UNIVERSITY OF GOTHENBURG

DEPARTMENT OF EARTH SCIENCES

LATERAL PHYSICAL AND CHEMICAL DYNAMICS OF BOREAL PEATLANDS IN SOUTHERN SWEDEN

A Study of Mycklemossen Mire

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Abstract

Peatlands are important ecosystems that play a crucial role in global carbon cycling, water regulation, and biodiversity conservation. Investigating the lateral physical and chemical properties of mires, such as changes in peat depth, bulk density, organic matter content, and pH, can provide valuable insights into how these ecosystems are responding to environmental changes, and how they may contribute to climate change mitigation efforts. This study has investigated the physical and chemical properties of a typical boreal mire in southern Sweden, in order to create an overview of current physical and biochemical state of boreal peatlands. Historical data of the surface area of Mycklemossen mire has been used to assess the change of its lateral extent, which has shown to decrease by 34% between 1963 – 2021 by the means of shrubification. The surface area decrease has shown to be accelerating overtime, as nearly a third of the mire was lost in the recent five years (2016-2021). In order to investigate the physical and chemical properties of the peat, peat sampling was conducted on the mire using hand saw and a stainless-steel Russian corer in the field, followed by further elemental analysis. The peat sampling has enabled the estimation of the following parameters: bulk density, root mass, SOM content and pH values, as well as total C and N stocks, C:N ratio and the $\delta^{13}C$ and $\delta^{15}N$ values, all of which showed to be significantly affected by the depth of the peat horizon, while root mas showed to also be significantly affected by surface layer vegetation communities. Total C and N values along with ground-penetrating radar data were used for upscaling total C and N to the entirety of the mire, estimating the total C content of Mycklemossen mire to 34.8 kt and total N content to 0.9 kt, as well as showing a decreasing trend with depth for both parameters. The retrieved data was used as a proxy to gain a better understating of the physical and chemical properties of boreal peatlands in a changing climate.

Keywords: Peatlands, boreal mires, upscaling, shrubification.

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1. Introduction

Peatlands, also known as bogs, moors, or mires, are a type of wetland ecosystem that are characterized by the accumulation of partially decayed plant material, called peat. Peat is formed when dead plant material, such as mosses and sedges, accumulates in a waterlogged environment, where it decomposes more slowly than it would in drier conditions. Over time, the accumulation of peat can form a layer that can be several meters thick. Peatlands can be found in many different regions around the world, from tropical to boreal climates, and are typically found in areas with cool, wet conditions and low levels of oxygen in the soil. Peatlands are home to a wide range of plant and animal species that are adapted to the unique wetland environment. They are also an important carbon sink, storing large amounts of carbon in the form of peat. Moreover, peatlands provide important habitats for a wide range of plant and animal species that are adapted to the unique wetland environment, many of which are rare or endangered. Additionally, peatlands act as natural sponges, storing and slowly releasing water. This helps to regulate water flow and reduce the risk of floods and droughts. They also have the ability to filter pollutants from water, improving water quality and reducing the impact of agricultural and industrial runoff (Limpens et al., 2008).

In recent years, the concern regarding the anthropogenic emissions of greenhouse gases has directed an increased attention to peatland areas. The most distinguished attribute of peatlands in today's changing climate is their ability to store terrestrial carbon (C), storing more C globally than all vegetation types combined (IUCN, 2017). Peatlands only cover 3% of the Earth's surface, yet they are the largest terrestrial carbon store with highest carbon density per unit area of any terrestrial ecosystem containing an estimated 546 gigatons of carbon, which is more than twice the amount of carbon stored in all the world's forests combined (IUCN, 2017). Moreover, peatlands are estimated to sequester 0.37 GT of CO_2/year, representing 42% of all soil C (IUCN, 2017). In order to protect the stored soil C from decomposition the peat must be wet, as as long as peatlands remain intact and waterlogged, carbon is stored in the form of peat and does not contribute to climate change. However, about 15% of the world's peatlands have been drained for agricultural conversion purposes and mining activities among others (IUCN, 2017; Joosten & Clarke, 2002), while others dry out naturally as a consequence of global warming. When peatlands dry out, the C stored in the peat dries and oxidizes gradually to carbon dioxide (CO_2) and is permanently lost from the system (Joosten & Clarke, 2002). The release of CO_2 is contributing to global warming, causing a positive feedback effect where warmer temperatures further accelerate peat degradation

(Craft, 2016). When disturbed, peatlands can also act as a source of nitrous oxide (N_2O), a highly powerful greenhouse gas (GHG), caused by the increased oxidation of nitrogen (N) contained in the peat. The ongoing degradation of peatlands is contributing 10% of GHG emissions from the land use sector, which is equivalent to 5.6% of the global anthropogenic CO_2 emissions (IUCN, 2017).

Damaged peatlands are a significant contributor to climate change, and it is therefore important to gain an extensive understanding of the peatland systems and the environmental consequences of peatland degradation. By investigating the chemical and physical properties of a peatland, we can gain a more comprehensive understanding of the ecosystem and how it responds to environmental changes. This study aims to reveal changes in the lateral physical and biogeochemical properties of the peat profile of Mycklemossen mire, a typical boreal mire located in Skogaryd, southern Sweden. Peat sampling on the mire has enabled the upscaling of the total C and N stocks, C:N ratio as well as the $\delta^{13}C$ and $\delta^{15}N$ values of the mire, as well as bulk density, root mass, soil organic matter content (SOM) and pH values, which are used as a proxy to gain a better understating of the physical and chemical properties of boreal peatlands in a changing climate and provides valuable information on the characteristics of the mire contributing to the existing knowledge base on peatland ecology. By investigating the C and N stocks of peatlands, the total C and N stocks of these ecosystems can be estimated, which aids in global carbon budgeting and climate change mitigation efforts. Meanwhile, investigating the carbon-to-nitrogen (C:N) ratio of peatlands can shape a better understanding of how changes in environmental conditions can affect the rate of peat decomposition and consequently GHG emissions. Moreover, by studying how the $\delta^{13}C$ and $\delta^{15}N$ values change with depth and across different locations within a peatland, we can better understand the processes that control the accumulation and decomposition of organic matter, as well as the uptake and release of nitrogen. This information can inform management strategies for maintaining or enhancing ecosystem productivity and resilience. Additionally, comparing these properties across different peatlands can provide insights into the variation in peatland functioning across different regions and climatic conditions.

1.1 Definition of peatlands

Peatlands are terrestrial ecosystems which constantly remain in waterlogged conditions. The waterlogged conditions prevent the full decomposition of plant material, which leads to formation of a peat layer. In order for a terrain to be classified as peatland, the peat profile has to reach a certain depth, which is defined differently depending on country. In Sweden, the peat profile must be no less than 30 cm deep in order for an area to be classified as peatland, as land that lacks a peat layer is classified as mineral soil, while land that has a peat layer <30 cm is classified as wetland (Hånell, 2006).

The terms bogs, moors, and mires are often used interchangeably to refer to peatland ecosystems. However, there are some subtle differences in their definitions. According to Limpens et al. (2008), a bog is a type of peatland that accumulates peat mainly from rainfall, resulting in a nutrient-poor and acidic environment. A mire, on the other hand, is a general term used to describe a wetland that is dominated by peat-forming vegetation. Moors, meanwhile, are peatlands that are more nutrient-rich and can support a greater variety of plant species compared to bogs. The article also notes that the terminology used to describe peatlands can vary depending on the region and the researcher, with some terms used interchangeably or with slightly different meanings.

1.2 Peat formation

Peat formation occurs due to incomplete decomposition of moss and vascular plants, which is caused by waterlogged conditions of the terrain. Such conditions may occur during inconsistent high rainfall or in areas where standing water is present. The partly decomposed plant material becomes compacted overtime, leading to changes in the physical and chemical properties of the substrate which enables a succession of plant communities. Such succession is known as *hydrosere* and generally begins in open water, followed by stages of groundwater nourished fen growth, and finally reaching a bog stage, which only receives nutrients and water supply from rainfall. The habitat required for peat initiation is similar in all geographical locations, consisting of waterlogged conditions, low pH, low nutrient availability, low oxygen availability and a low decomposition rate. However, the physical and chemical characteristics of peat can vary depending on the specific characteristics of a given location, such as topography, climate, water depth, water flow and nutrient availability (IPS, 2021).

1.3 Peatland ecosystem services and biodiversity

Peatlands provide several ecosystem services which are of great importance to the wellbeing and resilience of its biodiversity. First, peatlands provide climate regulation on global as well as regional and local scales, through regulation of greenhouse gases, precipitation, air temperature and other climatic processes. Secondly, peatlands regulate water storage, water recharge and discharge, water purification and regulation of water hydrochemistry through waste treatment, where excess nutrients and pollutants are retained, recovered, and removed from the ecosystem. Thirdly, peatlands also play a large role in regulating soil conditions through soil erosion protection and soil formation. The soil underlayer beneath the peat is protected from erosion by the peat layer on top, while the presence of peat aids with accumulation of soil organic matter. Finally, peatlands also contribute to nutrient cycling, where nutrients are stored, recycled, processed, and acquired through the various physical and chemical processes that take place within the ecosystem (IPS, 2021).

As a result of the ecosystem services described above, peatlands sustain a rich and unique range of habitats and species. The abundance of certain species contributes to an improved health and resilience of the peatland habitat, as the presence of certain plant and animal species is essential for the process of peat formation. A large issue in the recent years has been the loss of peatland. There are several drivers behind the loss of peatland biodiversity, which include: loss of habitat, invasive species, agriculture, forestry, peat extraction, nutrient pollution, and climate change. These drivers have led to a lack of peat-forming plant species, such as Sphagnum mosses, as well as a lack of animal species which aid in the regeneration of these plants, such as willow ptarmigan birds (IPS, 2021).

1.4 Peatlands and climate change

Peatlands have the ability to interact with the climate through the uptake and release of GHGs due to the presence of large amounts of organic matter in peat, which contains soil C that has been taken up by peatland plants from the atmosphere as CO_2 through the process of photosynthesis. When C is deposited in the soil, it accumulates due to the waterlogged conditions present in the peatlands, which prevent the plant material from fully decomposing. This causes a net uptake of CO_2, which makes peatlands act as a *carbon sink*, i.e., a C capturing ecosystem which absorbs more C from the atmosphere than it releases (IPS, 2021). The removal of CO_2 from the atmosphere, caused by a carbon sink, has a cooling effect on the climate, thus impeding global warming. However, peatlands can also act as a *carbon source*, i.e., a C releasing ecosystem which releases more C into the atmosphere than it absorbs. As waterlogged soils, such as peat, have low oxygen availability, methane (CH_4) is produced as a result of anaerobic decay. CH_4 is a potent GHG with a 100-year global warming potential approx. 28 times that of CO_2 (IPS, 2021). Naturally, the CH_4 emissions of peatlands have a warming effect on the atmosphere, however, as the lifetime of CH_4 in the atmosphere is relatively short in comparison to the on the CO_2, many peatlands may have a net warming effect on the atmosphere over shorter periods of time, while still having a net cooling effect over longer time scales when the total uptake of CO_2 is considered (IPS, 2021; Whiting and Chanton, 2001). Furthermore, CO_2 and CH_4 are not the only GHGs produced by peatlands, as peatlands also can act as a source of N_2O, a GHG 300 times more potent than CO_2 (Whiting and Chanton, 2001). When peatlands are undisturbed, the emissions of N_2O are generally relatively small. However, changes in the ground water level caused either by anthropogenic disturbances, such as drainage and fertilization, or climate change feedback effects, can greatly increase the N_2O emissions to the point where N_2O becomes a significant contributor to global warming.

Climate change can affect the ability of peatlands to store soil C, as the warmer temperatures increase the rate at which organic material decays, thus increasing the release of carbon from peat. Warmer climate also leads to changes in the hydraulic conditions of the soil, which can further increase the speed at which the decomposition of organic matter takes place. In boreal and subarctic peatlands, thawing permafrost is responsible for a large portion of the peatland GHG emissions, as the carbon stored in frozen peat is released as the peat thaws. In tropical peatlands, the increased frequency of wildfires has led to an increase in carbon emissions, as peat fires release a significant amount of GHGs (IPS, 2021).

1.5 Peat properties

1.5.1 Bulk density

Bulk density is calculated as the dry weight of soil divided by its volume. It indicates the level of soil compaction and is typically expressed in g/cm^3 (Blake, 2015). Bulk density determines the structural support, water flow, and the aeration of the soil. High bulk density implies low soil porosity and high soil compaction, causing restrictions to root growth due to poor air and water flow through the soil. Soil compaction leads to shallow plant rooting and poor plant growth, and can lead to increased runoff and erosion, especially in humid conditions (Chaudhari et al., 2013). Generally, bulk density increases with soil depth, as the deeper parts of the profile tend to contain less organic matter, aggregation, and root penetration, causing a reduction in pore space (Chaudhari et al., 2013).

1.5.2 Root mass

Root mass includes the vascular roots of a given soil area, and refers to the actual plant roots, rather than the root zone or the rhizosphere. As roots grow in the microporosity of the soil, high root mass leads to a decrease in soil porosity as well as tortuosity The modification of the pore space in the soil caused by root elongation may have an impact on the hydraulic properties of peat, such as an increase in water-holding capacity or a decrease in saturated hydraulic conductivity (Cannavo, 2011). According to Mahlrota et al. (2020), the drying of peatlands caused by global warming has led to shrub encroachment due to increased fine-root plasticity of thinly rooted shrubs. This has led to rapid shrubification of peatlands, which may lead to a decrease in peat-producing *Sphagnum* species, thus decreasing the C storage capacity of peatlands due to the slower decomposition rate of Sphagnum litter in comparison to shrub litter (Mahlrota et al., 2020).

1.5.3 Soil organic matter

Peatland ecosystems build up substantial layers of organic soil due to the continuous process of plant growth surpassing decomposition across the entire depth of the organic soil column (Turetsky et al., 2015). Soil organic matter (SOM) includes, in the broadest sense, all living and dead organisms, however, the term is usually used to refer to the remains of animals and plants in the decomposition phase. SOM serves as a vital nutrient source for plants. The organic material consists mostly of carbon, which is a nutrient source for soil organisms, however the organic matter includes all elements that are components of organic compounds, not just carbon (Chaudhari et al., 2013). Among the macronutrients, nitrogen, phosphorus, and sulfur are essential, while iron, manganese, zinc, copper, boron, molybdenum, and chlorine are considered crucial micronutrients (Chaudhari et al., 2013). SOM is measured as mass of soil organic matter per unit weight of dry soil and is usually expressed as percentage by weight (Agus et al., 2011). Generally, the organic matter content is highest at the top layer of a given soil profile and tends to decrease with depth (Magdoff, 2021).

1.5.4 Peat pH

Peatlands are naturally acidic ecosystems. Approximately one-third of the Earth's peat-covered area consists of peat bogs primarily dominated by acid Sphagnum (Clymo et al., 1984). Peatlands in which the Sphagnum species are present, such as the mire investigated in this study, generally have pH values ranging between 3.2 and 4.0 (Clymo et al., 1984). Soil pH has a major influence on the chemical properties of peat. For instance, in a study by Bobuľská et al. (2015), enzymatic and biological potential for organic matter mineralization showed to be strongly correlated to soil pH, along with soil moisture and soil organic matter content.

Sphagnum plants are a key driver of acidity of peatlands, as Sphagnum plants take up cations from solution selectively, where a large part of the process is cation exchange with H^+ (Clymo et al., 1984). The exchange takes place through the polymers of uronic acids in the cell walls. According to Clymo et al. (1984), rainwater, which trickles over a Sphagnum plant, becomes much more acid: typically pH 3.0-3.2 at the top layer of the peat horizon. However, the pH tends to rise as the rainwater makes its way to the deeper peat layers, as the H^+ initially present in the peat decreases as COOH is gradually removed. Consequently, in order for peatlands to maintain a low pH, the production of new COOH groups in required and thus growth of new plant material (Clymo et al., 1984).

1.5.5 Peat carbon

Peatlands contain one-third of soil carbon, and, as discussed in 1.4, may act as a carbon sink or as carbon source, depending on external factors such as air and soil temperature (Liu, 2016; Wilson, 2016). Moreover, research shows that temperature conditions play a major role in C stock accumulation rates, where generally, cooler temperatures support an accumulation of total C, while hotter temperatures prevent or lead to a reduction in total C (Liu, 2016). The loss of C, however, is often not only dependent on temperature, but also on the depth of the water table. A lower water table exposes peat to oxygen, which facilitates the binding between C stored in peat and oxygen gas in the atmosphere, forming CO_2 molecules. A higher water table, on the other hand, reduces peat decomposition and prevents CO_2 formation, but leads nonetheless to a greater CH_4 production, as CH_4 forms in anaerobic conditions (Liu, 2016; Huttunen et al., 2003).

1.5.6 Peat nitrogen

Among terrestrial ecosystems, peatlands store one of the highest amounts of N per unit area as well as storing nearly 15% of the world's soil N (Novak et al., 2014; Wieder and Vitt, 2006). The main inputs are N deposition from the atmosphere, N_2 fixation by bacteria or algae, and N inflow through upland runoff or discharge (Wieder and Vitt, 2006). Among managed Northern soils, drained peatlands emerge as major sources of N_2O due to their high N stocks and rapid

N mineralization rates, which drive substantial N_2O production (Liimatainen et al., 2018). The global warming potential of N_2O is 265 times greater than that of CO_2 and almost ten times greater than that of CH_4 (Liimatainen et al., 2018). Although N_2O remains stable in the troposphere, in the stratosphere N_2O participates in reactions destroying the ozone layer (Liimatainen et al., 2018). Natural peatlands typically exhibit minimal N_2O emissions and may even serve as net sinks for N_2O, however, upon drainage, exposure of peat to O_2 can significantly elevate N_2O emissions Thus, drainage and associated lowering of the water stands out as a pivotal factor enhancing N_2O emissions from peatlands (Liimatainen et al., 2018). The soil C:N ratio, more closely described in 1.5.7, is commonly used to estimate the magnitude of N_2O emissions, with drained peatlands characterized by low (<30) C:N ratios typically exhibiting the highest emissions (Liimatainen et al., 2018).

1.5.7 C:N ratio

Carbon to nitrogen ratio (C:N) is the ratio between the amount of C and the amount of N in a soil or organic material. C/N ratios of organic soils formed by peat accumulation are much higher than those of mineral soils: An extensive study of peatland sites in the northern hemisphere revealed a median C/N ratio of 49.0 (Loisel, 2014), whereas the average C/N ratio of mineral soils globally is 10.9 (Batjes, 2009). However, the ratio in undisturbed peat soil varies considerably depending on the disparities in vegetation, site conditions, the specific soil layer, and atmospheric nitrogen deposition (Leifeld, 2018). At high ratios, the substantially larger amount of C compared to N in the soil leads to competition for N between terrestrial organisms, which slows down decomposition processes potentially resulting in a lack of N in the soil. A lower C:N ratio, however, indicates a higher decomposition rate and enhanced N content in the peat material. The C:N ratio is generally expected to decrease with depth as peat is more strongly transformed by microbes the deeper and older the material is (Leifeld et al., 2020).

1.5.8 $\delta^{13}C$

Stable isotopes are atoms of the same chemical element that are non-radioactive and vary only in their number of neutrons. There are two stable C isotopes: $\delta^{13}C$ and $\delta^{12}C$. In natural peatlands with low decomposition rates, the ratio of $\delta^{13}C$ to $\delta^{12}C$ is generally nearly constant along a depth profile due to the limited oxygen availability in water-saturated soils which reduces organic material decomposition and thus minimizes isotopic fractionation (Lorentz et al., 2020; Krüger et al., 2015).

However, in conditions of anaerobic decomposition, there may be a slight decrease in $\delta^{13}C$ with depth. This occurs because substances like lignin, which require aerobic conditions for decomposition, tend to be relatively enriched in ^{13}C (Krüger et al., 2015). Following drainage, however, an increase in $\delta^{13}C$ can be expected due to the preferential use of the lighter $\delta^{12}C$ by the decomposers, which in turn leads to the accumulation of heavier ^{13}C in the remaining organic matter and an increase in $\delta^{13}C$ values with depth (Krüger et al., 2015). Transitioning from anaerobic to aerobic conditions, such as through peatland drainage, is expected to shift the uniform $\delta^{13}C$ depth profile towards increasing $\delta^{13}C$ values with depth (Lorentz et al., 2020; Krüger et al., 2015). Thus, higher $\delta^{13}C$ values indicate increased decomposition rate in soils.

1.5.9 $\delta^{15}N$

N has two stable isotopes: $\delta^{15}N$ and $\delta^{14}N$. The variation of the isotopes is caused by a cumulative faster loss of $\delta^{14}N$, which contributes to an increase of $\delta^{15}N$ during decomposition in soils, provided that the $\delta^{14}N$ is lost from the system. Higher $\delta^{15}N$ to $\delta^{14}N$ ratios therefore suggest increased decomposition rates (Lorentz et al., 2020). This process leads to higher soil $\delta^{15}N$ values in aerobic soils which are expected to rise with depth (Krüger et al., 2015). However, a factor worth considering is the variation in $\delta^{15}N$ signature of plant species within undisturbed peatlands, that can range from -11.3 to +2.7‰ (Krüger et al., 2015). This diversity could, according to Krüger et al. (2015), impact the $\delta^{15}N$ signature of the peat material that remains.

1.6. Aim

As wetlands contain nearly half of all global soil carbon (42%), the preservation of natural wetlands and their carbon stocks can contribute to a reduction in global greenhouse gas emissions, as well as protect the wetland ecosystems and the biodiversity which thrives there. The aim of this study is to, firstly, estimate the historical surface area extent of a typical boreal mire, Mycklemossen, located in southern Sweden, in order to gain an overview of the historical changes of the lateral extent of this peatland ecosystem. Secondly, through peat sampling and analysis, this study aims to reveal changes in physical and chemical properties of the peat profile of Mycklemossen mire. The study focuses on investigating the following peat physical and chemical properties: bulk density, root mass, soil organic matter (SOM) content, peat pH, C content, N content, C:N ratio and $\delta^{13}C$ and $\delta^{15}N$ values. The data is analysed in relation to the surface layer vegetation communities of the mire, as well as depth of the peat profile. Finally, the study aims to assess the C and N stocks of Mycklemossen by 3D modelling and elemental analysis. The collected data is used to present an overview of the mire ecosystem, providing an insight into the current state of the mire in relation to the UN-sustainable development goals for wetland conservation. The questions this study is intended to answer are:

1. How has the surface area of Mycklemossen mire changed between 1963 – 2021?
2. Does surface layer vegetation type and/or soil depth influence the peat properties of Mycklemossen mire?
3. What is the total C and N content of Mycklemossen mire?

2. Methods

2.1 Site description

Peat samples were collected at Mycklemossen mire (58.36533N, 12.16956E, 80 m asl.), located approx. 80 km north of Gothenburg in Västra Götaland county in southern Sweden (Figure 1). The site is part of the Skogaryd Research Catchment and Swedish Infrastructure for Ecosystem Science (SITES) network. In order to gain an overview of the historical changes of the lateral extent of Mycklemossen, the historical land use as well as an existing watercourse were mapped using readily available data from the SITES database (2021).

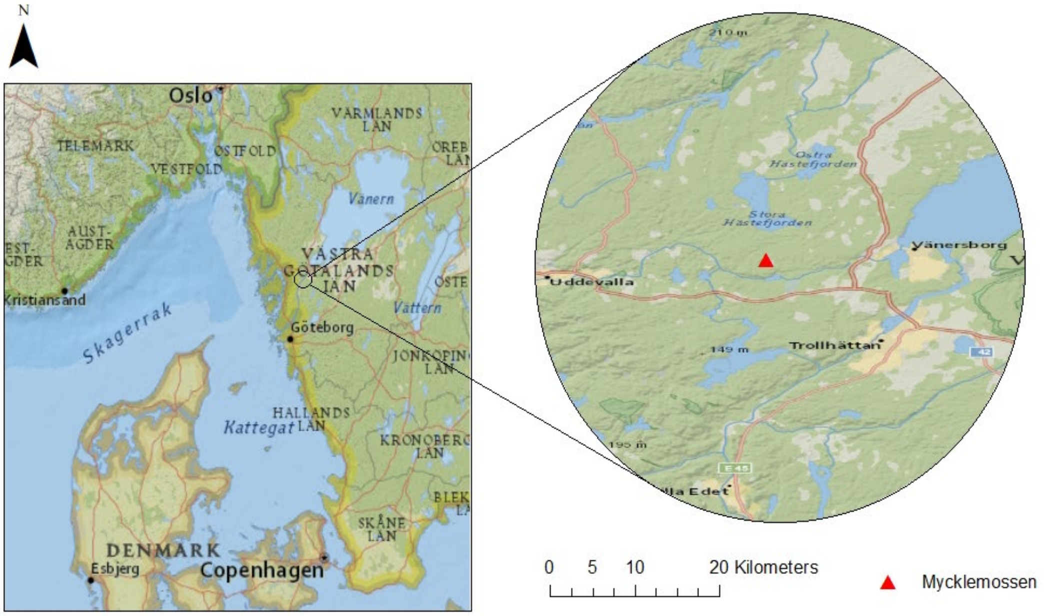


Figure 1. Location of Mycklemossen mire, Västra Götaland county, southern Sweden. The mire is located approx. 80 km north of Gothenburg and is a part of the Skogaryd Research Catchment and SITES network.

Mycklemossen is a hemi-boreal, oligotrophic mire with an area of approx. 0.23km^2 (2021). The mire holds peat deposits extending up to 6 m below the surface, holding its deepest deposits in the central area of the mire while gradually becoming shallower towards the edges (Figure 2).

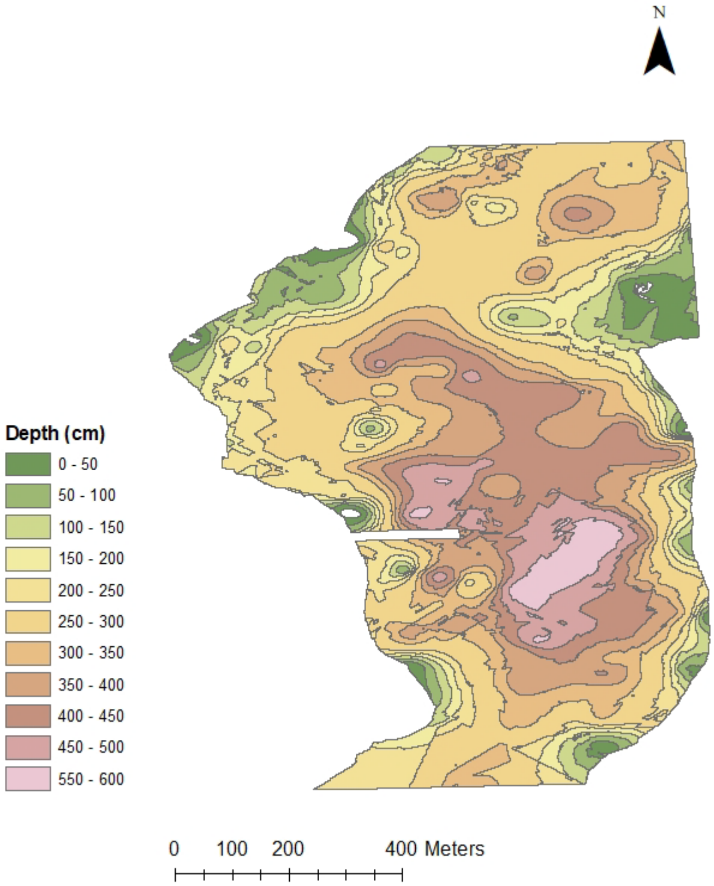


Figure 2. 2-dimensional bathymetry map of Mycklemossen mire. Bathymetry measurements are based on peat bathymetry data collected in 2014 by Persson & Banzhaf for SITES database using ground penetrating radar (SITES, 2021). The dark green areas indicate ground level. The light pink areas indicate the deepest point of the mire up to 600 cm depth.

The mire is made up of homogeneously distributed wet hollows, semi-wet intermediate areas, and dry hummocks (Figure 3). The long-term (1981-2010) mean air temperature and precipitation of the mire are 6.9°C and 802 mm respectively, as reported by the nearest national monitoring stations (Uddevalla and Vänersborg).

Figure 3. Three types of vegetation communities at Mycklemossen mire, southern Sweden, a.) wet hollows, b.) semi-wet, flat intermediate areas, c.) dry hummocks. Photographs were taken in the field by author between the 2nd and 4th of March 2021.

According to Påhlsson (1998), the vegetation at the mire can be classified as either Hare's-tail Cotton grass-Sphagnum rubellum type or Heather-Sphagnum rubellum type. As reported by a vegetation survey completed by Lorimer-Olsson in 2017, the species present at the dry hummocks are mainly *Eriophorum vaginatum* and dwarf shrubs such as *Calluna vulgaris* and *Erica tetralix*, while the hollows maintain various *Sphagnum* species: *S. rubellum*, *S. fallax* and *S. austinii*, as well as *Rhyncospora alba*. The conditions are drier at the central part of the mire, where the vegetation is more forest-like and is dominated by *Pinus sylvestris*, as well as dwarf shrubs such as *Vaccinium uliginosum*, *V. myrtillus* and *V. vitis-idaea* (Lorimer-Olsson, 2017).

2.2 Field measurements

The peat sampling locations of this study were established around five location points where peat depth data ware previously collected by Persson & Banzhaf in 2014. One core per vegetation community (hummock, hollow and intermediate) was taken in close proximity to each sampling point, resulting in a total of fifteen sampled locations (Figure 4).

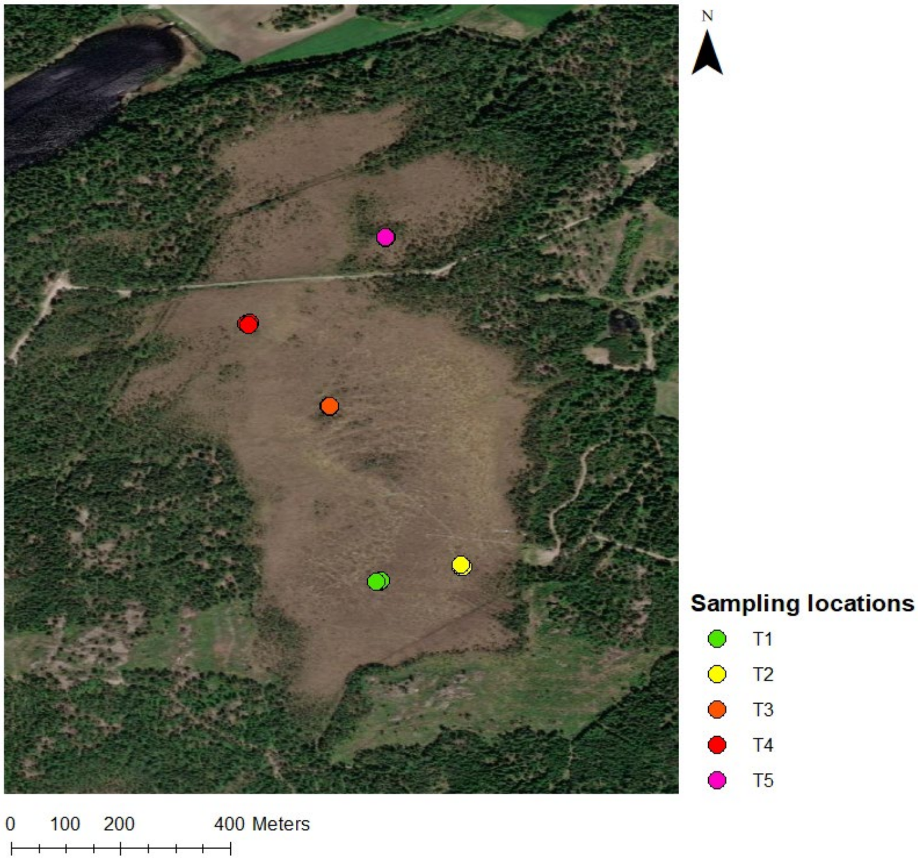


Figure 4. The peat sampling locations of Mycklemossen mire, southern Sweden, collected between 2nd and 4th of March 2021. A total of fifteen locations were sampled. One sample was taken per vegetation type (hummock, hollow and intermediate) in close proximity to each of the five sampling locations of Persson and Banzhaf (2014).

Each peat core was ≤4.5 m deep and taken to the full extent of the peat profile until bedrock was reached. The samples of the top 0.5 m layer were retrieved using a hand saw due to the low soil temperatures at the time of sampling, which resulted in a frozen upper layer. A stainless-steel, cylinder-shaped Russian corer (inner dimensions: 5 cm in diameter) was used for the remaining depth of the profile. The collected peat cores were sliced into 5 cm sections in the field and stored in refrigerator until further processing.

2.3 Laboratory analysis and calculations

The top 5 cm of each meter depth (0-5 cm, 100-105 cm, 200-205 cm, 300-305 cm and 400-405 cm; total of five samples per location) were analysed in the laboratory for the following data: bulk density, root mass, pH, ash content, C:N ratio and $\delta^{13}C$ and $\delta^{15}N$. The samples used were assumed be representative of the remaining meter of the profile.

Bulk density. Peat samples were dried in an oven at 50°C for 48 hours or to a constant weight. The total dry soil weight was measured after drying, using a four decimal analytical balance. The soil volume was calculated based on the diameter of the Russian corer used to collect the samples. As the top layer was collected using hand saw, samples, equal in volume to the ones collected by the Russian corer, were cut out using a knife. Bulk density was calculated by dry weight using the following formula:

$$\rho = m_t/V_b$$

where

ρ = soil density (g cm^{-3})

m_t = the total dry soil weight (g)

V_b = soil volume (cm^3)

Root mass. Vascular plant roots were manually separated from the peat samples. The separated vascular roots were washed using a 0.025 mm sieve and dried in an oven at 50°C for 48 hours or to a constant weight. The dry roots were weighed using a four decimal analytical balance and the results were calculated to three decimal places.

Soil organic matter content. Subsamples of approx. 5 g were dried in an oven at 50°C for 48 hours or to a constant weight and weighed on a four decimal analytical balance to determine the dry weight as well as the gravimetric soil moisture. The samples were then placed in a muffle furnace and heated at 550°C for 8 h in order to remove the organic matter. Once cooled down, the samples were weighed to determine the dry weight free from organic matter.

pH. The water from the peat sample was passed through a paper filter into a conical flask using a glass funnel. The sample was pressed through the paper filter manually using nitrile gloves. A calibrated pH meter was used to measure the pH directly in the filtered water.

Elemental and isotopic analysis (C, N, $\delta^{13}C$ and $\delta^{15}N$). 5 mg of the dry (50°C) sample was weighted into tin capsules and analysed for total C and N content, as well as $\delta^{13}C$ and $\delta^{15}N$, using IRMS (Sercon). The standard material used was high organic content sediment standard.

2.4 Statistical analysis

2.4.1 Vegetation type and peat depth effect on dependent variables

When multiple factors are involved, common non-parametric tests are unable to examine interaction effects, which makes them inadequate for multivariate analysis. For this reason, the Aligned Rank Transform (ART) ANOVA was chosen as the appropriate non-parametric test, as it allows for the dependent variable to be continuous or ordinal, the testing of interactions, and data that is not normally distributed (Elkin et al., 2021; Wobbrock et al., 2011). The ART ANOVA aligns the data before applying averaged ranks, after which point two-way ANOVA procedures can be used (Wobbrock et al., 2011). The ART ANOVA was used on the two main effects (vegetation type and peat depth), as well as the interaction effects, however, vegetation type was only significant for root mass, and no dependent variables had significant interaction effects. Thus, a series of non-parametric tests were used for each dependent variable in relation to peat depth only, followed by post-hoc tests to determine the significant differences between the various depth layers. Furthermore, the Shapiro-Wilks test was used in order to test whether the same variables stayed significant when using a one-way ANOVA. As the Shapiro-Wilk test allows for higher degrees of freedom, the p-values resulted to be slightly lower for all variables, however, it showed the same variables to be significant as the ones shown by the ART ANOVA.

Statistics were done using R 4.1.1 (R Core Team, 2021) and RStudio 1.4.1717 (RStudio Team, 2020). The ggplot2 v3.3.5 (Wickham, 2016), and ggpubr v0.4.0 (Kassambara, 2020) packages were used to visualize the data. The car v3.0.11 (Fox & Weisberg, 2019), dplyr v1.0.7 (Wickham et al., 2021), FSA v0.9.1 (Ogle et al., 2021), ARTool v0.11.0 (Wobbrock et al., 2011) and rcompanion v2.4.1 (Mangiafico, 2021) were used for statistical analysis.

2.4.2 Total C and N upscaling to mire

All the collected data was analysed together with available Mycklemossen mire bathymetry data (SITES, 2021) collected by Persson and Banzhaf (2014). The bathymetry data divides the peat profile into 12 peat profile sections, which all vertically measure 50 cm (0-50 cm, 50-100 cm, 100-150 cm etc. down to 600 cm depth) (Figure 5).

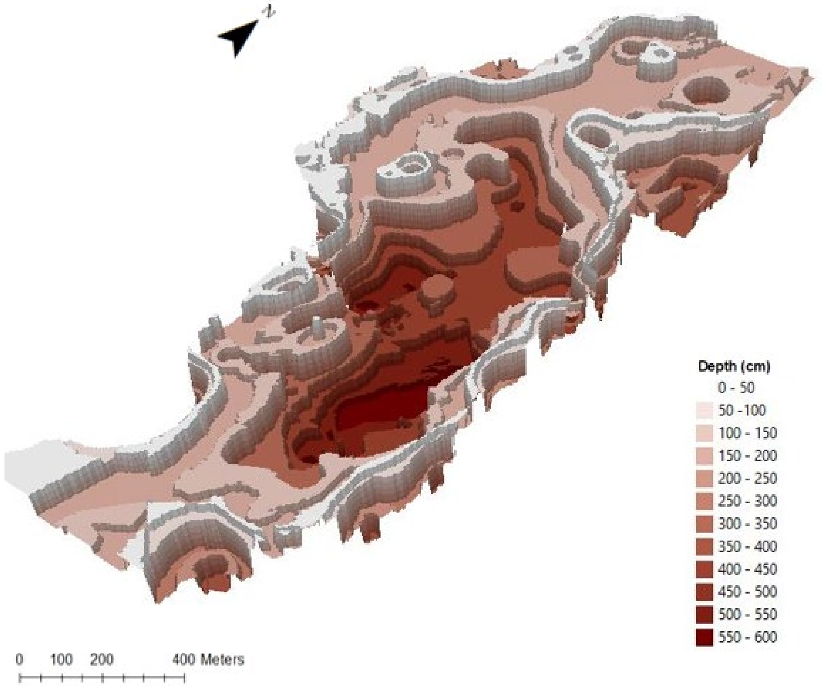


Figure 5. 3-dimensional bathymetry map of Mycklemossen mire, located in southern Sweden. Bathymetry is based on ground penetrating radar data (SITES, 2021) collected by Persson and Banzhaf in 2014. The white areas indicate ground level, while the darkest brown areas indicate the deepest point of the mire up to 600 cm depth.

The volume of every 50 cm section was calculated, and total C and N were upscaled to the full extent of the mire by applying the following formula to each section of the peat profile:

$$T_{CN} = (V_l * \rho) * A_{CN}$$

where

T_{CN} = Total C or N

V_l = total soil volume per layer (m^3)

ρ = soil density ($g\ m^{-3}$)

A_{CN} = Average C or N content (%)

The calculation was applied to each individual peat layer (dimensions: 50 cm x total layer area), and the total C and N of all layers were summed up to retrieve the value for the entire mire volume. The upper 5 cm of each meter depth was assumed to be representative for both upper (e.g. 0-50 cm) and lower (e.g. 50-100 cm) halves of the meter, as no sample was taken at the centre of the meter (e.g. 55 cm). Furthermore, the bottom 100 cm of the peat profile (500-600 cm) were not included in this study due to a lack of data, as the peat cores taken in the field did not reach depths further than 450 cm. However, as the 500 - 600 cm layer only covers 0.03% of the mire, the exclusion of data from this layer is not considered to substantially affect the accuracy of the results.

3. Results

3.1 Historical surface area extent

The surface area of Mycklemossen mire has shown to decrease overtime, measuring 0.35km^2 in 1963, 0.28 km^2 in 2016 and 0.23km^2 in 2021, which shows an accelerated decrease in the more recent years (Figure 6).

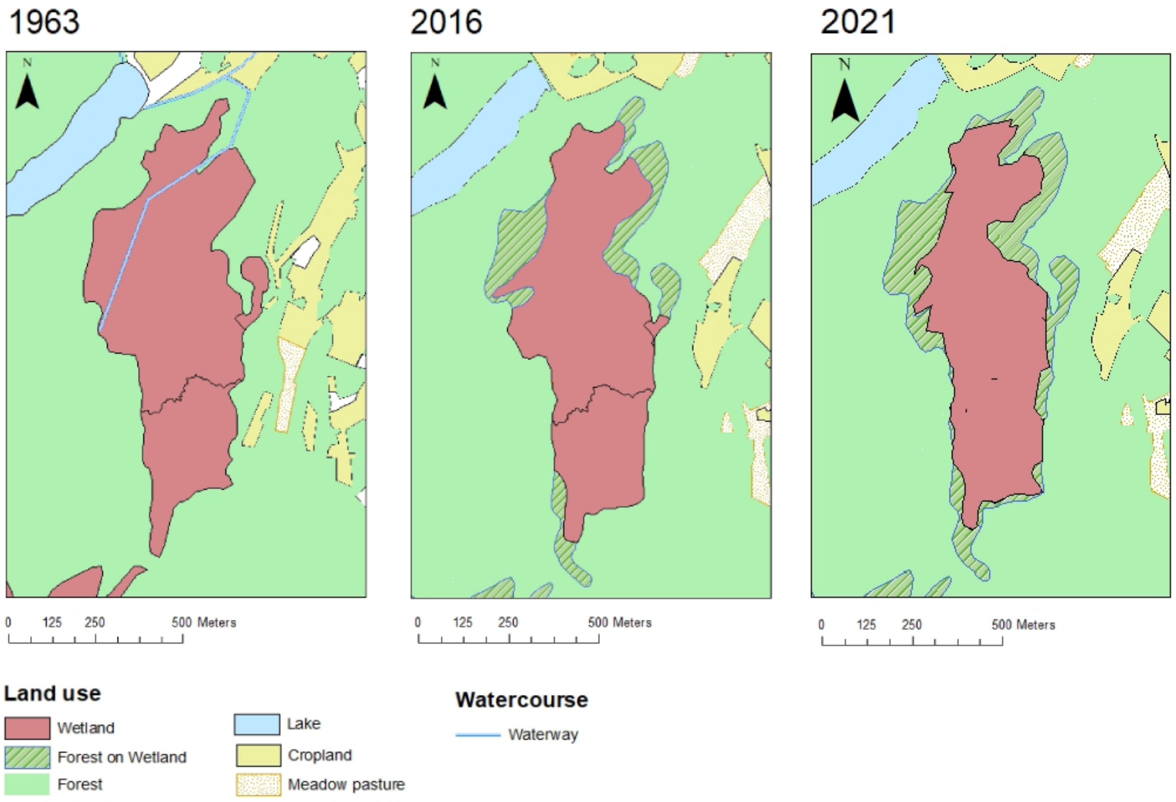


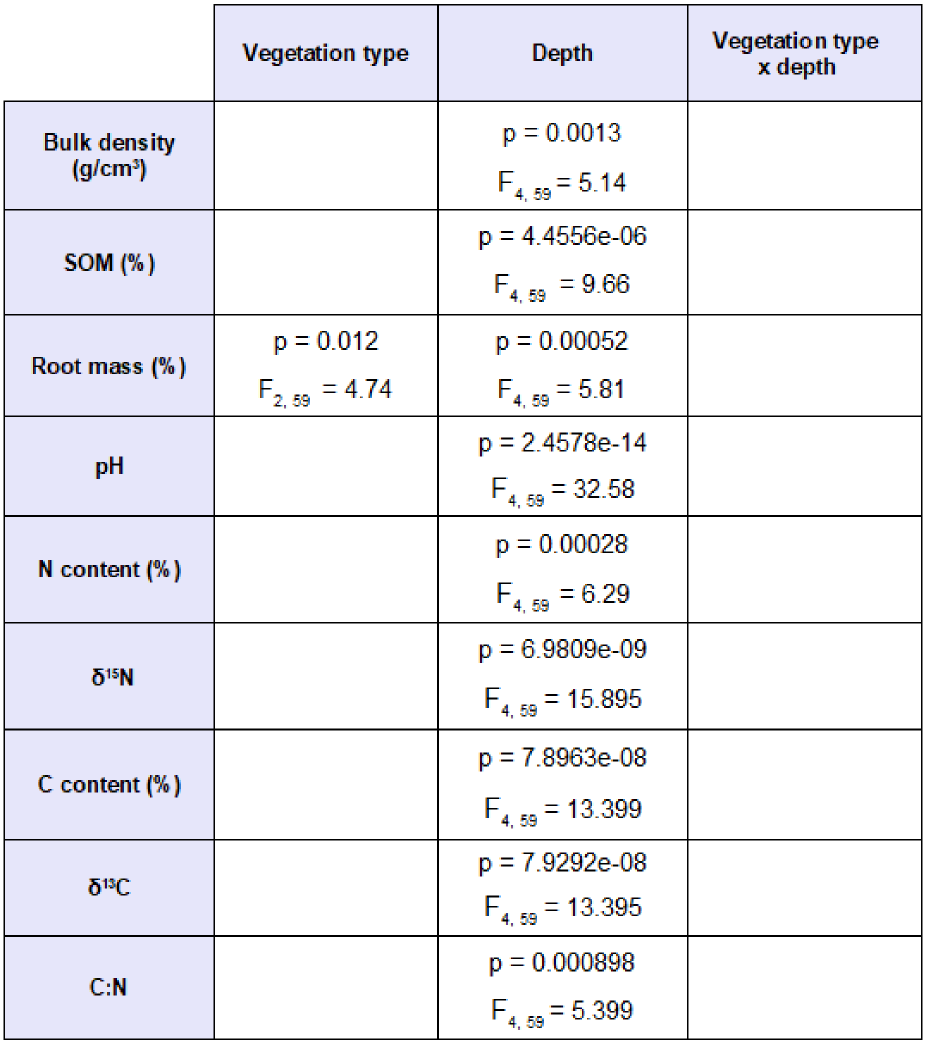
Figure 6. Mycklemossen land use and watercourse in 1963, 2016 and 2021 based on data from SITES database (2021). The lateral parts of the mire have become visibly overgrown over the time period, which has shrunk the total area of the mire from 0.35km^2 in 1963 to 0.28 km^2 in 2016 and finally 0.23km^2 in 2021. Furthermore, a waterway that traversed the northern part of the mire in 1963 is no longer existent in 2016 and 2021.

The lateral parts of the mire have shown to gradually overgrow with forest vegetation in 2016 and 2021.

3.2 Peat depth and surface level vegetation type influence on peat properties

The peat depth showed to have a significant effect on all dependent variables and root mass showed to be the only dependent variable significantly affected by vegetation type, while the interactions of vegetation type and peat depth did not show to have a significant effect on any of the physical and chemical peat properties (Table 1).

Table 1. Significant effects of peat depth, surface level vegetation type and the interaction of the two, on chemical and physical peat properties of Mycklemossen mire, southern Sweden.



	Vegetation type	**Depth**	**Vegetation type x depth**
Bulk density (g/cm^3)		$p = 0.0013$ $F_{4, 59} = 5.14$	
SOM (%)		$p = 4.4556e-06$ $F_{4, 59} = 9.66$	
Root mass (%)	$p = 0.012$ $F_{2, 59} = 4.74$	$p = 0.00052$ $F_{4, 59} = 5.81$	
pH		$p = 2.4578e-14$ $F_{4, 59} = 32.58$	
N content (%)		$p = 0.00028$ $F_{4, 59} = 6.29$	
$\delta^{15}N$		$p = 6.9809e-09$ $F_{4, 59} = 15.895$	
C content (%)		$p = 7.8963e-08$ $F_{4, 59} = 13.399$	
$\delta^{13}C$		$p = 7.9292e-08$ $F_{4, 59} = 13.395$	
C:N		$p = 0.000898$ $F_{4, 59} = 5.399$	

The post-hoc test revealed a significant effect of the interaction between hummock and hollow communities on root mass (Table 2).

Table 2. Significant effects of peat depth layers and surface level vegetation communities on chemical and physical peat properties of Mycklemossen mire, southern Sweden.

	Bulk density (g/cm^3)	**SOM (%)**	**Root mass (%)**	**pH**	**N content (%)**	**$\delta^{15}N$**	**C content (%)**	**$\delta^{13}C$**	**C:N**
HUM – HOL			$p = 0.0099$						
HUM – INT									
HOL – INT									
D1 – D2	$p = 0.0183$		$p = 0.0074$	$p = 0.0066$				$p = 0.0001$	
D1 – D3	$p = 0.0030$	$p = 0.0013$	$p = 0.0053$	$p = 0.0010$	$p = 0.0216$		$p = 0.0256$	$p = 0.0004$	
D1 – D4			$p = 0.0302$	$p < .0001$		$p = 0.0121$	$p < .0001$		
D1 – D5				$p < .0001$		$p < .0001$	$p < .0001$		
D2 – D3						$p = 0.0008$			
D2 – D4				$p = 0.0012$			$p = 0.0003$	$p = 0.0012$	
D2 – D5		$p = 0.0008$		$p < .0001$	$p = 0.0498$	$p = 0.0121$	$p = 0.0245$	$p < .0001$	
D3 – D4				$p = 0.0066$		$p < .0001$	$p = 0.0030$	$p = 0.0037$	
D3 – D5	$p = 0.0341$	$p = < .0001$		$p < .0001$	$p = 0.0001$	$p < .0001$		$p < .0001$	$p = 0.0002$
D4 – D5		$p = 0.0099$		$p = 0.0021$					

Vegetation communities: HUM = Hummock, INT = Intermediate, HOL = Hollow
Peat depth: D1 = 0 – 5 cm, D2 = 100 – 105 cm, D3 = 200 – 205 cm, D4 = 300 – 305 cm, D5 = 400 – 405 cm

The highest number of significant depth combinations was found for peat pH values, where the pH differed significantly between all depth levels except for the D2 – D3 cm depth range. Root mass percentage showed to vary significantly between the surface layer and the remaining depth layer of the peat profile, however, no significant difference between D1 and D5 was shown.

3.3 Bulk density

Bulk density values ranged from 0.012 to 0.24 g/cm^3, where the median appeared to be the highest at 0-5 cm depth of the peat profile for ball vegetation communities (Figure 7).

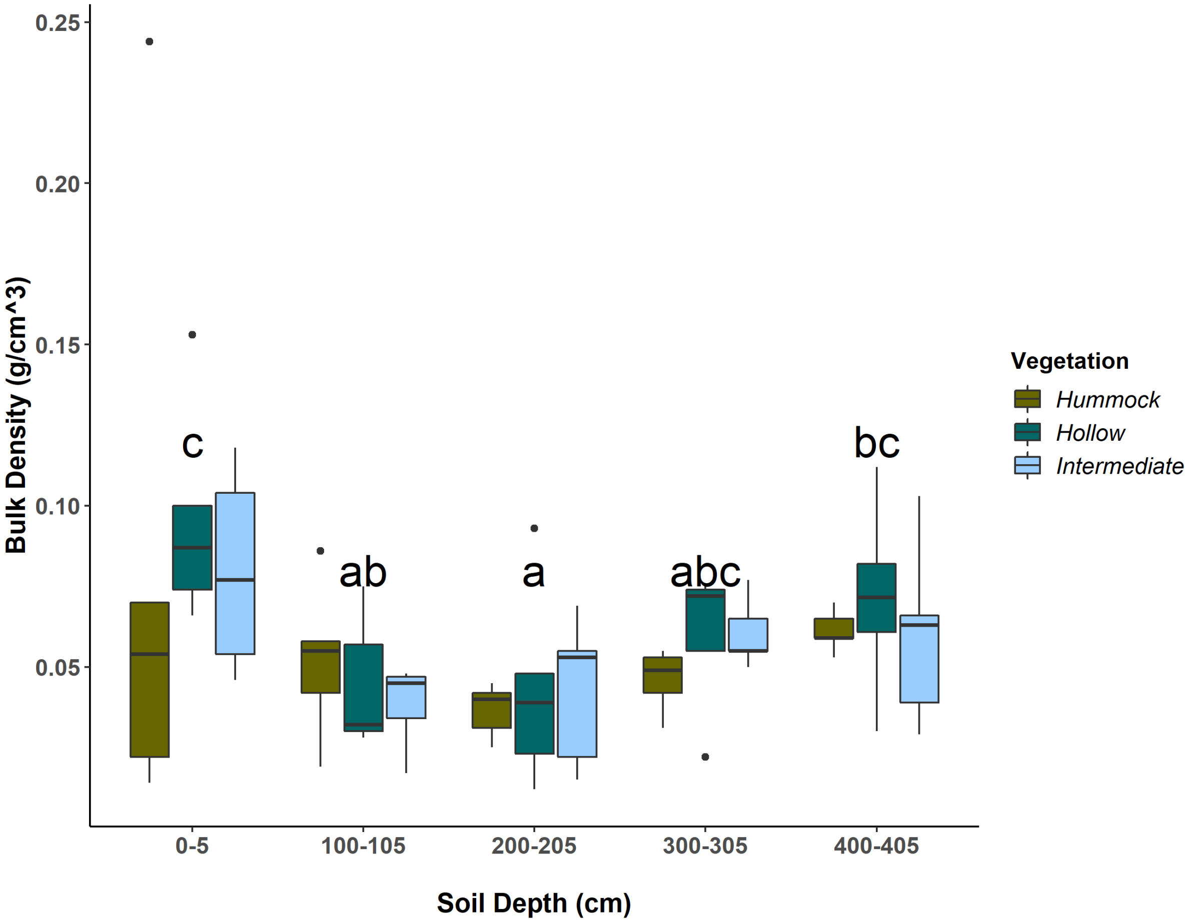


Figure 7. Bulk density (g/cm^3) per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a, b, and c) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

A two-way non-parametric ANOVA revealed that there was no statistically significant difference in bulk density between the different vegetation communities nor the interaction between vegetation communities and depth. There was however a statistically significant difference in bulk density between the various depths of the peat profile ($F_{4, 59} = 5.14$, $p = 0.0013$).

3.4 Root mass

Root mass values ranged between 0 and 3.29%, where the median showed to be the highest at 0-5 cm depth of the peat profile for all vegetation communities (Figure 8).

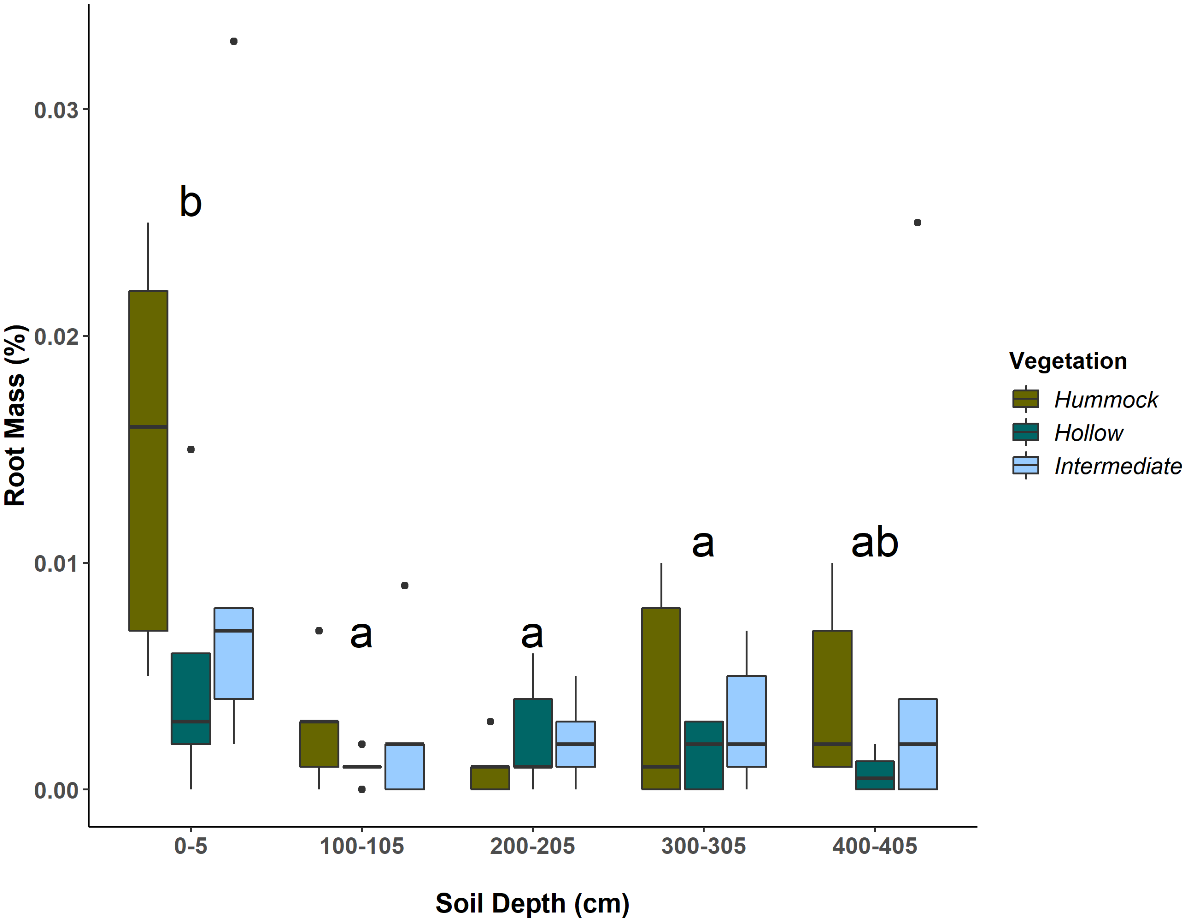


Figure 8. Root mass (%) per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a and b) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

Root mas appears to be the highest in hummock communities at the surface layer. A two-way non-parametric ANOVA showed no statistically significant difference in the interaction between vegetation communities and depth of root mass. A statistically significant difference was however shown between the various depths of the peat profile ($F_{4,\ 59} = 5.81$, $p = 0.00052$), as well as between hollow and hummock vegetation types ($F_{2,\ 59} = 4.74$, $p = 0.0099$) (Figure 9).

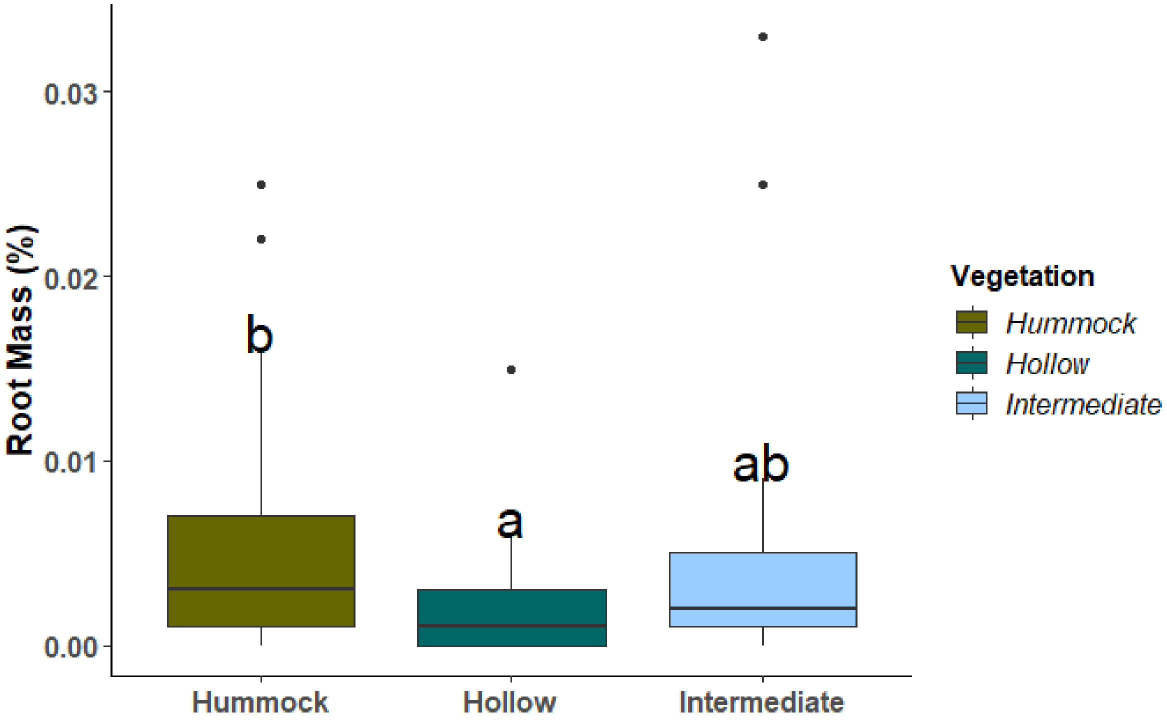


Figure 9. Root mass (%) per vegetation community on Mycklemossen mire, southern Sweden. Letters (a and b) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

The percentage of root mass appears to be mostly concentrated in hummock vegetation communities and least concentrated in hollow communities.

3.5 Soil organic matter content

SOM content varied between 72 and 96%, where the median of all vegetation communities showed an increasing trend up until 200 cm depth, and a decreasing trend for the remaining depth of the peat profile (Figure 10).

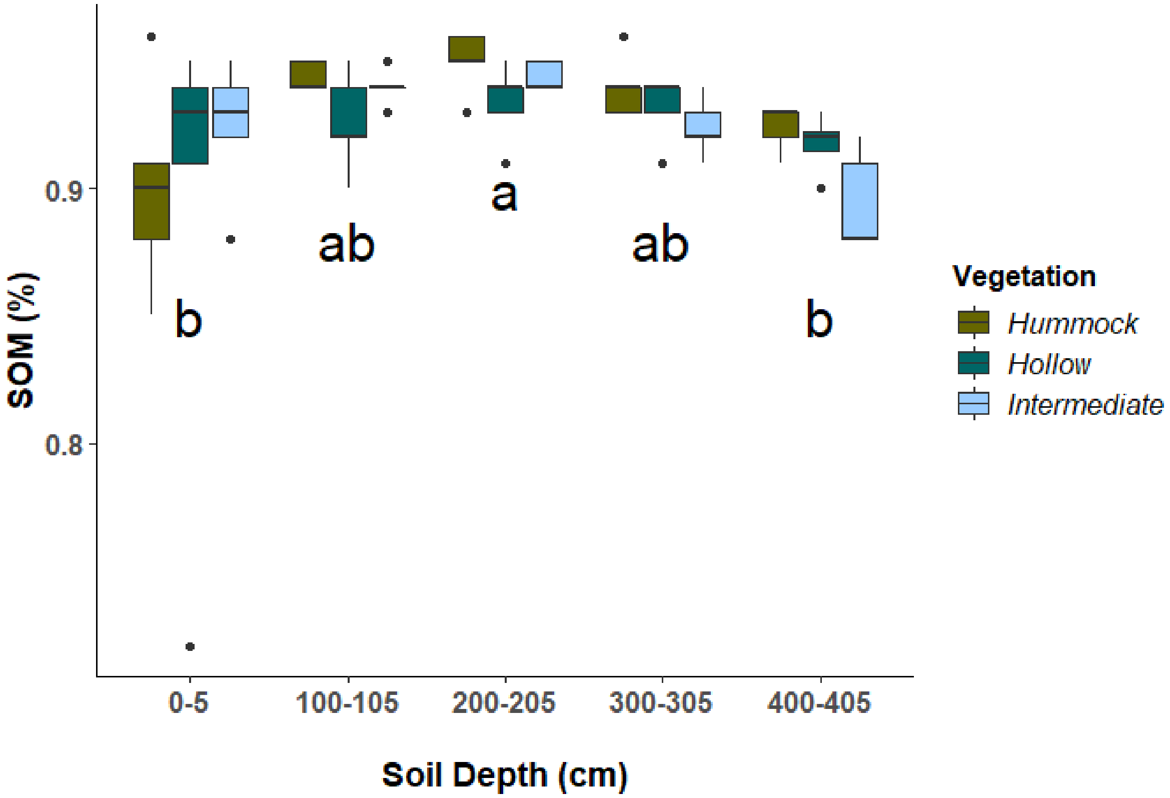


Figure 10. Soil organic matter (SOM) content (%) per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a and b) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

A two-way non-parametric ANOVA revealed that there was no significant difference in SOM content between the different vegetation communities nor between the interaction of the two, however the data does show a significant effect of depth on SOM content ($F_{4,\ 59} = 9.66$, $p = 4.4556e\text{-}06$).

3.6 Peat pH

Peat pH values ranged between 3.75 and 5.96, where the median shows and increasing trend with depth for hollow and intermediate communities (Figure 11).

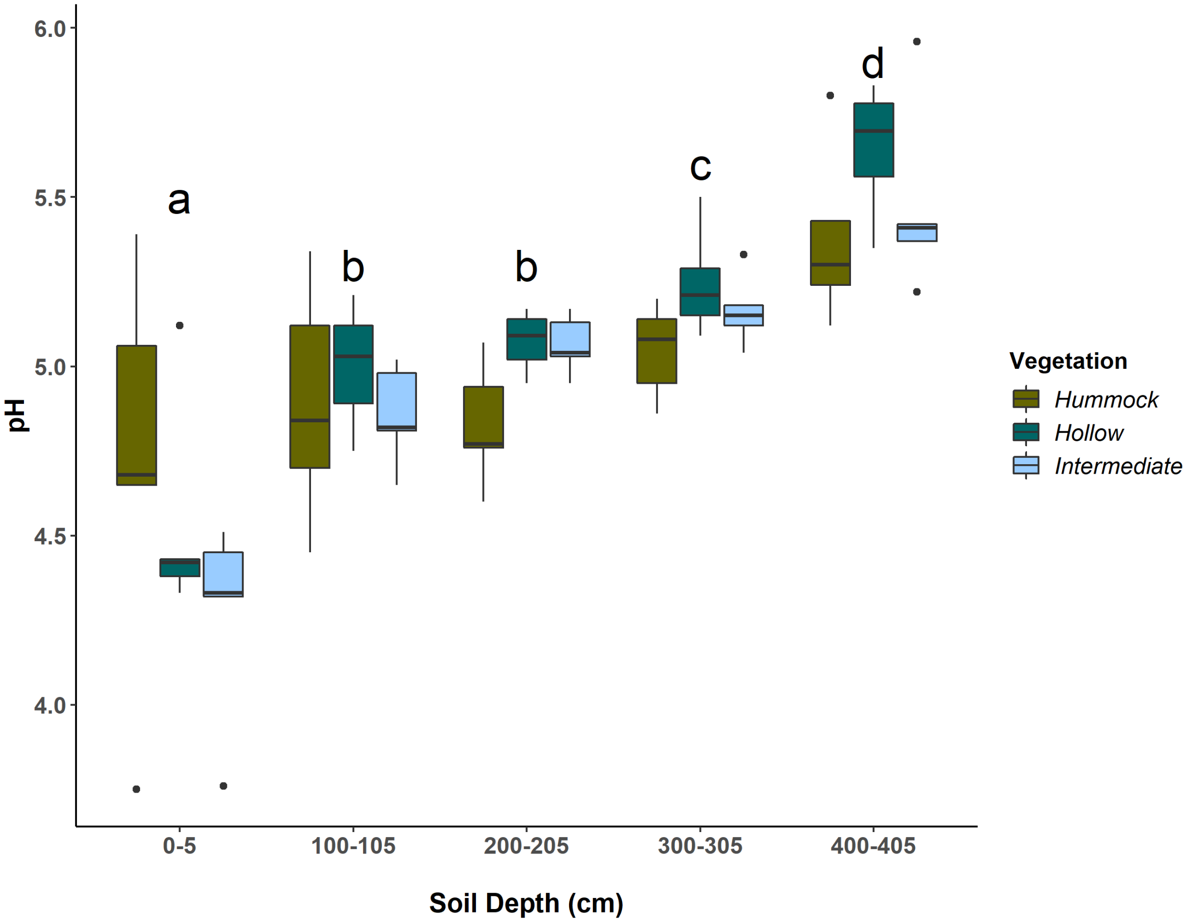


Figure 11. Peat pH values per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a, b, c and d) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

A two-way non-parametric ANOVA revealed that there was no statistically significant difference in peat pH values between the different vegetation communities nor the interaction between vegetation communities and depth, while the difference between the various depths of the peat profile has shown to be statistically significant ($F_{4, 59} = 32.58$, $p = 2.4578e-14$).

3.7 Carbon and nitrogen content and C:N ratio

C content values ranged from 36.05 to 54.55%, with an increasing trend with depth. The median value tended to increase successively up until 300 cm depth for hummocks, and steady increase through the peat profile for hollows, with exception for a decrease at 200 cm depth (Figure 12).

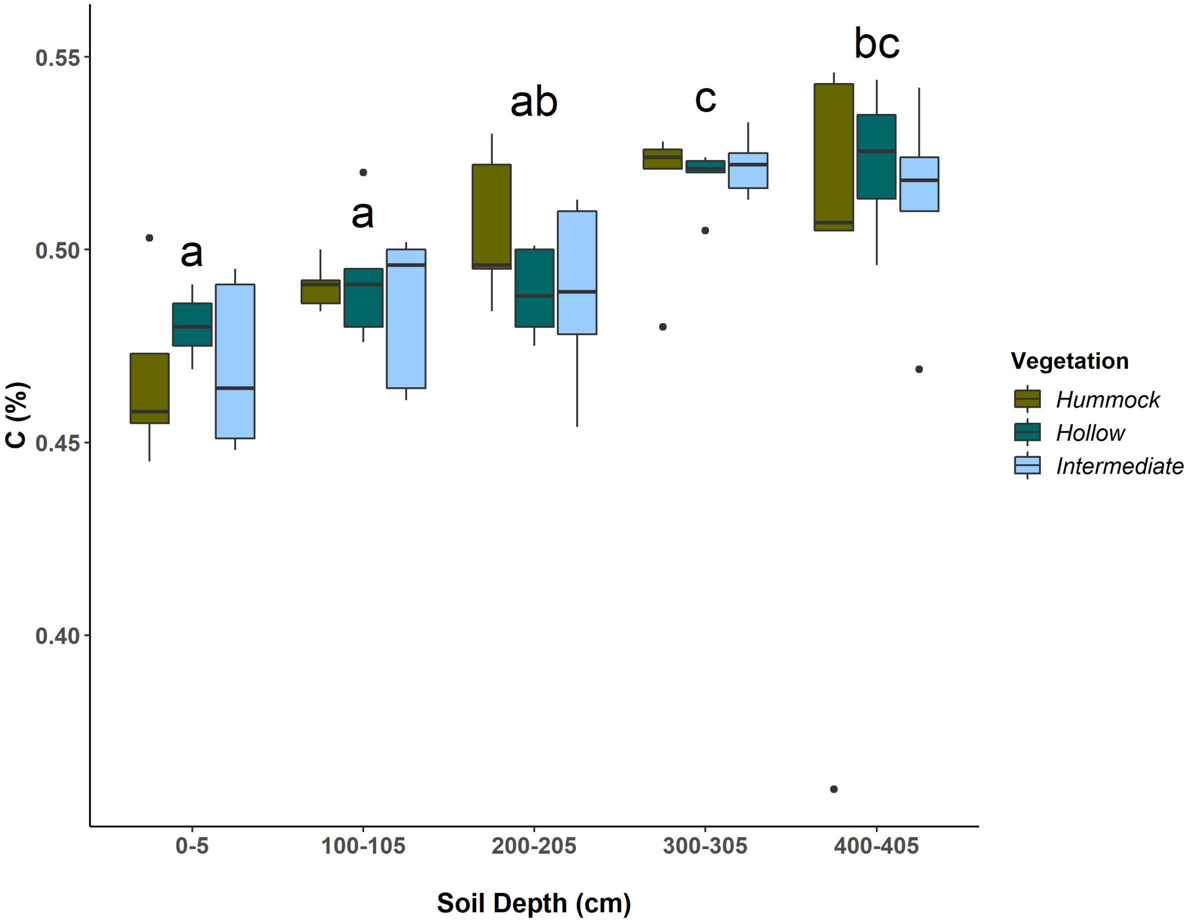


Figure 12. Carbon (C) content (%) per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a, b, and c) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

A two-way non-parametric ANOVA showed that there was no statistically significant difference in C content between the different vegetation communities nor the interaction between vegetation communities and peat depth. However, the difference between the various depths of the peat profile has shown to be statistically significant ($F_{4,\,59}$ = 13.399, p = 7.8963e-08).

N content ranged between 0.37% and 2.51%. The variation in N content showed to vary greatly in the top layer of the peat profile between the various vegetation communities, where hollow and intermediate communities followed a U-shaped trend with the lowest median at 200 cm depth (Figure 13).

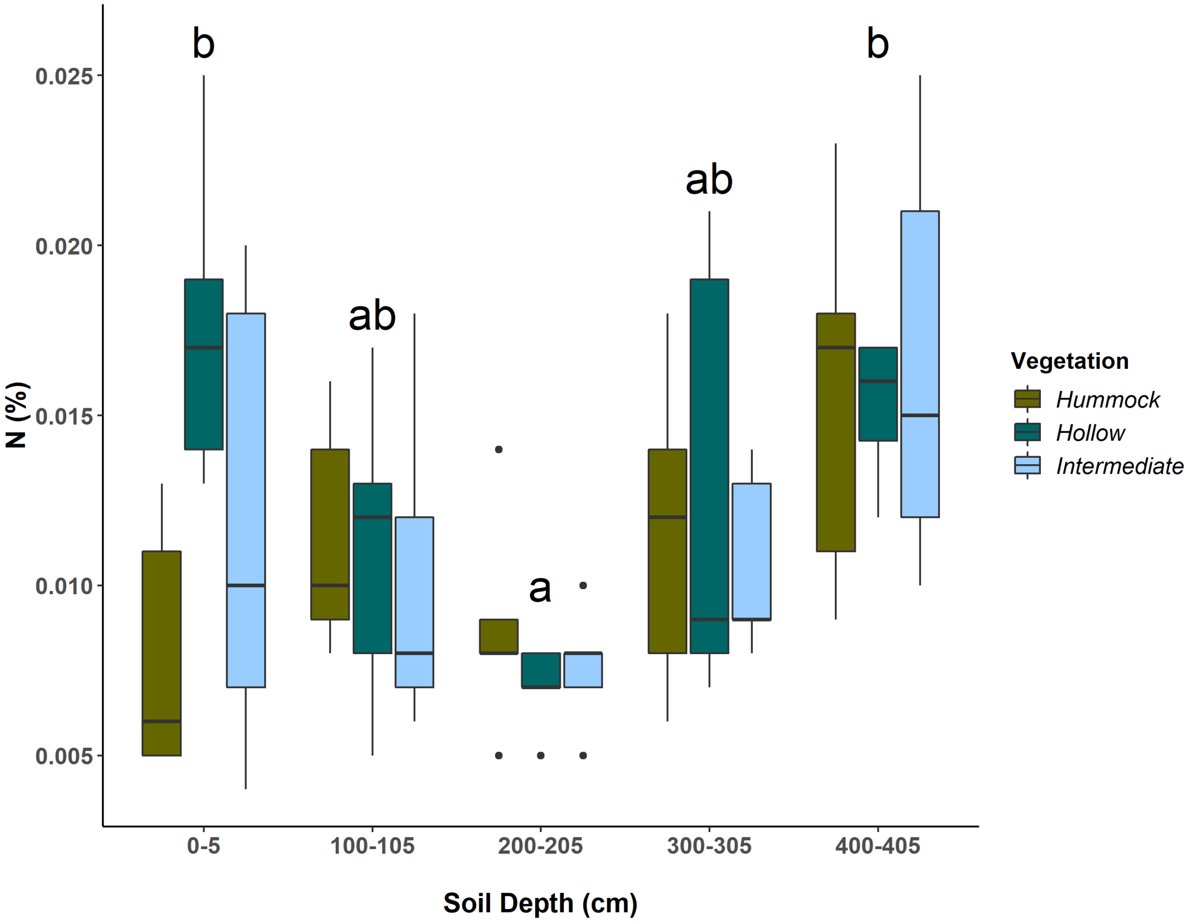


Figure 13. Nitrogen (N) content (%) per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a and b) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

A two-way non-parametric ANOVA revealed that there was no statistically significant difference in N content between the different vegetation communities nor the interaction between the vegetation communities and peat depth. There was however a statistically significant difference in N content between the various depths of the peat profile ($F_{4, 59} = 6.29$, $p = 0.00028$).

The C:N ratio varied between 18.67 and 121.95, where the median showed to be the highest in hummocks and the lowest in hollows at the top layer of the peat profile, and very similar in all vegetation communities at the bottom 100 cm layer of the profile (Figure 14).

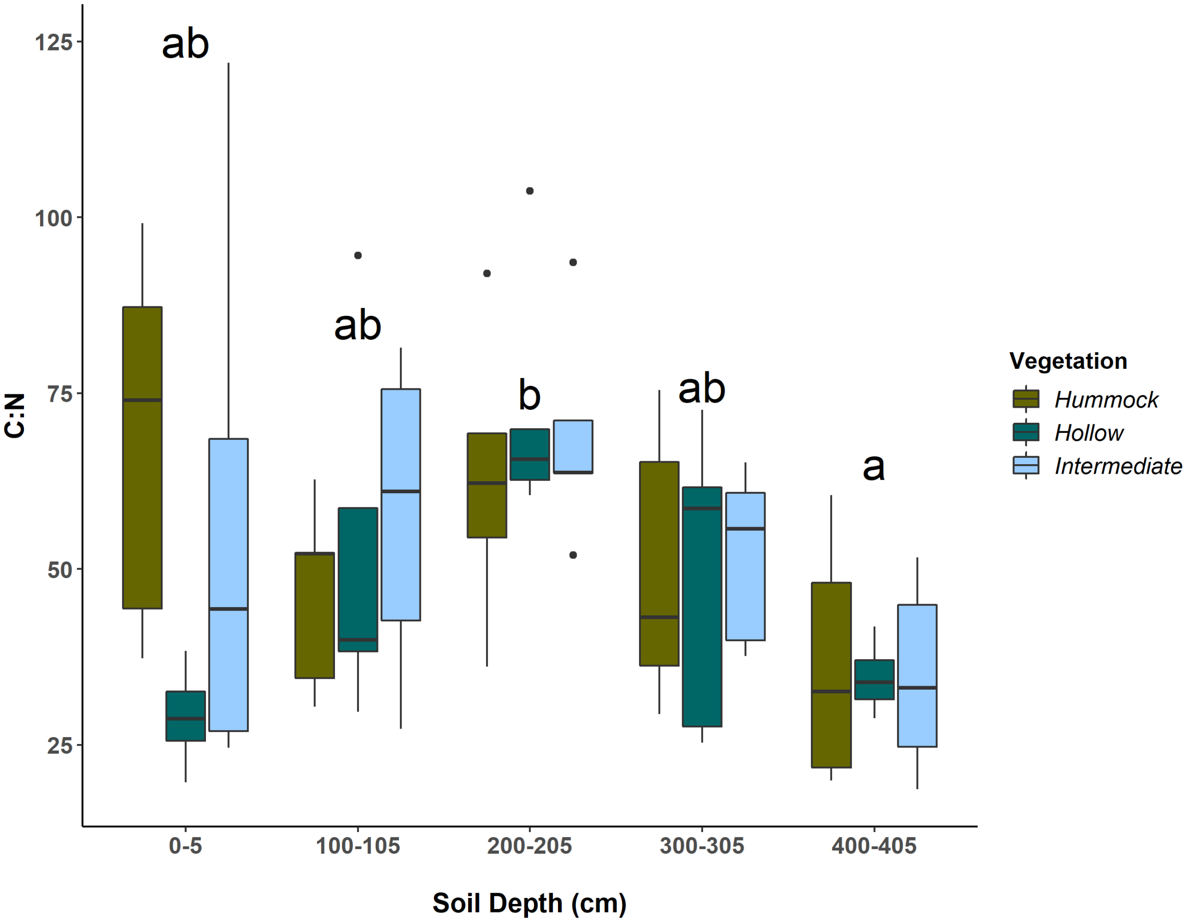


Figure 14. C:N ratio per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a and b) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

A two-way non-parametric ANOVA showed no statistically significant difference in C:N ratio between the different vegetation communities nor in the interaction between vegetation communities and peat depth. However, the difference between the various depths of the peat profile did show to be significant ($F_{4,\ 59} = 5.399$, $p = 0.000898$).

3.8 δ^{13}C and δ^{15}N

Peat δ^{13}C values ranged between -29.31 and -23.37‰, where the median showed to increase within the 0 – 105 cm depth span for all vegetation communities, with a decreasing trend with depth thereafter (Figure 15).

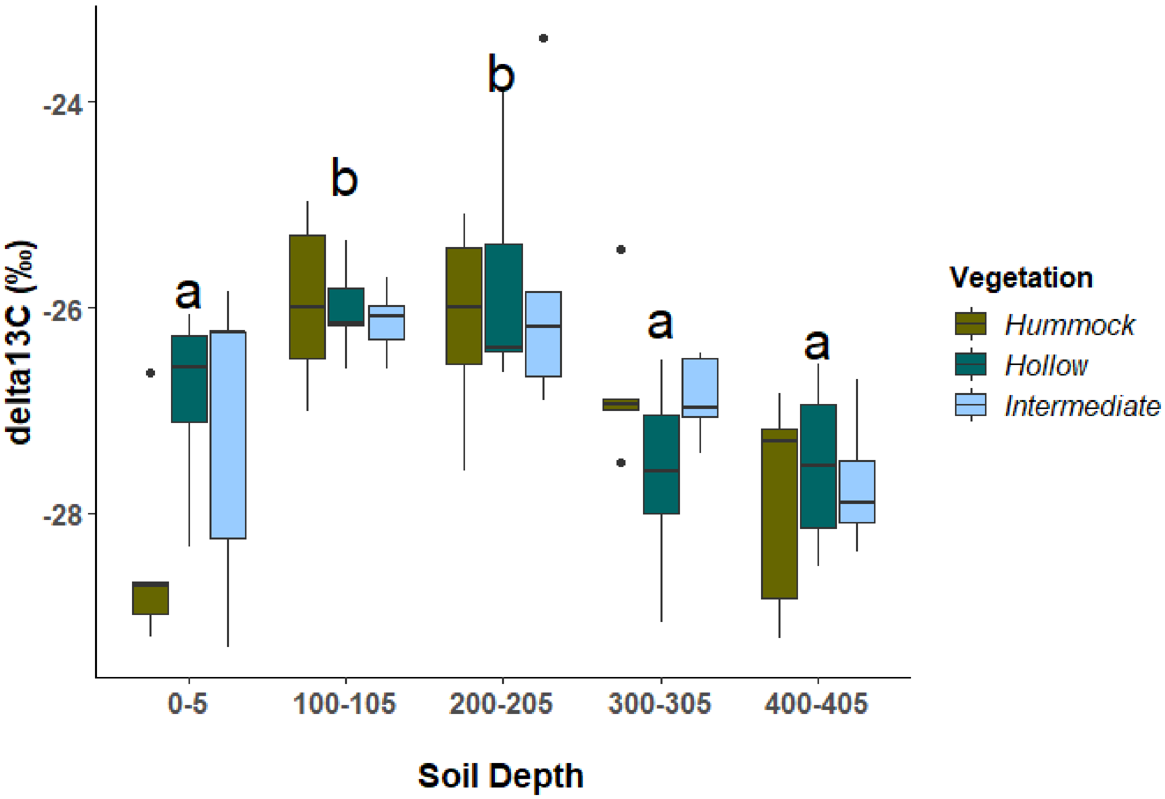


Figure 15. $\delta^{13}C$ (‰) per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a and b) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

A two-way non-parametric ANOVA revealed that there was no statistically significant difference in $\delta^{13}C$ between the different vegetation communities nor in the interaction between vegetation communities and depth, however the difference between the various depths of the peat profile has shown to be statistically significant ($F_{4, 59} = 13.395$, $p = 7.9292e\text{-}08$).

Peat $\delta^{15}N$ values ranged between -4.69 and 4.03‰. Average peat $\delta^{15}N$ showed hollows and hummocks following a similar trend of an increase at 100 cm depth, followed by an increase at 200 cm and once again followed by a decrease through the remaining depth of the profile (Figure 16).

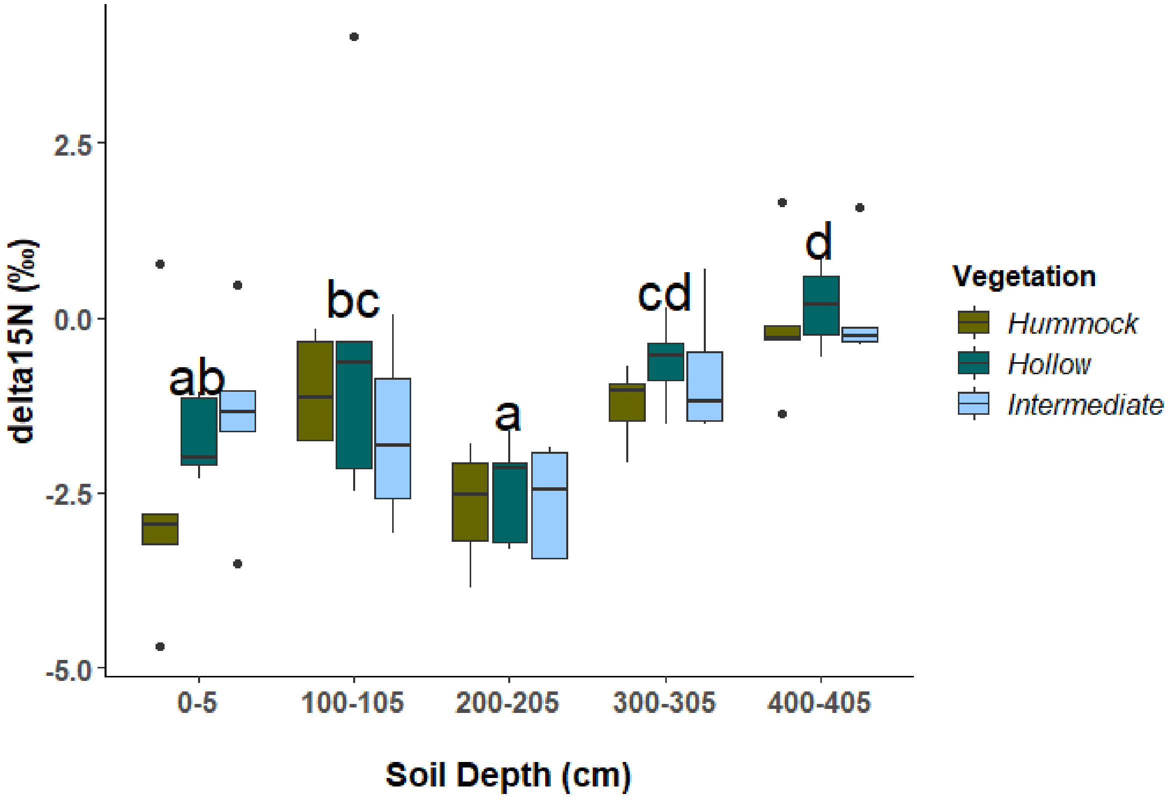


Figure 16. δ^{15}N (‰) per vegetation community across the peat profile of Mycklemossen mire, southern Sweden. Letters (a, b, c and d) indicate significant differences between the different depths, where depths with matching letters have shown to not be significantly different.

A two-way non-parametric ANOVA revealed that there was no statistically significant difference in δ^{15}N between the different vegetation communities nor in the interaction between vegetation communities and peat depth. There was however a statistically significant difference in δ^{15}N between the various depths of the peat profile ($F_{4,\,59}$ = 15.895, p = 6.9809e-09).

3.9 Upscaled C and N

The total C content of Mycklemossen mire has been upscaled to 34.8 kt and has shown to be the highest in the top 50 cm layer of the peat profile (Figure 17).

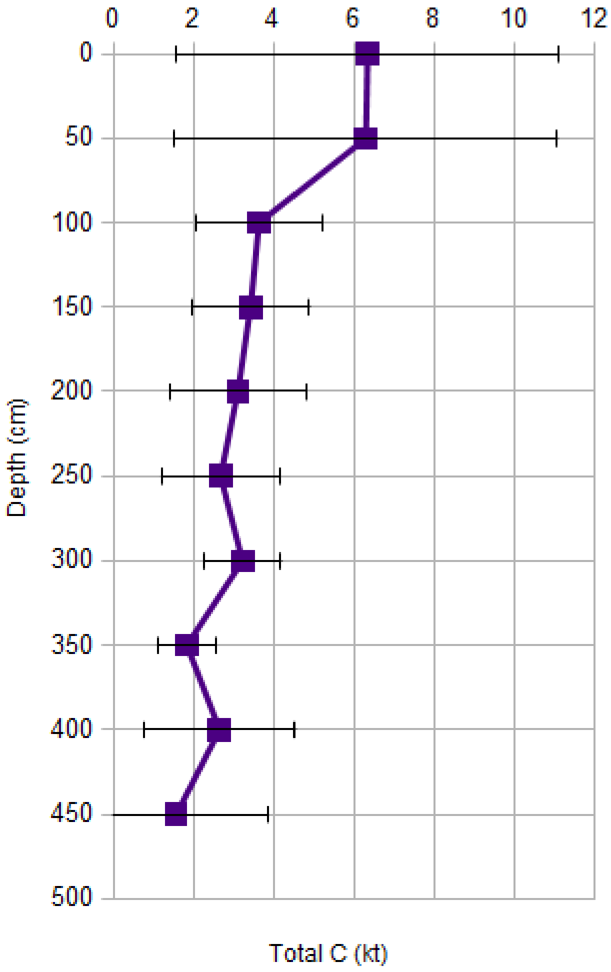


Figure 17. Average total carbon (C) of all vegetation communities (hollow, intermediate and hummock) of Myckelmossen mire, southern Sweden. Shown in 50 cm sections of the peat profile.

Total C has shown a great decrease between 50 and 100 cm depth. Thereafter, total C gradually decreases with depth, with exception for a slight increase at 300 and 400 cm depth.

The total N content of Mycklemossen mire has been upscaled to 0.9 kt and has shown to be the highest in the top 50 cm of the peat profile (Figure 18).

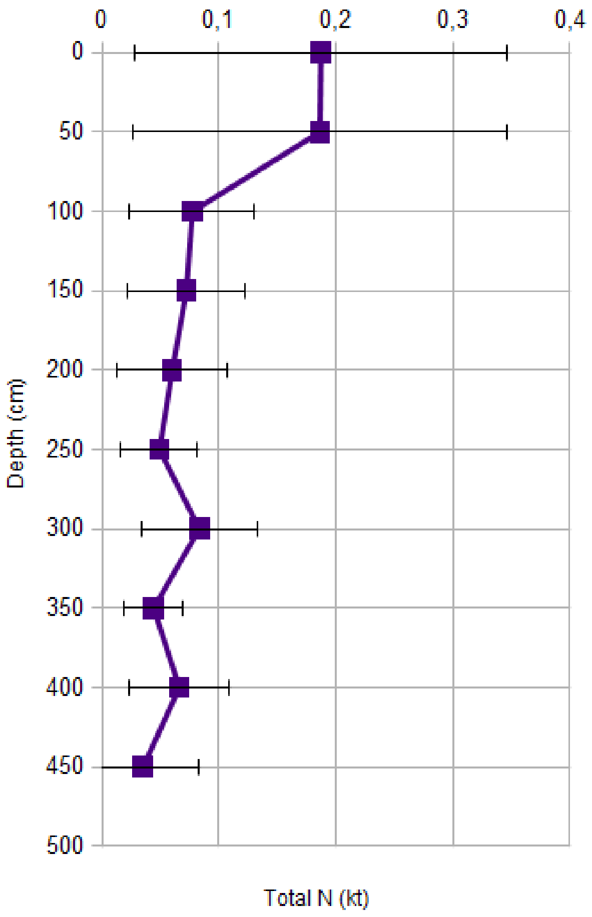


Figure 18. Average total nitrogen (N) of all vegetation communities (hollow, intermediate and hummock) of Myckelmossen mire, southern Sweden. Shown in 50 cm sections of the peat profile.

Following the trend of total C, total N has shown to greatly decrease between 50 and 100 cm depth. A gradual decrease in total N continues with depth, with the exception of an increase at 300 and 400 cm depth.

4. Discussion

4.1 Mycklemossen surface area extent

The historical mapping of the surface area of Mycklemossen mire revealed a gradual loss of surface area in the past 58 years. The mire has lost 0.12 km^2 of the total area from 1963, which equals to a loss of 34% of surface area. The loss of surface area appears to be accelerating, as 0.05 km^2, or 14% of the total surface area from 1963, was lost in the recent five years. The historical mapping shows ongoing shrubification in the lateral parts of the mire and can also be seen in the root mass data, where root mass at the surface layer has shown to increase with reduced water content, appearing to be greater in dry, hummock areas. This suggests that the shrubification may not only be ongoing in the lateral parts of the mire, but simultaneously occurring at the medial part of the mire surface where hummocks are present.

The observed shrubification at Mycklemossen is in line with Bu et al. (2011), who predict that climate warming will facilitate the growth of vascular plants as well as supress endangered plant species in peatlands. Additionally, they found that water availability in peatlands will reduce, as climate warming is expected to alter the moisture level and lower the water table, which is also a potential threat to Mycklemossen (Bu et al., 2011). Increased shrubification in wetlands can also in turn lead to further changes in the water table due to increased evapotranspiration, in a process called the peatland shrubification-evotranspiration feedback (Moore et al., 2022).

4.2 Physical and chemical peat properties and depth

All physical and chemical peat properties measured in this study varied significantly by depth (two-way non-parametric ANOVA) and are discussed in the next paragraphs.

High bulk density values were observed in the surface layer of the peat profile, suggesting a human influence or possible compression by local fauna. The surface bulk density appeared to be the highest in the wet, hollow areas, which may be caused by the reduced particle friction which wet conditions allow for, thus leading to greater soil compaction (ITEP, 2009). The bulk density values of the remaining depth showed an increasing trend with depth, which suggests none or little anthropogenic disturbance in the depth of peat profile.

The pH values showed to increase with depth, which is in line with the processes discussed in Clymo (1984), where the surface layer generally has lower pH, while the pH tends to rise in the deeper peat layers, as the H^+ initially present in the surface layer decreases with depth due to the gradual decrease of COOH groups. Such increase in pH suggests higher decomposition rates with depth, as the organic acids in litter become oxidised, the anions are replaced by carbonate making the decomposed product more alkaline (Haslam & Tibbett, 2009). Furthermore, pH values of the surface layer have shown to be the lowest in semi-dry, intermediate areas, which is not in line with the commonly observed trend of lower pH values in wetter conditions caused by leaching (USDA, 2014). This may however be explained by reduced acidification processes at the surface layer potentially caused by low soil and air temperatures at the time of sampling.

The data suggests that C content is increasing with depth, which is likely due to the lack of input of mineral material in the deeper parts of the peat profile. As consumption of C compounds occurring at greater depths in turn increases the total C to mineral material ratio (Tfaily et al. 2014). Total N, similarly to total C, has also shown to increase with depth, which may suggest increased mineralization rates with depth, as higher decomposition rate generally increases N content (Zhou et al., 2018). This result is also in line with the increased C content and increased pH with depth, which also suggests higher decomposition rates and higher humification.

The data generally shows a decrease in $\delta^{13}C$ with depth, which is in contrast to the observed pattern of increased decomposition with depth suggested by total C, N and increased pH values. This is due to the fact that enrichment of $\delta^{13}C$ is dependent on the preferential loss of ^{12}C, which implies that higher $\delta^{13}C$ values suggest increased decomposition rates (Fry, 2006). The $\delta^{15}N$ values, however, showed to remain similar through the peat profile, with a slight increase with depth. The lower $\delta^{15}N$ at the surface layer suggest little N input from atmospheric N. As $\delta^{15}N$ are dependent of $\delta^{14}N$ consumed during decomposition (Fry, 2006), the data suggests a slight increase in decomposition rates with depth. Removal of mineralized N from the surface layer through plant uptake and leakage also explains the slightly lower $\delta^{15}N$ values at the top meter of the peat profile.

Generally, SOM content tends to have a decreasing trend with depth (Magdoff, 2021). In this study the decreasing trend can be seen from 200 cm depth and onwards, however the top 200 cm layer of the peat horizon appears to have lower SOM content than expected. Moreover, the lowest SOM content was observed in hummock areas in the near-surface layer, likely due to the inhibition of plant residues to convert into stable substances such as humic materials which are resistant to biological decomposition, as in order for SOM to form, restricted drainage is needed to create anaerobic conditions which reduce the activity of the decomposing organisms (Magdoff, 2021).

When it comes to root mass content variations through the peat profile, the results show root mass values to be considerably greater at the surface layer in comparison to the remaining depth, which is an expected trend, as the root mass likely has decomposed before reaching greater depths.

4.3 Physical and chemical peat properties and vegetation type

A significant effect of the surface layer vegetation communities (hollows, intermediate and hummocks) was shown on root mass percentage (two-way non-parametric ANOVA), where root mass has shown to be the greatest in hummock areas as well as to be significantly different from hollow areas. Regarding the remaining dependent variables, the results suggest that the differences between the vegetation communities are only present at surface level rather than at the deeper layers of the peat profile, which is in line with Kelly et al., (2021), who show that differences in surface and soil temperatures do occur between different vegetation communities, as they discovered a significant difference in monthly means of surface and soil temperature between hummocks and hollows, where the mean surface temperature of the hollows showed to be 3°C warmer than the hummocks, while the mean soil temperature of the hollows was ~1°C cooler than the hummocks. Similarly, differences between vegetation type and physical or chemical peat properties limited only to the surface layer have been discovered in this study; bulk density, N content and $\delta^{13}C$ have all shown to be the highest in the wet, hollow areas and decrease with reduced water content, while root mass and C:N ratio showed to increase with reduced water content (higher in dry, hummock areas).

Although some variations have been noted in vegetation communities and the physical and chemical properties of peat, it is unlikely that vegetation type and/or soil depth will affect the deeper soil layers. This is due to the shifting nature of vegetation types across the mire, coupled with a generally slow growth rate of the bog averaging at 0.5 – 1mm per year (Lindsay et al., 2014). Not accounting for this in the study design is a significant shortcoming of the study.

4.4 Upscaled C and N

While peat C content has shown to increase with depth, upscaled C shows a slight decrease in total C. This is arguably due to the funnel shaped bathymetry of the mire, as the data in this study is shown as C content relative to the volume of the peat layer. Similar to the upscaled C data, upscaled N also shows a slight decrease with depth, while total N has shown an increase, this can equally be explained by the below surface shape of the mire. In further studies it would be interesting to consider the C content in weight rather than in precent, as this could provide a more accurate representation of the total carbon stock.

The fact that neither root C nor N was not measured in this study is a factor that must be kept in mind when interpreting the estimations of both C and N content as well as total upscaled C and N of the mire. According to Strakova et al., (2020), root-mediated C fluxes represent a major information gap when estimating C stocks and C transformations of any ecosystem that supports plant communities. Plants are the main drivers of the whole ecosystem productivity, and plant roots may comprise an equal or even greater part of the biomass or the annual biomass production compared to the aboveground part of the plants (Strakova et al., 2020).

Conclusion

A 34% decrease in the lateral extent of the Mycklemossen mire within the period of 1963-2021 showed an ongoing shrubification of the mire, which may consequently cause decreased vegetation diversity as well as a deeper active layer due to alterations in ecosystem carbon exchange and associated feedback processes. Upscaled total C content of Mycklemossen was estimated to 34.8 kt and total N content was estimated to 0.9 kt, and is expected to decrease overtime, as loss of C and N is likely to be ongoing in line with global warming. The depth of the peat horizon showed to have a significant effect on bulk density, root mass, SOM, pH, C content, N content, C:N and δ^{13}C and δ^{15}N values, while the variation of the above surface layer vegetation communities appeared to have a significant effect on root mass, and may additionally have an effect on the ongoing biogeochemical processes in the upper near-surface peat layer. A significant shortcoming of this study is that it did not account for the shifting nature of the mire vegetation and its slow growth rate. This oversight means that the surface layer vegetation is unlikely to affect the lower levels of the mire.

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