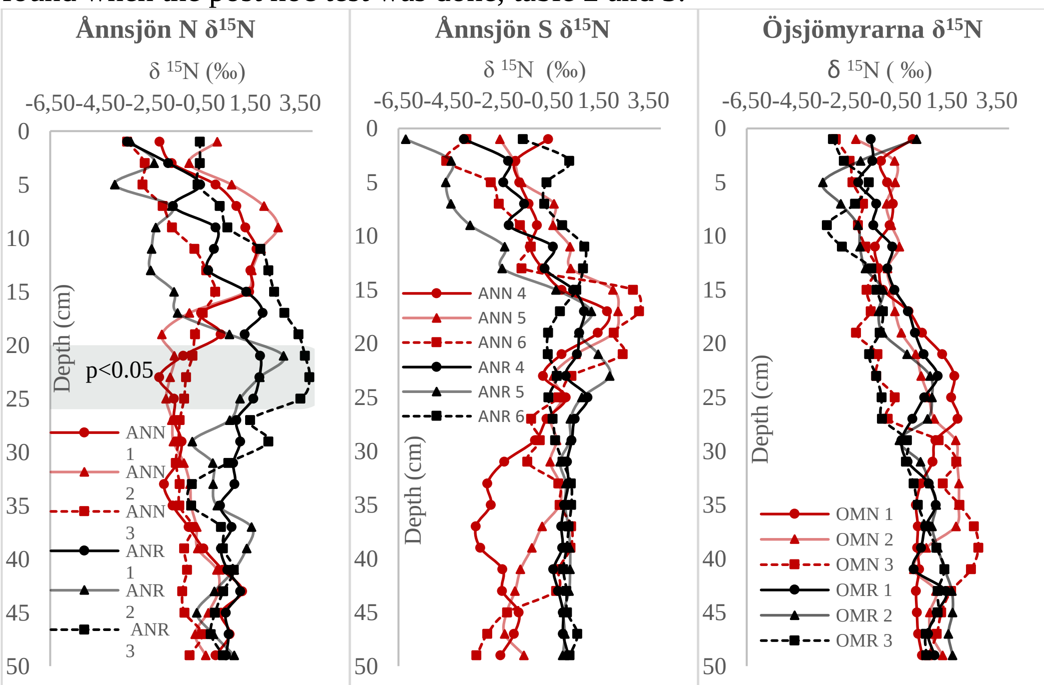

Figure 16. The $\delta^{15}N$ values across the profiles at the Jämtland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

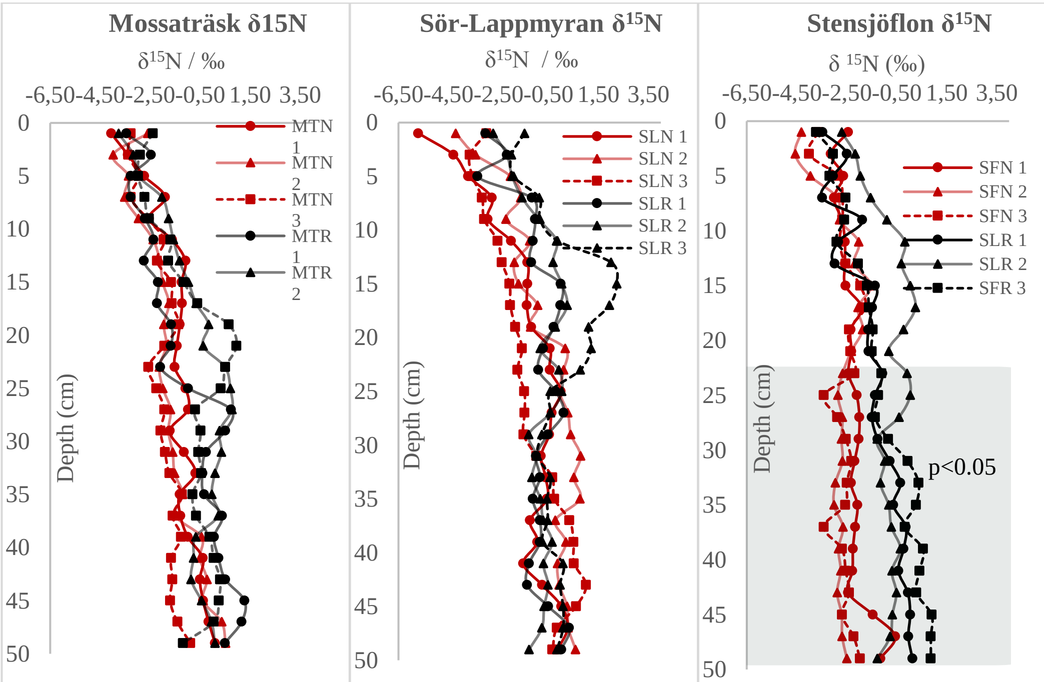

Figure 17. The $\delta^{15}N$ values across the profiles at the Västernorrland peatlands. Red (N) = the cores from the natural peatland, black (R) = the cores from the restored peatland. The areas makred in blue displays the depths were the post hoc test indicated a statistically significant difference between the natural and restored peatlands.

4. Discussion

4.1 Bulk density and organic matter

The observed bulk densities at the restored and drained peatlands were within the range typical for peatlands (Agus et al., 2011). The results from the PCA, depth profiles and spearman correlations indicated that the BD increased with depth at most peatlands. This is expected since deeper and older peat typically is more decomposed. Increasing decomposition results in a loss of strength in the organic matrix, which leads to compaction and thus higher bulk densities (Minkkinen & Laine 1998; Leifeld et al., 2020). However, Ånnsjön S and N had peaks in the BD at lower depths (ca 15-20 cm) and below that depth appeared to have decreasing bulk densities with depth. Several of the other investigated peat properties also had an abrupt change in their depth trend at this depth at Ånnsjön S. This change in depth trends is visible in both the cores from the natural and restored peatlands. This turning point is thus unlikely a result of drainage since both the natural and restored peatland have been affected. It could be the results of that the peat above the turning point accumulating during a drier climate at both the restored and natural peatlands. A drier climate can cause the water table at peatlands to decrease (Slowinski et al., 2016). A lower water table could thus have affected the peat properties at the natural and restored peatlands in similar ways to the changes that are expected following drainage (Krüger et al., 2015).

The BD was significantly higher at the restored peatlands at four of the six paired peatland sites. Drainage is known to induce subsidence and increase the BD at peatlands (Minkkinen & Laine 1998). These results are thus in line with the general expectation since the restored peatlands previously have been drained. The drainage effect on the BD was observed at quite dissimilar depths at the different paired peatlands. This could for example be a result of differences in the time since drainage, vegetation composition, mean groundwater level or sampling distance from the ditch at the peatlands. However, none of the peatlands had drainage effect on BD above 20 cm depth. The drainage effects on BD observed in this study thus appear at quite high depths compared to earlier studies. Minkkinen & Laine (1998) who did research on drained peatland forests in Finland found that BD increased along the peat profile following water level drawdown until ~30 cm depth due to enhanced decomposition. Krüger et al. (2015) did research on biogeochemical parameters as indicators for peat degradation in drained peatlands in Germany and the results of their study showed increasing BD in the ~10-60 cm depth.

The observed OM content at the restored and drained peatlands were mostly within the normal range expected for Swedish peatlands (Sohlenius et al., 2013). The OM typically decreases with depth in peatlands since the peat further down is older and more degraded (Leifeld et al., 2020). This trend, however, was not systematically observed in the depth profiles, spearman correlations or depth profiles in this study. The statistical tests suggested a difference in the OM between the natural and restored peatland at only one of the six paired peatlands. At Stensjöflon the OM was lower at the restored peatland compared to the natural peatland. This is in line with the reasoning that drainage will increase the decomposition of the OM in peat (Krüger et al., 2015). Krüger et al. (2015) observed the lowest OM at drained peatlands from 10-60 cm depth. The drainage effect on OM was thus observed at similar depths in this study. The OM content of peat strongly affects its BD since the particle density of the mineral content is almost twice that of OM. It is thus rather unexpected that the negative correlation between the OM content and BD was rather weak, and that not all peatlands that had drainage effects for the BD also had drainage effects for the OM content.

4.2 Carbon content, nitrogen content and C/N ratio

The cores from the natural and restored peatlands all had $_{OM}$C content and $_{OM}$N content within the normal range expected at peatlands (Agus et al., 2011; Tfaily et al., 2014). They had a median $_{OM}$C/N ratio of 55 which is a little higher than the normal median C/N ratio of northern peatlands which is 49 (Leifeld et al., 2020). This indicates that these peatlands might consist of a little more carbon than what is typical for northern peatlands. The results from the PCA, depth profiles and spearman correlations indicated that the $_{OM}$C content and $_{OM}$N content increased with depth, while the $_{OM}$C/N content decreased with depth at the peatlands. Older and deeper peat is typically more decomposed than more shallow peat (Leifeld et al., 2020)**.** During decomposition the remaining peat increases its carbon and nitrogen content, which mean that the carbon and $_{OM}$N content typically increases with depth in peat (Tfaily et al., 2014; Leifeld et al., 2020). The C/N ratio typically becomes lower during decomposition because of preferential loss of C over N during microbial decomposition. Therefore, decreasing C/N ratios with depth is expected in peat (Leifeld et al., 2020). My results are thus in line with the general expectations following drainage.

The statistical tests indicated differences at certain depths for the $_{OM}$C content $_{OM}$N content and $_{OM}$C/N ratio at Ånnsjön S and Stensjöflon. At these depths, the restored peatlands had higher $_{OM}$C and $_{OM}$N content but lower $_{OM}$C/N ratios. Following drainage, the carbon content and nitrogen content of peat typically increases while the C/N ratio becomes smaller (Tfaily et al., 2014; Leifeld et al., 2020) These results thus match the general expectations for these peat properties following drainage. That the differences in $_{OM}$C content, $_{OM}$N content and $_{OM}$C/N ratio were observed at the same paired peatlands is also logical since these peat properties are so linked (Kruger et al., 2015). In the biplot one can also observe that these properties correlate strongly to each other. The drainage effects on $_{OM}$C content and $_{OM}$N content were at similar depths at Ånnsjön S and Stensjöflon. These are quite high depths for drainage effects on these properties, for example Laiho et al. (1999) found that following drainage the concentration of N increased in the topmost layer (0-10 cm). The drainage effect on $_{OM}$C/N were not observed at similar depths at these Ånnsjön S and Stensjöflon. Probably of the same reasons why the drainage effect for BD was observed at different depths at the different paired peatlands. The high $_{OM}$C/N ratios observed in the uppermost layer (0-5 cm) samples were expected as they contained fresh and poorly decomposed peat forming vegetation, other studies have also found their highest C/N ratios close to the peat surface (Malmer, 1984; Tfaily et al., 2014).

Kruger et al. (2015) and Alewell et al. (2011) have argued for that a linear relationship for the δ^{13}C values, δ^{15}N values and the C/N ratio is expected with peat degradation. When the peat degrades, and the C/N ratio changes the decomposers prefer the lighter isotopes in both δ^{13}C and δ^{15}N and thus they argue for that these properties should change linearly to each other. This trend was not observed in this study. The $_{OM}C/N$ ratio had a negative correlation with the $\delta^{15}N$ but the $\delta^{13}C$ did not correlate with $\delta^{15}N$ or the $_{OM}C/N$ ratio.

The results from the t-test indicated that the restored peatlands had statistically higher total surface C content compared to the natural peatlands. This might seem unexpected since it is believed that drainage increases the decomposition of organic material in peatlands. However, drainage is also known to induce subsidence and compaction of peat material as well as relatively increasing the $_{OM}C$ content in the remaining peat (Minkkinen & Laine 1998, Tfaily et al., 2014). This means that it is possible that the restored cores contain older more compacted peat with a higher carbon percentage compared to the natural cores. This is probably the reason why the restored peatlands had higher total surface C content. Another possible explanation for the higher total surface C content is that the primary production is higher at drained sites allowing for more OM to enter the system thus increasing the $_{OM}C$ content in the mire (Minkkinen, 1999).

In the graph for the total surface N content, one can see that the restored peatlands have higher total surface N content at all paired peatlands except for at Öjsjömyrarna. However, the results from the t-test did not indicate a statistically significant difference between the natural and restored peatlands N content, although the trend was strong ($p = 0.07$). Drainage is expected to compact the peat and relatively increase the nitrogen content in the remaining peat material (Minkkinen & Laine 1998, Tfaily et al., 2014)**.** Therefore, it would be expected that there should be a statistically significant difference between the natural and restored peatlands, with the restored peatlands having higher total surface N content. The sample size used for this t-test was small and one of the peatlands had higher total surface N content at the natural peatland. The results from the t-test still gave a low but not statistically significant p-value. One can assume that with a larger sample size there would be a quite large chance of the t-test indicating a difference between the natural and restored peatlands, with the restored peatlands having higher total surface N content. Öjsjömyrarna was the only paired peatland site where the cumulative N content was higher at the natural compared to the restored peatland. The ANOVA and post hoc test did not indicate any statistically significant difference in the $_{OM}N$ content between the natural and restored peatland. However, Öjsjömyrarna was the only paired peatland site where there existed depths where it seemed like the natural cores had higher $_{OM}N$ content compared to the restored cores. The OMN 1 (Natural core) also had high $_{OM}N$ content throughout most of the depth profile. It’s possible that these were the reasons why the total surface N content was higher at the natural peatland at this site.

4.3 Stable isotopes

The values for the stable carbon and nitrogen isotopes at the natural and restored peatlands were within the normal ranges expected at peatlands. Krüger et al. (2015) and Alewell et al., (2011) have suggested that in natural (pristine) peatlands the $\delta^{13}C$ and $\delta^{15}N$ values have a uniform trend with depth and that after drainage the $\delta^{13}C$ and ^{15}N values are expected to increase with depth. This trend was not observed in this study. Both the natural and restored peatlands mostly had increasing trends with depth. However, very few studies have compared the isotope values of paired natural and drained sites which were similar before the artificial drainage (Nykänen et al., 2020). There thus is not a lot of support for that the isotopes change with depth in this way in peat soils. Nykänen et al. (2018) found that the $\delta\ ^{13}C$ values decreased from 0-25 to 25-50 cm depths in both drained and undrained mires. There appears to be a need for more studies that support Kruger et al. (2015) and Alewell et al. (2011) in their theory of how the stable peatlands changes with depth.

The statistical tests suggested differences at certain depths for the $\delta^{13}C$ and $\delta\ ^{15}N$ values at Ånnsjön S and Stensjöflon. At these depths the $\delta\ ^{13}C$ values were higher at the natural peatlands while the ^{15}N was higher at the restored peatlands. In general, aerobic microbial decomposition increases $\delta^{13}C$ and $\delta^{15}N$ at of the remaining peat since the decomposers prefer the lighter isotopes (Nykänen et al., 2020). The results for ^{15}N match this theory, while the results for $\delta^{13}C$ are the opposite of this theory. Drollinger et al. (2020) argues that the applicability of $\delta^{13}C$ and $\delta^{15}N$ signatures at the natural abundance level as indicators of the degree of peat decomposition is still debatable. They state that while several studies promote the kinetic isotope fractionation (e.g., Krüger et al., 2014). Others could not support these hypotheses or propose that other mechanisms are dominating in regulating $\delta^{13}C$ and $\delta^{15}N$ patterns, for example, the Suess effect, methane formation or variations in plant components (Nykänen et al., 2020). A possible explanation for the restored peatlands having higher $\delta^{13}C$ values at certain depths in this study is that CH_4 production and methanotrophy are known to decrease when the water table drops, which can also cause $\delta^{13}C$-enrichment of aerobic peat layers (Nykänen et al., 2020). The results from the PCA also indicated that the $\delta^{13}C$ values had very low correlation to the $\delta^{15}N$ values and other variables affected by drainage, for example the BD, nitrogen content, carbon content and C/N ratio. This also support the theory that there is some other mechanism controlling how the $\delta^{13}C$ patterns change following drainage compared to the mechanisms affecting these other peat properties.

With these uncertainties of how the stable isotopes of carbon and nitrogen are affected following drainage. I would not recommend using these isotopes as indicators of peat degradation in future research. Especially not when trying to construct a set of easily identified wetland soil characteristics that will tell whether a specific wetland will turn into a hot-spot for methane emissions or mercury net methylation following restoration. To use these isotope signatures as indicators of peat degradation there is a need for more research on what mechanism actually control their values following drainage, especially the $\delta^{13}C$ values.

4.4 Investigated peat properties

The statistical tests gave results indicating drainage effects at certain depths for at least one of the investigated peat properties at four of the six peatlands. This could be interpreted as that the drained conditions prior to the restoration have affected the properties at these depths. Peat grows very slowly (0-3mm/year) and the studied peatlands were restored between 2010 and 2015. A substantial amount of peat has thus not grown since the restoration. Kreyling et al. (2021) states that rewetting might not restore natural conditions promptly or even within decades. It is thus logical that most of the differences observed at the paired peatlands are a result of the drained conditions prior to the restoration. It would have been good if more peatlands in more regions were sampled. More samples could have given more support to if there really was a difference between the peatland categories or if these results only were a result of local variations.

It would also have been interesting to do this study on peatlands where a more substantial amount of peat had grown since the restoration. However, it is only recently that peatlands have begun being restored in Sweden. For example, according to Öberg (2021) the Swedish state did not begin restoring peatlands at a larger scale until 2010. There thus don’t exist many peatlands that were restored before the peatlands in this study were restored within the EU “Life to ad(d)mire” project. This study could be repeated in 50 years when a more substantial amount of peat has grown after the restoration. The general expectation would then be that there shouldn’t be any differences between the natural and restored peatlands in the upper parts of the peat profiles. The reason being that the new peat has grown in water saturated conditions both at the natural and restored peatlands. This theory is partly supported by the results from this study. In these results there did not exist any significant differences in the top centimetres between the natural and restored peatlands for any peat properties except the $\delta^{13}C$ values at Ånnsjön N. If the sampling was repeated in 50 years, the depths with differences in peat properties observed in this study would probably still exist. These depths would however probably be at higher depths and over smaller depth ranges. The reason for this being that more peat will grow above these depths and this new peat will further compact the peat layers below it.

At Ånnsjön N the drainage appeared to have affected the peat properties over a smaller depth range and at more shallow depths compared to the other paired peatlands. The other paired peatlands in most cases showed evidence of drainage effects at higher depths. It is more typical for peat to have drainage effects at more shallow depths like Ånnsjön N (Minkkinen & Laine (1998; Laiho et al. 1999 Krüger et al., 2014). It is acknowledged that when comparing natural and drained pairs from the same depth using current peat surface as a reference level, we are not comparing the same original peat depth layers. In the restored peatlands compaction, subsidence, shrinkage and respiratory carbon loss have deepened the surface from the original level (Nykänen et al., 2018). This could have had an impact on what depths the differences between the natural and restored peatlands were observed at in this study.

All restored peatlands had previously been drained; it was thus expected to be indications of drainage effects on more of the peat properties at more of the paired peatlands. At Mossaträsk and Öjsjömyrarna the statistical tests did not indicate any drainage effects. There are several possible reasons of why no drainage effects were observed. It is possible that the sampling was done too far from the drainage ditches. The general expectation would be that the peat properties would be more affected by drainage closer to the ditches where the drainage effect is more substantial (Casselgård, 2020). In this study we tried to sample the cores approximately five meters from the drainage ditches. This was however a rule of thumb and not something that was exactly measured. In some cases, it was also due to practical reasons not possible to take the cores this close to the ditch. It is thus possible that the cores at some peatlands were taken too far from the ditches and that is why no drainage effects were observed in them. If someone would repeat this study, I would recommend that the sampling distance from the ditch would be more precisely measured. This could give results with less variation both within the sites and between the different peatlands.

It is also possible that Mossaträsk and Öjsjömyrarna have not been drained that intensively and that there do not have any noticeable drainage effects. For example, in Länsstyrelsen description of Öjsjömyrarna it is mentioned that the mire only has been slightly affected by ditching (Länsstyrelsen jämtland, 2018). However, except for at Öjsjömyrarna there did not exist much available information about the drainage history at the sites. Information about when the ditches were first constructed and if there had been ditch-cleaning at the sites would have been useful for this study. This could have helped in explaining why there is much larger differences between the natural and restored peatlands at some of the paired sites compared to others. For example, a peatland that was drained for a longer time would be expected to have more drainage effects compared to a peatland that was not drained for as long. If ditches are not cleaned, they also lose their water transportation capacity because of occupation by wetland vegetation (Nieminen et al., 2018). If the ditches were cleaned it would then be expected that there should be larger differences between the natural and restored peatlands compared to if the ditches were not cleaned. Thus, another possible explanation of why there wasn't any observed differences at certain peatlands could be that there was no ditch-cleaning at those peatlands. However, with the current available information about the drainage history at these sites this is impossible to conclude. Thus, when doing further research on these sites there might be a need to find more information about the drainage history at these sites. This could for example be achieved by conducting interviews with local people or getting access to more archival documentation.

Another reason why the statistical test didn't indicate drainage effects for more peat properties at more paired peatlands could be a result of how the statistical model works. In the depth graphs, there were indications of the differences between the natural and restored peatlands for properties that didn't show any differences in the statistical tests. These differences were observed at certain depths at Ånnsjön 1-3 (OM, $_{OM}$N and $_{OM}$C/N), Ånnsjön 4-6 (OM, δ^{13}C and δ^{15}N), Öjsjömyrarna ($_{OM}$C, $_{OM}$N and δ^{13}C), Mossaträsk (δ^{15}N) and Sör-Lappmyran (OM, $_{OM}$C, $_{OM}$N and δ^{15}N). The reason the statistical tests didn't indicate any statistical differences at these depths could be that there was rather large variation within the cores for the groups (natural and restored) at these peatlands. For example, for the OM content at Sör-Lappmyran the SLR 2 core (restored) had much lower values compared to the other two cores from that restored peatland. The model is then unsure of what the group average is since there is a lot of statistical noise. This makes it harder for the statistical test to find differences between the natural and restored peatlands. If for example more samples would have been taken at the peatlands there is a chance that there would be less noise in the data. There would then be a greater chance for the model to find statistically significant differences between the properties at the natural and restored peatlands. A higher significance level could also have been used to indicate drainage effects for more peat properties at more paired peatlands. Given the inherent variability in the studied system, a significance level of 0.1 could probably have been used. However, most other studies on peat properties have used 0.05 as the significance level when comparing peat properties (Krüger et al., 2014, Leifeld et al., 2020). That significance level was thus used in this study so that the results would be more comparable to the results from earlier studies**.** If a significance level of 0.1 would have been used the ANOVA would have indicated statistically significant differences for the interaction effect at the $_{OM}$C content and δ^{15}N values at Sör-Lappmyran, and the OM content at Mossaträsk.

Previous studies have showed that the BD have a significant effect on the microbial community structure at peatlands which affect their methane emissions (Zhou et al., 2017). Putkinen et al. (2018) showed results indicating that the methane production decreased with higher bulk densities at peatlands. This could be an effect of the peat with higher BD having lower water holding capacity (Putkinen et al., 2018). The restored peatlands had higher bulk densities at certain depths compared to the natural peatland. Taking only the bulk density into account, this could indicate that a restored peatland should have lower methane emissions in relation to a comparable natural peatland. The other peat properties that have changed during the drained conditions might however have different effects on the methane production at the restored peatlands. The result from this study is thus not enough to tell how the soil properties that have changed during the drained conditions will affect biogeochemical processes like the methane production or mercury methylation following restoration. These are complicated processes, and more research is needed to determine how the changed soil properties affect them. However, when these results are combined with the results from the more extensive SLU project, they will hopefully help in developing a set of easily identified wetland soil characteristics that will tell whether a specific wetland will turn into a hot spot for methane emissions or mercury net methylation following restoration.

5. Conclusion

Differences in peat properties between a natural and restored peatland:

This study shows significant differences at certain depths between the natural and restored peatlands at four of the six investigated paired sites. For the BD, OM content, $_{OM}C$ content, $_{OM}N$ content, $_{OM}C/N$ ratio $\delta^{15}N$ values and total surface C content these statistical differences were always those expected after drainage i.e., the restored peatlands had higher BD, $_{OM}C$ content, $_{OM}N$ content, $\delta^{15}N$ values, as well as lower OM content and $_{OM}C/N$ ratios at these depths. The natural peatlands had higher $\delta^{13}C$ values at these paired sites which is the opposite of what's expected following drainage. However, Drollinger et al., (2020) argues that the applicability of $\delta^{13}C$ and $\delta^{15}N$ signatures at the natural abundance level as indicators of the degree of peat decomposition is still debatable. These results indicate that investigated properties at the restored peatlands still are affected by the drained conditions they had prior to the restoration. More research is needed to determine what effects these changed soil conditions have on biogeochemical processes like methane production and mercury methylation following restoration. Hopefully this will be answered when the result from this study is combined with the results from the more extensive SLU project.

Differences in peat properties across the peat profile:

The BD, $_{OM}C$ content, $_{OM}N$ content, $\delta^{13}C$ and $\delta^{15}N$ increased with depth at most of the restored and natural peatlands, while the $_{OM}C/N$ ratio decreased, and OM content decreased with depth at most peatlands. Deeper peat is typically more decomposed than shallower peat. This depth trend was thus expected for BD, $_{OM}C$ content, $_{OM}N$ content, OM content and $_{OM}C/N$ ratios since decomposition is known to induce subsidence and compaction of peat material as well as relatively increasing the carbon and nitrogen content in the remaining peat. It was expected that the $\delta^{13}C$ and $\delta^{15}N$ values would have more uniform trends with depth since Krüger et al. 2015 and Alewell et al., 2011 have suggested that this is the case in in natural (pristine) peatlands. Their theory of how stable carbon and nitrogen isotopes change with depth in natural and restored peatlands was not supported by the results from this study. The results from this study thus indicates that more research is needed on the mechanism that regulate the patterns of these isotopes if they are to be used as indicators of peat degradation in future research.

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SENASTE UTGIVNA NUMMER

2021:10 Författare: Kazi Samiul Islam
Effects of warming on leaf – root carbon and nitrogen exchange of an ericaceous dwarf shrub.

2021:11 Författare: Ellika Hermansson
Ett riktigt hästarbete –skogsarbete med häst i sydvästra Sverige, förr, nu och i framtiden

2021:12 Författare: Fabian Balele
Wildfire dynamics, local people's fire use and underlying factors for wildfires at Liwale

2021:13 Författare: Martina Lundkvist
Samband mellan ståndortsfaktorer, genetik och historiska skördedata från tall- och granfröplantager – krävs ökad precision vid val av lokaler för nyafröplantager?

2021:14 Författare: Maria Grånemo
"I stand here. I will not move" – Women in forestry in northern Sweden during the 20th century

2021:15 Författare: Tim Schacherl
Evaluating Drought Impacts on Ecosystem Water Use Efficiency of Three Different Boreal Forest Sites

2022:01 Författare: Alice Cosatti
The end of the timber frontier in northern Sweden – Early logging, natural forests and the frontier concept

2022:02 Författare: Pontus Nyqvist
Utvärdering av metod för att morfologiskt särskilja björkarterna Betula pendula och Betula pubescens

2022:03 Författare: Julia Nygårdh
Mosippans (Pulsatilla vernalis L.) reaktion på brandstörning
– En populationsstudie på en av Sveriges rikaste mosippslokaler

2022:04 Författare: Oskar Karlsson
Effects on natural seed regenerated Silver birch (Betula pendula Roth) and Downey birch (Betula pubescens Ehrh) by mechanical soil scarification and environmental factors

2022:05 Författare: Eric Lundqvist
Riparian forests – a comparison of tree diversity, deadwood and canopy cover between primary and production riparian forests along headwaters

2022:06 Författare: Louise Nordström
Growth and development of Eucalyptus grandis seedlings in response to arginine phosphate application

2022:07 Författare: Alice Falk
Towards climate optimised riparian buffer zones in boreal forests. Investigation of clearcutting effects on soil temperature, soil moisture and greenhouse gas fluxes in riparian buffer zones with different widths

2022:08 Författare: Pelle Kronborg
Biogeochemistry and Peat Properties of Restored Peatlands