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Effects of 100 years of drainage on peat properties in a drained peatland forests in northern Sweden

Effekter av 100 års dränering på torvegenskaper i en dränerad torvskog i norra Sverige

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Abstract

Natural peatlands provide a small but persistent long-term carbon (C) sink. However, within the last century their extent in Sweden has declined by about 1.5-2.0 million hectares due to drainage activities. When a peatland is drained, the groundwater level is lowered which leads to changes in peat properties, increased microbial activity and larger C and nitrogen (N) losses. The resulting changes in the ecosystem also influence fauna and flora communities and reduce biodiversity. The overall aim of this master's thesis was to investigate how 100 years of drainage has affected the physical and chemical properties of peat in a drained peatland forest (Trollberget) in northern Sweden.

Analyses of peat bulk density, ash content, C content, N content, C:N ratio, $\delta_{13}C$ and $\delta_{15}N$ data were conducted in relation to ditch distance (i.e. 5, 25 and 50 m) and across the peat profile (up to a depth of -55 cm). Similar data were further available for comparison from a nearby natural mire (Degerö mire).

The results showed significant differences in bulk density, C content and $\delta_{13}C$ between the different distances from ditch. Specifically, most of these parameters (except for $\delta_{13}C$) indicated a generally stronger drainage effect and decomposition in samples further away from the ditch which is in contrast to expectation. This was also confirmed by the ash and N content as well as C:N ratio and $\delta_{15}N$ data though the patterns were not as clear and statistically not significant. The $\delta_{13}C$ data, on the contrary, suggested highest drainage effect and decomposition closer to the ditch.

Across the vertical peat profile, significant differences were found for all of the studied variables at the drained peatland forest. It is interesting to note that the depth profiles of bulk density, ash and N content, C:N ratio and $\delta_{15}N$ indicate that drainage and decomposition has been strongest in the upper ~10-30 cm layer.

The comparison with the natural mire suggests that the drained site had significantly higher bulk density, due to lowering of the groundwater level and subsequent subsidence, compaction and decomposition of the peat. Similarly, higher C and N content and lower C:N ratio compared to the natural mire indicate that the peat is strongly decomposed at the drained site. In comparison to the natural mire, a significant difference could also be detected for the $\delta_{15}N$ values with an enrichment of $_{15}N$ occurring in the upper layer due to enhanced decomposition following drainage. Peat $\delta_{13}C$ data on the other hand was rather similar between the drained and natural sites.

Overall, this thesis results demonstrate manifold changes in peat physical and chemical properties following drainage of natural mires. While most of these could be associated with increased decomposition rates in the upper ~30 cm layer, additional impacts might occur in relation to hydrological variations on the site or in connection to the forest edge surrounding the site, which may further alter nutrient content and water supply at specific locations across the drained peatland site. In summary, it can be said that ditching of mires has significant effects on physical and chemical peat properties with important subsequent effects on peatland ecosystem functioning such as greenhouse gas emissions, hydrology and biodiversity.

Keywords: Ash content, biodiversity, bulk density, carbon, climate, compaction, ditch, drainage, greenhouse gas emissions, nitrogen, peatland, restoration

Sammanfattning

Naturliga torvområden utgör en liten men långvarig kol (C) sänka på jorden. Under förra seklet minskade torvområden i Sverige med cirka 1,5–2,0 miljoner hektar på grund av dränering. När torvmarker dräneras sänks grundvattennivån vilket leder till förändringar i torvegenskaper, så som ökad mikrobiell aktivitet och större förluster av C och kväve (N). Förändringar i ekosystemet leder till andra typer av fauna och flora samhällen och minskar den biologiska mångfalden. Det övergripande syftet med denna masteruppsats var att undersöka hur 100 års dränering har påverkat torvens fysiska och kemiska egenskaper i en dränerad torvskog (Trollberget) i norra Sverige.

Analyser av torvbulkdensitet, askinnehåll, C-innehåll, N-innehåll, C:N-kvot samt δ^{13}C och δ^{15}N data utfördes i relation till dikningsavståndet (dvs 5, 25 och 50 m) och torvprofilen (upp till -55 cm). Liknande data fanns för jämförelse från en närliggande naturlig Degerö-myr.

Resultaten visade signifikanta skillnader i bulkdensitet, C-innehåll och δ^{13}C mellan de olika avstånden från diket. Dessa parametrar (förutom δ^{13}C) indikerade en generellt kraftigare dräneringseffekt och nedbrytningskapacitet i prover längre bort från diket, vilket var motsatsen till de förväntade resultaten om högre hastigheter av nedbrytning närmare diket där dräneringseffekten borde vara som störst, inte visade sig stämma. Detta bekräftades också av ask- och N-innehållet såväl som C:N-kvoten och δ^{15}N data, även om mönstret i data inte var lika tydligt och statistiskt sett inte signifikant. δ^{13}C data visade omvänt resultat med högre dräneringseffekt och nedbrytning närmast diket.

I den vertikala torvprofilen kunde signifikanta skillnader konstaterades för alla de studerade parametrarna i den dränerade torvskogen. Det intressanta att notera är att torvprofilerna för bulkdensitet, ask- och N-innehåll, C:N-kvoten och δ^{15}N indikerade att dräneringseffekten och nedbrytningen var starkast i det övre ~10-30 cm-skiktet.

Jämförelsen med den naturliga myren antyder att det dränerade området hade betydligt högre densitet på grund av sänkning av grundvattennivån och efterföljande sänkning, kompaktering och nedbrytning av torven. På liknande sätt indikerar även högre C- och N-innehåll och en lägre C:N-kvot att torven bryts ner kraftigare på den dränerade myren jämfört med den naturliga myren. I jämförelsen med den naturliga myren kan en signifikant skillnad också detekteras för δ^{15}N värdena med en anrikning av ^{15}N som uppträder i det övre skiktet på grund av den intensifierade nedbrytningen efter dränering. δ^{13}C data hade och andra sidan väldigt lika värden mellan den dränerade och naturliga myren.

Överlag visade dessa resultat många förändringar i både fysiska och kemiska egenskaper hos torv som blivit dränerad. Flest resultat visade sig vara förknippade med ökade nedbrytningshastigheter i det övre ~30 cm-skiktet, vilket kan ha uppstått i förhållande till ytterligare påverkande faktorer så som hydrologiska variationer på platsen eller prover tagna i anslutning till skogskanten som omger platsen, vilket kan ge ytterligare förändringar i näringsinnehållet och vattentillgången på specifika platser på det dränerade torvområdet. Sammanfattningsvis kan man säga att dikning av våtmarker har betydande effekter på fysikaliska och kemiska torvegenskaper med viktiga efterföljande effekter på torvmarkens ekosystem så som växthusgaser, hydrologi och biodiversitet.

Nyckelord: Ask innehåll, biodiversitet, bulkdensitet, dike, dränering, klimat, kol, kompaktering, kväve, restaurering, torvmark, växthuseffekter

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Introduction

Due to increasing concern regarding the anthropogenic emissions of greenhouse gases, peatlands have received increasing attention in recent years. The Swedish land area consists of 10 million hectares of peatlands and shallow peat areas, which corresponds to about one fourth of the total land area (Hånell 2009).

Since the 19th century, approximately 1.5-2 million hectares of peatlands have been drained to increase forest production in Sweden (Hånell 2006). However, interest in ditching is not as great today as it once was and over the past 10 years attempts to restore ditched peatlands been made (Öberg 2018).

One reason for restoring drained peatlands is the increasing knowledge of climate change and recent studies suggesting that drained peatlands may be acting as large greenhouse gas emission sources to the atmosphere (He et al. 2016; Roulet & Moore 1995). Another reason is to increase biodiversity in the landscape (Laine et al. 1995). Drainage also alters the physical and chemical peat properties significantly (Krüger et al. 2015). Since these peat properties affect peatland hydrology and biogeochemistry (e.g. greenhouse gas production), it is important to understand how they change following drainage.

1.1. Definition of peatlands

Peatlands can be defined as terrain that is covered with a naturally accumulated layer of peat. Usually, a minimum depth of peat is required for a site to be classified as peatland. In Sweden, this limit is 30 cm. In contrast, land without peat or with a peat layer <30 cm is called wetland or mineral soil (Hånell 2006). Definitions in other countries could for example use >40 cm depth of peat to define peatlands, or even up to >70 cm (Rudqvist 1999; Gorham 1991).

1.2. Peat formation

Peat consists of partially decomposed dead organic material. Under anaerobic conditions, peat is created from the remnants of mosses and vascular plants that would ordinarily be decomposed. In this case the decomposition of the dead organic material has been constrained by a lack of oxygen, which is caused by water saturation (Joosten & Clarke 2002).

1.3. History of previous use of peatlands until today

In Sweden, drainage of peatlands has been going on for over 150 years and started in the 19th century primarily for the purpose of cultivation, e.g. grazing and haymaking (Holmen 1964; Hånell 2009). Forest ditching was first implemented relatively late in connection with the increasing forest industry that also was late to develop in Sweden (Holmen 1964). The first available forest statistics about ditching was between 1873-1890 (Holmen 1964). At the end of the 19th century forest ditching was occurring to a great extent in Sweden. It was most intense between 1920-1940 and became a way to decrease unemployment during the 1930s depression (Holmen 1964). A second peak occurred around the 1980s when interest in ditching was again as high as it was in the 1930s because of a new type of ditching on clear-cuts, i.e. remedial ditching (Hånell 2009). Until 1990 the state provided the industry subsidies for ditching before it expired and today the interest in ditching is as low as it has ever been, mainly due to the restriction from an environmental point of view (Hånell 2009). Since 1986, forest owners have been obliged to seek permission for traditional ditching, depending on the size of the object (Hånell 2009).

1.4. Peatland restoration today

Peatland restoration plays a key part in the landscape in creating biodiversity and decreasing net release or even removing CO_2 from the atmosphere (Laine et al. 1995; Jungkunst et al. 2012). In order to ensure a successful restoration, it is important to understand the various impacts drainage has had on the peatland ecosystem, e.g. on the peat properties.

From 2010 to 2018 approximately 3600 hectares of peatlands have been successfully restored in Sweden and a lot of these peatland restoration projects were financed through the European Union LIFE programme between 2010-2015. However, the time required for the restoration process is slow and the scale is too small to successfully reverse the negative development at a national level. During 2018, approximately 623 hectares of drained peatlands were restored with funding from the state (Öberg 2018).

The decision of which drained peatlands should be selected for restoration in Sweden is linked to the EU Council Directive (2013). The directive covers the Natura 2000 areas that are protected for conservation of natural habitats and wild fauna and flora to protect Europe’s biodiversity (The council of the European communities).

1.5. Drainage impacts on peatland ecosystem functioning and peat properties

1.5.1. Ecosystem services

Natural peatlands deliver many important ecosystem services such as climate regulation through carbon (C) sequestration and storage, water purification and regulation, biodiversity maintenance, habitat for wildlife etc. Peatlands have been drained for various purposes (e.g. afforestation), which has contributed to a reduction of natural peatlands and habitat loss in the landscape. In summary, it can be said that the negative effects of peatland drainage are (Hånell 2006; Henrikson 2006):

- Changed water input leading to changing temperature in the surface area
- Increased greenhouse gas emissions
- Nutrient leakage due to altered water flow (water levels, waterways)
- Negative effect on water quality, i.e. pH and toxins (e.g. mercury)
- Erosion and further transport of dissolved organic material which can later cause clogging of the water channels
- Impaired natural cleaning ability

1.5.2. Greenhouse gases

Natural peatlands are important net sinks for CO_2 but can be large sources for CH_4 emissions to the atmosphere. Despite the fact that trees are a valuable source for uptake of atmospheric carbon dioxide (CO_2), forests on peatland can also act as a source for greenhouse gases. Peatlands are most efficient net C sinks in the northern latitudes between 50° N to 70° N (Jungkunst et al. 2012). The CO_2 emissions to the atmosphere often increase following drainage because of the increased peat decomposition rates (Jungkunst et al. 2012; Minkkinen K. & Laine 1998). Drained peatlands also release methane (CH_4) and nitrous oxide (N_2O) and the net exchanges of these gases depend on several factors such as climate zone, forest productivity, peat nutrient status, tree species and groundwater level (Hånell 2006).

1.5.3. Water quality

The runoff of water from a drained peatland has often raised levels of dissolved organic material, which can later clog the water channel. Moreover, the pH and N leakage in the surrounding water ecosystem can affect species in the bottom fauna of streams (Hånell & Magnusson 2005).

1.5.4. Biological diversity

The fauna and flora that are adapted to natural peatlands, will become affected when drainage effects make the peatland drier. First of all, tree growth will likely increase in the first few years following drainage. Ground vegetation composition will also change significantly. The ground vegetation (e.g. sedges and mosses) which benefit from the wet surface area and the oxygen-poor soil environment will likely disappear, and the numbers of shrubs that are adapted to drier ground layer conditions will increase (Laine et al. 1995). The effects will be greatest the first five to ten years after drainage and slightly decrease as new plants establish and shade the ground vegetation (Vasander 1987). The ground layer will gain other species as tree groups shade the original species, and the flora will change to more typical forest species. These changes lead to improved fertility of the soil and a new type of ecosystem is developed (Laine et al. 1995).

Oligotrophic and mesotrophic peatlands are characterized by *Sphagnum* mosses but could also include vascular plants, which produce rhizomes and roots which could be converted to organic matter in the deeper layer (Paavilainen & Päivänen 1995). After peatland drainage, the *Sphagnum* species are replaced by other mosses that are more likely to grow in drier soils (e.g. *Hylocomium splendens, Pleurozium schreber*i etc.) (Hånell 2009).

The fauna of peatlands includes birds specially adapted to peatlands (e.g. the wading bird) but there could also be other birds that are dependent on wetlands for predation (e.g. owls and grouse) (Simonsson 1987). There are also different insects and water fauna that could be affected of different ground vegetation and changed water content (Hånell 2009).

1.5.5. Peat physical properties

The groundwater level on drained peatlands is usually ~0.5 m below the ground (Simonsson 1987). Water level drawdown following drainage causes first a physical collapse of plant structures and compaction of the peat matrix. After that, increased aerobic decomposition of organic matter as well as the increasing mass of the establishing tree stand will further increase peat subsidence and compaction (Laine et al. 2006). The result of this is an increase in peat bulk density which further affects the water retention ability and hydraulic conductivity of the peat material (Minkkinen & Laine 1998). In addition, lowered groundwater levels also reduce the fraction of accumulated organic material due to peat oxidation resulting in an accumulation of mineral matter (i.e. ash). The temperature dynamics of peat also change following drainage. Specifically, the surface peat becomes warmer, with rising temperature depending on less water content in the peat (Paavilainen & Päivänen 1995).

1.5.6. Peatland carbon

Research shows that temperature conditions play a major role in C stock accumulation rates (Yu et al. 2010; Davidson & Janssens 2006). The loss of C is often dependent on the depth of the water table (Holden 2005). When the water table decreases, peat becomes more exposed to oxygen, which contributes to increasing CO_2 emissions (Arnold 2006). A higher water table results in less oxygen and therefore a reduced peat decomposition and greater CH_4 production (Huttunen et al. 2003).

Stable C isotopes are good indicators of biogeochemical processes in the soil (Alewell et al. 2011). Specifically, there are two stable C isotopes called ^{13}C and ^{12}C (Fry 2006). In natural peatlands with low decomposition rates, the ratio of ^{13}C to ^{12}C (i.e. $\delta^{13}C$ value) is almost constant along a depth profile. Following drainage, however, an increase in ^{13}C can be expected due to the preferential use of the lighter ^{12}C by the decomposers (Ågren et al. 1996; Alewell et al. 2011; Krüger et al. 2015). Therefore, higher (i.e. more positive) $\delta^{13}C$ values indicate an increased decomposition (Alewell et al. 2011; Fry 2006).

1.5.7. Peatland nitrogen

Unlike mineral soils, peatlands contain a lot of N but have a shortage of mineral nutrients, mainly phosphorus and potassium (Hånell & Magnusson 2005). After drainage, the emissions of N_2O usually increase in nutrient-rich peatland sites, i.e. with C:N ratios <25 (Klemedtsson et al. 2005). A lower C:N ratio indicates higher degradation rate and enhanced N content in the peat material (SLU 2019). N_2O production occurs primarily through nitrification and denitrification processes (Jungkunst et al. 2012). It is when N is denitrified to N_2O instead of nitrogen gas (N_2) that the emissions become an environmental issue since N_2O is a strong greenhouse gas (Skogsstyrelsen & Magnusson 2015).

Stable N isotopes can be used to trace the biogeochemical process in the soil. Specifically, N has two stable isotopes, i.e. ^{15}N and ^{14}N (Fry 2006). Differences in these isotopes in transects and vertical depth profiles can reveal shifts in the ecosystem and are valuable for the analysis of sources and sinks in the atmosphere and soil (Fry 2006). The variation of the isotopes is created due to a cumulative faster loss of ^{14}N which contributes to an increase of ^{15}N during decomposition in soils (Fry 2006), provided that the ^{14}N is lost/translocated from the system. Higher (i.e. more positive) ^{15}N to ^{14}N ratios (i.e. $\delta^{15}N$ values) are therefore indicative of increased decomposition rates.

1.6. Aim

The purpose of this master’s thesis is to investigate how 100 years of drainage have affected peat properties in a drained peatland forest (Trollberget) in northern Sweden. The thesis focuses on investigating the following peat physical and chemical properties: bulk density, ash content, C content, N content, C:N ratio as well as δ_{13}C and δ_{15}N values. Similar readily available data from a nearby natural mire (Degerö Stormyr) are used as a reference for undrained conditions. The questions this study is intended to answer are:

- How do the physical and chemical peat properties change with distance from the drainage ditch?
- How do the physical and chemical peat properties change with depth along the peat profile?
- What are the differences in physical and chemical peat properties between a drained peatland vs. a natural peatland?

2. Material and Methods

2.1. Site description

Peat samples were collected from a nutrient-poor drained peatland forest, Trollberget (64.15943N, 19.92439E), located 45 km northwest of Umeå in the county of Västerbotten, northern Sweden (Figure 1). In its natural state, the site was described as being mostly a flark-and-string mire (*flarkmyr*), i.e. a wet mire with areas of open water. The ditches on the mire were dug sometime before 1924, i.e. approximately 100 years ago. In 1939, the site was marked as a forested mire (*skogsklädd myr*) (Nordstedt, 2019). Today, the drainage ditches on the site no longer function properly and the mean groundwater level is around -25 cm. Peat depth extends to about 3 m. The vegetation of the site is characterized by a moderately sparse cover of Scots pine but also some small deciduous trees (e.g. dwarf birch) (Länsstyrelsen Västerbotten 2019a).

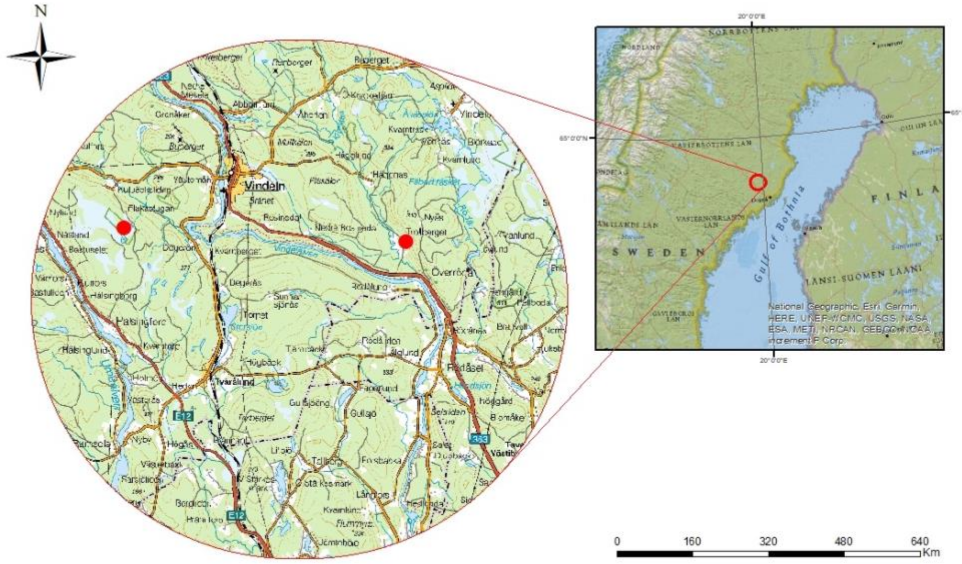

Figure 1. Locations of the Trollberget drained peatland forest and the natural Degerö mire northwest of Umeå, Sweden (ESRI 2016).

Already available data are used for comparison from the nearby (<15 km distance) natural peatland Degerö Stormyr – a minerogenic oligotrophic mire (i.e.

a nutrient-poor fen) (Figure 1). The Degerö mire (64.17641N, 19.57644E) belongs to Vindelns research forests, called Kulbäcksliden Experimental Forest (Länsstyrelsen Västerbotten 2019b). This is an undisturbed mire with no management and it has a similar characterized biotope as the investigated peatland at Trollberget. The peat depth on the site is mainly ranging between 3 and 4 m, however, depths of up to 8 m have been measured. The mean groundwater level is around -15 cm. The site is dominated by lawn and carpet plant communities (e.g. tussock cottongrass, tufted bulrush, bog cranberry, bog-rosemary and *Sphagnum* spp.) (Nilsson et al. 2008).

The climate of the region is characterized by an annual mean temperature and precipitation of 4 °C and 700 mm, respectively (SMHI 2018).

2.2. Field measurements

Trollberget. A total of 36 peat cores were collected with a stainless-steel rectangular soil corer (custom-made; inner dimensions 8×8.4 cm). The peat cores were taken from the top 55 cm of the peat profile along 6 transects established perpendicular to the main drainage ditch with 3 measurement locations (5, 25 and 50 m from the ditch) on both sides of the ditch (Appendix Figure 1). The collected peat cores were sliced into 5 cm sections in the field (resulting in a total of ~400 samples) and stored in a cooler at 4 °C until further processing in the lab.

2.3. Laboratory work and calculations

Bulk density. The collected peat samples were dried in a drying cabinet at 60 °C until constant weight (5-7 days), cooled down in a desiccator (Nalgene) and weighed on a digital scale (Thermo Fisher Scientific) to determine their dry weight. Bulk density (g/cm^3) for each sample was calculated based on the dry weight and total volume.

Bulk density (BD) was determined following Formula (1):

$$BD = (M_i - M_e)/V_i \qquad (1)$$

where

M_i is the mass in g of the dish plus the sample;

M_e is the mass in g of the empty dish;

V_i is the volume of the total peat sample (the inner dimension of the corer).

The result was calculated to two decimal places.

Ash content. Subsamples of 2-5 g were dried at 105 °C to a constant weight, cooled down in a custom-made desiccator box and weighed on a four decimal scale (Mettler AG204) to determine the dry weight of each sample before combustion. The samples were then placed in a muffle furnace (Nabertherm) and heated at 550 °C for 6 h. Following this, the samples were again cooled down in a desiccator and weighed to determine the dry weight of the sample after heating at 550 °C.

Ash content was calculated from loss on ignition data following Formula (2):

$$Ash = 100 - [((m_2 - m_1)-(m_3-m_1))/(m_2-m_1) \times 100] \qquad (2)$$

where

m_1 is the mass in g of the empty dish;

m_2 is the mass in g of the dish plus the sample portion;

m_3 is the mass in g of the dish plus ash.

The result was calculated to two decimal places and the mean value was rounded to the nearest 0.01%.

Chemical analysis (C, N, δ_{13}C and δ_{15}N) of peat. The required preparation work for the chemical analyses consisted of grinding, drying and weighing of smaller subsamples of the collected peat material. The samples were ground using a tube mill (IKA Tube Mill control) and disposable grinding chambers (IKA MT 40.100). Thicker tree roots were removed prior to grinding. The grinded samples were dried at 70 °C until constant weight (~16 hours), cooled down in a desiccator and weighed into small tin cups on a four decimal scale (Mettler Toledo). The samples were analysed for C and N contents (%) 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 and Biogeochemical Analyses Laboratory at the department of Forest Ecology and Management, SLU, Umeå.

2.4. Reference data from a natural mire

Degerö. The readily available data from the Degerö mire included information on peat bulk density, C and N contents as well as δ_{13}C and δ_{15}N values. The peat cores were collected in August 2015 from the top 36 cm of the profile from 8 different locations around the eddy covariance flux tower on the mire. The samples were originally analysed in 2 cm sections but for the purpose of this thesis 10 cm averages were also calculated in order to facilitate statistical comparisons with the drained Trollberget site.

2.5. Statistical analysis

The effects of the two factors ‘distance from ditch’ and ‘peat depth’ on the response variables (BD, ash content, C content, N content, C:N ratio, δ_{13}C and δ_{15}N) were statistically evaluated at the Trollberget site. The factor ‘distance from ditch’ included 3 groups (5, 25 and 50 m) and the factor ‘peat depth’ included 11 groups (-5, -10, …, -55 cm). Outlier values in the data occurring possibly due to disturbance during sampling or processing were defined as > mean ± 3SD and removed prior to analysis. In total, 3.5% of the ash content data and <1% of data for each of the remaining variables were identified as outlier. Initially, the data for each of the response variables were tested for normal distribution using the Ryan-joiner test (similar to Shapiro-Wilk test). Based on these test results, none of the data were normally distributed, even after applying a log-transformation. Therefore, the parametric 2-way analysis of variance (ANOVA) to explore the effects of both factors at the same time could not be applied. Instead, the non-parametric test Kruskal-Wallis test for multiple groups combined with a Bonferroni post-hoc multiple comparison was used to explore the effect of one factor at a time. In an additional Kruskal-Wallis test, the available peat properties data (BD, C content, N content, δ_{13}C and δ_{15}N) from the natural Degerö mire was included as a fourth ‘group’ to test for its difference with the three ditch distances at the drained Trollberget peatland for 0-30 cm depth (for which data from Degerö was available). Effects were statistically significant if P<0.05. P is the statistical probability value, for a given model, indicating evidence to reject the null hypothesis with less than 5 % probability that the null hypothesis is correct. All statistical analyses were carried out using the Minitab software (Minitab 2019).

3. Results

3.1. Bulk density

BD values ranged from 0.05 to 0.13 g/cm3 and generally increased with distance from the ditch and with peat depth at the Trollberget drained peatland site (Figure 2). The statistical analysis suggested that BD was significantly higher at 50 m compared to 5 and 25 m distances from the ditch (Table 1). Across the peat profile, BD was significantly lower at I) -5 cm compared to all other depths and II) -10 cm compared to -15 and -20 cm depths (Table 2). BD was significantly higher at the Trollberget drained peatland at all 3 ditch distances compared to the natural Degerö mire (Figure 2, Table 1).

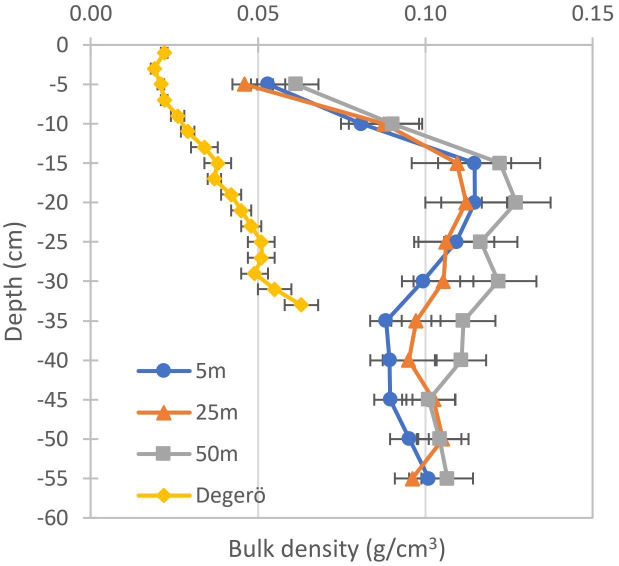

Figure 2. Bulk density (g/cm3) across the peat profile at the Trollberget drained peatland (5, 25 and 50 m distances from the ditch) and at the natural Degerö mire.

Table 1. Ditch distance effects on peat properties, averaged over the sampling depths, including bulk density (BD), ash content, carbon (C) content, nitrogen (N) content, C:N ratio, δ^{13}C signature and δ^{15}N signature from both Trollberget peatland and Degerö mire. Values with different letters are significantly different.

Distances	**BD (g/cm^3)**	**Ash (%)**	**C (%)**	**N (%)**	**C:N ratio**	**δ^{13}C (‰)**	**δ^{15}N (‰)**
5	0.1 a	3.0 a	51.9 a	1.2 a	45.8 a	-26.4 a	-0.9 a
25	0.1 a	4.2 a	51.9 a	1.3 a	45.6 a	-26.7 a	-0.9 a
50	0.1 b	3.8 a	52.7 b	1.3 a	47.5 a	-27.0 b	-0.7 a
Degerö	0.0 c	-	47.9 c	0.8 c	66.5 c	-27.3 c	-1.8 c

Table 2. Peat depth effects on peat properties including bulk density (BD), ash content, carbon (C) content, nitrogen (N) content, C:N ratio, δ^{13}C signature and δ^{15}N signature at the Trollberget peatland. Values with different letters are significantly different.

Depth	**BD (g/cm^3)**	**Ash (%)**	**C (%)**	**N (%)**	**C:N ratio**	**δ^{13}C (‰)**	**δ^{15}N (‰)**
-5	0.0 a	2.2 a	51.0 a	1.1 a	47.0 a	-28.5 a	-0.7 ac
-10	0.0 b	5.9 a	50.3 a	1.5 b	38.0 bc	-27.4 ab	0.3 b
-15	0.0 c	5.1 a	50.9 a	1.5 b	38.0 c	-26.8 bc	0.2 b
-20	0.1 c	4.0 ab	51.8 ab	1.5b	45.5 bcd	-26.5 c	-0.3 ab
-25	0.1 bc	3.5 ab	52.3 ab	1.4 ab	49.9 acd	-26.4 c	-0.8 bc
-30	0.1 bc	3.3 b	52.8 ab	1.3 ab	50.4 acd	-26.3 c	-1.1 ac
-35	0.1 bc	4.4 b	52.5 ab	1.2 ab	49.9 abd	-26.2 c	-1.3 c
-40	0.1 bc	2.8 b	52.5 ab	1.2 ab	50.4 ad	-26.3 c	-1.2 c
-45	0.1 bc	2.2 b	53.2 b	1.2 ab	50.0 ad	-26.4 c	-1.3 c
-50	0.1 bc	2.1 b	53.2 b	1.2 ab	50.0 ad	-26.5 c	-1.5 c
-55	0.1 bc	4.3 b	53.5 b	1.2 ab	43.8 a	-26.5 c	-1.4 c

3.2. Ash content

In general, ash content varied between 1.73 and 7.20% with somewhat lower values at the 5 m distance from ditch compared to the 25 and 50 m distances (Figure 3). However, none of these differences were statistically significant (Table 1). In the peat depth profiles, ash content was significantly higher at I) -10 cm vs. -30 to

-55 cm depths and II) -15 cm vs. -30 to -55 cm depths (Table 2). Similar data from the Degerö mire was missing and not available for comparison.

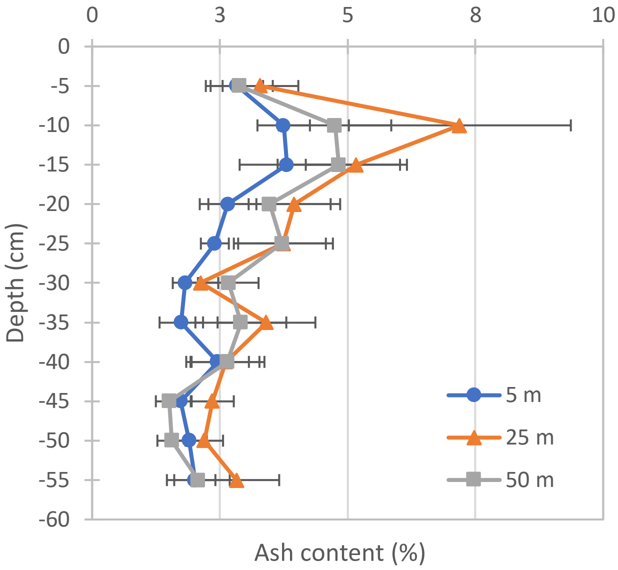

Figure 3. Ash content (%) across the peat profile at the Trollberget drained peatland at 5, 25 and 50 m distances from the main drainage ditch.

3.3. Carbon and nitrogen contents and C:N ratio

C content varied between 48.9 % to 54.0% and generally increased with distance from the ditch and with peat depth at the drained Trollberget site. The statistical analysis showed that the C values were significantly higher at 50 m compared to 25 m distances from the ditch (Table 1). Across the peat profile, C content was significantly lower at I) -5 cm vs. -45 to -55 cm depths, II) -10 cm vs. -45 to -55 cm depths and III) -15 cm vs. -45 to -55 cm depths (Table 2). C content was significantly higher at the Trollberget drained peatland at all three ditch distances compared to the natural Degerö mire (Figure 4, Table 1).

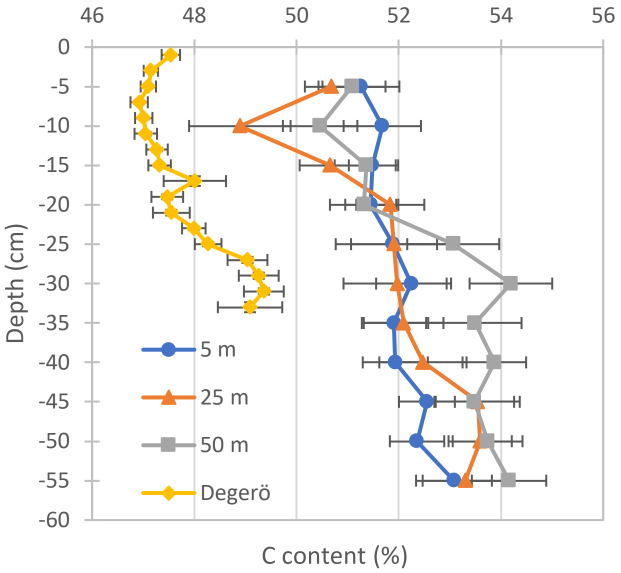

Figure 4. Carbon (C) content (%) across the peat profile at the Trollberget drained peatland (5, 25 and 50 m distances from the ditch) and at the natural Degerö mire.

N content varied between 0.95% and 1.65% at the Trollberget peatland with slightly higher values observed for distances further away from the ditch (Figure 5). However, none of the differences were statistically significant (Table 1). N content showed a generally decreasing trend with peat depth with the exception of the uppermost peat layer where the values were higher. Across the peat profile, N content was significantly higher at -10 to -20 cm depths compared to the -5 cm depth (Table 2). N content was significantly higher at the Trollberget drained peatland for all 3 ditch distances compared to the natural Degerö mire (Figure 5, Table 1).

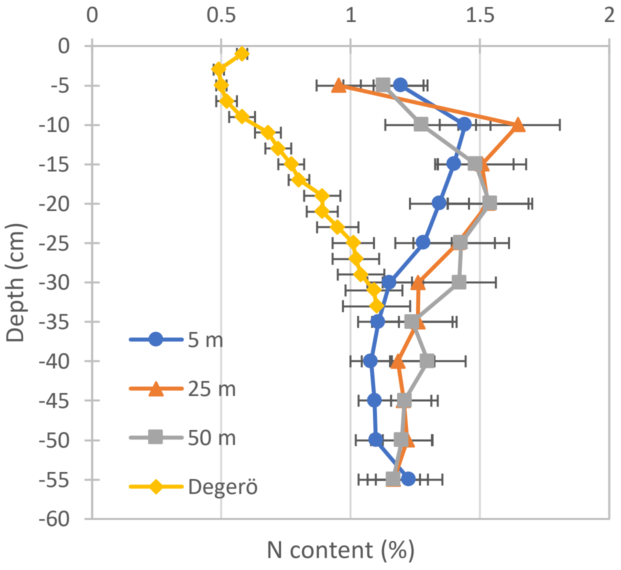

Figure 5. Nitrogen (N) content (%) across the peat profile at the Trollberget drained peatland (5, 25 and 50 m distances from the ditch) and at the natural Degerö mire.

The C:N ratio at the Trollberget peatland ranged from 35.5 to 58.8 and in general increased with peat depth (Figure 6). No clear pattern was observed for the distances from the ditch and the statistical analysis showed no significant differences (Figure 6, Table 1). Across the peat profile, C:N ratio was significantly I) higher at -5 cm vs. -10 to -20 cm depths, II) lower at -10 cm vs. -40 to -55 cm depths, III) lower at -15 cm vs. -35 to -55 cm depths and IV) lower at -20 cm vs. -55 cm depth (Table 2). The C:N ratio was significantly lower at the Trollberget drained peatland for all three ditch distances, as compared to the natural Degerö mire (Figure 6, Table 1). The C:N ratios at the drained and undrained sites converged at ratios between 40 to 45 at around -30 to -35 cm depth.

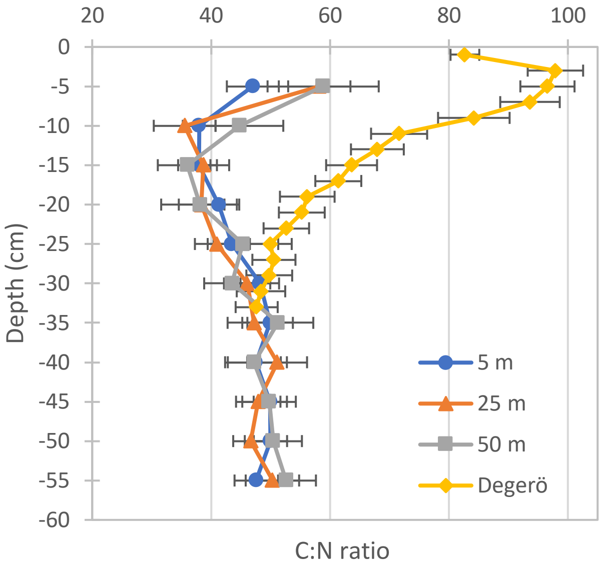

Figure 6. The C:N ratio across the peat profile at the Trollberget drained peatland (5, 25 and 50 m distances from the ditch) and at the natural Degerö mire.

3.4. δ_{13}C and δ_{15}N

Peat δ_{13}C values exhibited a generally decreasing trend with increasing distance from the drainage ditch (Figure 7). The statistical analysis showed significantly higher (i.e. more positive) values for the 5 and 25 m distances compared to the 50 m distance from ditch (Table 1). Across the peat depth profile, δ_{13}C values increased from about -28.5‰ in the upper 5 cm to about -26.5‰ in the deeper layers. In general, δ_{13}C was relatively constant below the depth of approximately -25 cm (Figure 7). The statistical analysis showed that the δ_{13}C was significantly lower at I) -5 cm vs. -15 to -55 cm depths and II) -10 cm vs. -20 to -55 cm depths (Table 2). δ_{13}C values were significantly higher at the Trollberget drained peatland at the 5 m distance from ditch compared to the natural Degerö mire (Figure 7, Table 1).

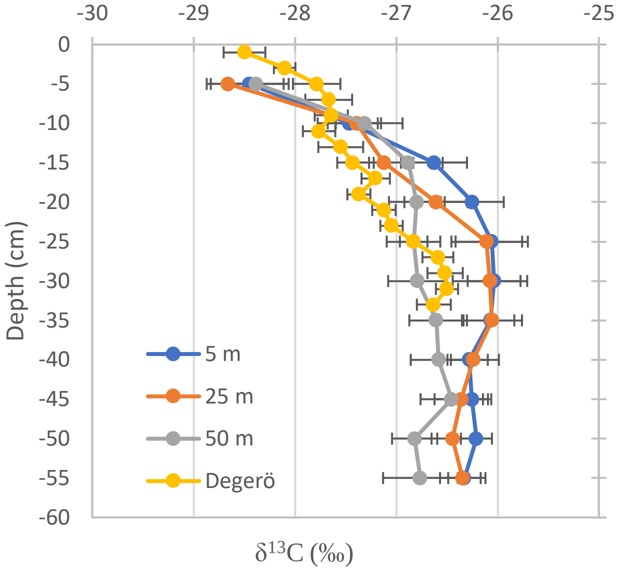

Figure 7. δ13C (‰) across the peat profile at the Trollberget drained peatland (5, 25 and 50 m distances from the ditch) and at the natural Degerö mire.

The δ15N values were somewhat higher at the 50 m from the ditch, however, no significant differences were observed in the relationships between δ15N and distance from ditch (Figure 8, Table 1). Across the peat profile, δ15N values first increased from -0.5‰ or more negative to about 0.5‰ at the -10 cm depth and then decreased to about -1.5‰ in the deeper layers (Figure 8). The statistical analysis showed that δ15N was significantly I) lower at -5 cm vs. -10 to -15 cm depths, II) higher at -10 cm vs. -30 to -55 cm depths, III) higher at -15 cm vs. -35 to -55 cm depths and IV) higher at -20 cm vs. -40 to -55 cm depths (Table 2). Down to about -25 cm depth, the δ15N values were significantly higher at the Trollberget drained peatland for all three ditch distances, as compared to the natural Degerö mire (Figure 8, Table 1).

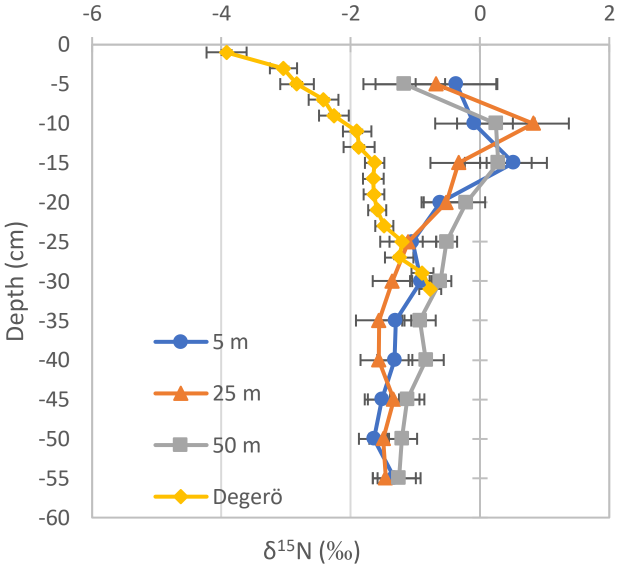

Figure 8. δ15N (‰) across the peat profile at the Trollberget drained peatland (5, 25 and 50 m distances from the ditch) and at the natural Degerö mire.

4. Discussion

4.1. Bulk density

The significantly lower BD at 5 m compared to 25 and 50 m away from the ditch could be interpreted as a generally larger drainage effect and enhanced decomposition rates further away from the ditch which in turn has resulted in more compacted peat material. This is in contrast to the expectation of higher BD occurring closer to the ditch where the drainage is supposed to be larger. One possible explanation for this unexpected result could be additional effects from hydrological variations on the site due to differences in e.g. the terrain sloping or the topography of the underlying mineral soil. Such factors could create differences in physical and chemical peat properties that could mask the drainage effects which otherwise might occur in relation to ditch distance. Another explanation could be that the areas closer to the surrounding forest edge (i.e. further away from the ditch) are generally better drained due to a higher water loss via tree transpiration leading to higher decomposition rates compared to those located closer to the ditch. In support of our findings, Minkkinen & Laine (1998) also showed a positive relationship between the tree stand volume and BD.

BD peat profile analysis suggested that the highest drainage effect occurred down to a depth of approximately -30 cm at the drained Trollberget peatland. Similarly, 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. Furthermore, 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 higher BD in the upper layers was interpreted as the result of enhanced oxidation and decomposition of organic matter (Krüger et al. 2015). The results from Trollberget are, thus, overall similar to these studies, showing an initially increasing BD to a certain depth following which BD decreases again in the deeper layers. The differences in depths where maximum BD occurred in Trollberget and the abovementioned studies could reflect both different effects of water level drawdown or e.g. contrasting site histories, differences in the time since drainage was conducted, vegetation composition, mean groundwater level.

The comparison between the drained Trollberget peatland and the natural Degerö mire showed that BD at Trollberget was significantly higher demonstrating clearly the effect of drainage. It is further noteworthy that the effect was most pronounced in the depth interval of -15 to -30 cm. This result was expected since the altered hydrology following drainage commonly results in a physical collapse of the peat matrix, higher decomposition rates and thus an increase in BD as also previously shown by other studies (Minkkinen & Laine 1998; Krüger et al. 2015; Wells & Williams 1996).

4.2. Ash content

The results of ash content showed no significant difference between the different ditch distances. Nevertheless, the data indicate that ash content was somewhat higher at the 25 and 50 m locations compared to the 5 m distance from ditch. This suggests that higher decomposition rates occurred further away from the ditch reducing the fraction of remaining organic material due to peat oxidation and resulting in an accumulation of mineral material (i.e. ash). These results are similar to the results of BD and might therefore be attributed to the same underlying reasons, i.e. additional effects from variations in hydrology and/or from the nearby forest edge, which may mask the distance-to-ditch effects. In agreement with our findings, Leifeld et al. (2011) who investigated peatlands with contrasting hydrological conditions found that ash content was generally higher in heavily disturbed (i.e. drained) peatlands.

The ash content results at Trollberget further suggest highest accumulated amounts of mineral material in the upper -25 cm of the peat profile. Likewise, Krüger et al. (2015) reported higher ash contents in the uppermost peat layers of the drained and managed peatland sites. Together with higher BD observed in the upper horizons at all three ditch distances at the Trollberget site, these data support the notion of a higher drainage effect and enhanced decomposition rates occurring in the upper -25 cm layer (Krüger et al. 2015).

Unfortunately, no ash content data were available from the natural Degerö mire for comparison with the drained Trollberget peatland. However, it was reported by Krüger et al. (2015) that ash content in the deeper undisturbed layers of a near-natural peatland scattered around 2.5% which means that below a depth of about -25 cm, ash content in our study falls within the same range. Moreover, Leifeld et al. (2011) who compared peatlands with various drainage states showed that ash contents were lowest in the undrained natural bog.

4.3. Carbon and nitrogen content and C:N ratio

In general, C content in peat was higher in locations further away from the ditch. A significant difference was, however, only found between the 25 vs. 50 m distances and this was primarily the result of higher C contents at lower depths (i.e. below -25 cm) at the 50 m distance. Thus, a clear effect of distance from the ditch on the C content could not be observed in this study. The generally higher C content further from the ditch may, however, be interpreted as a greater drainage influence (Krüger et al. 2015). The data further suggests that the amount of C generally increased with depth across the peat profile. This is in line with Minkkinen (1999) and Tfaily et al. (2014) who also showed increasing C content with depth in the peat profile. This occurs because as C compounds are consumed in peat, there is no inert mineral material to increase in relative concentration and thus as a result the relative C content in the remaining material increases (Minkkinen 1999; Tfaily et al. 2014).

The N content was overall slightly higher away (i.e. 25 and 50 m) from the ditch, as compared to close to the ditch (5 m). However, these differences were not significant and thus, a clear ditch distance effect was not evident in this study. Higher values of N can indicate increased mineralization rates (Damman 1988) and thus, more decomposed peat could explain the elevated N contents further away from the ditch observed in our study. This result is also in line with the BD, ash and C content data which all suggest higher decomposition rates, and higher degree of humification, with increasing distance from the ditch. The data further suggest highest N contents in the upper ~10-30 cm layer and relatively constant values thereafter. This is supported by findings from Laiho et al. (1999) who showed increased N content in the topmost peat layers after forestry drainage. These higher N contents could be explained by microbial N immobilization (Wells & Williams 1996). On the other hand, uptake by vegetation and an increase of N mineralization may have contributed to a decrease in N content in the deeper peat layers (Wells & Williams 1996).

The vertical C:N ratio profiles at Trollberget were practically identical at the different ditch distances. The observed values for C:N had no significant pattern relative to distance from ditch which suggests that the drainage impact was not strong enough to cause a change. According to Borgmark and Schoning (2006), site-specific conditions can play a major role, e.g. different water content depending on slopes of the terrain. Significant differences in C:N ratio occurred across the peat profiles with lower values of 35 in the upper ~10-30 cm layer and relatively constant values of about 50 deeper down. These results are in line with the findings by Borgmark and Schoning (2006) who report low C:N ratios and high N concentrations in response to peat decomposition. In our study, the lowest C:N ratio is just above 35 but mainly around 50 which is indicative of decomposition under aerobic conditions (Kuhry & Vitt 1996).

The observed values for C and N contents and the C:N ratio at the drained Trollberget peatland differed considerably from those at the natural Degerö mire. For instance, while C content increased with depth throughout the upper layers at both sites, the values remained in general significantly lower at the natural mire. This could be a result of differences in plant composition at the two sites since the C content may vary across plant species (Jones et al. 2010; Broder et al. 2012; Krüger et al. 2015). At Degerö, a higher contribution of *Sphagnum* mosses to the surface peat would explain the lower C content. However, the higher C contents at Trollberget also clearly demonstrate the effect of drainage (Tfaily et al. 2014). Furthermore, the N content increased steadily with depth at the natural mire, whereas a maximum at around -10 to -20 cm depth and a subsequent decrease was observed at the drained peatland. The observed patterns at the drained site indicate an accelerated decomposition of the peat in the upper layers due to drainage as previously suggested also in other studies (Krüger et al. 2015; Kuhry & Vitt 1996).

The combined changes in C and N contents also caused contrasting patterns for the C:N ratio at the drained and natural peatland sites. Specifically, the C:N ratio was reduced by more than half in the upper 20 cm layer at the drained Trollberget peatland. However, increasing and decreasing C:N ratios within the upper layer at the drained Trollberget and natural Degerö sites, respectively, lead to similar C:N ratios below a depth of -30 cm and downward. Thus, although the natural Degerö mire cannot be considered as a true reference for pre-drainage conditions, this comparison provides a strong indication for drainage impacts on the peat chemistry within the upper 30 cm layer. These results are supported by a previous study comparing drained and undrained peatlands, which also attributed lower C:N ratios in the drained site to higher microbial activity and decomposition in the upper layers (Krüger et al. 2015). In further agreement with our results, Krüger et al. (2015) showed that the C:N ratio increased with depth under drained conditions while in a natural mire also the surface C:N ratios were high due to low microbial activity.

4.4. δ13C and δ15N

The result of the stable C isotope analysis suggested that significantly higher (i.e. more positive) δ13C values occurred at the 5 and 25 m distances compared to the 50 m distance from the ditch. The higher values closer to the ditch could be interpreted as increased decomposition rates (Krüger et al. 2015). Since the enrichment of ^{13}C is dependent on the preferential loss of ^{12}C, higher $\delta^{13}C$ values generally indicate increased decomposition (Fry 2006). This observed pattern in $\delta^{13}C$ is in contrast to the results of BD and ash, C and N contents which all indicated higher decomposition rates occurring at the distances further away from the ditch. It is important to note, however, the differences in $\delta^{13}C$ between distances were primarily driven by contrasting values in the lower depths (i.e. below -20 cm) where decomposition rates are generally lower.

Significantly lower $\delta^{13}C$ values across the depth profile were found in the upper ~20 cm layer. Below this depth, the variations in $\delta^{13}C$ were relatively small, which could be attributed to low decomposition. For instance, Krüger et al. (2015) showed a vertical decrease of $\delta^{13}C$ along the depth profile when studying peat degradation on a drained peatland characterized by high aerobic decomposition in the upper horizon. An increase of 4-5‰ with depth in $\delta^{13}C$ has previously been reported for well-drained peatlands (Krüger et al. 2015; Nadelhoffer & Fry 1988). Therefore, the increase of ~2‰ observed at the Trollberget peatland is below the range reported by these previous studies but fell into the range of other studies (Broder et al. 2012; Rice & Giles 1996).

In comparison with the natural Degerö mire, the $\delta^{13}C$ was significantly higher at the 5 m distance at the drained Trollberget peatland. Alewell et al. (2011) did research on climate effects on stable isotopes in natural mires in northern Sweden. They found that $\delta^{13}C$ was almost constant with depth on natural mires, due to the lack of oxygen in water-saturated soils. They further reported higher values (i.e. less negative) of $\delta^{13}C$ in the depth between 4 and 25 cm, which is similar to the values in this study. Alewell et al. (2011) also showed an increase of $\delta^{13}C$ values with increasing depth due to the changes in the hydrology and decomposition rates, which overall agrees well with the results from the Trollberget and Degerö sites.

The $\delta^{15}N$ values were not significantly different at the three distances from the ditch. This indicates that the drainage impact on $\delta^{15}N$ was not strong enough to create a pronounced spatial pattern. The $\delta^{15}N$ values are strongly dependent on the ^{14}N consumed during decomposition (Fry 2006). Fry (2006) provided that the mineralized N is removed through plant uptake or leakage. The variation in $\delta^{15}N$ is, however, also driven by other factors such as vegetation composition, N deposition and root N uptake (Jones et al. 2010; Fry 2006, Krüger et al. 2015). Thus, the effects from one or more of these processes could have interfered with the fractionation originating from enhanced decomposition following drainage.

The $\delta^{15}N$ values decreased significantly with increasing depth. Higher values of $\delta^{15}N$ in the upper layer that decrease further down (below -15 cm) in the profile, can be interpreted as a result of increased aerobic decomposition (Krüger et al. 2015). According to Broder et al. (2012) the largest changes of $\delta^{15}N$ occurred in the upper layers between 5-10 cm depth while no significant variation was found deeper in the profile. According to Asada et al. (2005) the δ_{15}N enrichment in the upper layer occurred because of the presence of *Sphagnum* mosses as well as atmospheric N deposition. Thus, relatively constant values from -30 cm and downwards at Trollberget were probably due to the reduced impacts from the vegetation and the atmospheric N input (which probably is the only N sources for the peatland) (Broder et al. 2012; Jones et al. 2010).

In comparison with Degerö data the results were the opposite, i.e. suggesting increasing δ_{15}N with deeper depth at the natural mire. According to Krüger et al. (2015) the inversion of the δ_{15}N at natural mires is located at 20-40 cm depth and can vary between -11 to +2‰. However, no such inversion of δ_{15}N was present at Degerö and instead an inversion of δ_{15}N could been seen in the upper layer of the drained Trollberget peatland.

5. Conclusions

Differences in peat properties with distance from the drainage ditch:

Peat bulk density and C content data suggested a higher drainage effect and decomposition rates further away from the ditch at the Trollberget drained peatland forest. Similarly, the ash and N contents, C:N ratio and δ^{15}N data indicated slightly stronger decomposition in the locations furthest from the ditch though these patterns were not statistically significant. In contrast, however, peat δ^{13}C suggested higher drainage effect and decomposition occurring closer to the ditch. Overall, it can be concluded that drainage effects on peat properties did not vary as expected in relation to distance from the ditch, possibly due to other interfering effects from terrain sloping and/or the nearby forest edge, which might alter the peatland hydrology, drainage effects and decomposition rates across the peatland area.

Differences in peat properties across the peat profile:

Bulk density, ash and N contents and δ^{15}N data at Trollberget increased with depth in the upper layers and decreased again in the deeper layers suggesting strongest drainage effects and decomposition in the ~10-30 cm peat layers. This is further supported by the observed lower C:N ratios in these respective depths. C content showed a generally increasing pattern with depth which may be interpreted as reflecting the decomposition of peat. Similarly, increasing δ^{13}C values along the peat profile also indicated enhanced decomposition deeper in the profile. Altogether, the data demonstrate the effect of the lowered groundwater level. Specifically, a strong drainage effect and active decomposition is visible in the upper layers of the peat profile and a reduced level of degradation in the deeper parts.

Differences in peat properties between a drained peatland and a natural peatland:

Peat bulk density was higher at the drained Trollberget peatland in comparison with the natural Degerö mire. This is in line with the general expectation, since drainage is known to induce subsidence, compaction and decomposition of the peat material. The C and N contents were higher at the drained peatland while the C:N ratio was lower compared to the natural mire which can also be interpreted as higher microbial activity and decomposition rates following drainage. Similarly, higher peat δ_{15}N values at the drained Trollberget site indicate enhanced decomposition compared to natural conditions. In contrast to expectation, peat δ_{13}C was similar between the two sites with significantly higher values observed only at the Trollberget 5 m ditch distance. Overall, it can be concluded that most the investigated peat properties differed between the drained and natural peatland sites highlighting the sensitivity of peatland biogeochemistry to human management activities.

Further research is needed to assess the long-term effects on ash content for different distances from the ditch and C losses for different depth profiles. Additional investigation of ground vegetation diversity on drained peatlands and the connection between vegetation and the physical and chemical properties in the peat, and their impact of greenhouse gas emissions, would also merit further investigation in the future.

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Appendix

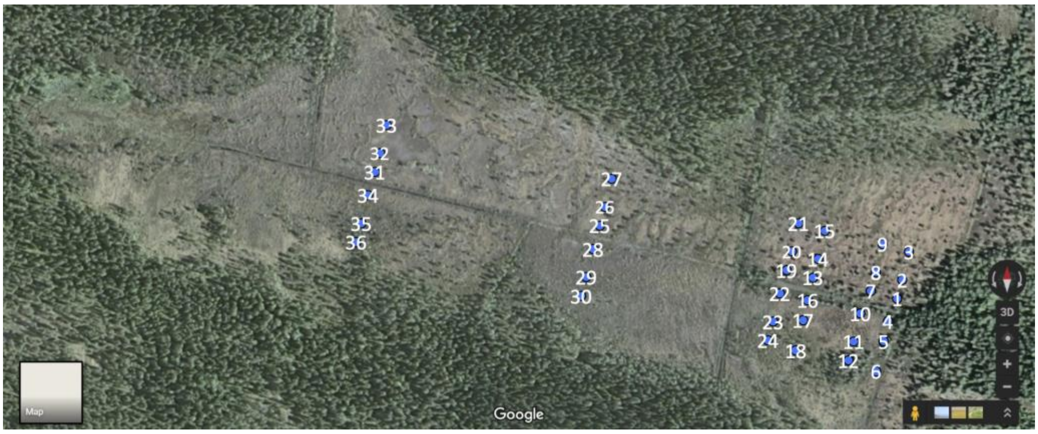

Figure 1. Peat sampling locations at the drained Trollberget peatland.

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