Norwegian University
of Life Sciences

Master's Thesis 2019 60 ECTS
Environmental Sciences and Natural Resource Management

Carbon stock and geological development of a peatland in Karlshaugen nature reserve

Vera Sklet
Environment and Natural Resources

Preface

This master's thesis marks the end of five years of studying at Norwegian University of Life Sciences. I want to give a thanks to my supervisor Mona Henriksen for good help with fieldwork, laboratory work and the writing process. My co-supervisors Line Tau Strand and Per Holm Nygaard, for the help you gave me with respectively carbon stock calculation and fieldwork. Leif Jacobsen have given me valuable help with both fieldwork, data collection and data processing. I would also like to thank Irene E. Eriksen Dahl and Magdalena Rygalska for the help they gave me with sample analysis in the laboratory.

I also want to thank my family for support and all the help you have given me. And lastly, my classmates for lunch company and interesting discussions through this year.

Norwegian University of Life Sciences (NMBU)

Ås, 12.05.2019

Vera Sklet

Abstract

Carbon stocks of peatlands is of growing interest due to the ability to store large amounts of carbon. To provide data of this subject this master thesis presents results from a study of a peatland within a forest nature reserve outside of Oslo, Norway. First, peat volume was estimated using a combination of ground penetrating radar survey and GIS tools (EkkoPulse software, ArcMap and Excel). Second, sediment cores retrieved from the peat were analysed in the laboratory to analyse the bulk density and carbon content of the organic material and to calculate the carbon stock of the peatland. The data were also used to explain how this peatland has developed.

The volume of the total peatland analysed by the ground penetrating radar was calculated to be 6487 m^3. Degree of decomposition, described by the von Post scale, shows similar trends for all four cores; it is low in the shallow peat and increases with depth where they stabilize at level 6-8. Using Loss On Ignition as total amount of organic material gave values well above 90%, except for the samples that visibly contain minerogenic material. These results were consistent with results from total carbon analysis using LECO Truspec instrument finding total carbon content of peat core MM1to be 47-55%. The total carbon content of the remaining three cores were determined by regression analysis to be 50-53% in core MM2, 51-54% in core MM3 and 52-54% in core MM4. Carbon stocks in MM1 range from 2 kgC/m2 to 7 kgC/m2. The total amount of carbon stored in this peatland is calculated to be 278 ton. For the top meter the carbon stock is 41.1 kg/m^2.

The hypothesis for the formation of this peatland being a depression in bedrock filled with water to form a pond, later filled with sediments and organic material was supported by the shape of the peat basin illustrated in the GPR survey, and the fine minerogenic material in the bottom part of peat core MM1. Further field observations support peatland boundary is changing, and it can be predicted that the rise in temperature and changes in precipitation might cause degradation of organic material in the peatland. This process may be part of a positive feedback loop with climate change.

Sammendrag

Karbonlager i myr er av økende interesse grunnet deres evne til å lagre store mengder karbon. For å belyse dette temaet presenterer denne oppgaven resultater fra en studie av en myr i Karlshaugen naturreservat i Nordmarka, Oslo. Volum av myra ble kartlagt ved en kombinasjon av georadar og GIS-verktøy (EkkoPuls-programvare, ArcMap og Excel). Videre ble fire sediment kjerner hentet opp fra myra, og analysert for tetthet og karboninnhold. Dette er brukt til å estimere mengde karbon lagret i myra. Basert på data fra undersøkelsen er det også utformet en forklaring på hvordan denne myra er dannet og har utviklet seg.

Volumet av den delen av myra som er kartlagt med georadar er estimert til 6487 m3. Grad av nedbrytning i materialet, beskrevet ved hjelp an von Post skalaen, viser lignende utvikling i de fire kjernene. I det grunne myrmaterialet er det en lav grad av nedbrytning, mens den øker i dybden, og stabiliserer seg på nivå 6-8. Ved bruk av glødetap er mengde organisk materiale i prøvene bestemt, dette ga resultater på godt over 90%, bortsett fra de prøvene som inneholdt mineralsk materiale. Disse resultatene samsvarer med analysene for karbon innhold gjennomført ved bruk av LECO Truspec instrument. Disse viser karboninnhold på 47-55% for kjerne MM1. Karbon innholdet i de resterende kjernene er bestemt med en regresjonsanalyse, som ga resultater på 50-53% for kjerne MM2, 51-54% for kjerne MM3 og 52-54% for kjerne MM4. Karbonlager utregninger for kjerne MM1 variere fra 2 kgC/m2 til 7kgC/m2. Den totale mengden karbon lagret i denne myra er estimert til 278 tonn. For den øverste meteren i myra er karbonlageret beregnet til 41.1 kg/m2.

Hypotesen for hvordan denne myra er dannet går ut på at en nedsenkning i grunnfjellet ble fylt med vann og dannet et tjern, som senere ble fylt med sedimenter og organisk materiale. Denne hypotesen er støttet av formen på myrbassenget som er godt illustrert i georadar undersøkelsen, og funn av mineral materiale i bunnen av den dypeste myrkjernen. Videre så støtter feltobservasjoner tidligere resultater om at denne myra er i endring, det kan antas at økning i temperatur og ening i nedbør kan føre til nedbrytning at organisk materiale og utslipp av karbon. Denne prosessen kan være en del av en positiv tilbakekoblingsmekanisme med globale klimaendringer.

Table of Content

1. Introduction

Peatlands have the ability to store large amounts of carbon, and therefore they are an important factor in the carbon cycle (Gorham, 1991; Yu et al., 2010). On a global scale, peatlands cover about 3% of the land surface. In boreal and subarctic climate zones, up to 15-30 % of soil carbon is stored in peatlands (Limpens et al., 2008). Large amounts of carbon are stored in the world's peatlands, but there is a gap in the knowledge when it comes to accurate estimates of both global and local peatland carbon stocks (Xu et al., 2018). The process of improving the state of knowledge on this subject is ongoing. Large differences in estimates of both peat area and carbon stocks reflects the uncertainties in area, volume and bulk density on a large scale (Turunen et al., 2002).

With a changing climate, it is important to improve our understanding of carbon distribution, and the potential for both release and sequestration of carbon in peatlands.

Carbon stock is a product of peat volume, bulk density and carbon content (Setiawan et al., 2015). In order to find accurate estimates of peat volume, detailed data about peat depth is necessary. As the depth is highly variable, methods as ground penetrating radar allows for a high resolution mapping of peat basin (Parsekian et al., 2012). In this study, I have gathered detailed data about the peat in Karlshaugen nature reserve (see Figure 1) required to make accurate estimations of peat volume. Carbon content of the peat cores is analysed at the laboratory to be able to estimate the carbon stock.

Though estimating area and volume on a small scale gives valuable information, there are large differences in estimating peatland area and volume on a small scale and on a national and global scale.

Peat area in Norway is estimated to be 28 300 km^2, which makes up 9% of the land surface (Rekdal et al., 2016). This number is an increase from previous estimates, a report from 2010 included an estimate of 6% of the land surface to be peat and wetlands (Grønlund et al., 2010).

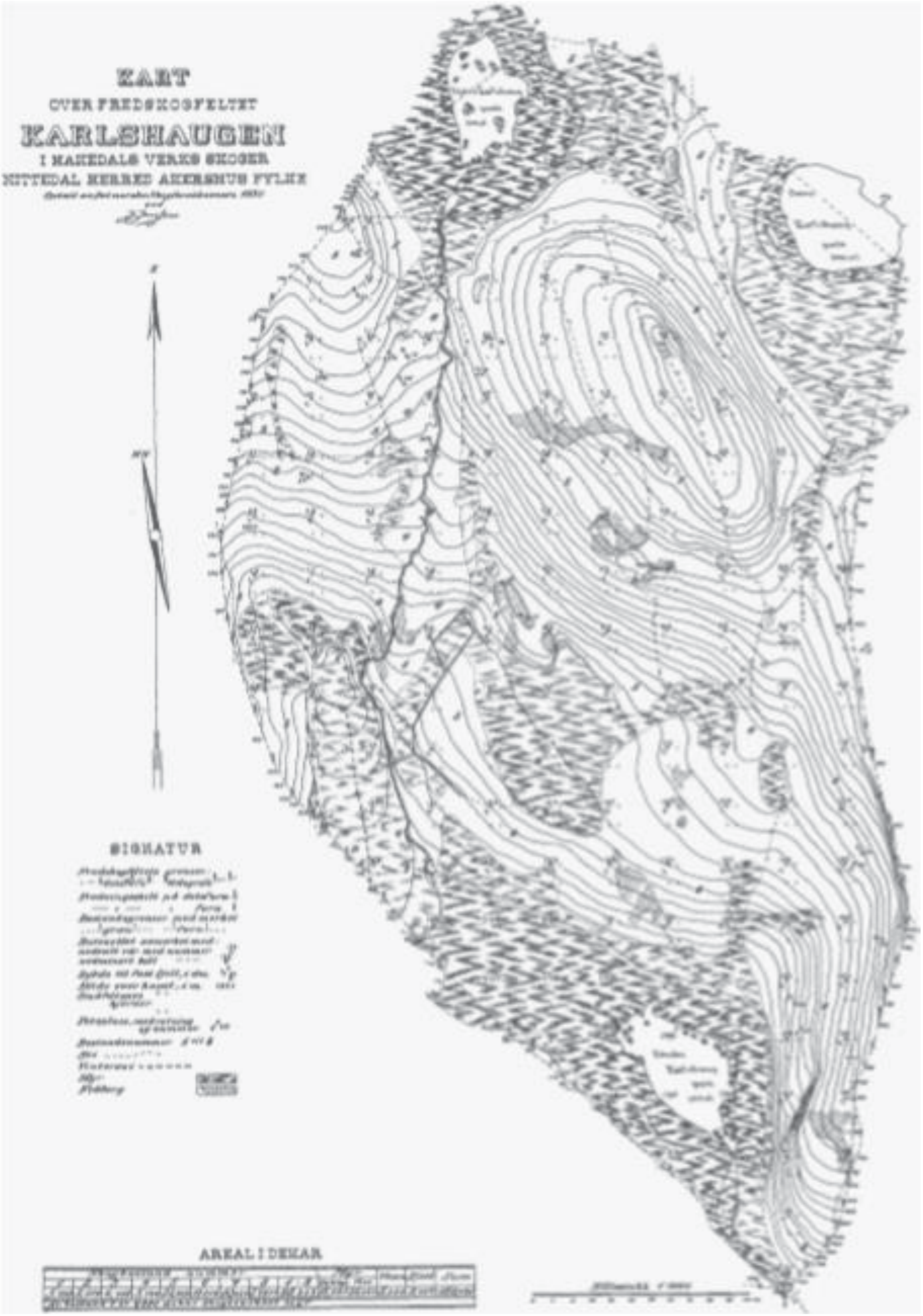


Figure 1: Map of Karlshaugen nature reserve from 1930. The scrabbled areas represent peat.

1.1 Purpose of the study

The topic of this master thesis is analysis of a peatland (Figure 2) within a protected forest area. Both carbon stocks and the geological development is of interest.

The purpose of this study is a detailed investigation of peat volume, carbon stock and development of a peatland in Karlshaugen nature reserve located in Nordmarka, a forest area north of Oslo. Detailed estimation of peat volume and carbon stock is challenging due to the requirement of detailed local knowledge of factors such as peat depth, bulk density and carbon content. These factors will be determined in order to estimate a precise carbon stock of this peat. Ground penetrating radar allows for a high resolution mapping of peat basin (Parsekian et al., 2012) and will be used to analyse the peat.

The aims of this study are:

- Estimate volume and carbon stock of a peatland within this nature reserve.
- Develop a theory on how this peatland has developed.

The hypothesis is that this peatland started to develop after the deglaciation of the area. It might have formed a pond that have been filled up with sediments and organic material and grown into a peatland.

This study will contribute with detailed knowledge about carbon stock in peat.

Figure 2: Photo of the peatland in Karlshaugen.
Photo: Vera Sklet

1.2 Study Site

Karlshaugen nature reserve was protected in 1922 with the aim of letting the forest develop without influence from human activity (Braathe, 1981). Therefore, this area gives a good opportunity to study peat in a natural ecosystem.

The study area is located in a forest area north of Oslo (Figure 3). Karlshaugen nature reserve is located in Nittedal municipality in southern Norway Figure 3. The nature reserve is situated at 420-450 m.a.s.l. Karlshaugen resides within the south boreal climate zone (Nygaard & Ødegaard, 1999). Average yearly temperature is 2.7 °C, and yearly precipitation is 992 mm (NVE, 2019). This area has been the subject of ecological and botanical studies and thorough mapping. Bedrock in the area consist of Nordmarkitt. A thin moraine cover is above the bedrock, with exposed bedrock in some areas. The area was first protected in 1922. The reserve consists of 116 acres coniferous forest (76% of total area), 32 acres wetland (21%) and 5 acres water (3%) (Skog_og_Landskap, 2007).

Figure 3: Overview map where the study area is marked in red.(Kartverket, 2019)

Figure 4: Map of the Quaternary sediments in the study area. The area has a moraine cover with variable thickness, areas of peat formation and exposed bedrock. (Modified from NGU,2019)

The area was deglaciated after 9800 year before present (Jørgensen et al., 1997). The sea followed after the deglaciation and filled the valleys with water. Marine limit is a just over 200 m.a.s.l. in this area (Jørgensen et al., 1997). The study site is located above 400 m.a.s.l, this is well above marine limit.

Small peatlands like the ones found in Karlshaugen is common in the areas above marine limit in this part of Norway. The map in Figure 4 shows that the landscape is rich in peat areas like these. In this study, the small peatland in the middle of the nature reserve will be the main focus. The peatland does not have an official name, but we unofficially named it Midtmyra, which in Norwegian means "peatland in the middle".

The topography in the area is inclining/ sloping slightly toward the south west. The small drainage that occurs from Midtmyra is drained towards the south west. In the south of the nature reservate a small stream draines the south peatland toward south.

Age and development of the studied peatland is unknown. It is likely that the peatland started developing sometime after the deglaciation of the area, which happened around 10 000 years ago.

The purpose of giving Karlshaugen a status as nature reserve was to preserve a forest area from human activity and let the nature develop. It is an interesting area with several ecological perspective, one of them is to see the distribution of tree species (furu og gran), and how this develops in a natural ecosystem A different perspective is the development of forest versus peat, and peat versus open water (Braathe, 1981).

Figure 1 shows a map of the nature reserve from 1930 with the grid that was made during the mapping (Braathe, 1981). During the initial mapping the depth to bedrock was measured at each point in the grid. The deepest measurement in the middle peatland was 3.5 m approximately in the middle of the peatland. This information can be used to look for possible changes in peat depth from 1930 until today.

The peat area has been mapped several times before, and the peat area appears to have become smaller as shown in Figure 5. The change in peat area was estimated to a reduction of 676 m^2 from 1930 to 2008 (Unhjem, 2011). In association with the process of protection of the area as a nature reserve, a thorough botanical mapping was conducted.

Previously one master thesis has been written on carbon balance of Karlshaugen nature reserve. However, this thesis only studies the top 80 cm of the peat (Unhjem, 2011). Figure 6 shows the results of this study. The results for carbon stock vary between 2 and 8 kgC/m^2 for samples at 8 different location on the peatland, down to 60 cm depth.

Studies of sub-arctic peatlands in Fennoscandia showed a major initiation and rapid expansion of peatlands during the early Holocene (10 to 8 ka cal. yr BP) and lateral expansion during the neoglacial cooling period from 4000 cal. yr BP (Weckström et al., 2010).

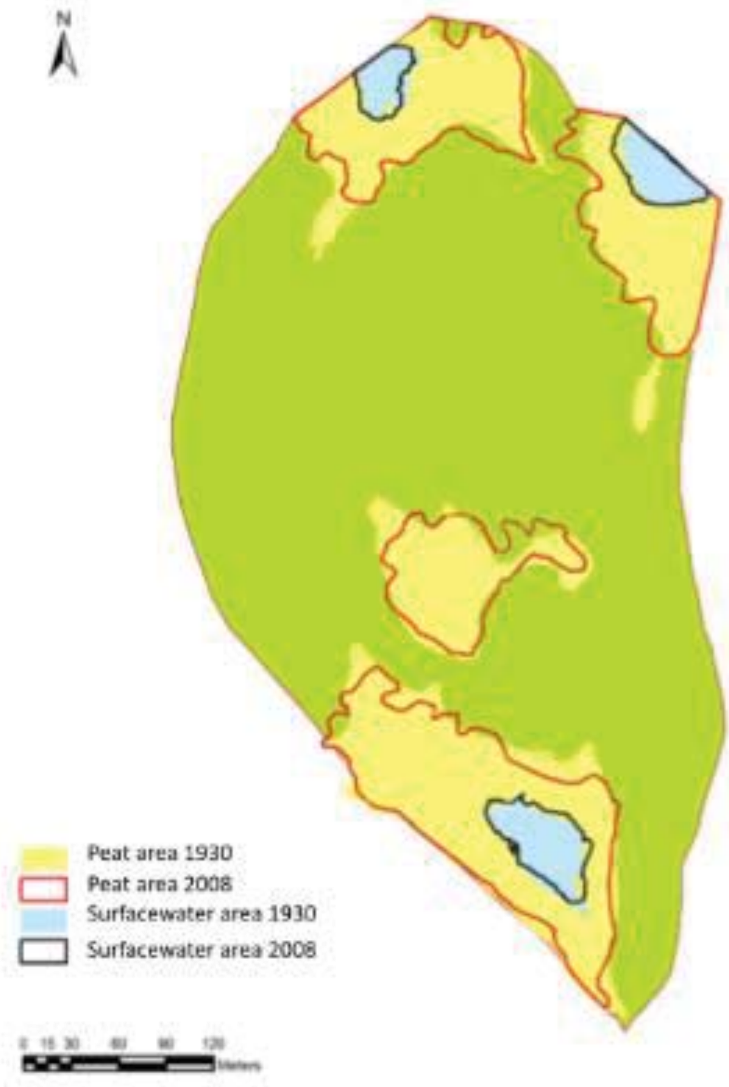


Figure 5: Map of the Karlshaugen nature reserve displays changes in peat and surface water area from 1930 to 2008.There seem to have been a small decrease in peat area during this time period. Figure modified from Unhjem (2011).

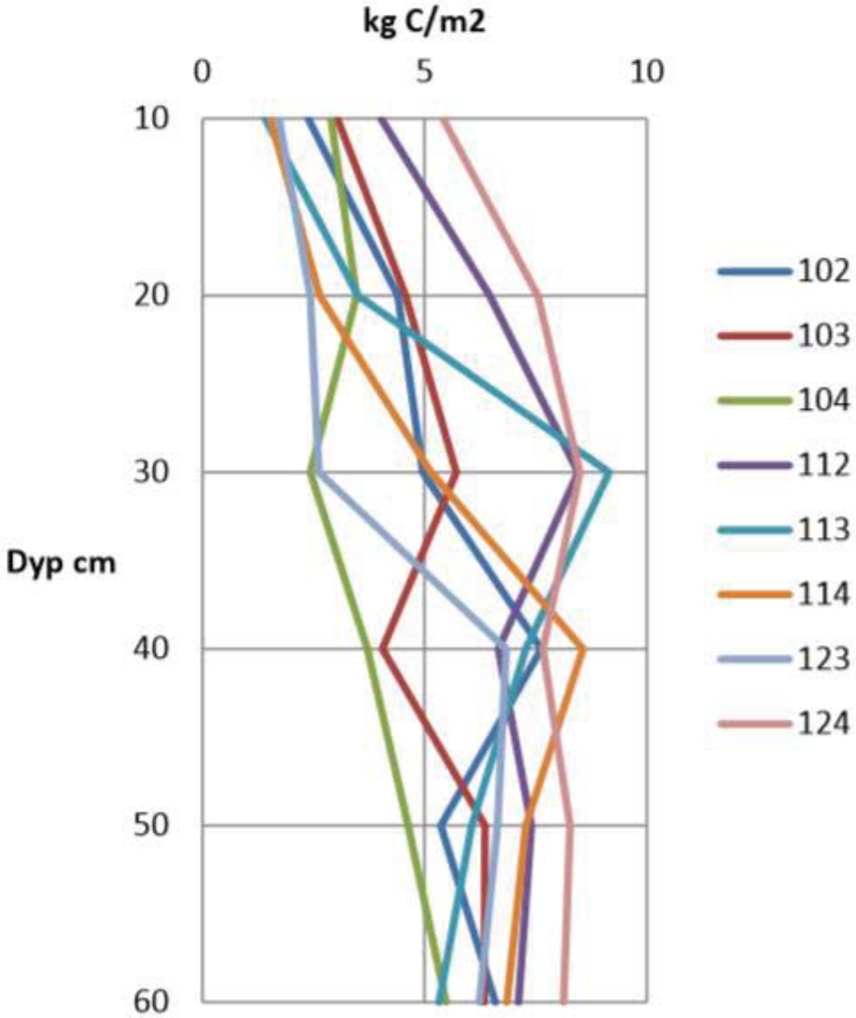


Figure 6: Carbon stock distribution with depth in kgC/m2 for the top 60 cm in Unhjem (2011) thesis.

1.3 Background/ theory

On a global scale, peatlands cover about 3% of the land surface. In boreal and subarctic climate zones, up to 15-30 % of soil carbon is stored in peatlands (Limpens et al., 2008).

A definition of peat given in Brady et al. (2010) is “Unconsolidated soil material consisting largely of undecomposed, or only slightly decomposed, organic matter accumulated under conditions of excessive moisture”. Peat consist of an accumulated amount of plant rests that has not been properly decomposed due to anaerobic conditions caused by water saturation (Rydin & Jeglum, 2006). Due to a larger net primary production than the decay of dead plants and animals in the ecosystem, organic matter is accumulated over a long period of time (Fenner & Freeman, 2011; Gorham, 1991). This gives a delay between the sequestration of carbon into plants and the decomposition of the organic material. Peatlands have therefore the ability to store large amounts of carbon, and because of this, they are an important factor in the carbon cycle (Gorham, 1991; Yu et al., 2010). Peatlands are an important part of the global carbon cycle with soil organic carbon being one of an important storage for carbon (Hartemink & McSweeney, 2014).

There is four ways that peatlands form. The first is called paludification, a process where rise in water table causes organic material to accumulate over inorganic soil. Paludificaion is the most common initiation of peatlands. The second peat initiation occurs on mineral soil surfaces that are recently deglaciated or risen above water due to isostatic rebound. The third peat formation process is terrestrializing where a small body of water are filled up with vegetation and thus turned from pond/lake to peatland. An example of this is shown in Figure 7. The fourth, and last, option is peat development in small basins that was occupied by shallow lakes during the early Holocene (Wieder & Vitt, 2006).

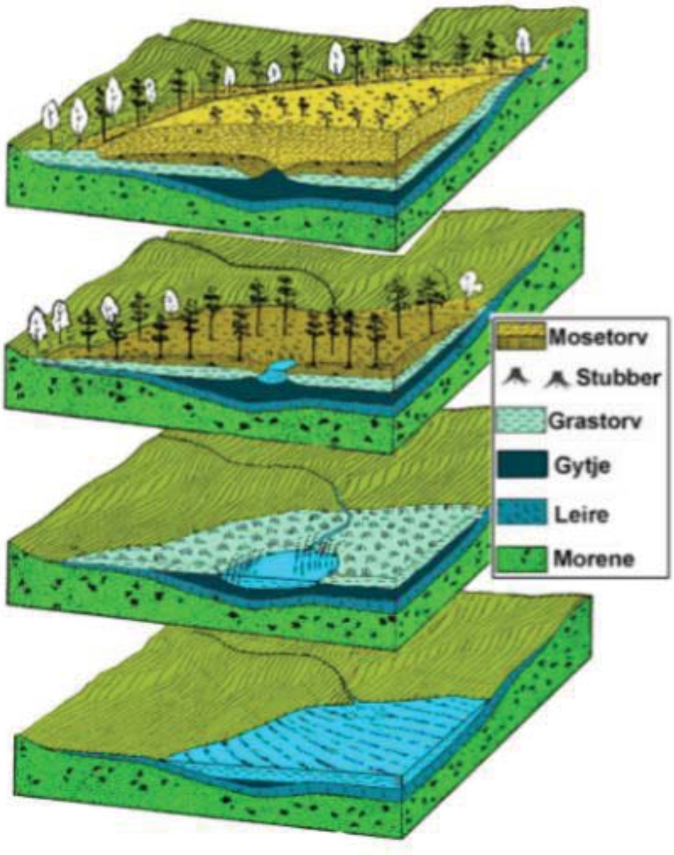


Figure 7: Example of ecological development of a peatland trough terrestralisation. Here a lake is gradually filled up with sediments and overgrown into a peatland. (Jørgensen et al., 2013).

Water saturation and low temperatures are two factors that may contribute to the formation of peatlands (Fenner & Freeman, 2011). There are five factors that have a mayor influence on peatlands, these are hydrology, climate, chemistry, substrate and vegetation/flora (Wieder & Vitt, 2006). A consistency in water supply is important in order to maintain the anaerobic condition (Wieder & Vitt, 2006). Temperature is an important factor for decomposition of organic material. In areas with temperature below ideal for microbial decomposition, this process will go slower then under ideal conditions. This is the reason that histosols are most common in cold climates (Brady et al., 2010). In a study of peat profiles in northern high latitudes, Charman et al. (2013) found that the net primary production has a higher influence on long term carbon accumulation rates than decomposition.

Wetlands are ecosystems in constant development and they often change characteristics over time (Jørgensen et al., 2013). Figure 7 shows an example of an ecological succession of a wetland, where the area starts out as a lake with deposition of fine-grained lacustrine sediments. They will later work as an impermeable layer that detains water within this confined area. The area will still be saturated with water once the vegetation growth increases, and the growth will surpass the decomposition. This is when the accumulation of undecomposed organic material, and formation of peat starts.

Photosynthesis in plants bring carbon as CO_2 into the terrestrial biosphere (Field & Raupach, 2004). It is brought back into the atmosphere through plant respiration or microbial respiration (decomposition).

Accumulation of peat is a slow process, and the rate at which the organic matter accumulates can not be directly measured. However, there are ways to find the long-term accumulation rates of peat. This can be done by radiocarbon dating of peat samples, and making an age-depth model for the peatland (Gorham, 1991). A study of three bogs in north west Scotland found a carbon accumulation rate of 21.3g C m^{-2} yr^{-1} (Anderson, 2002).

Carbon stock is a product of peat volume, bulk density and carbon content (Setiawan et al., 2015). Carbon content usually lies within the range of 40 to 60%, and varies in different locations with factors like temperature and degree of decomposition (Huat et al., 2011). Vegetation type also influences the % of carbon in the organic material. This variability with species usually lies within the interval of 51 to 58% carbon in organic material (Anderson, 2002).

Peatlands deliver several ecosystem services that humans benefit greatly from, examples of such services are groundwater recharge and water storage, flood control, water quality control, it works as a habitat for a high diversity of both plant and animal species and it has a moderating effect on climate (Mitra et al., 2005). Peatlands naturally regulates water levels and runoff, and therefore serve as a natural prevention of flood (Mitra et al., 2005; Mitsch et al., 2013). High content of organic material affects the ground water table. Due to its water holding capacity, the ground water table might increase, causing a positive feedback-loop with decomposition rates (Ise et al., 2008).

Carbon/nitrogen (C/N) ratio represent the amount of carbon in relation to nitrogen. A decrease in C/N ratio with depth is common, due to anaerobic decay of carbon in the catolem while the nitrogen stays at the same level (Anderson, 2002).

Von Post degree of decomposition in peat was developed by the Swedish geologist Lennart von Post. It is a common method for describing peat and to which degree the material has been humified. The method is often used in paleoclimatic studies, as it can be used as a proxy for palaeohydrological conditions as well as vegetation compositions (Yeloff & Mauquoy, 2006).

Peatlands are often divided into two types of layers, acrotelm and catotelm. The top layer, acrotelm, is active with aerobic decay of organic material in the zone of fluctuating water level. On the other hand, the lower layer, catotelm, is permanently saturated with water and has anaerobic decay (Anderson, 2002; Rydin & Jeglum, 2006). Typical properties of both layers are listed in Figure 8.

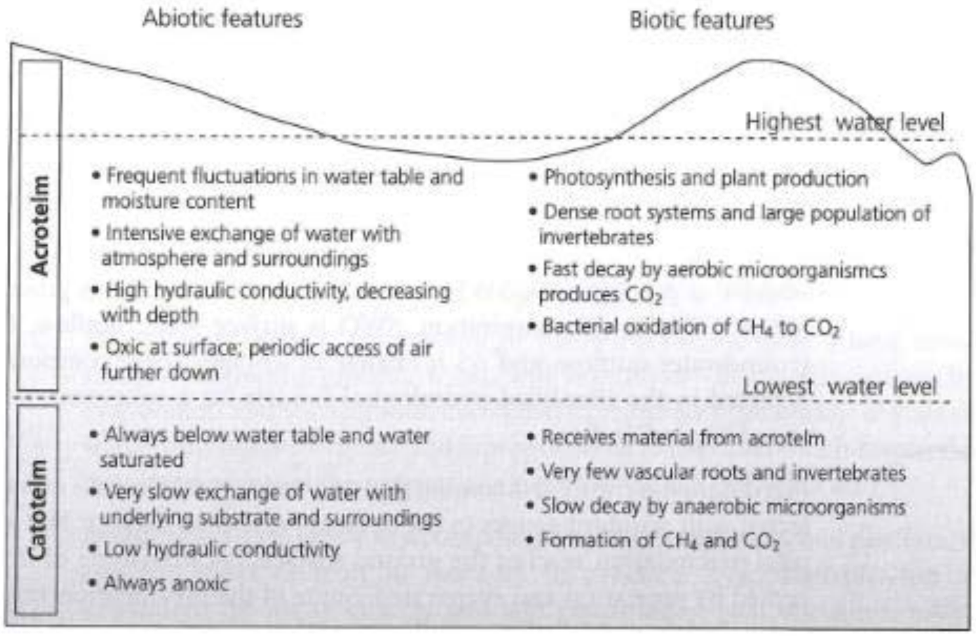


Figure 8: Peatland acrotelm and catotelm with both abiotic and biotic features of both layers (Rydin & Jeglum, 2006).

Water flows more easily trough the acrotelm as the undecomposed material at the top have a higher porosity and hydraulic conductivity than the material in the catotelm with a higher degree of decomposition.

Wetlands contribute to about 20-25 % of global methane emissions (Mitsch et al., 2013). Carbon in soil can be released in form of CO_2 or CH_4 (Grønlund et al., 2010).

Peatlands have the potentials to be both sinks and sources for carbon (Mitra et al., 2005). With the changes in climate that is currently taking place, peatlands can transfer from being carbon sinks to carbon sources (Wellock et al., 2011). Over the past thousands of years, peatlands have formed, and been a steady carbon sink. However, on a short term peat can rapidly change between being a sources or a sink of both methane and carbon dioxide (Belyea &

Clymo, 2001). It is believed that an increased temperature will cause better condition for decay of peat, and therefore contribute to the positive carbon feedback cycle.

There are many factors that can affect carbon stores in peatlands. Climate change, peatland drainage, burning and changes in land use can cause degradation of peat that ultimately will lead to emission of carbon currently stored in peatlands (Xu et al., 2018).

Drought may cause a reduction in water table, thus introducing oxygen in layers that are usually saturated. This can lead to increase in decay of organic material, and eventually release of carbon from the peatland.

Sphagnum plants are typical in boreal peatlands and are a factor in their dynamics. These plants create an environment that are wet, anoxic, nutrient poor and acidic. The plants themselves tolerate environments that are poor in nutrients and minerals, they are resistant to decomposition and different species are specialized in typical peatland characteristics with regards to water content, pH and light exposures (Wieder & Vitt, 2006).

Boreal forest and peatlands have the highest density of carbon stored in the soil (Grønlund et al., 2010). A majority of peatlands in the boreal region started to develop after the last glacial period (Bradley, 2014).

Bulk density and von Post degree of decomposition for peat in Norway and Finland showed that a high degree of decomposition is linked to a higher bulk density (Grønlund et al., 2010).

2. Methods

A brief outline of how the work with this thesis have been structured is found in Figure 9. Preparation of this master thesis started with defining the aims of the study and determining what methods to use. The next step was planning of field work.

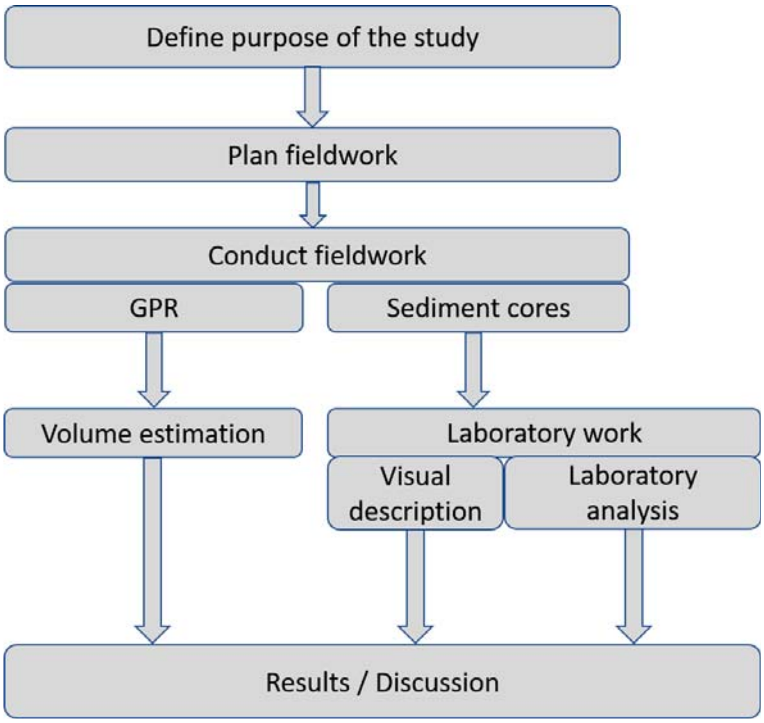


Figure 9: Outline of the study.

In order to find the carbon stock, the first step in this study was to estimate the volume of the peat. This was done by using a combination of ground penetrating radar survey and GIS tools. Ground penetrating radar survey of the peatland was used to map the transition between peat and the underlying material, before the volume was calculated by using a combination of ArcMap and Excel. Sediment cores were retrieved from the peat, and laboratory analysis of this core determined other factors that is necessary to know before the carbon stock can be calculated. These factors include bulk density and carbon content of the organic material.

2.1 Ground Penetrating Radar

Ground penetrating radar (GPR) is a non-destructive geophysical method. It is a system that sends electromagnetic waves (EMW) into the ground with a transmitter and records the signals that is reflected to the surface with a transceiver. Changes in the electromagnetic properties in the ground causes part of the signal to be reflected back to the transceiver on the surface (Everett, 2013). Pathways of the signals in this system is showed in Figure 10. The first signal is sent directly from the transmitting antenna to the receiving antenna. There is one signal that is reflected of the ground surface between the transmitter and receiver antennas.

It sometimes happens that a reflector is registered two times. The second registrations is often weaker than the first. This is called a multippel, and is an disturbance in the signals (Neal, 2004).

GPR systems operate with frequencies from 12.5 to 1000 MHz, depending on what material is studied and how deep you want the signals to reach, and what resolution the data will be. Low frequencies have a deeper reach, but with this deeper reach the resolution of the data is lower. High frequencies are used for detailed studies of shallow structures.

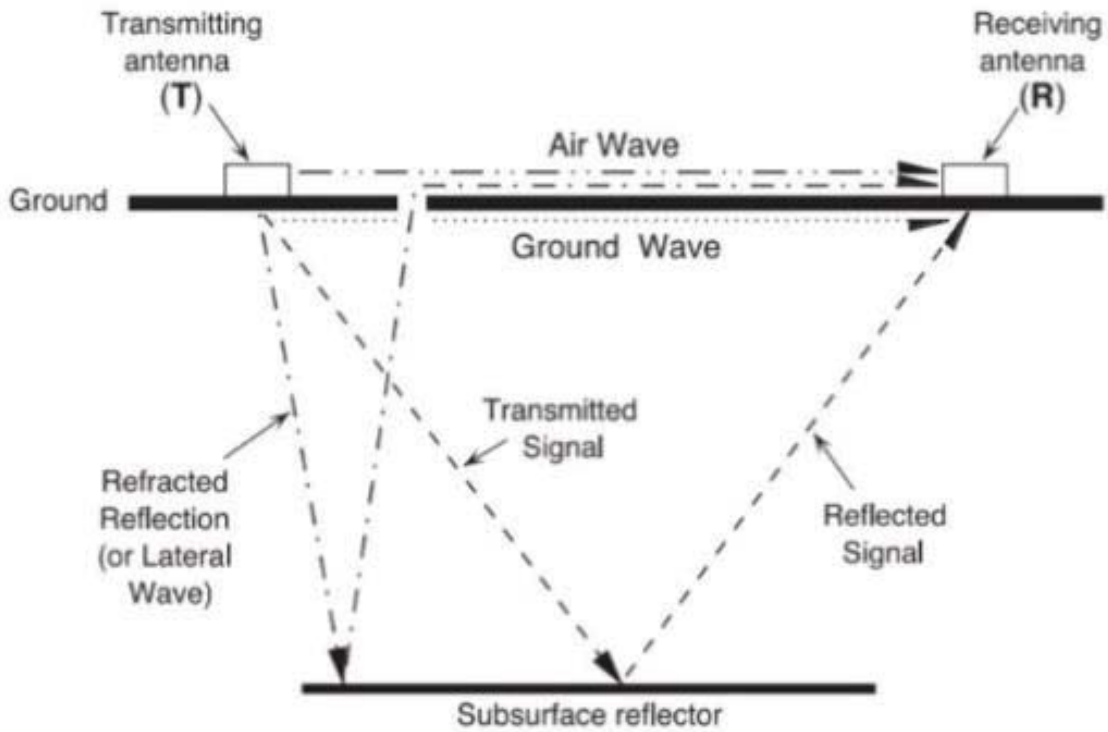


Figure 10: Schematic figure of wave pathways of the electromagnetic waves in the GPR system, from transmitting antenna to receiving antenna. One wave is sent directly from the transmitting to receiving antenna, one is reflected of the ground and one is reflected in the subsurface before returning to the surface. From Neal (2004).

GPR gives a continuous data record and therefore allows for investigation of large areas in a relatively short time (Rosa et al., 2009). Using GRP to investigate peat thickness is a well-developed technique, and there is also an increasing use of GPR to investigate peat stratigraphy and morphology (Rosa et al., 2009).

Parry et al. (2014) conducted a study that evaluated different approaches to estimating peat depth. They investigated the use of GPR for this purpose and found that different studies have found a velocity of 0.038 m/ns with a standard deviation of 0.003.

It is important to know the velocity the EMW have in the studied material for the conversion of depth from time to meters to be accurate (Parry et al., 2014).

Moisture content, bulk density and degree of decomposition determine the dielectric permittivity (ε_r) which again determine the EMW velocity in peat. EMW velocity might differ within a peat body (Parry et al., 2014).

The setup of the GPR device used is displayed in Figure 11, with both transmitting and receiving antenna and the GPS. The device also includes a wheel that is used to record the length of each line. During data collection 200 MHz antenna is used, they are mounted on a wagon used to move across the peatland (Figure 11). Ekko_Project 5 software from Sensors & Software's is used to process the data from the GPR survey. The included LineView is used to visualize the individual profiles. SliceView module is used to generate and display depth slices. This software generated depth slices of the peatland by interpolating the strong reflector between the peat and the underlying material. These depth slices show the interface between peat and the underlying material at 12.5 cm intervals.

Figure 11: Setup of the GPR system used during fieldwork. The wheel that is used to measure the correct length of each profile is not showed in the picture. Photo: Per Holm Nygaard

GPR data was collected on the 20. and 21. of August 2018. The focus was to collect GPR data in a XY-grid with 1 m distance between the X lines using a 200 MHz antenna. In order to get a grid with parallel lines with 1 m distance, measuring tapes was put down on the ground. Lines in the GPR grid is presented in Figure 13. Sampling of the grid started in the north-western part of the peatland with even numbered lines from the northwest to southeast, while uneven numbers started in the southeast towards northwest. As seen from the aerial photo in Figure 13, the edges of the grid does not coincide with the outline of peat area. This is partly due to vegetation making it difficult to move the GPR device.

In addition to the grid several independent lines were collected across the peatland (Figure 28). Several of these supplementary lines extend beyond both the grid and the peatland boundary. These data are meant to supplement the results of the GPR grid and give information about the peat bedrock interface outside of the grid.

Based on literature the estimated velocity for GPR signal in this material was 0.040 m/ns (Parry et al., 2014). During the fieldwork manual probing was conducted at several places in the field. This data was used to compare with depth in GPR profile and might indicate if there are large gap between estimated and actual velocity.

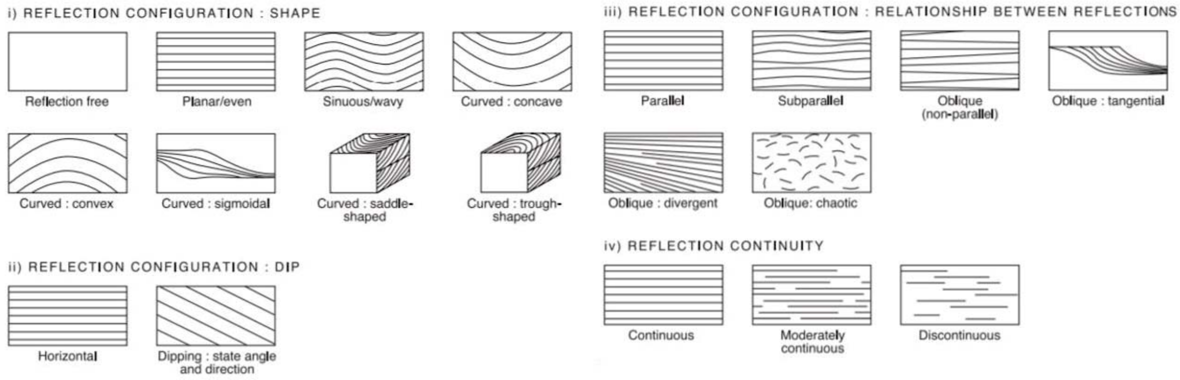


Figure 12: Classification of GPR facies based on shape, dip, relationship between reflections and continuity of reflections. These classifications are used when describing and interpreting GPR profiles. Modified from (Neal, 2004)

GPR profiles are interpreted and divided in to different units, based on strong reflectors and facies with identified structures. These profiles are divided into units based on reflections in the profiles. Description of facies is based on classification from Neal (2004) demonstrated in Figure 12. The most important interpretations in this study is based on the mayor reflectors that are identified.

Table 1: GPR facies and reflection classification used in this study.

Colour code	Reflection pattern	Description
	Planar, horizontal, parallel, continuous	Interpreted to represent peat
	Mainly reflection free to oblique chaotic	Interpreted to represent bedrock
	Oblique chaotic	Interpreted to represent minerogenic material
	Major reflectors	Reflection interpreted to represent boundary between units
	Minor reflectors	Reflector interpreted to represent minor differences within units
	Minor reflectors	Interpreted to be multiples of other reflectors

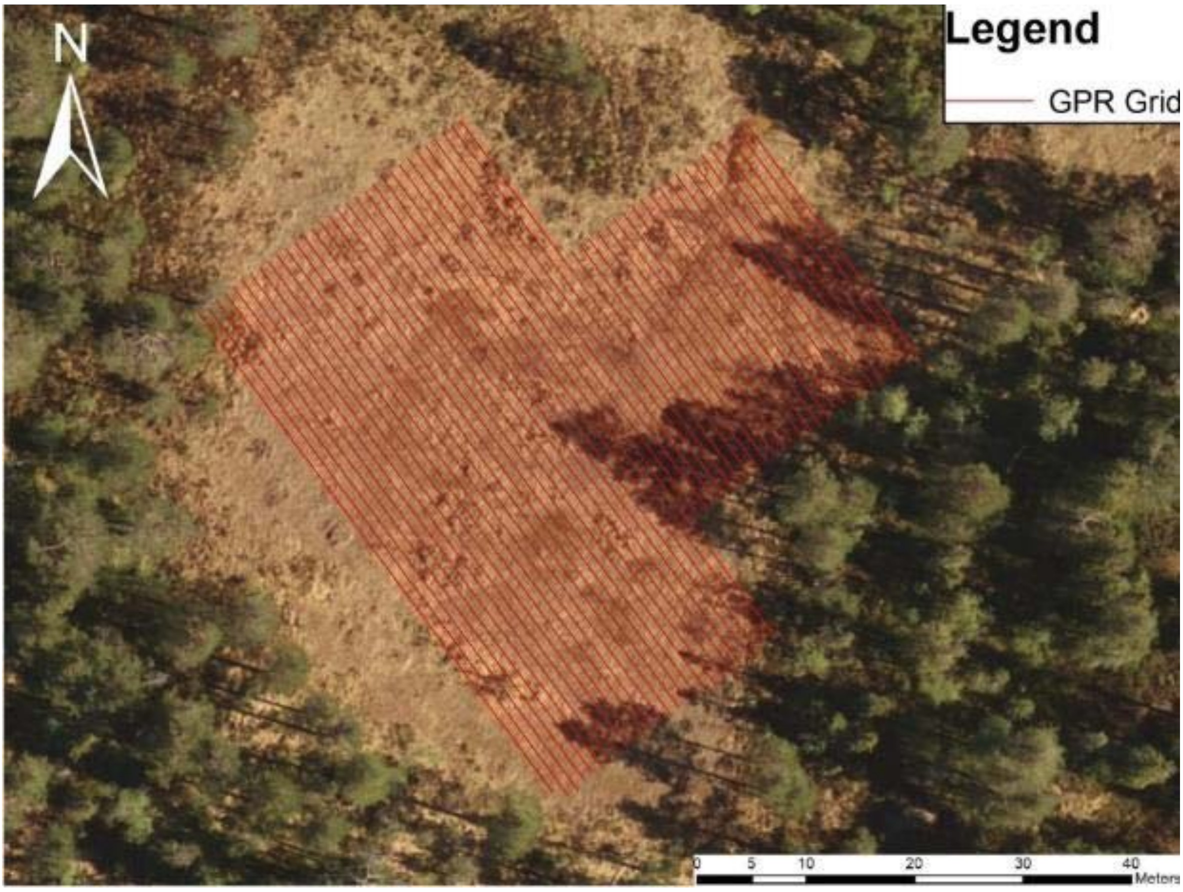


Figure 13: Aerial photo with GPS lines from the GPR grid. The grid starts in the northwest. Due to vegetation making it difficult to move the GPR device, the length of the lines in the grid was altered to fit an area as large as possible. Modified from Kartverket (2019).

The plan was to also collect the same grid with 500 MHz antenna, to obtain a more detailed mapping of internal structures in the peat body. However, as this gave no apparent signal (Figure 14) only one line was sampled. The location of this line is found in Figure 28 as Line 05.

The profile taken with 500 MHz antenna in the middle of Midtmyra starts in the north and moves towards the south-east. No apparent reflectors area recorded in this profile, is difficult to interpret much from the 500MHz profile.

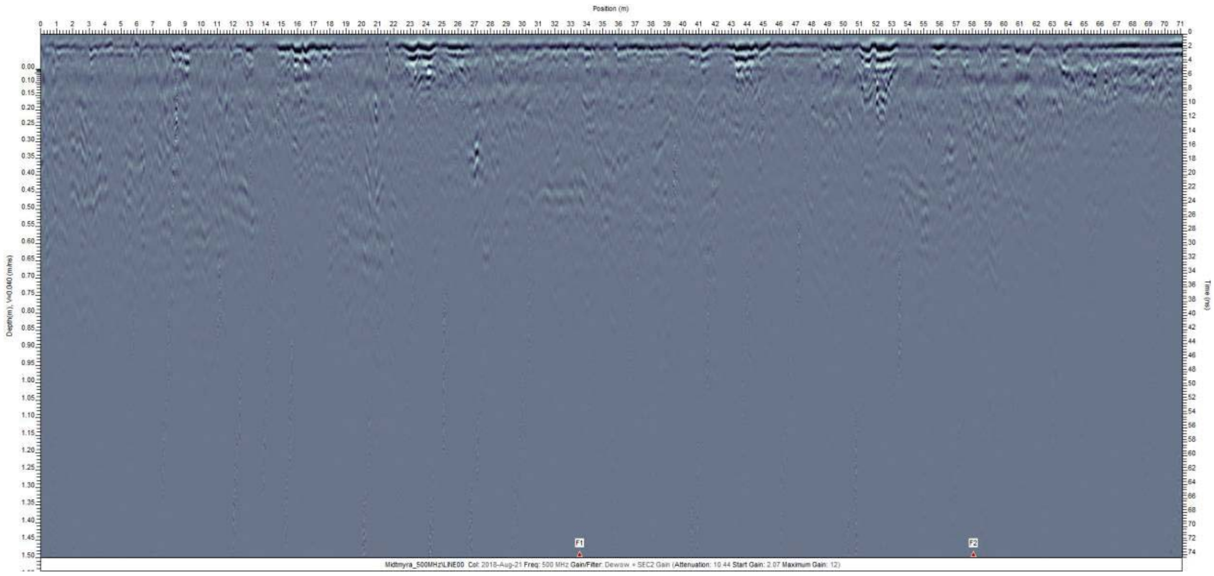


Figure 14: LINE 05 taken with 500 MHz antenna. There are very little reflection in this profile.

2.2 ArcGIS

Depth Slice generated in the EkkoPulse software was imported to ArcGIS 10.6.1. There, each depth slice had to be georeferenced in order to have a special reference and an accurate scale. The area of each depth slice was calculated by making a polygon with the same area as the peat. Given that the depth interval is 12.5 cm, the volume of each depth slice was calculated by assuming that the area is representative for the 12.5 cm. After this, the total volume of the peatland was calculated in Excel, by multiplying the area and a depth of 12.5 cm. All volumes were then summed together for the total volume of the peatland. A sketch of the concept is displayed in Figure 15.

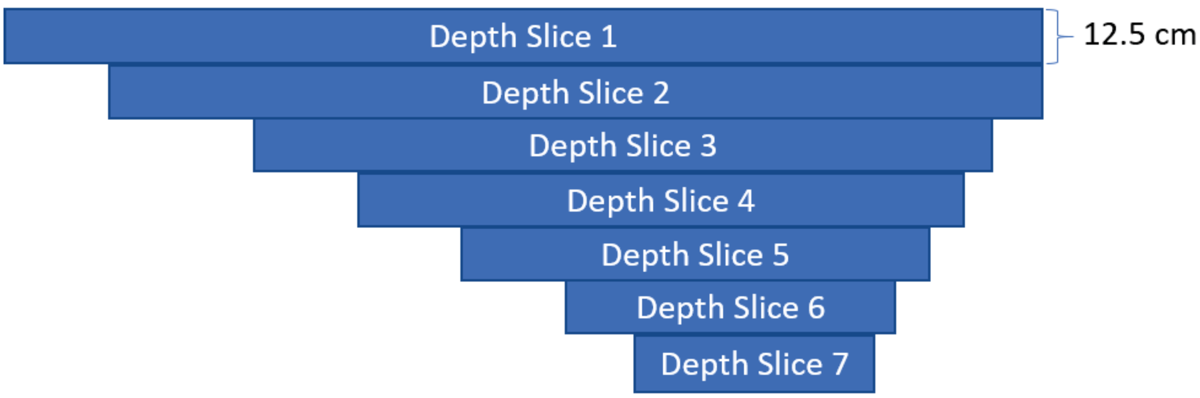


Figure 15: A sketch of the depth slice concept that was used to calculate area and volume of the peatland. Each depth slice has a depth of 12.5 cm and their width represent the area of this depth in the peatland.

The exported depth slices have a depth of 12.5 cm, this does not correspond to the sampling interval of 10 cm taken from the peat core. The results from the depth slices was converted to give an area at 10 cm interval.

Linear interpolation is used to calculate the area of the slices with height of 10 cm from the slices with height of 12.5 cm. Figure 16 illustrates the relation between the different type of slices for a height of 50 cm. Column 1 denotes the area of the original slices, column 2 denotes the height of the original slices, column 3 denotes the area of the new 10 cm slices, while column 4 denotes the height of the new slices.

A0	HA0 = 12,5	B0	HB0 = 10
A1	HA1 = 2*12,5	B1	HB1 = 2*10
A2	HA2 = 3*12,5	B2	HB2 = 3*10
A3	HA3 = 4*12,5	B3	HB3 = 4*10
		B4	HB4 = 5*10

Figure 16: Illustration of the relation of the different slices with a depth of 50 cm.

The areas of the new slices for ach 50 cm are calculated by the formulas in Table 2.

Table 2: Formulas for calculation for new areas for a height of 50 cm.

B0 = A0
B1 = A0 * (HA0 – HB0) + A1 * (HB1 - HA0)
B2 = A1 * (HA1 – HB1) + A2 * (HB2 – HA1)
B3 = A2 * (HA2 – HB2) + A3 * (HB3 – HA2)
B4 = A3

2.3 Sediment cores

2.3.1 Russian peat sampler

Sediment cores were retrieved from Midtmyra on the 4 of September 2018, using a manually operated Russian peat corer from Eijkelkamp at four locations on the peat (Figure 32). The Russian peat sampler collects half a cylinder of 5.5 cm and 50 cm length. By adding segments at 50 cm lower depth, each core site was sampled down to bedrock or other impenetrable material was reached. A brief description of colour and structure was done in the field (see appendix B). The peat cores were packed in plastic tubes and wrapped in plastic and aluminium foil. To avoid evaporation of moisture content and biological activity the cores were stored in a refrigerator until processed.

Locations of the main peat core, MM1, was taken in the area where the peat was assumed to be deepest, determined from the GPR profiles. For the other peat cores the aim was to find any changes in soil properties where it changes from peat to forest soil.

The remaining three cores was taken in a transect in the transitioning from peat to forest, where the second core, MM2, was taken from the peat, the third core, MM3, taken close to the transitioning and the fourth core, MM4, was taken from forest soil (Figure 32).

Figure 17: Picture of the Russian peat corer used during the fieldwork. Photo: Vera Sklet.

2.3.2 Laboratory analysis

The first step of the laboratory analysis was a visual description of sediments that include colour (Munsell colour chart, see appendix A), peat structure, moisture content and degree of decomposition (von Post, described below). Peat structure was described using a scale from 0 to 4 where 0 represents a coarse structure of completely undecomposed plants and 4 represents well decomposed plant residue where the plants are no longer recognisable (Figure 18). Moisture content was also described using a scale from 0 to 4 where 0 represents low moisture and 4 represents fully saturated material.

Figure 18: Example of coarse and fine structure in the peat cores.

After the visual descriptions, half of the cylinder was withdrawn in 10 cm segments, each subsample with a volume of ca. 59 cm^3. The samples were put in a beaker, they were weighed and dried at 40 °C for 72 hours. In order to make representable, homogenous subsamples for further processing, these 10 cm segments were crushed and sieved at 2mm.

2.3.2.1 Degree of decomposition of peat (von Post scale)

The degree of decomposition was assessed using the von Post scale, classifying the degree of decomposition of peat. The scale goes from H0 to H10, and each class and all the steps in the von Post scale are described in Table 3 (Stanek & Silc, 1977).

Degree of humification in a peat sample can give information on past hydrological situations and vegetation compositions (Yeloff & Mauquoy, 2006). There are difficulties with the correlation between degree of decomposition and changes in climatic factors because degree of decomposition is also related to different species. Species specific scale of decomposition might be useful to get reliable correlations (Yeloff & Mauquoy, 2006).

Table 3: von Post peat humification scale from Stanek and Silc (1977).

H1	Completely unhumified and muck-free peat: when squeezed in the hand releases only colourless, clear water.
H2	Almost completely unhumified and muck free peat; when squeezed releases almost clear but yellow-brown water.
H3	Little humified or very little muck-containing peal: when squeezed releases turbid water, but no peat substances pass between the fingers, and the residue in the hand is not mushy.
H4	Poorly humified or some muck-containing peat: when squeezed releases very turbid water. The residue is somewhat mushy.
H5	Peat partially humified or with considerable muck content. The plant structures are still evident but somewhat obscure. When squeezed some of the peat substances pass between the fingers together with very turbid water. The residue in the hand is very mushy.
H6	Peat to some degree humified or with fair muck content. The plant structures are vague. When squeezed, at the most, one third of the peat substances pass between the fingers. The residue is very mushy bur shows the plant structures more clearly than the unsqueezed peat.
H7	Peat quite well humified or with considerable muck content, in which much of the plant structures is still discernible. When squeezed. about half of the peat substances pass between the fingers. If water separates, it is thick, soupy, and very dark in colour.
H8	Peat well humified or with considerable muck content. The plant structures are little apparent. When squeezed, about two thirds of the peat substances pass between the fingers. If water separates at all, it is thick and soupy. The remains consist mainly of more resistant root threads, etc.
H9	Peat almost completely humified or mucklike in which hardly any plant structures are apparent. When squeezed, nearly all of the peat substances pass between the fingers like a homogeneous mush.
H10	Peat completely humified or muck-like in which no plant structures are apparent. When squeezed, all of the peat substances pass between the fingers, without separating free water.

2.3.2.2 Bulk Density

The samples were dried to analyse the bulk density. Here bulk density is given as mass per volume (g/cm^3) after drying at 40 °C for 72 hours. The bulk density is corrected for dry matter by multiplying the weight of the sample after drying at 40 °C with the % dry matter found after drying at 105 °C.

BD (g/cm^3) = dry weight (g) / volume (cm^3)

2.3.2.3 Loss on Ignition

Loss on Ignition (LOI) is a method where the material is burned in an oven at 550 °C for a minimum of 3 hours (Krogstad, 1992). During this process organic material is burned from the sample. The weight was noted down between each step in the process. Figure 19 shows samples from peat core MM2 and MM3 before and after LOI. The values from this test represent the loss of material during burning at 550 °C.

A sample from each 10 cm interval was put in a crucible and dried at 105 °C to determine the % dry matter in the sample. Dry matter is the amount of material in the sample after the water is removed. After this they were put in the oven at 550 °C for at least 3 hours before the final weighing and calculation of % dry matter and % LOI.

The calculation of dry matter and LOI was done with the following equations, from Krogstad (1992).

% Dry Matter = ((m3-m1)/m2)*100

% LOI = ((m3-m4)/(m3-m1))*100

m1 – weight of crucible
m2 – weight of soil sample before drying
m3 – weight of crucible and soil sample after drying
m4 – weight of crucible and soil sample after burn at 550 °C

Figure 19: Photos of peat samples from core MM2 and MM3 before (left) and after (right) they were burned at 550 for the LOI test. Photos: Vera Sklet.

2.3.2.4 Total carbon and nitrogen analysis

To analyse total carbon and nitrogen, dried samples were crushed into a fine powder using a Retsch Mortar Grinder (Figure 20) The analysis of 28 of the samples were done in a LECO Truspec instrument. The instrument uses CO_2 gas in an infrared radiation chamber after the sample have been burned at 1050 °C. After this N oxides are reduced to N_2 in order to determine the amount of nitrogen in the sample (Nelson & Sommers, 1996). The results is given in % of carbon/ nitrogen of the total sample (Nelson & Sommers, 1996).

Figure 20: Picture of a peat sample before and after it was crushed in the mortar grinder. The samples were crushed in preparation of the total carbon and nitrogen analysis. Photo: Vera Sklet.

Due to technical errors, the remaining samples could not be analysed by the LECO Truspec instrument. Instead, total C and N are calculated from LOI by using a regression analysis (Figure 21)

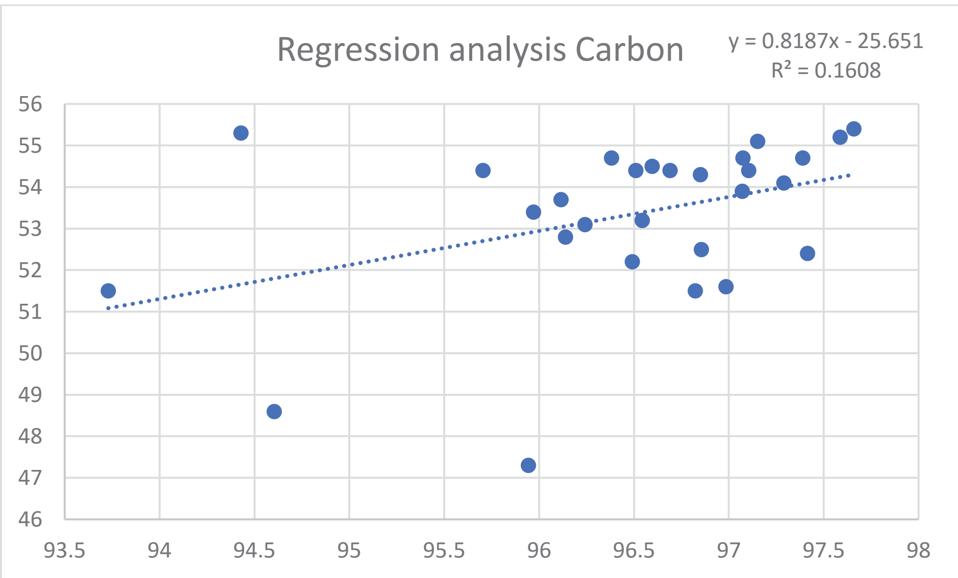


Figure 21: Regression analysis for carbon content. The x-axis represents % carbon in the sample, while the y-axis represents LOI value. The formula resulting from this linear regression is used to calculate % carbon from LOI for the remaining samples.

The regression analysis was done in Excel. Afterwards, the formulas they gave was used to calculate carbon and nitrogen content. The calculation was done in excel.

The regression analysis (Figure 21) gave the following formula for carbon content:

Y=0.8187x-25.651

With LOI as input data both carbon and nitrogen values have been calculated. The formula for carbon content is found in Figure 21.

A separate regression analysis was conducted for nitrogen content (Figure 22).

The formula for nitrogen content from the regression analysis:

Y= -0.8x+9.1864

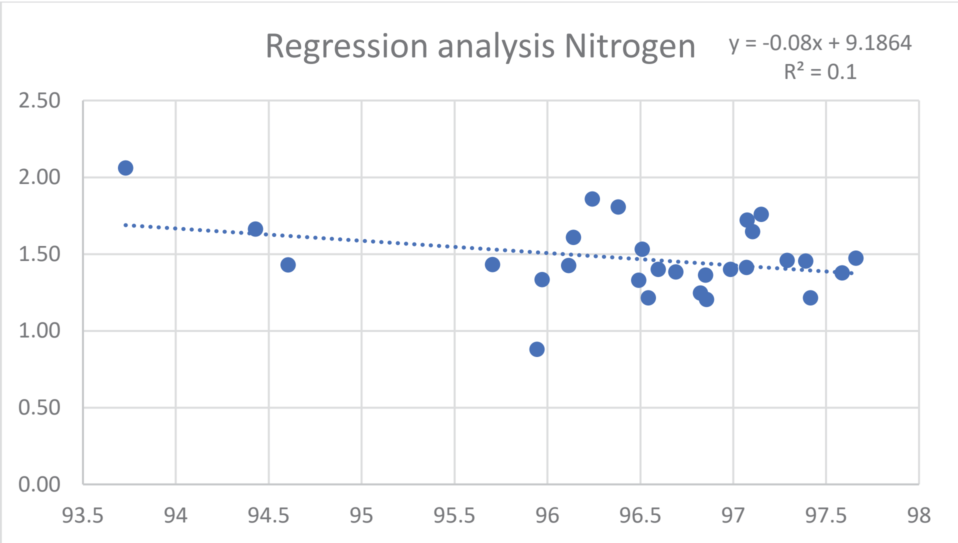


Figure 22: Regression analysis for nitrogen content. X-axis represent % nitrogen, while the y-axis represents LOI. The formula resulting from the linear regression is used to calculate % nitrogen content in the remaining samples.

C/N ratio is a measure on the amount of carbon in relation to nitrogen in a peat sample.

2.4 Estimation of carbon stock

The carbon stock of a peatland can be found as a function of carbon content (in %) and bulk density (Jaenicke et al., 2008). When the amount of carbon per volume is found, the total carbon stock of this peatland can be calculated.

Formula for calculating carbon stock taken from: Akumu and McLaughlin (2013).

Carbon stock (kg C m^{-2}) = C * BD * SD

Where:

C = carbon concentration (kg/kg)

BD = Bulk density (kg/m^3)

SD = Soil depth (m)

3. Results

3.1 Ground Penetrating Radar

3.1.1 GPR Grid

The GPR grid started with a length of 55 meters. Due to vegetation, the length of the lines had to be reduced. The GPR profiles include depth in meters on the left axis, depth in time on the right axis and distance from the starting point of the y-axis.

The GPR grid consists of 51 GPR lines. Only four representative profiles from the grid are presented here (Figure 23). These are lines 6, 16, 21 and 27 (Figure 24 - Figure 27), and all are presented with a NW (left) to SE (right) orientation.

Profiles are divided into three different units based on dividing reflectors in the profiles. These three units represent peat, minerogenic material and bedrock.

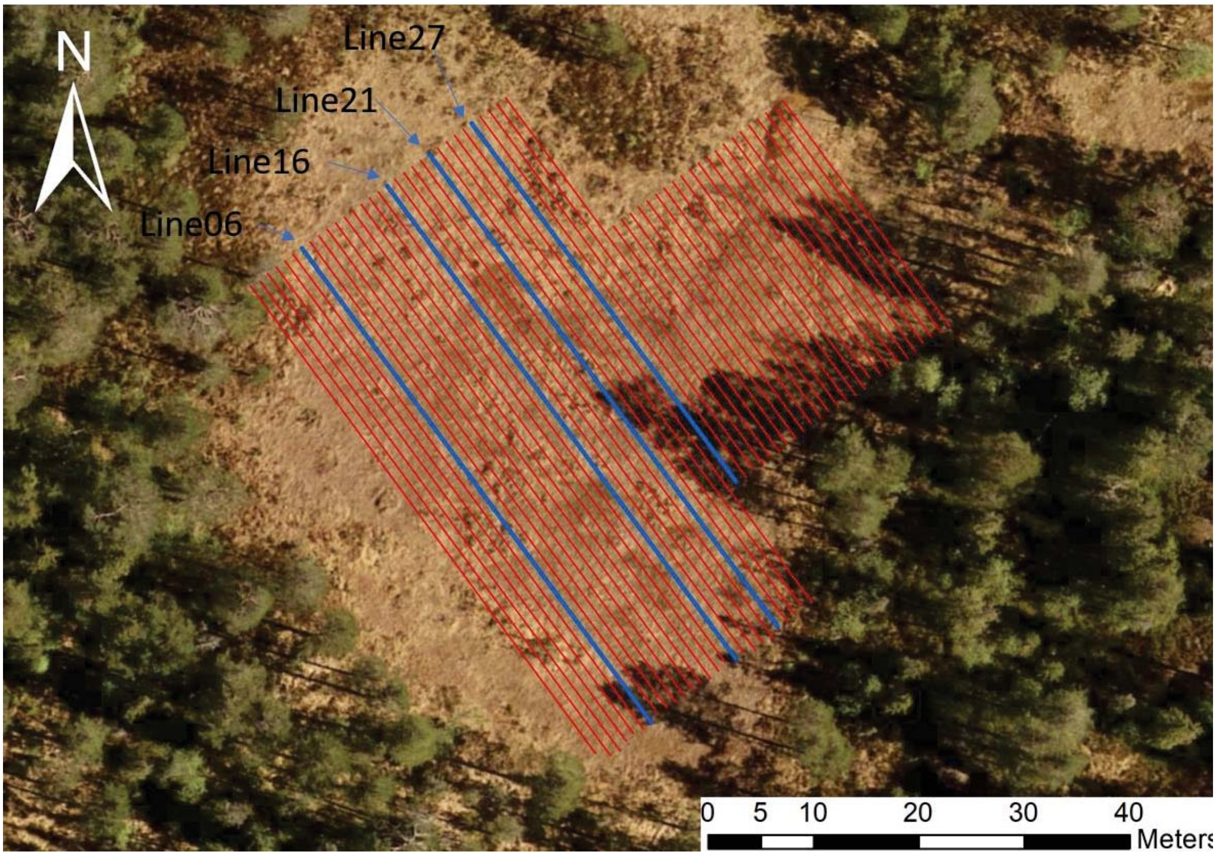


Figure 23: GPR grid collected during fieldwork. The profiles presented in the result chapter is marked in blue. Modified from Kartverket (2019).

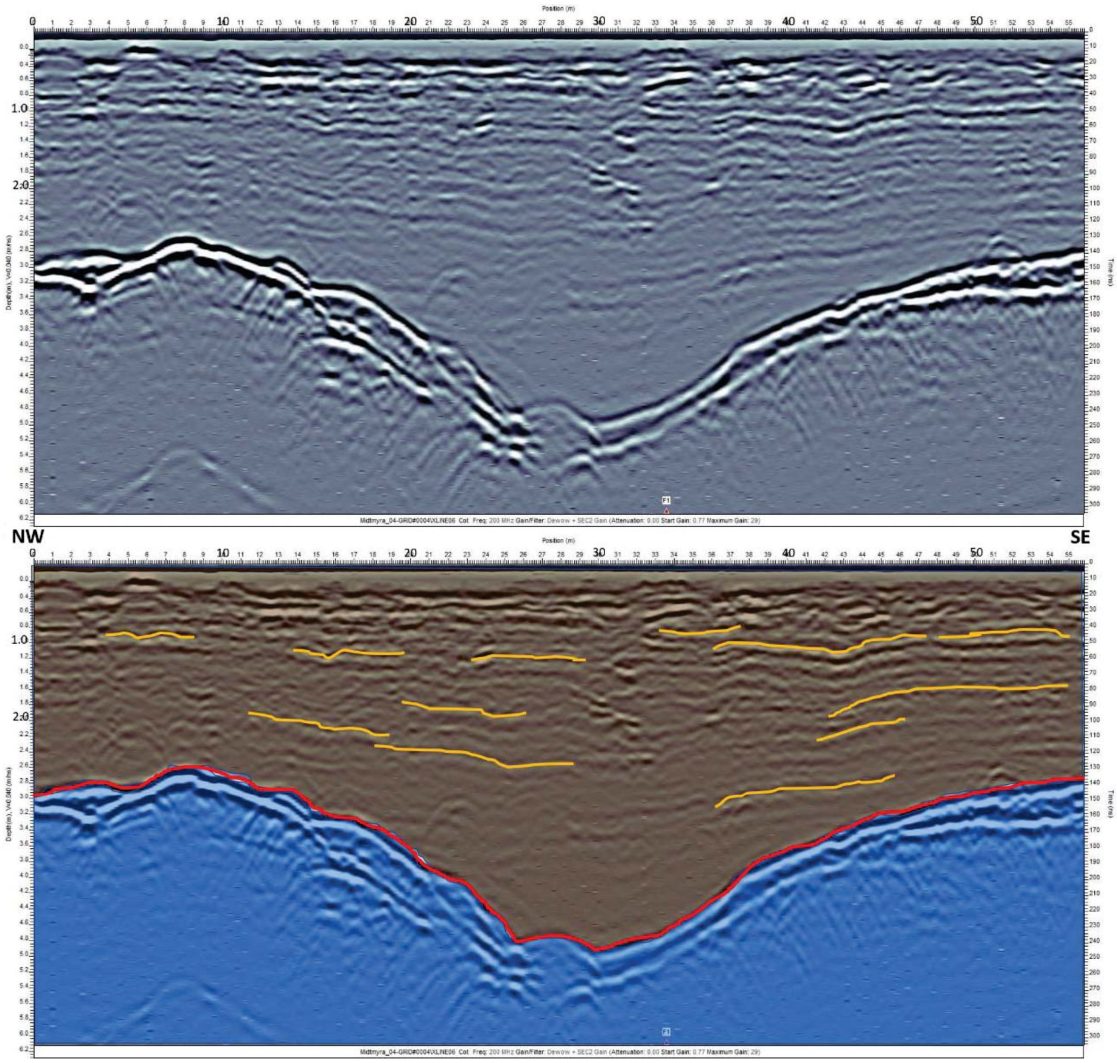


Figure 24: Line 06 from the grid. The top figure is the profile without interpretation. The lower figure presents the profile with interpretations based on reflections. The profile is divided into two units, these two units are interpreted to represent peat (brown) and bedrock (blue). This separation of the profile is based on the reflector marked with a red line. Yellow lines represent a few of the identified minor reflections within the peat unit.

Line 06 (Figure 24) is in the south east part of the grid (Figure 23). Distinctive reflectors are found continuously thorough the entire profile, marked in red in the profile. In the northwest such reflector starts at 3 m depth and rises up to 2.6 m depth 8 m towards southeast. Further, the reflector spits in two and both fall down to the lowest point approximately 4.2 and 4.8 m depth, respectively, 30 m in to the profile. Towards the southeastern end of the profile the reflectors rise up to 3 m depth. Based on the strong reflector, this profile is divided into two units. One above the red reflector, and one below. The unit interpreted as peat (colour) contain less distinctive moderately continuous to discontinuous subparallel lines.

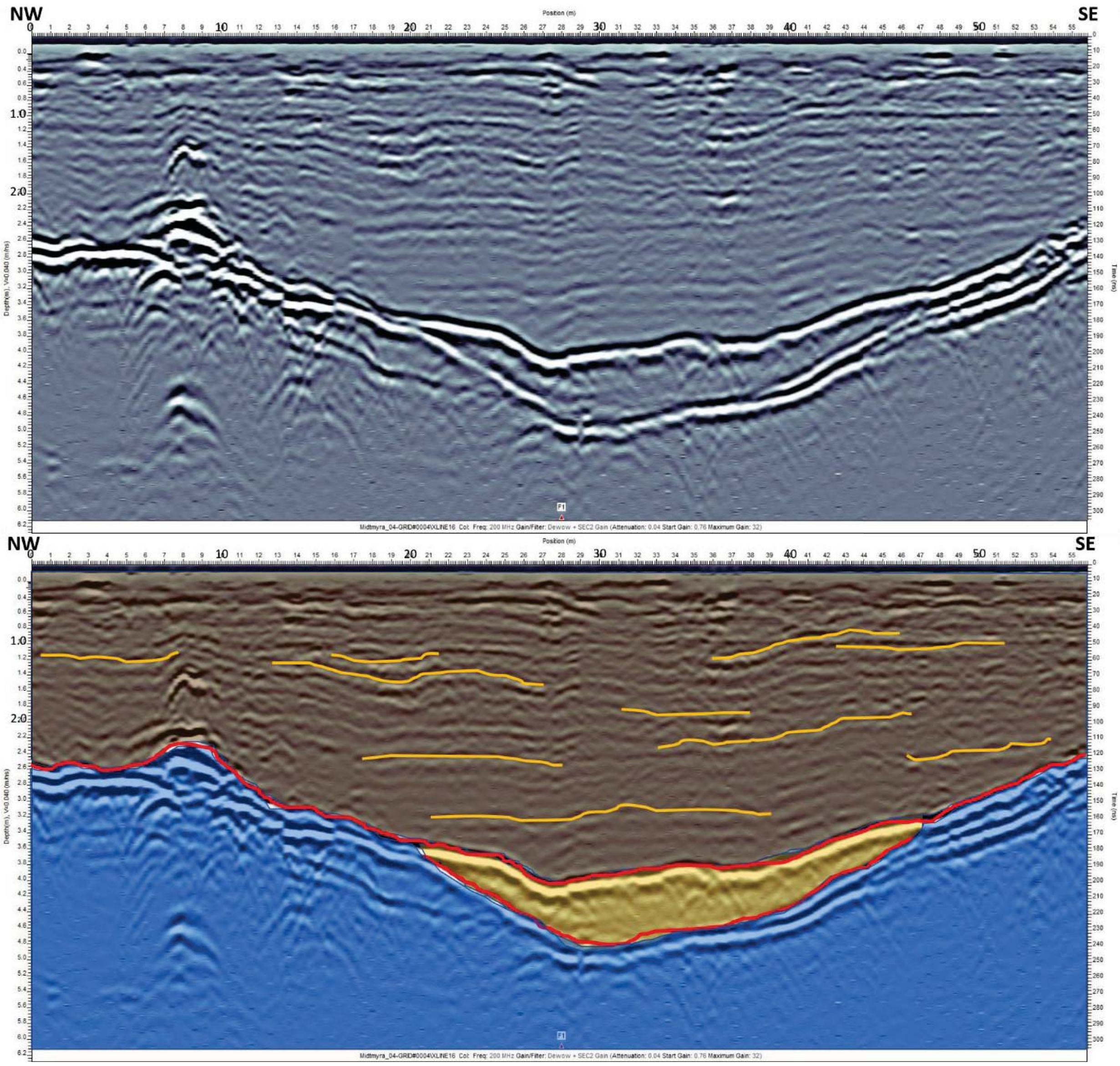


Figure 25: Line 16 from the grid, top figure is the original profile, the bottom figure is the profile with interpretations, found in Table 1.

Line 16 contain one strong reflector throughout the profile. Between 22 and 47 m there are two reflectors registered, and a unit between these reflectors. Strong reflectors that separates different units are marked in red. Included in the top unit is several parallel to sub parallel lines, these are marked in yellow. This profile is divided in three units, representing peat, minerogenic material and bedrock. Interpretations of the three units are based on field observations of peat material, exposed bedrock in close proximity to the peat and the shape of the bedrock depression.

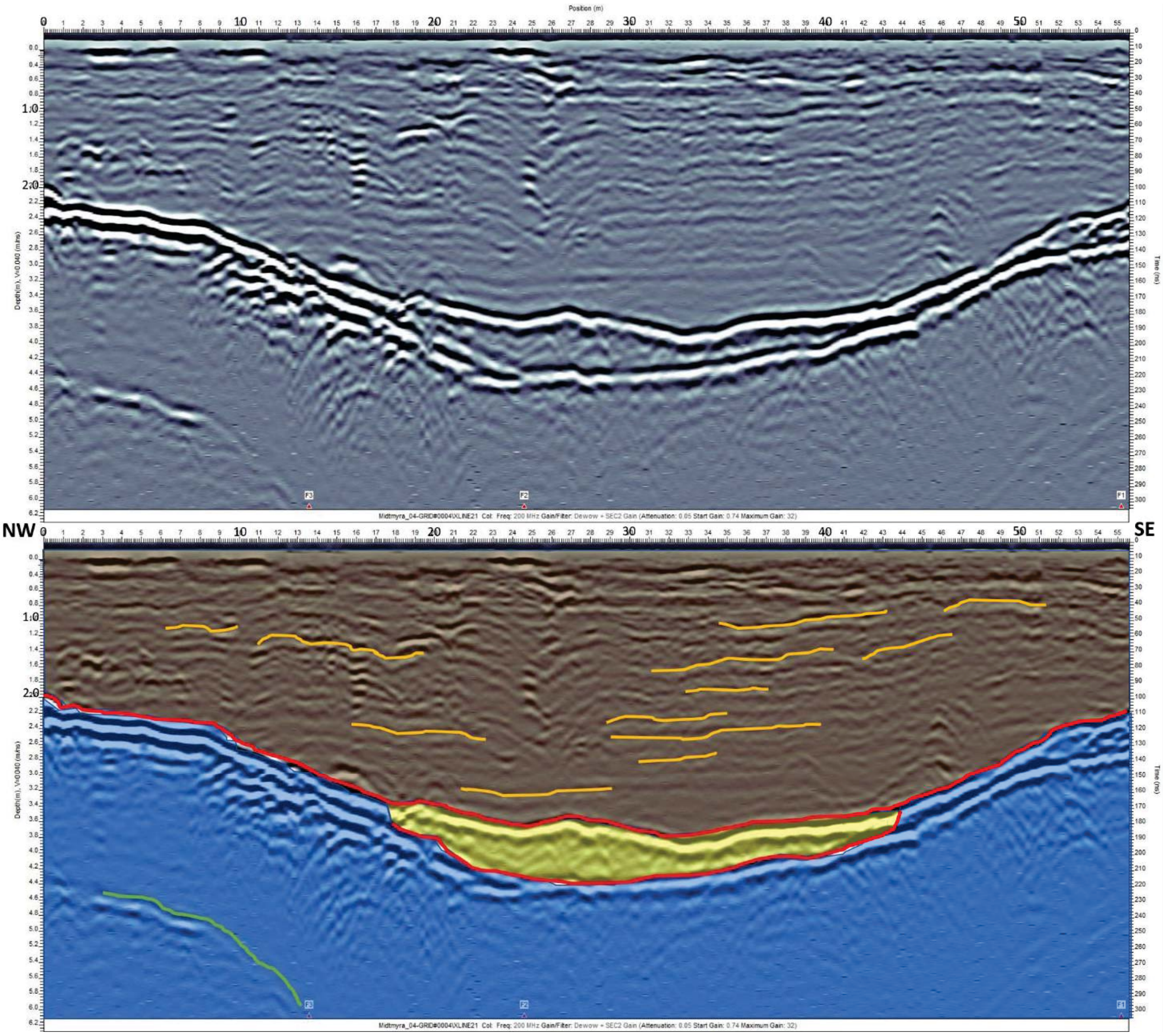


Figure 26: Line 21 in the GPR grid. The profile starts in the north west and goes in the direction of south east.

Some strong reflector is found in all the GPR profiles taken with the 200 MHz antenna. This reflector is assumed to represent the transition between peat and bedrock. Figure 26 shows line 21 from the GPR grid. It is displayed in the top part as the original profile, the bottom profile includes the strongest reflectors and the three units the profile is divided into. The three different units are interpreted to represent; peat, minerogenic material and bedrock.

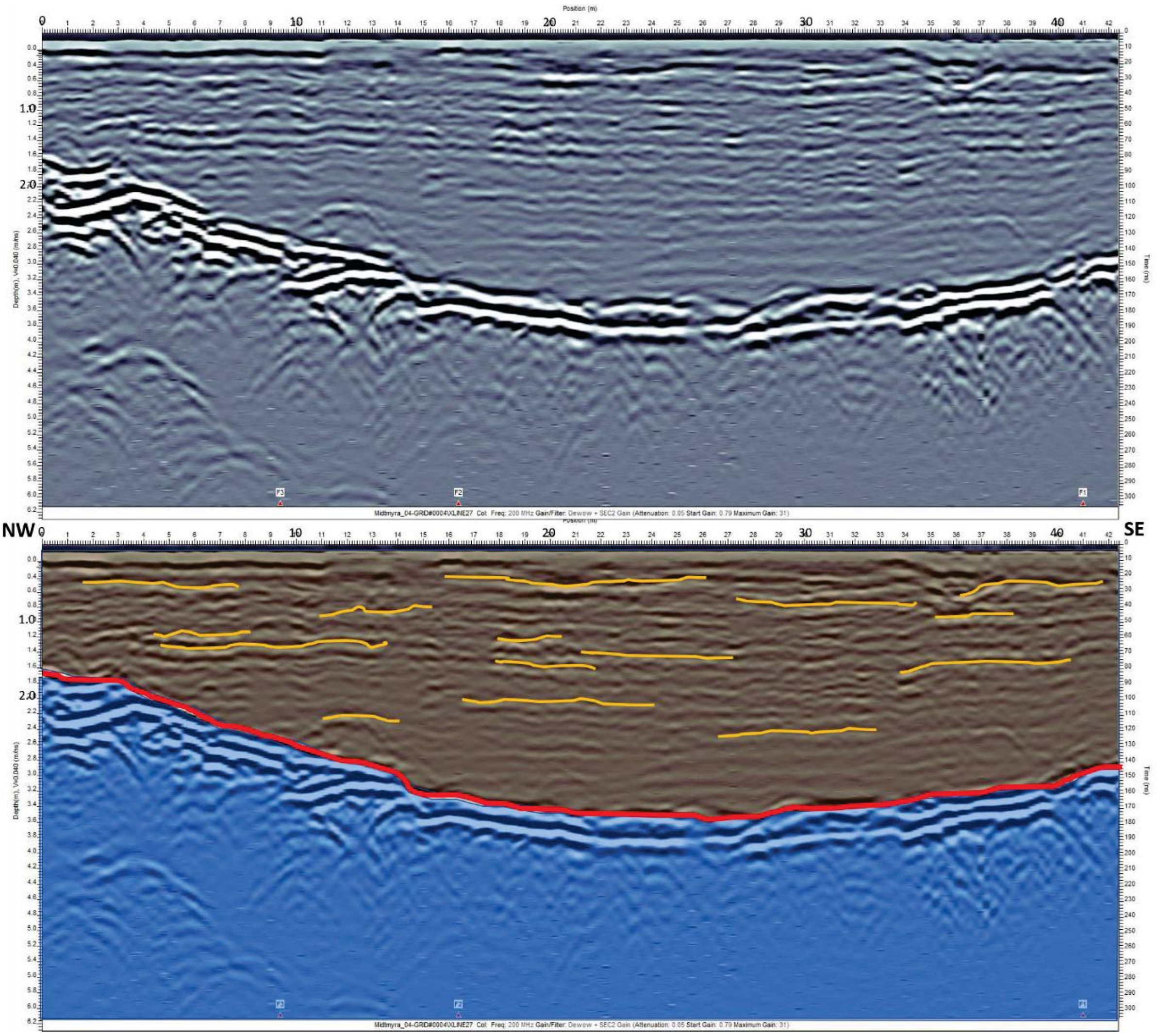


Figure 27: LINE 27 from the grid. This line is shorter than the previous lines that are displayed.

Line 27 is one of the shorter profiles, taken after the length of the grid was reduced due to trees and vegetation making it difficult to move the GPR device.

It also includes the strong reflector throughout the entire profile. Some subparallel reflectors are found in the peat facies. It is possible that these lines represent some form of layering in the peat stratigraphy.

The same reflector is present in all profiles, though the shape of the reflector changes between the profiles. The GPR study illustrates the shape of the peat basin well. It is evident that Midtmyra is situated in a depression in the bedrock.

3.1.2 Supplementary GPR lines

The grid only covers parts of the peatland. Several lines were taken to supplement the grid (Figure 28). Line 00 covers a large part of the peatland perpendicular to the grid.

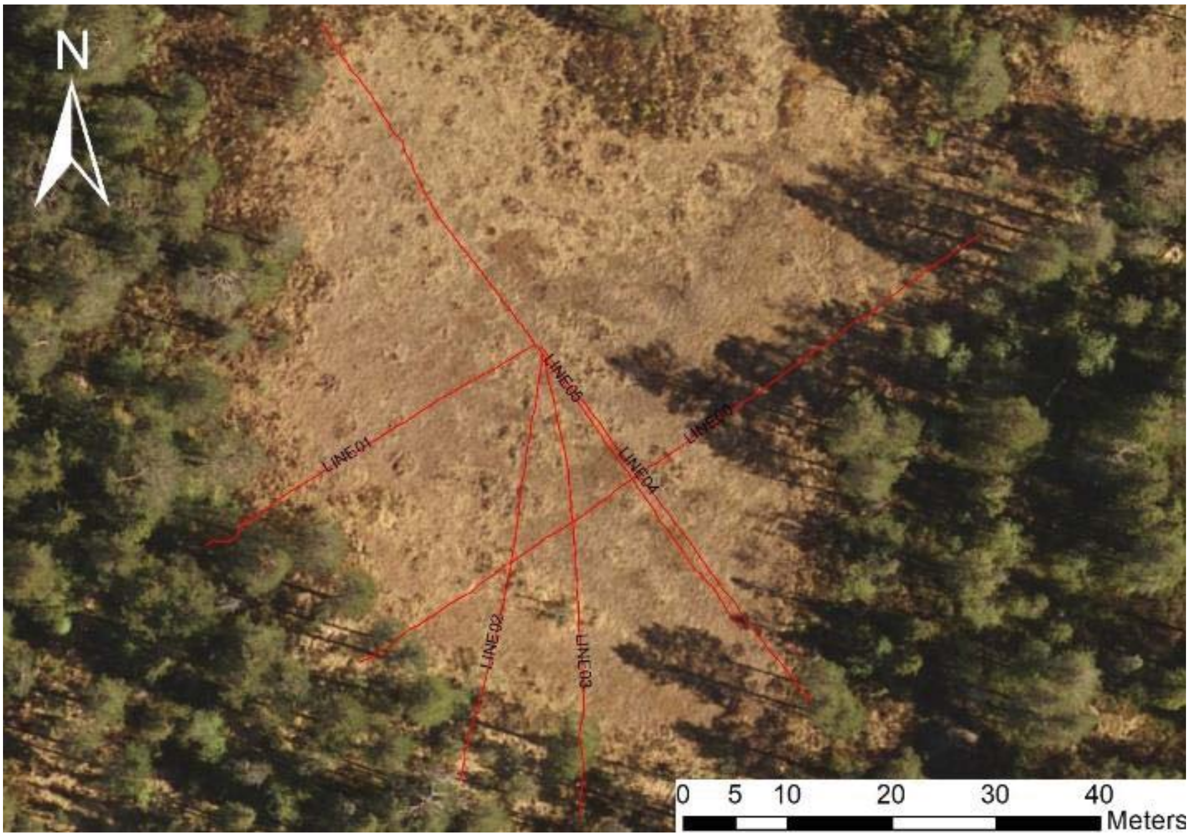


Figure 28: GPR lines taken additional to the grid. Lines 00 – 004 is taken with 200 MHz antenna, while line 05 is taken with 500 MHz antenna. Modified from Kartverket (2019).

GPR Line 00 (Figure 29) starts in north-eastern part of the peatland and moves towards the south west boundary of the peat. In this profile continuous strong reflectors is present, this reflector starts at 1 m depth in the north-eastern part. It drops down to its deepest points at 4.5 m, then rises up to 2 m depth in the south-western end of the profile.

In the lower part two reflectors are visible. A small unit is located between peat and bedrock. This unit, marked in yellow is interpreted to represent minerogenic material. The two other interpreted units are peat (brown) and bedrock (blue).

Some discontinuous subparallel lines are present in the peat unit. These lines indicate some changes

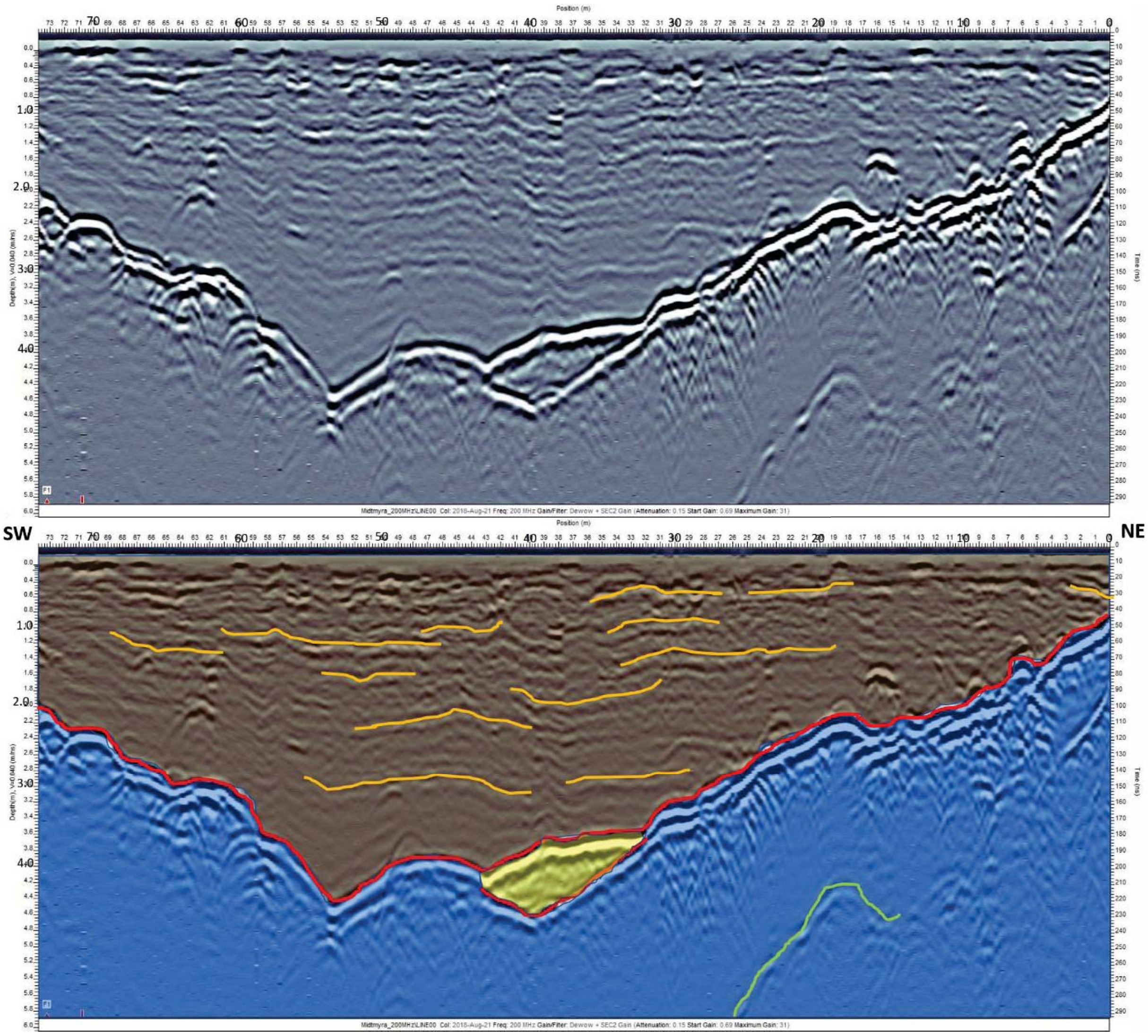


Figure 29: LINE 00 representing the peatland from the north east to the south west. Two strong reflectors are interpreted to represent peat-bedrock interface, peat mineral interface and mineral bedrock interface.

GPR Line 01 (Figure 30) starts in the middle of the peatland and moves towards the south west beyond the peat boundary. In this profile one continuous strong reflector is present, this reflector starts at 3.6 m depth and rises up towards the surface towards west. From 3-18 meter in to the profile there are two reflectors indicating a unit between these two reflectors.

In the lower part towards the east two reflectors are visible. A small unit is located between peat and bedrock.

Some discontinuous subparallel lines are present in the peat unit. These lines indicate some changes

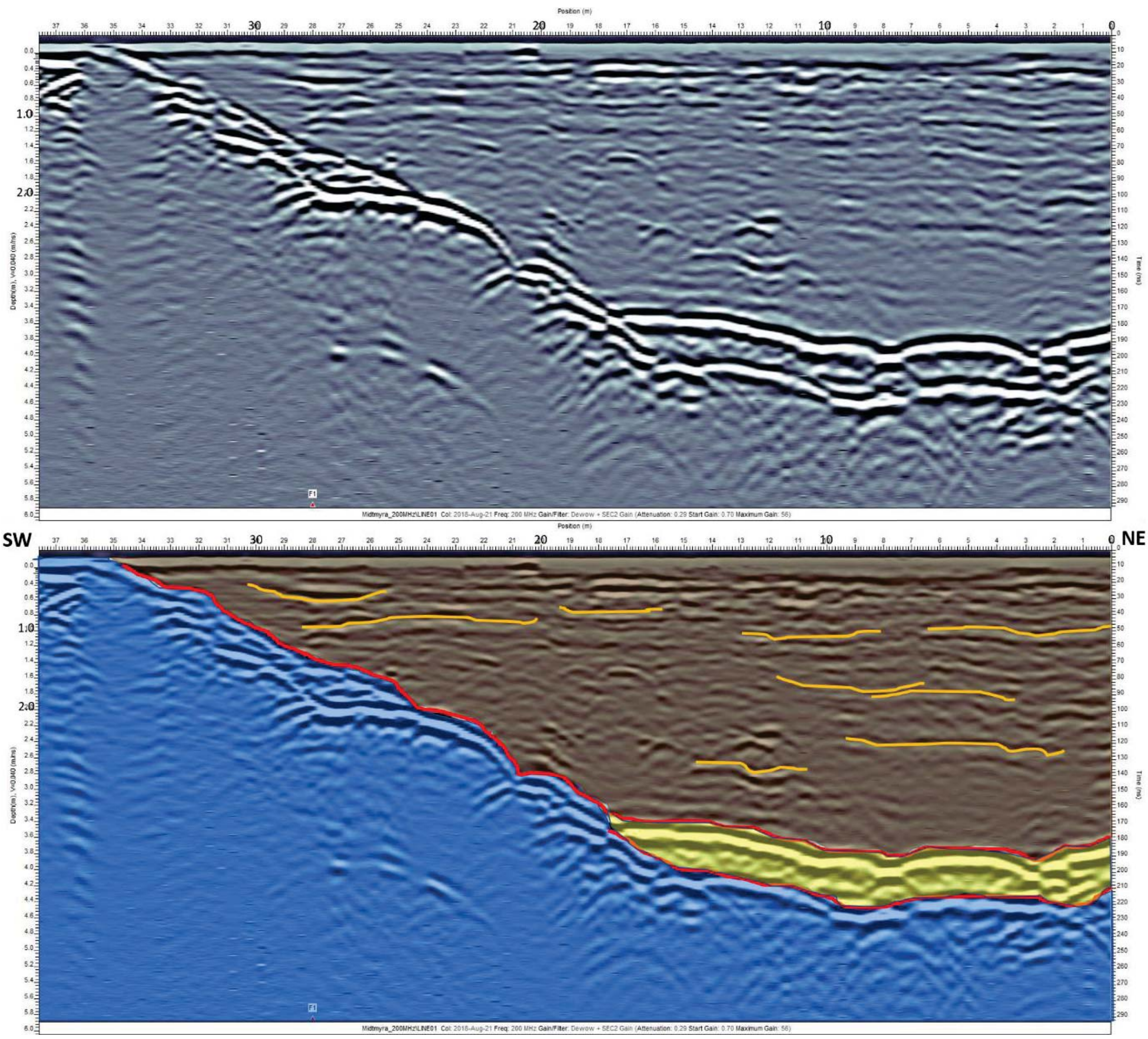


Figure 30: Line taken in addition to the grid. The line moves toward the south-east. This line is marked as LINE 01 in Figure 28.

3.1.3 Depth slices

Depth slices are generated based on the GPR grid, and each slice represent a horizontal view at a specific depth. Areas where strong reflectors are found are displayed as red in the images in Figure 31, and are the same reflectors as indicated with red lines in the interpreted GPR profiles in Figures 21-24. Areas in the depth slices without any particular reflectors are blue Figure 31. This makes it easy to make out the peat bedrock interface at different depths, and thus find the peat area at this depth.

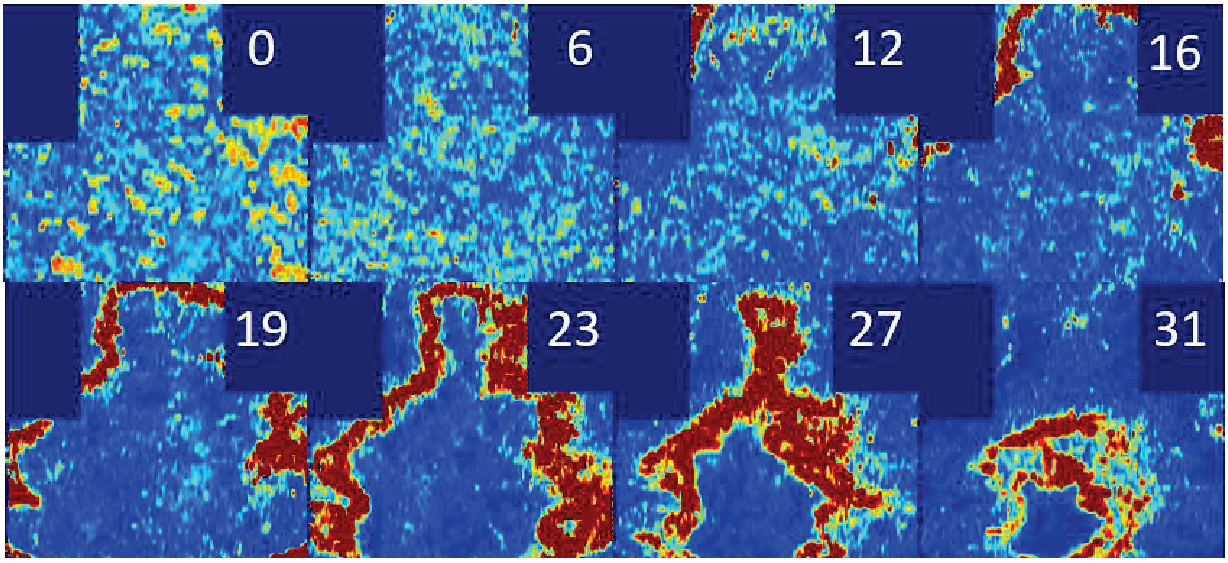


Figure 31: A few examples of depth slides generated from the GPR grid. These are the depth slices number 0 (0-0.125 m), 6 (0.75-0.875), 12 (1.5-1.625 m), 16 (2–2.125 m), 19 (2.375-2.5 m), 23 (2.875-3.0 m), 27 (3.375-3.500 m) and 31 (3.875-4.00 m).

3.2 Volume calculations

Calculation of area and volume of each individual depth slice as well as the total volume of the peatland are found in Table 4. These values represent only the part of the peatland covered in the GPR grid. The areas outside are not included the volume calculations (see Figure 28).

The area for the top slices, which also represents the mapped area of the peatland is 2156.6 m^2. This gives the first depth slice a volume of 269.8 m^3. Volume of the total peatland is 6487 m^3. Area, depth and volume of each individual depth slice is found in Table 4.

Table 4: Area and volume calculation for the peatland based on depth slices produced from GPR grid in Ekko_project. Each depth slice in georeferenced in ArcMap before the area was calculated.

Depth Slice	Area (m^2)	Depth (m)	Volume (m^3)
0	2158.6	0 to 0.125	269.82
1	2158.6	0.125 to 0.250	269.82
2	2158.6	0.250 to 0.375	269.82
3	2158.6	0.375 to 0.500	269.82
4	2158.6	0.500 to 0.625	269.82
5	2158.6	0.625 to 0.750	269.82
6	2158.6	0.750 to 0.875	269.82
7	2158.6	0.875 to 1.00	269.82
8	2157.9	1.00 to 0.125	269.73
9	2156.6	1.125 to 1.250	269.57
10	2148.3	1.250 to 1.375	268.53
11	2141.8	1.375 to 1.500	267.72
12	2128.6	1.500 to 1.625	266.07
13	2108.3	1.625 to 1.750	263.53
14	2083.1	1.750 to 1.875	260.38
15	2051.2	1.850 to 2.000	256.40
16	2015.5	2.000 to 2.125	251.93
17	1916.7	2.125 to 2.250	239.58
18	1900.1	2.250 to 2.375	237.51
19	1790.7	2.375 to 2.500	223.83
20	1700.3	2.500 to 2.625	212.53
21	1529	2.625 to 2. 750	191.12
22	1327	2.750 to 2.875	165.87
23	1150.1	2.875 to 3.000	143.76
24	962.16	3.000 to 3.125	120.27
25	779.22	3.125 to 3.250	97.40
26	659.01	3.250 to 3.375	82.37
27	481.65	3.375 to 3.500	60.20
28	377.43	3.500 to 3.625	47.17
29	284.35	3.625 to 3.750	35.54
30	226.16	3.750 to 3. 875	28.27
31	178.22	3.875 to 4.000	22.27
32	151.04	4.000 to 4.125	18.88
33	114.29	4.125 to 4.250	14.28
34	73.18	4.250 to 4.375	9.14
35	37.29	4.375 to 4.500	4.66
Total			6487.25

3.3 Sediment cores

3.3.1 Description of peat cores

Placement of the cores are found in Figure 32. The main peat core MM1 have a depth of 425 cm. Depth of the second core is 240 cm. Depth of the third core is 157 cm. The fourth core is 100 cm The colour gets darker with depth in the peat cores. Core MM4 have a darker colour than cores MM1-MM3 (see appendix B for details).

During visual examination and sample preparation there were no visible coal particles found in the peat cores.

Figure 32: Placement of the four peat cores on Midtmyra is marked in red in this aerial photo. The location of core MM1 was chosen from where the deepest area was found from the GPR profiles. The location of the other three peat cores was chosen to find changes in soil properties in a transect from peat to forest soil. Modified from Kartverket (2019).

3.3.2 Von Post degree of decomposition

Degree of decomposition described by the von Post scale (Table 3) for all four peat cores are displayed in Figure 34. The full 50 cm cores were described by degree of decomposition and the results have been altered to give a value for every 5 cm in the core. This was done to better display the results in the figure.

Degree of decomposition in core MM1 decreases from the lower samples towards the uppermost samples in the core (Figure 34). The lowermost samples have a high degree of decomposition, degree 8. For the minerogenic material found below 415 cm depth degree of decomposition is not applicable. In an interval from 400–380 cm depth there is a distinctive decrease in humification of the material. This 20 cm interval has still visible plant structure (Figure 33). Higher up in the core, there is a slow decrease form level 9 to level 7, up to 100 cm depth. In the upper meter there is a higher decrease of decomposition of the peat material until the uppermost sample.

Core MM2 have similar decrease in the core as MM1. The lower are at level 7, with a drop down to 6 until 60 cm. Here the level of decomposition sharply decreases in the upper 60 cm of the core, to a level 0 in the uppermost sample.

The lowermost 10 cm in core MM3 is at level 6. Degree of decomposition drops down to 5 for 50 cm, before is increases back to level 6 until 50 cm depth. In the upper 50 cm the degree drops down to level 1.

Core MM4 seem to stabilize at a shallower depth. From 100 to 10 cm depth the level decrease from 8 to 6, while only the uppermost 5 cm drops down to a decomposition at level 3. This is a higher level than the uppermost samples in cores MM1-MM3.

Figure 33: Core MM1 at the interval 380-390 cm with low von Post degree. Photo: Vera Sklet

A similarity in the peat cores is the jump in degree of decomposition from the uppermost to the second sample. Further below, they show similar patterns with a higher von Post degree with depth, but at what depths they increase differs between the cores.

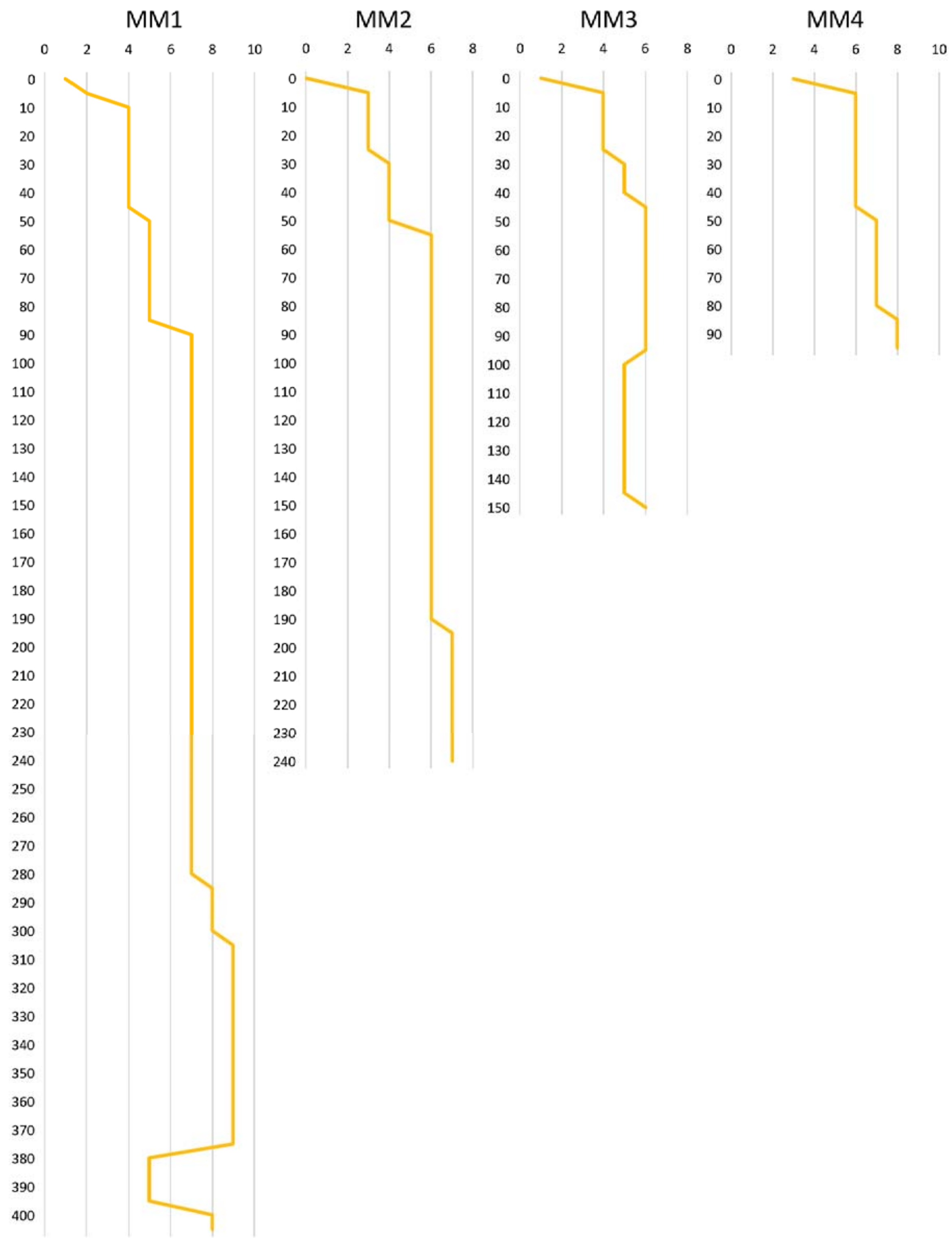


Figure 34: Von Post degree of decomposition for cores MM1 - 4. The von Post scales goes from 0 – 10, with 0 representing the lowest degree of decomposition and 10 the highest. Detailed description of all steps in the scale is found in table 1. Depth is displayed as cm below the surface.

3.3.3 Bulk Density

Bulk density for the four peat cores is found in Figure 35. Bulk density in core MM1 varies with depth, but it appears that there is a general trend that the bulk density increases with depth. Bulk density for most of the core lies within the interval 0.05 to 0.1 g/cm^3, with the exception of the samples 415 to 425 that has a value of 0.63 g/cm^3. Bulk density of MM1 increases in the lowest 25 cm of the core, to 0.6 g/cm^3 in the lowermost 10 cm sample. This part consists of a mix of organic and minerogenic material. Minerogenic material generally have a higher density than organic material. The change in material in this part of the core is pronounced in both the high bulk density and low LOI.

In core MM2 the first 30 cm have increasing bulk density values from 0.01-0.04 g/cm^3. For the rest of the core the values are slightly higher, ranging between 0.05 and 0.1 g/cm^3. There are also some variations in bulk density with depth in this core, but the trend is higher bulk density with depth.

MM3 have low values for the top 40 cm, ranging from 0.01-0.04 g/cm^3. At 40 cm the bulk density has a sudden jump up to 0.11 g/cm^3. From 40 cm to 190 cm the values have only small variations, with most of the values ranging from 0.10-0.12 g/cm^3. The last 10 cm sample at 200 cm depth have a slightly higher bulk density of 0.15 g/cm^3.

Bulk density in core MM4 is higher than the first three cores, with all values above 0.1 g/cm^3. This core also stands out with regards to changes in bulk density, as it does not appear to have a trend of higher bulk density with depth.

Cores MM1-3 all have an increase in bulk density with depth, while core MM4 have no apparent trend of a higher bulk density with depth. Core MM4 has the highest bulk density of the four cores, in the top meter. MM3 also seems to have a higher bulk density than MM2 and MM1.

Based on spatial distribution of these peat cores, it appears that bulk density is lowest in the middle of the peatland and higher the further out the samples are taken.

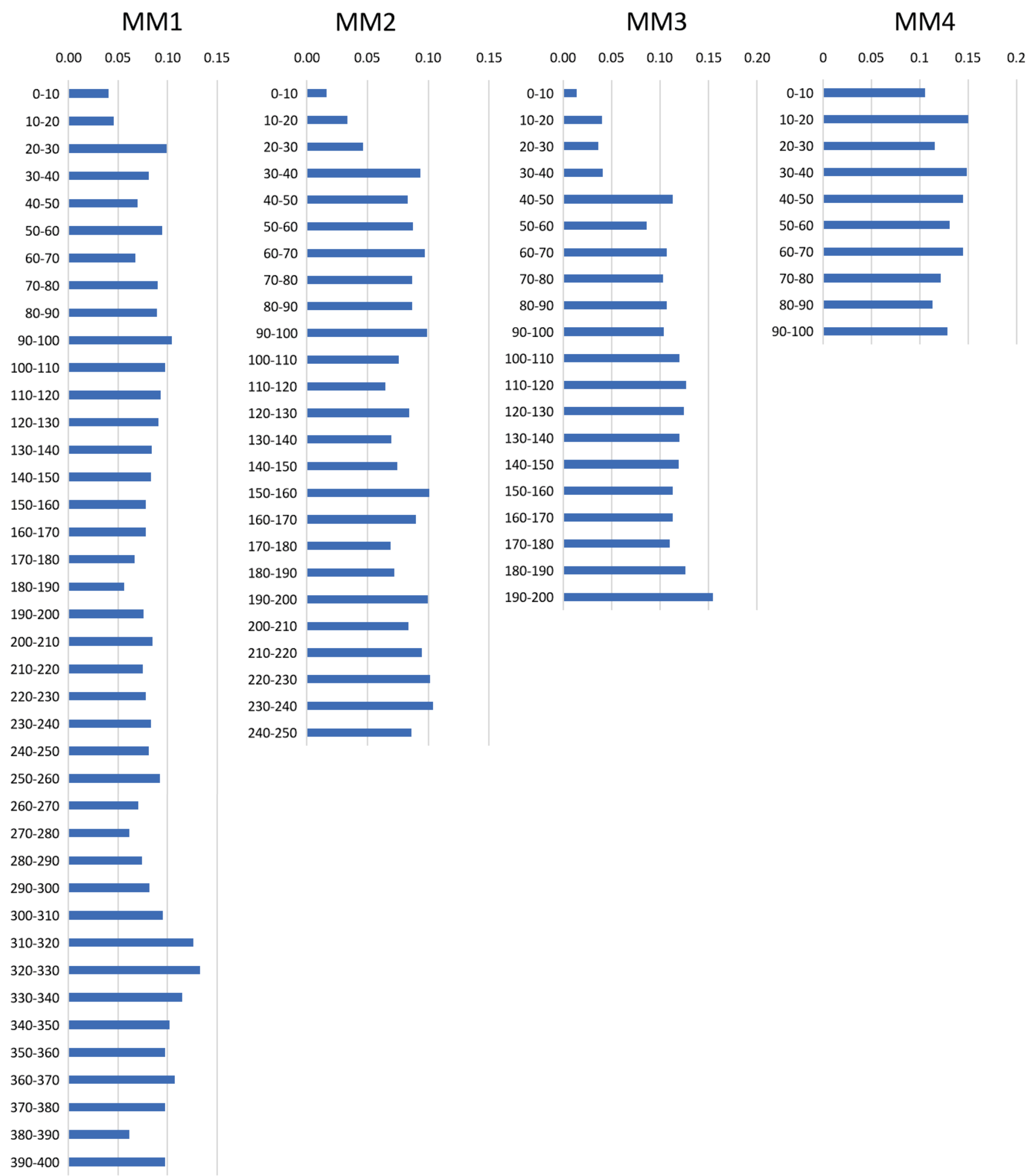


Figure 35: Bulk density in peat cores MM1 to MM4 (from left to right). The bulk density is given in g/cm3. The lower 25 cm of core MM1 is not included in this graph. For the rest it appears that core MM4 have a higher.

3.3.4 Loss on Ignition

All peat in the cores have high values for LOI, in general ranging around 94-98%, with only a few samples with LOI values below 92%. This is expected as peat mostly consist of organic material.

Peat core MM1 have small variations between 30-290 cm depth. Some values stand out as different from the rest of the core. The LOI value for sample 390-400 cm is 85%, this is the lowest value presented in the graph in Figure 36. There are some samples not included in the graph, samples 405-415 and 415-425 have values of respectively 60% and 6%. The lowermost 7 cm of core MM1 (418 to 425 cm), consist of minerogenic silt and fine sand.

MM2 have a slight increase in LOI values from the lowest samples up to around 50 cm depth. The variations are small, from 94-97% One sample at 30-40 cm depth have a slightly lower value than the rest of the core.

MM3 only have small variations in the core, with within the interval from 94-98%. There is no clear trend in the values. The lowest LOI value is observed in the uppermost sample.

LOI values in core MM4 increase from the lowermost samples at 95 % up towards 30 cm depth, where the LOI is 98 %. LOI decreases in the three highest samples, back down to 95%.

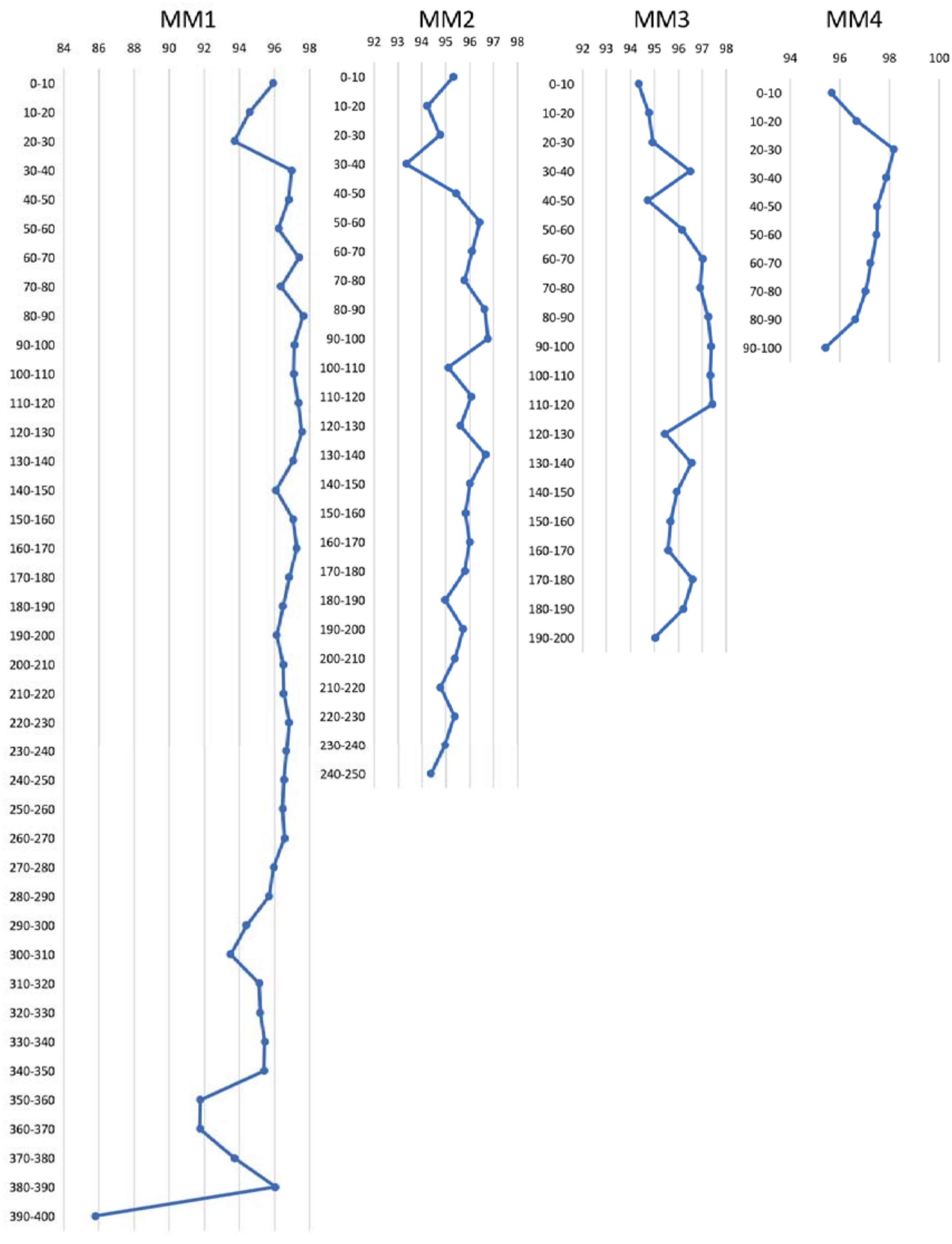


Figure 36: Loss on ignition results for peat cores MM1 - MM4. Results is given in % of dry sample. MM1 is the longest core of 425 cm, whit the lowermost 25 cm is excluded from this graph. Note that the scales are different. The scales for the different cores are based on the highest and lowest values of the individual cores, and this causes the scales to differ between the cores.

3.3.5 Total carbon and nitrogen

Table 5 shows LOI, total carbon and nitrogen values for core MM1. Total carbon content of peat core MM1 is in the interval between 47-55%. The upper 20 cm have lower content for carbon (47 and 48%). Samples from 20 to 50 cm depth have a carbon content of 51.5%, and deeper than 50 cm have values varying around 52-55% carbon content. Total carbon and nitrogen content for the samples from core MM1 that was analysed in the laboratory. Both carbon and nitrogen are given in % of the total sample.

Samples from 0 to 300 cm depth have been analysed in the LECO Truspec instrument, with exception of samples 240-260. The other samples could not be analysed by the laboratory, due to technical errors, and data for these are calculated from the regression analysis. Table 6 - Table 8 have the results for carbon and nitrogen content calculated from LOI for samples in core MM1 and cores MM2-MM4.

The statistical model gives results that are similar to the results from the laboratory. LOI is the input variable in the model, and it is only a reliable model for samples with similar LOI as the results received from the laboratory. The model is therefore not representative for the two samples in the bottom of core MM1 that have different values for LOI. These numbers are displayed in the results but are not accurate numbers. Tables 4, 5, 6 and 7 show the values for carbon and nitrogen that are calculated from LOI by using the formula from the regression analysis.

Table 5: LOI, % Carbon and % Nitrogen in core MM1. Values for C and N for samples

Depth (cm)	LOI	Tot C %	Tot N %
0-10	95.94	47.30	0.88
10-20	94.60	48.60	1.43
20-30	93.73	51.50	2.06
30-40	96.98	51.60	1.40
40-50	96.82	51.50	1.25
50-60	96.24	53.10	1.86
60-70	97.41	52.40	1.22
70-80	96.38	54.70	1.81
80-90	97.66	55.40	1.48
90-100	97.15	55.10	1.76
100-110	97.10	54.40	1.65
110-120	97.39	54.70	1.46
120-130	97.59	55.20	1.38
130-140	97.07	54.70	1.72
140-150	96.11	53.70	1.43
150-160	97.07	53.90	1.41
160-170	97.29	54.10	1.46
170-180	96.85	52.50	1.21
180-190	96.49	52.20	1.33
190-200	96.14	52.80	1.61
200-210	96.51	54.40	1.53
210-220	96.54	53.20	1.22
220-230	96.85	54.30	1.36
230-240	96.69	54.40	1.38
240-250	96.55	53.40	1.46
250-260	96.48	53.34	1.47
260-270	96.59	54.50	1.40
270-280	95.97	53.40	1.33
280-290	95.70	54.40	1.43
290-300	94.43	55.30	1.66
300-310	93.52	50.92	1.70
310-320	95.14	52.24	1.58
320-330	95.21	52.30	1.57
330-340	95.45	52.49	1.55
340-350	95.41	52.46	1.55
350-360	91.80	49.51	1.84
360-370	91.77	49.48	1.84
370-380	93.74	51.09	1.69
380-390	96.06	53.00	1.50
390-400	85.82	44.61	2.32
375-385	96.09	53.02	1.50
385-395	96.48	53.34	1.47
395-405	93.95	51.27	1.67
405-415	60.34	23.75	4.36
415-425	6.65	-20.21	8.65

Table 6: Total carbon and nitrogen values for core MM2. Both carbon and nitrogen is given in % of dry sample. The numbers are calculated from the LOI results with the regression analysis.

Depth (cm)	LOI	%C	%N
0-10	95.32	52.39	1.56
10-20	94.23	51.50	1.65
20-30	94.77	51.94	1.60
30-40	93.35	50.77	1.72
40-50	95.43	52.48	1.55
50-60	96.42	53.29	1.47
60-70	96.1	53.03	1.50
70-80	95.79	52.77	1.52
80-90	96.62	53.45	1.46
90-100	96.77	53.57	1.44
100-110	95.11	52.22	1.58
110-120	96.08	53.01	1.50
120-130	95.62	52.63	1.54
130-140	96.67	53.49	1.45
140-150	96.02	52.96	1.50
150-160	95.83	52.81	1.52
160-170	96	52.94	1.51
170-180	95.8	52.78	1.52
180-190	94.98	52.11	1.59
190-200	95.73	52.72	1.53
200-210	95.38	52.44	1.56
210-220	94.78	51.95	1.60
220-230	95.37	52.43	1.56
230-240	94.96	52.09	1.59
240-250	94.38	51.62	1.64

Core MM2 have values for total carbon content varying from 50-53%. Carbon values varies with depth, but no apparent trend is observed. Values for nitrogen content range between 1.4 and 1.7%. Sample 30-40 cm depth have the lowest value for carbon (50.77%) and the highest value for nitrogen content (1.72%).

Table 7: Total carbon and nitrogen values for core MM3.

Depth	% LOI	% C	%N
0-10	94.34	51.59	1.64
10-20	94.76	51.93	1.61
20-30	94.93	52.07	1.59
30-40	96.5	53.35	1.47
40-50	94.72	51.90	1.61
50-60	96.17	53.08	1.49
60-70	97.02	53.78	1.42
70-80	96.92	53.70	1.43
80-90	97.24	53.96	1.41
90-100	97.38	54.07	1.40
100-110	97.33	54.03	1.40
110-120	97.42	54.11	1.39
120-130	95.44	52.49	1.55
130-140	96.56	53.40	1.46
140-150	95.93	52.89	1.51
107-117	95.68	52.68	1.53
117-127	95.57	52.59	1.54
127-137	96.59	53.43	1.46
137-147	96.22	53.12	1.49
147-157	95.03	52.15	1.58

Total carbon content in core MM3 are 51.5 and 51.9% for the two top samples, and slightly higher for the rest of the core where the values vary from 52-54%. Nitrogen values starts at 1.64% for the first sample, which has the highest value, and varies between this value and 1.4% for the rest of the values.

Table 8: Total carbon and nitrogen for core MM4.

Depth	% LOI	%C	%N
0-10	95.67	52.67	1.53
10-20	96.71	53.53	1.45
20-30	98.2	54.75	1.33
30-40	97.89	54.49	1.36
40-50	97.53	54.20	1.38
50-60	97.5	54.17	1.39
60-70	97.27	53.98	1.40
70-80	97.06	53.81	1.42
80-90	96.65	53.48	1.45
90-100	95.41	52.46	1.55

Carbon content for core MM4 starts at 52.6% and rises up to the highest values at 54.75% before it gradually decreases down to 52.46%. Nitrogen values are highest at the top and bottom and the values between are slightly lower. For the first 10 cm the value is 1.53%, and the next two samples decrease to 1.33% at 20-30 cm, this is the lowest value in the core. The nitrogen content increases again from 30-40 cm until the highest value at 1.55% for the bottom sample at 90-100 cm.

Figure 37 shows the C/N-ratio for core MM1. C/N-ratios for core MM1 are varying, with highest variations in the uppermost meter of the core. There is still a trend that the C/N-ratio declines slightly with depth in the core. The uppermost sample have the highest C/N-ratios, while the deepest sample have the lowest ratio

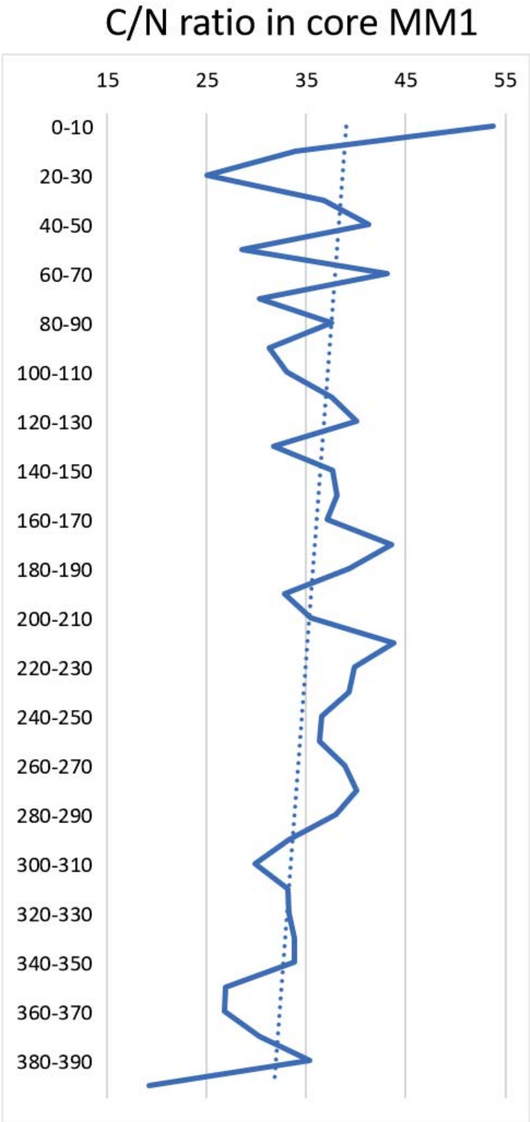


Figure 37: C/N ratio of peat core MM1. There are large variations within the core, but the trendline indicates a decrease of C/N ratio with depth.

.

3.4 Carbon stock calculation

Distribution of carbon stock with depth in core MM1 is presented in Figure 38 and Table 9. Values range from 2 kgC/m2 to 7 kgC/m2. Carbon stock varies with depth.

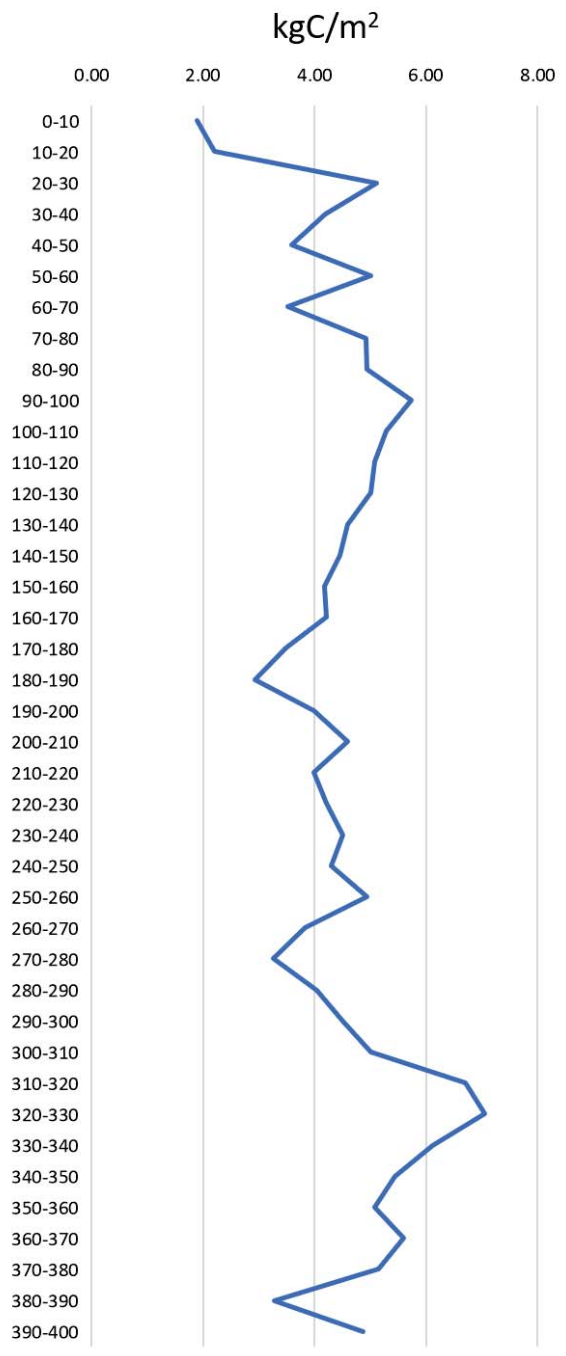


Figure 38: Distribution of carbon content in kg/m2 with depth in core MM1.

Table 9 presents carbon stock in kgC/m2 for each 10 cm sample for all peat cores. The same results are presented in the graph in Figure 39.

Carbon stock values are similar for core MM1 and MM2, they both have variations with depth, but they are within the same interval. MM3 have similar values as MM1 and MM2 for the top meter, below the first meter the value increases for core MM3. MM4 have higher carbon stock than the three other cores.

Carbon stock values for sample 415-425 are not representative for the actual value, as the regression analysis gave unrealistic values for carbon content.

The total amount of carbon stored in this peatland is calculated to be 278.8 ton. This estimate is based on the assumption that carbon values in peat core MM2 is representative for the entire peatland. For the top meter the carbon stock is 41.1 kg/m^2.

Table 9: Carbon content in %, area and carbon in kg/m2 for each 10 cm sample in core MM1. The total amount of carbon in kg at the bottom.

Depth	kgC/m2	Area (m)	Carbon (kg)
0-10	1.89	2158.6	4084.5
10-20	2.20	2158.6	4759.7
20-30	5.11	2158.6	11035.3
30-40	4.19	2158.6	9042.6
40-50	3.58	2158.6	7735.6
50-60	5.02	2158.6	10826.1
60-70	3.52	2158.6	7605.1
70-80	4.92	2158.6	10615.6
80-90	4.94	2158.6	10667.2
90-100	5.73	2158.6	12365.9
100-110	5.29	2157.9	11412.3
110-120	5.08	2156.9	10954.3
120-130	5.01	2152.5	10778.0
130-140	4.59	2146.7	9849.4
140-150	4.46	2141.8	9542.2
150-160	4.18	2128.6	8903.6
160-170	4.21	2113.4	8890.8
170-180	3.49	2095.7	7304.0
180-190	2.94	2075.1	6101.0
190-200	4.00	2051.2	8196.9
200-210	4.60	2015.5	9272.2
210-220	4.00	1941.4	7758.2
220-230	4.21	1908.4	8039.4
230-240	4.50	1872.8	8433.8
240-250	4.31	1790.7	7711.6
250-260	4.93	1700.3	8389.6
260-270	3.83	1571.8	6020.0
270-280	3.26	1428	4660.7
280-290	4.04	1282.8	5180.5
290-300	4.50	1150.1	5178.4
300-310	4.83	962.2	4645.7
310-320	6.58	825	5426.3
320-330	6.93	719.1	4979.8
330-340	6.01	614.7	3694.0
340-350	5.36	481.7	2581.5
350-360	4.82	377.4	1819.4
360-370	5.31	307.6	1634.7
370-380	4.97	255.3	1269.9
380-390	3.24	214.2	695.0
390-400	4.33	178.2	772.4
Total amount of carbon:			278833.64

Table 10: Carbon content in kg/m2 for every 10 cm for all four cores.

Depth	MM1	MM2	MM3	MM4
0-10	1.89	0.86	0.73	5.58
10-20	2.20	1.78	2.10	8.04
20-30	5.11	2.47	1.89	6.34
30-40	4.19	4.93	2.18	8.09
40-50	3.58	4.44	5.86	7.86
50-60	5.02	4.69	4.58	7.12
60-70	3.52	5.20	5.75	7.81
70-80	4.92	4.63	5.55	6.57
80-90	4.94	4.65	5.77	6.05
90-100	5.73	5.34	5.61	6.76
100-110	5.29	4.04	6.48	
110-120	5.08	3.48	6.86	
120-130	5.01	4.50	6.55	
130-140	4.59	3.75	6.40	
140-150	4.46	4.00	6.29	
150-160	4.18	5.39	5.97	
160-170	4.21	4.81	5.96	
170-180	3.49	3.69	5.90	
180-190	2.94	3.82	6.68	
190-200	4.00	5.33	8.07	
200-210	4.60	4.46		
210-220	4.00	5.04		
220-230	4.21	5.41		
230-240	4.50	5.52		
240-250	4.31	4.58		
250-260	4.93			
260-270	3.83			
270-280	3.26			
280-290	4.04			
290-300	4.50			
300-310	4.83			
310-320	6.58			
320-330	6.93			
330-340	6.01			
340-350	5.36			
350-360	4.82			
360-370	5.31			
370-380	4.97			
380-390	3.24			
390-400	4.33			
375-385	3.18			
385-395	2.52			
395-405	3.85			
405-415	2.63			
415-425	-12.84			

Figure 39 illustrates carbon stock for 10 cm samples in kg C/m^2 in the four peat cores.

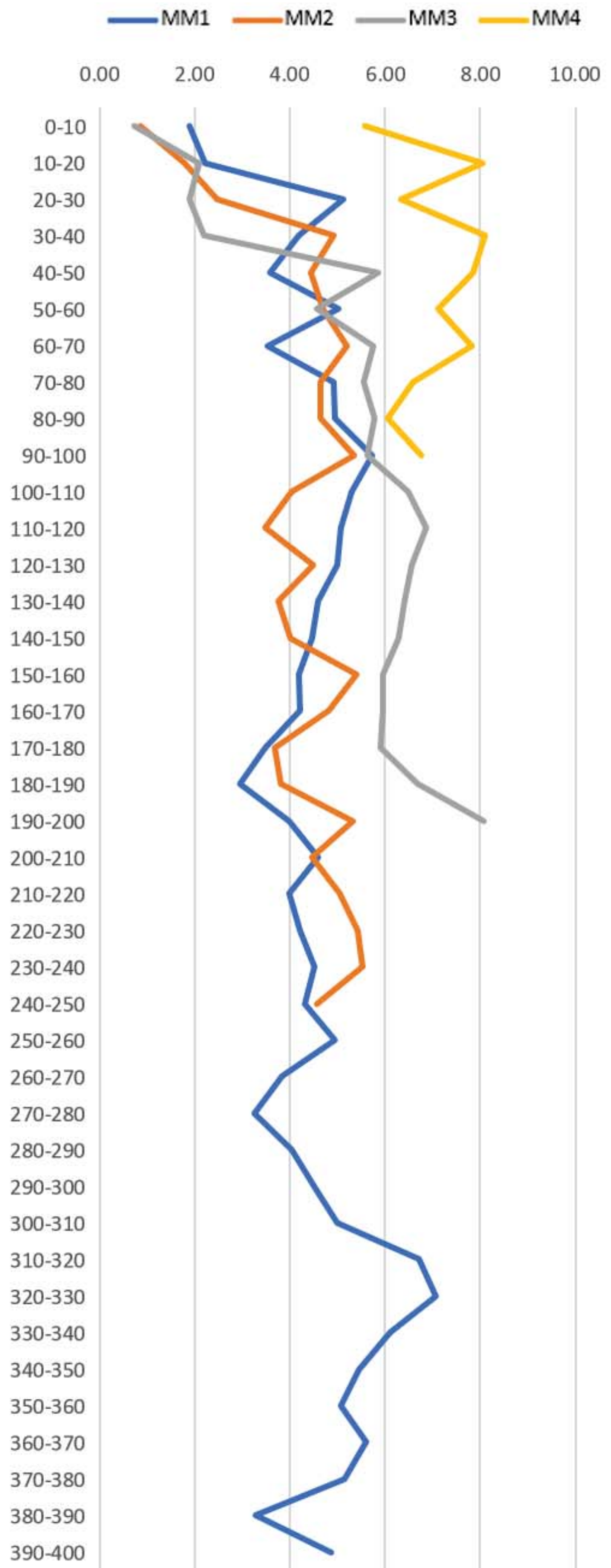


Figure 39: Distribution of carbon stock with depth of all four peat cores, given in kg C/m2. The data for the first 30 samples in core MM1 is analysed in the laboratory, while the rest of the results are calculated from these 30 samples and LOI.

Figure 40 shows the full MM1 core with values for von Post, bulk density, LOI, carbon and nitrogen content and carbon stock.

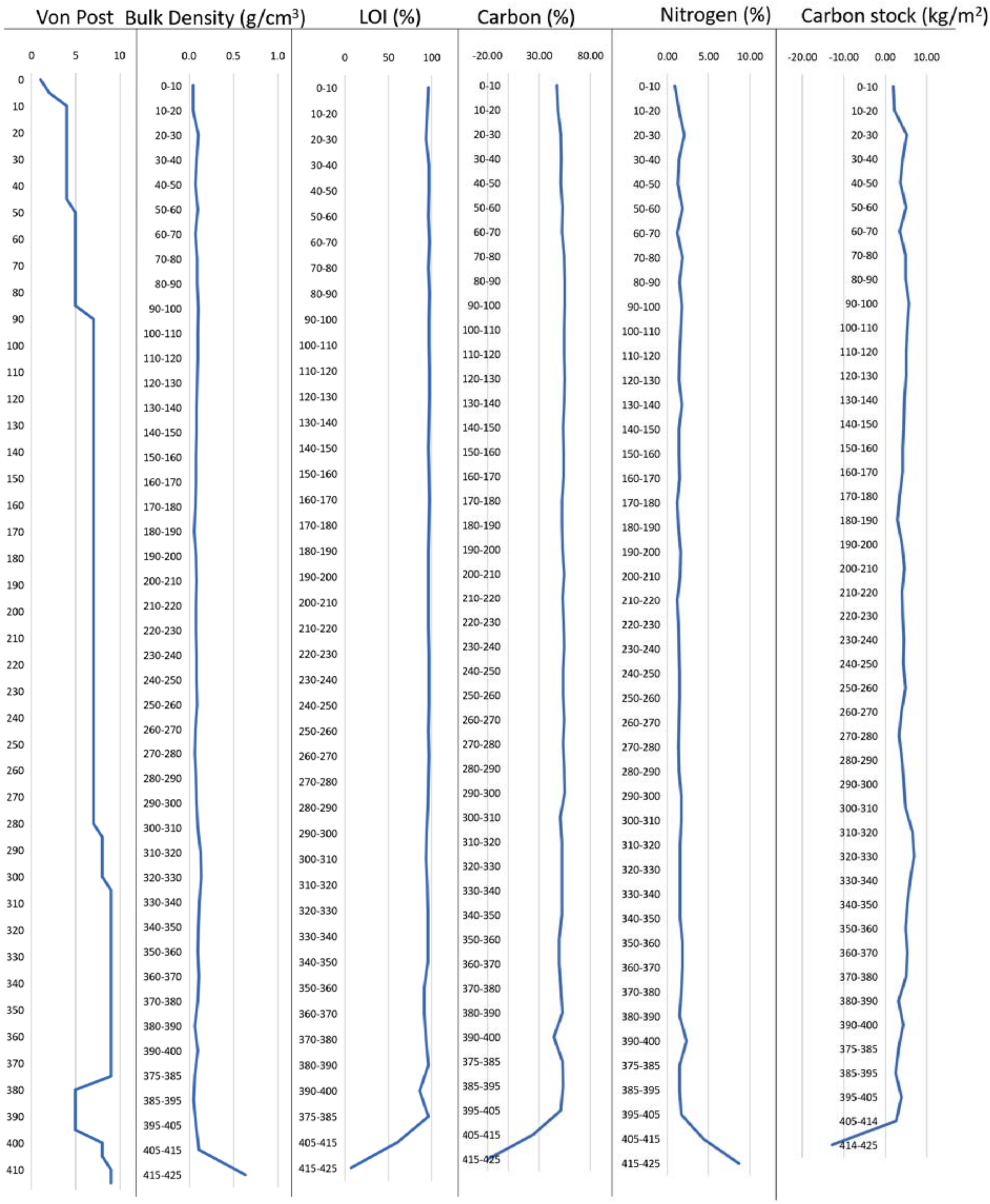


Figure 40: von Post degree of decomposition, Bulk Density, Loss On Ignition, % carbon, % Nitrogen and carbon stock for core MM1.

4 Discussion

In this chapter the results presented in the previous chapter are discussed and put into a broader context.

4.1 GPR and volume calculations

All methods of estimating peat depth have uncertainties. There are two common ways of estimating peat depth, manual probing and ground penetrating radar surveys. Manual probing is done by sticking a metal probe down into the sediment, and measure at what depth the probe enters the mineral soil layer. The sharp change in physical and chemical properties between organic matter and mineral material in peat stratigraphy, gives good conditions for the use of ground penetrating radar to detect this limit (Rosa et al., 2009). Different approaches for estimating peat depth was evaluated by Parry et al. (2014). They conducted an experiment where both manual probing and ground penetrating radar was used to estimate the depth of peatland in a catchment in Lancashire, United Kingdom. Both methods have each individual strengths and weaknesses. In their conclusion they suggest that manual probing can be used to improve the calculations of velocity in ground penetrating radar surveys (Parry et al., 2014). GPR gives a more continuous dataset with a high spatial resolution, compared with manual probing, where it would be highly demanding to conduct a survey with the same detail as GPR grid studies.

The main GPR survey in this study was done with a grid consisting of parallel X lines with 1 meter distance. In order to get optimal results, Sensors & software recommend collecting both X and Y lines in a grid. However, we decided that only X lines would suffice in this study, as collecting both would be more time consuming.

Strong, continuous reflectors are identified in all 200 MHz GPR lines in the grid, marked as red lines in Figure 24 - Figure 27 and Figure 29 and Figure 30. The profiles from the grid and the supplementary lines show similar reflector patterns. The profiles are divided into units based on these prominent reflectors, as they are interpreted to represent the interface between peat and bedrock, peat and mineral material as well as mineral material and bedrock. It is unlikely that there are any other possibilities for a reflector that is this strong. Thus, the reflectors visualise the bedrock surface and that the peat has a form like a round shaped basin. This interpretation of the peat unit is supported by the peat cores.

In several of the GPR profiles, both within the grid and the supplementary lines, there are two strong reflectors identified in the bottom of the peat basin, indicating that there is a unit between the units interpreted as peat and bedrock. This third unit is interpreted to represent minerogenic material. This interpretation is supported by the 20 cm of minerogenic and gyttja material found at the bottom of peat core MM1.

In the 200 MHz profiles some moderately continuous to discontinuous subparallel lines have been identified within the peat unit. This indicates that there is some horizontal layering in the peat likely caused by changes in water content due to changes in size and structure of the material. Exactly what types of changes in the material that causes these reflectors is difficult to know without additional information. Given that the reflectors are moderately continuous to discontinuous, it is difficult to identify distinctive layers from these profiles. Correlation with the peat cores was not possible because reflectors are not continuous and distinctive layers are not identified.

The interpretation of both peat and bedrock units are well supported by field observations. The most uncertain interpretation is that of the minerogenic material. Since the peat core reached through the entire peat body and included minerogenic material, this strengthens the original interpretation.

Several of the profiles include reflectors that are interpreted to be multiples of major reflectors.

The GPR lines that was collected to supplement the grid gives useful information when trying to understand the functioning and development of the peatland. These profiles show the peat bedrock interface in some areas that are not covered by the grid. Line 01(Figure 30) include a strong reflector from the middle of the peatland that continues past the forest boundary, over the lowest terrain surrounding the peatland. Here, the reflector interpreted as peat-bedrock interface, rises up towards the surface (Figure 30).

The strong reflector interpreted to represent the bedrock is present in all GPR profiles. The combination of the GPR grid and the supplementary lines gives a well illustrated impression of the shape of the bedrock depression, in which the peatland is situated.

At the southwestern end of the two supplementary GPR lines, the bedrock rises towards the surface. It appears that the bedrock rises almost all the way up to the surface in Line 01, while at the end of Line 01 the peat bedrock interface is at 2 m depth.

There is no independent study of EMW velocity in this peatland, and this is a value that differ between peat material, and even within a peatland. Velocity used in the processing of the GPR data is decided from literature and is not verified with this specific peatland. There are some uncertainties in whether the velocity that is used is accurate. A study of the use of GPR to estimate peat depth by Parry et al. (2014) reported EMW velocities ranging from 0.035 to 0.046 m/ns in similar peat materials. They found an average value of 0.038 m/ns with a standard deviation of 0.003. EMW velocity used in processing data collected in this study (0.04 m/ns) is within the range of EMW velocity reported in the literature for similar material (Parry et al., 2014). It is therefore possible to assume that the velocity used is most likely representative for the studied material, and the margin of error in depth estimations are small. However, in order to minimize the margin of error in data processing and depth estimation a site-specific velocity study to determine the actual velocity could have been conducted. If the EMW velocity in the studied material is higher than what is estimated, it would cause an overestimate of the peat depth. A lower velocity would lead to an underestimate of peat depth. The velocity used in this study is similar to, or maybe slightly higher than velocities other studies have found in peat material (Parry et al., 2014).

Boreal peatlands that are formed through terrestralization often have a soft layer of gyttja below the peat, this might influence the attempt of manual probing to determine peat depth because the probe might enter the gyttja material without the person operating it noticing. This makes it is difficult to determine when the probe hits the peat mineral interface (Parry et al., 2014).

The accuracy of depth slices and volume calculations is dependent on whether the EMW velocity used in data processing is accurate. The manual probing we conducted during fieldwork show similar depths as the GPR in proximal areas. This supports the use of 0.040 m/ns as velocity and it makes it likely that the depths from GPR profiles are reasonably accurate. The depths recorded during the manual probing conducted during fieldwork also indicate similar depths to what is found in the GPR profiles, thus supporting the velocity used in processing GPR data.

The volume of the peatland under the grid is estimated to 6487 m^2. This estimate is based on GPR survey of the peatland, that provide a good basis for volume calculations. This makes the volume estimate detailed, however, there are still uncertainties in the estimate.

One disadvantage with the GPR grid study is that it calculates the volume of the peatland in the same area as the GPR grid, and the peat outside of the grid is excluded from the volume estimate. Due to this, the actual volume is larger than the estimate presented in this study. The difference in total peat area and the area included in the GPR grid is well demonstrated in Figure 13, and is approximately 2000 m^2.

The part of the peatland with greatest depths are assumed to be included in the grid area. This assumption is supported by the fact that the bedrock rises up towards the surface in the periphery of the peatland, and the forms of the GPR profiles. The depth of the profiles decreases towards the end points, and the depth are also decreasing towards Line 01 and line 51. Since the depths of the peat is unknown outside of the grid area, the volume of this area has not been estimated. However, it is possible to estimate an average depth, similar to what is often done in peat volume and carbon stock studies and estimate a volume of the peat outside of the grid area. The estimated volume may be used to make an estimate of the total volume and estimate the carbon stock of the whole peatland.
During fieldwork we collected GPR profiles with 500 MHz antenna. The aim of this was to examine the internal structure of the peat with a higher resolution than what can be expected with the 200 MHz antennas. However, we could not see any reflective surfaces on the monitor during the data collection. Due to this only one profile was collected instead of the entire grid, as was initially intended. We tried to start on exposed bedrock and move out on the peatland, without any visible reflectors on the monitor.

4.2 Peat cores

von Post degree of decomposition

The von Post degree of decomposition shows similar trends for all four cores; it is low in the shallow peat and increases with depth where they stabilize at level 6-8 (Figure 34). The depth at where the degree of decomposition is stabilizing at level 6, is deepest at the centre of the peatland. Here it stabilises at 90 cm depth in core MM1, and decreases towards the forest boundary (10 cm depth in MM4). This indicates that the degree of decomposition at a certain depth, at least from 10-100 cm depth, is higher towards the peripheral areas of the peatland than it is in the middle.

The distinctive drop in degree of decomposition seen at 380-400 cm depth in core MM1 could represent a colder time period where the conditions for decomposition of organic material was poor. However, some studies, for example (Yeloff & Mauquoy, 2006) have suggested that degree of decomposition cannot be directly compared between different plant species. Since the plant material in this study have not been identified down to species, it is difficult to determine whether these changes in decomposition are caused by a shift in vegetation or changes in climatic variables. Then again, it can be argued that if the differences are caused by a change in flora, it is possible that this shift was caused by climatic changes.

Bulk Density

Bulk density values vary both with depth and between the peat cores. Bulk density of the peat cores shows similar values to what other similar studies have found, Gorham et al (1991) operated with a average value of 112 g/cm^3 for Canadian peatlands, this is similar to or slightly higher than some of the values found in this study. Due to possible packing of the material in the Russian corer during retrieval of the peat cores, bulk density is more likely to be overestimated than underestimated in this study.

For the three cores taken in the peatland, MM1-MM3, the trend is a higher bulk density with depth. This is most likely due to the weight of the overlying peat compacting the material. Higher degree of decomposition is also associated with smaller particle sizes, which also allows for the material to be more compacted. Unlike cores MM1-MM3, core MM4, which is the only core taken outside the peatland boundary, does not appear to have any particular trend in bulk density with depth. This could be because the material is well decomposed.

Sample 380-390 in MM1, that have a low degree of decomposition, also show a low bulk density compared to the overlying samples. This sample have a coarser structure than the adjacent material with visible plant rests and larger size of the particles. Due to this the material might be less compacted than the more decomposed fine material. It is also possible that the water retention capacity is lower in this section.

Transition from peat to forest soil appears to give the material a higher bulk density. This is demonstrated with the difference in bulk density between especially core MM1 and MM4. The top 100 cm in core MM1 have two samples with a bulk density above 0.1 g/cm3, while all samples in MM4 are above 0.1 g/cm3. Core MM4 taken outside the peat boundary also consist of organic material, suggesting that the peatland is shrinking, and the material is transforming into an organic soil. Similar trends are found in carbon content analysis, peat structure and von Post degree of decomposition. The values are increasing with depth, and stabilizes around 80-100 cm. This could mean that there is a link between degree of decomposition and carbon content in peat. Bulk density in the top 10 cm for cores MM1, MM2 and MM3 have small values, whereas core MM4 have values that reaches up to 0.15 g/cm^3. This is most likely because MM4 is taken outside of the peat boundary and represents forest soil. This soil, however, consists of organic material, and it is possible that this previously have been part of the peatland. Thus, suggesting the forest boundaries are moving in on peatland and the peat turns in to an organic soil.

For especially cores MM1-MM3 the top 10 cm of the samples are somewhat unreliable. In this data set, bulk density is higher in the top 10 cm in core MM4 than the three other cores. The upper 10 cm sample in was not filled up with material in cores MM1-MM3.

The 10 cm samples had weight differences, they were heavier with depth. After drying most of the difference between them disappears. This suggest that the difference in weight is caused by a difference in water content with depth. Water content is one of the factors influencing GPR reflections in material. If water content is the main factor controlling bulk density in the different samples, this could also cause the moderately continuous to discontinuous subparallel reflectors in the GPR profiles.

Loss On Ignition

LOI values represent the amount of organic material in the samples. All peat samples gave LOI values well above 90%, except the samples that visibly contain minerogenic material. These high values on LOI tests were expected, given that the material tested mostly consist of organic material. High LOI values are also consistent with results from total carbon analysis.

There are some variations, but most of them are at high levels. Samples from 390 cm and below have lower values, with the 415-425 sample as low as 6%. Hence, this sample consist of mostly mineral material.

In cores MM1-MM3 a low value is observed at a few decimetre depth. In the first core sample 20-30 cm have a low value before they increase and stabilize at a higher level. Core MM2 have a drop at 30-40 cm and core MM3 have a similar drop at 40-50 cm depth.

Also core MM4 that is taken from outside of the current peat-forest boundary have high LOI values ranging from 95-97%. This suggest that this material was formed by a peatland, and later overgrown by trees. In Figure 5 it looks like the peatland boundary hove moved in towards the peat.

The lack of coal particles discovered in the peat cores does not mean that they are not present in the peatland. Previous studies have discovered evidence of past forest fires in the peatland.

Carbon and nitrogen content

Due to some unfortunate technical problems at the laboratory, I only received results for the total carbon and nitrogen analysis for 28 samples. In order to use these results to calculate the total carbon stock, a linear regression analysis was done in Excel. Carbon and nitrogen values for the remaining samples were calculated with the formula from this regression analysis.

The statistical model used to find values for carbon for the samples are based on the results from the laboratory, and the model is only applicable for the samples that have characteristics as the ones that was analysed by the laboratory. Therefore, the model is not realistic for the two bottom samples in core MM1 that contain minerogenic material. Because of this the values presented for these samples are not correct. The regression analysis has a low R^2, this is due to the low interval of the results. The alternative would have been to take the average value of carbon content and use this in the carbon stock calculations.

It is uncertain how accurate the model is in estimating the carbon content for peat cores MM2, MM3 and MM4.

The four different peat cores have different values for carbon stock. Core MM4 have higher values than the other 3 cores. It seems that core MM3 also have a slightly higher carbon stock value than especially core MM1. The total amount of carbon stored in this peatland is based on the values of the main peat core, MM1, and higher values in the other cores could mean that the actual carbon stock might be somewhat higher than what is estimated here.

Effectively, carbon stock values for cores MM2-MM4 is calculated as a function of LOI and bulk density. Therefore, the differences in carbon stock reflects differences in these two factors, and not necessarily differences in carbon content, as was intended.

Core MM4 is taken outside the peatland forest boundary, and thus represent characteristics for the organic forest soil, and not the current peat.

C/N-ratio for core MM1 have highly variable results, though the highest C/N-ratio is recorded in the first 10 cm, while the lowest is the last 10 cm sample included. Some samples are not included due to the unreliable results in the regression analysis.

Locations for retrieval of the main peat core, MM1, was based on GPR profile. The goal was to retrieve a core in the deepest part of the peatland. The core is 425 cm deep and reaches minerogenic material below the peat. This means we managed to get a core that extends throughout the entire peat profile and included the underlying unit.

4.3 Carbon stock calculation

Based on the total carbon content in the main peat core, taken approximately in the middle of the peatland, the amount of carbon stored in this peatland is estimated to be 279.6 ton. Given that this is based on an extensive GPR survey of peat volume, bulk density and carbon content on 10 cm intervals in a peat core that covers the entire peat depth, this is a precise estimate compared with many other peat carbon stock estimates. However, there are still uncertainties associated with all these estimates. This estimate assumes that the carbon values from this core is representative for the entire area in that 10 cm depth. Carbon stock values for the four cores suggest that this might not be the case. Core MM1 have similar values as MM2, but both MM3 and MM4 have higher carbon stocks. If these values reflect actual distribution of carbon stocks, it is likely that the estimate in presented here is an underestimate.

Carbon stock values are linked to bulk density, this is reflected on similar distribution patterns between these two values. Figure 41 illustrates that the graph for carbon stock follow that of bulk density closely.

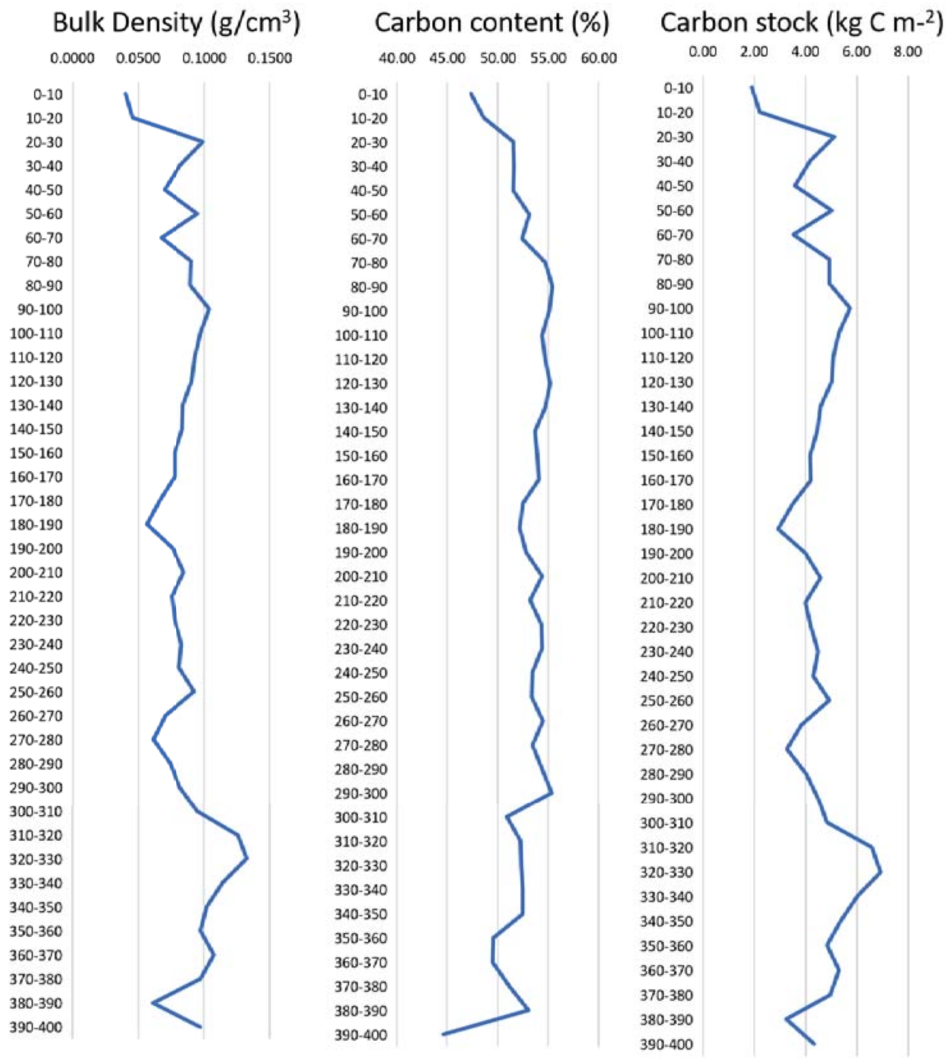


Figure 41: Bulk density, carbon content and carbon stock in peat core MM1.

Values for carbon content in the top 60 cm reported in Unhjem (2011) range within similar values as the ones found in this study (Figure 6). Sample 113 from Figure 6 is located closest to core MM1, while sample 124 is located close to core MM4. Sample 124, which is also taken outside the peat boundary, have some of the highest carbon stock values of the 8 samples.

Several uncertainties are connected to these carbon stock calculations. Among other, the volume calculation, where the gap between the mapped area and the grid cause an underestimation of the volume. It is not known how large this underestimate might be. Also, the EMW velocity is a little uncertain, and may cause either overestimate or underestimate of the peat depth. Further, there are uncertainties with the carbon analysis. If the carbon analysis equipment in the laboratory had worked, it would have been interesting to look at whether distribution of carbon content differs between cores, taken at the different places.

Given that the volume estimated is an underestimate of the actual volume, the carbon stock is also an underestimate. Even if the depth of the area outside the grid is most likely shallow, some carbon is stored in the peat area surrounding the GPR grid.

Differences in carbon stock in the different peat cores are caused by the difference in bulk density between the cores. Core MM4, taken outside the peat boundary, have a higher bulk density than the three cores taken within the peatland, it also has a higher carbon stock.

A detailed study with peat cores gives an accurate estimate of carbon stock in peatlands and will help improve the estimates on a regional scale. It is possible to use the results on carbon content from this study in larger scale estimates, however the depth and volume calculations will differ between localities, so this is not necessarily representative for other peatlands.

Grønlund et al. (2010) found carbon stock values for deep peat (average 2 m depth) of 88 kg/m^2. By dividing this value by 2, it gives a value of 44 kg C/m^2 for 1 m depth. This is close to the value of 41 kg C/m^2 estimated in this study.

Peat core MM4 taken outside the peatland boundaries have a high carbon content, thus forest soils formed by peat have a high content of organic material. Soil like these therefore also store large amounts of carbon.

4.4 Development of the peatland

The hypothesis for the formation of this peatland is that a depression in bedrock filled with water to form a pond, that later was filled up with sediments and organic material to form this peatland.

Data from this study supports this hypothesis for peatland formation. For example, the shape of the peat basin is well illustrated in the GPR survey, it shows a clear depression that could have been a natural place for a pond to form.

The fine minerogenic material at the bottom of the main peat core suggest that this peatland have developed from a small lake to peat. Also, the shape of the peat basin suggest that a pond could have been present before the peatland formed. It is important for our understanding of how the peatland formed that the main peat core extended deeper than the peat profile and included the minerogenic material at the bottom. The minerogenic material in the bottom part of peat core MM1 can indicate that this was a lacustrine environment that was filled up with sediments and turning into a peatland.

The growth of this peatland is probably limited by the water table. With drainage of water towards the south west, the water table will not rise above this threshold. The landscape has a slight sloping towards the south-east, and at the threshold over the bedrock in this direction is where the basin is currently drained. Drainage of excessive water could be a limiting factor in the possible future accumulation of peat in this basin. However, the peat material has a high water holding capacity, and the water table might rise above the threshold when held back in the peat. The shape of the basin trapped water in this pond and caused an oxygen depleted environment where the growth of organic material surpasses the decomposition, and this situation causes the peat to accumulate.

It is likely that the bedrock formations in this area was carved out by the ice during the last ice age. Sediments consists of moraine cover, deposited during the deglaciation. It is reasonable to assume that the peatland started to develop sometime after the deglaciation around 10 ka.

Karlshaugen nature reserve also contain other peat bodies, these with open water. This observation supports my hypothesis that also Midtmyra have once contained a body of open water.

This gives information on the point where, based on field observations, the peatland is currently drain of excessive surface water.

Figure 5 illustrates how the forest boundary have changed from 1930 to 2008. The peatland boundary is changing and several places the forest is growing into the peatland.

Small reflector in the peat unit in the GPR profiles might represent changes in factors controlling peat characteristics, such as temperature, water content/precipitation of botanical composition.

Combined observations from GPR survey, sediment cores and field observations all support the hypothesis on the development of this peatland.

In order to make an estimate of peat accumulation rates, it is possible to divide depth of the peatland by possible age of the peatland. The age is assumed to be approximately 9000 years, because the area was deglaciated at 10000 yr BD, and peatland formation usually takes a while to initiate.

425 cm / 9000 yr = 0.047 cm = 0.47 mm per year.

A comparison of boreal and subarctic peat accumulation rates conducted by Gorham (1991) showed peat accumulation rated ranging from 0.2 mm/yr (Siberia) to 0.75 mm/yr (Finland). Thus, the estimate from Midtmyra is well within the values reported in similar climate zones.

4.5 Future of the peatland

The future of this peatland is uncertain. It depends on factors like future precipitation patterns, and temperatures. Peatland boundary are changing, and several places the treeline have moved into the peatland during the last 70-80 years. It is possible that with more drought during summer, like the summer experienced in 2018 that the water table will lower, and cause degradation of organic material in the peatland.

The peatland forest boundary is changing. It is possible that this peatland at some point in the future will be totally overgrown by the forest, thus the peat is turned into an organic soil.

This process may be part of a positive feedback loop with climate change. Given that this process is reinforced by climate change, and it may cause additional release of greenhouse gases such as CO_2 and CH_4 to the atmosphere.

Further work

This report presents the results from my master thesis. However, there are still some possibilities to take the work with this material even further:

- To analyse the remaining samples in the LECO Truspec instrument to measure the actual carbon and nitrogen values. This could have been used to compare density and carbon stock in different areas of the peatland.
- Pollen analysis of the peat cores. This could be correlated to the established pollen stratigraphy in the area to establish the age depth relationship in the peat profile.
- In order to restrain the age of the peatland a radiocarbon analysis (^{14}C dating) of basal peat and throughout the peat core can give estimates of peat age and accumulation rates. This could also restrain the time of when the area changed from pond to peatland.
- Follow the future development of the peatland, and possible changes in the peat forest boundary.

Conclusion

A GPR survey of the peatland gave the basis for volume calculations. The volume of the grid covered by the GPR is estimated to be 6487 m^3. The grid only partially covers the peatland, which causes this to be an underestimate of the total volume of the peatland.

The peat samples have high values of LOI, ranging well above 90 %. A few of the lowermost samples in core MM1 stands out from these high LOI values, with the lowest value at 6%. Carbon content for the peat varies around 50 %, with the majority of sample resting around 50-54%.

When combining volume of the peatland with bulk density and carbon content of the peat cores, the total carbon stock was estimated to 278 ton carbon.

Shape of the bedrock depression where the peatland is situated together with the discovery of minerogenic material at lowermost part of the peat core supports the hypothesis that this peatland was formed through terrestrializing of an early Holocene pond. This likely happened sometime after the deglaciation of the area. However, from this study it is not possible to accurately tell when this happened.

References

Akumu, C. E. & McLaughlin, J. W. (2013). Regional variation in peatland carbon stock assessments, northern Ontario, Canada. *Geoderma*, 209-210: 161-167. doi: 10.1016/j.geoderma.2013.06.021.

Anderson, D. E. (2002). Carbon accumulation and C/N ratios of peat bogs in North-West Scotland. *Scottish Geographical Journal*, 118 (4): 323-341. doi: 10.1080/00369220218737155.

Belyea, L. R. & Clymo, R. (2001). Feedback control of the rate of peat formation. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 268 (1473): 1315-1321.

Braathe, P. (1981). *Meddelelser fra det norske skogforsøksvesen*, vol. 36: Norsk institutt for skogforskning.

Bradley, R. (2014). *PALEOCLIMATOLOGY (3rd edition)*.

Brady, N. C., Weil, R. R. & Brady, N. C. (2010). *Elements of the nature and properties of soils*. 3rd ed., international ed. Upper Saddle River, N.J: Prentice Hall.

Charman, D. J., Beilman, D. W., Jackson, S., Korhola, A., Mauquoy, D., Mitchell, F., Prentice, I., van der Linden, M., De Vleeschouwer, F. & Yu, Z. (2013). Climate-related changes in peatland carbon accumulation during the last millennium.

Cooper, M., Caritat, P. d., Burton, G., Fidler, R., Green, G., House, E., Strickland, C., Tang, J. & Wygralak, A. (2010). *National Geochemical Survey of Australia: Field Data*.

Everett, M. E. (2013). *Near-surface applied geophysics*: Cambridge University Press.

Fenner, N. & Freeman, C. (2011). Drought-induced carbon loss in peatlands. *Nature geoscience*, 4 (12): 895.

Field, C. B. & Raupach, M. R. (2004). *The global carbon cycle: integrating humans, climate, and the natural world*, vol. 62: Island Press.

Gorham, E. (1991). Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming. *Ecological Applications*, 1 (2): 182-195. doi: doi:10.2307/1941811.

Grønlund, A., Bjørkelo, K., Hylen, G. & Tomter, S. (2010). CO2-opptak i jord og vegetasjon i Norge. *Lagring, opptak og utslipp av CO2 og andre klimagasser. Bioforsk Rapport. Bioforsk*, 5: 38.

Hartemink, A. E. & McSweeney, K. (2014). *Soil Carbon*. Cham: Springer International Publishing : Imprint: Springer.

Huat, B. B., Kazemian, S., Prasad, A. & Barghchi, M. (2011). State of an art review of peat: General perspective. *International Journal of Physical Sciences*, 6 (8): 1988-1996.

Ise, T., Dunn, A. L., Wofsy, S. C. & Moorcroft, P. R. (2008). High sensitivity of peat decomposition to climate change through water-table feedback. *Nature Geoscience*, 1: 763. doi: 10.1038/ngeo331.

Jaenicke, J., Rieley, J., Mott, C., Kimman, P. & Siegert, F. (2008). Determination of the amount of carbon stored in Indonesian peatlands. *Geoderma*, 147 (3-4): 151-158.

Jørgensen, P., Sørensen, R. & Haldorsen, S. (1997). *Kvartærgeologi*. 2. utg. ed. Oslo: Landbruksforl.

Jørgensen, P., Sørensen, R. & Prestvik, O. (2013). *Norske jordarter*: Bioforsk.

Kartverket 2019. https://www.kartverket.no/.

Krogstad, T. (1992). *Metoder for jordanalyser*. Rapport, vol. 6/92. Ås: Norges landbrukshøgskole, Institutt for jordfag.

Limpens, J., Berendse, F., Blodau, C., Canadell, J., Freeman, C., Holden, J., Roulet, N., Rydin, H. & Schaepman-Strub, G. (2008). Peatlands and the carbon cycle: from local processes to global implications-a synthesis. *Biogeosciences*, 5: 1475-1491.

Mitra, S., Wassmann, R. & Vlek, P. L. (2005). An appraisal of global wetland area and its organic carbon stock. *Current Science*, 88 (1): 25-35.

Mitsch, W., Bernal, B., Nahlik, A., Mander, Ü., Zhang, L., Anderson, C., Jørgensen, S. & Brix, H. (2013). Wetlands, carbon, and climate change. *Landscape Ecology*, 28 (4): 583-597. doi: 10.1007/s10980-012-9758-8.

Neal, A. (2004). Ground-penetrating radar and its use in sedimentology: principles, problems and progress. *Earth Science Reviews*, 66 (3-4): 261-330.

Nelson, D. W. & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. *Methods of soil analysis part 3—chemical methods* (methodsofsoilan3): 961-1010.

NGU. 2018. Database for løsmasser [Online]. [Accessed 07.02. 2019].

NVE. (2019). *Nevina Rapport Ørfiskebekken*.

Nygaard, P. H. & Ødegaard, T. (1999). Sixty years of vegetation dynamics in a south boreal coniferous forest in southern Norway. *Journal of Vegetation Science*, 10 (1): 5-16. doi: 10.2307/3237155.

Parry, L., West, L., Holden, J. & Chapman, P. (2014). Evaluating approaches for estimating peat depth. *Journal of Geophysical Research: Biogeosciense*s , 119 (4). 567-576

Parsekian, A. D., Slater, L., Ntarlagiannis, D., Nolan, J., Sebesteyen, S. D., Kolka, R. K. & Hanson, P. J. (2012). Uncertainty in peat volume and soil carbon estimated using ground-penetrating radar and probing. *Soil Science Society of America Journal*, 76 (5): 1911-1918.

Rekdal, Y., Angeloff, M. & Bryn, A. (2016). *Myr i Noreg*.

Rosa, E., Larocque, M., Pellerin, S., Gagné, S. & Fournier, B. (2009). Determining the number of manual measurements required to improve peat thickness estimations by ground penetrating radar. *Earth Surface Processes and Landforms*, 34 (3): 377-383. doi: 10.1002/esp.1741.

Rydin, H. & Jeglum, J. K. (2006). *The Biology of Peatlands*. Biology of Habitats. Oxford: Oxford University Press, UK.

Setiawan, B. I., Arief, C., Saptomo, S. K., Gunawan, A. & Indriyanto, H. (2015). Estimating distribution of carbon stock in tropical peatland using a combination of an empirical peat depth model and GIS. *Procedia Environmental Sciences*, 24: 152-157.

Skog_og_Landskap. (2007). *Markslagstatistikk Karlshaugen naturreservat*: Norsk Instistutt for Skog og Landskap.

Stanek, W. & Silc, T. (1977). Comparisons of four methods for determination of degree of peat humification (decomposition) with emphasis on the von Post method. *Canadian Journal of Soil Science*, 57 (2): 109-117.

Turunen, J., Tomppo, E., Tolonen, K. & Reinikainen, A. (2002). Estimating carbon accumulation rates of undrained mires in Finland–application to boreal and subarctic regions. *The Holocene*, 12 (1): 69-80.

Unhjem, O. H. (2011). *Karbonlagre i Karlshaugen naturreservats myrer : og endringer i myrenes utbredelse fra 1930 til 2010*. Carbon stocks in the bogs of Karlshaugen Nature Reserve and change in the bogs extent from 1930 to 2010. Ås: UMB.

Weckström, J., Seppä, H. & Korhola, A. (2010). Climatic influence on peatland formation and lateral expansion in sub-arctic Fennoscandia. *Boreas*, 39 (4): 761-769. doi: 10.1111/j.1502-3885.2010.00168.x.

Wellock, M. L., Reidy, B., Laperle, C. M., Bolger, T. & Kiely, G. (2011). Soil organic carbon stocks of afforested peatlands in Ireland. *Forestry*, 84 (4): 441-451.

Wieder, R. K. & Vitt, D. H. (2006). *Boreal peatland ecosystems*, vol. 188: Springer Science & Business Media.

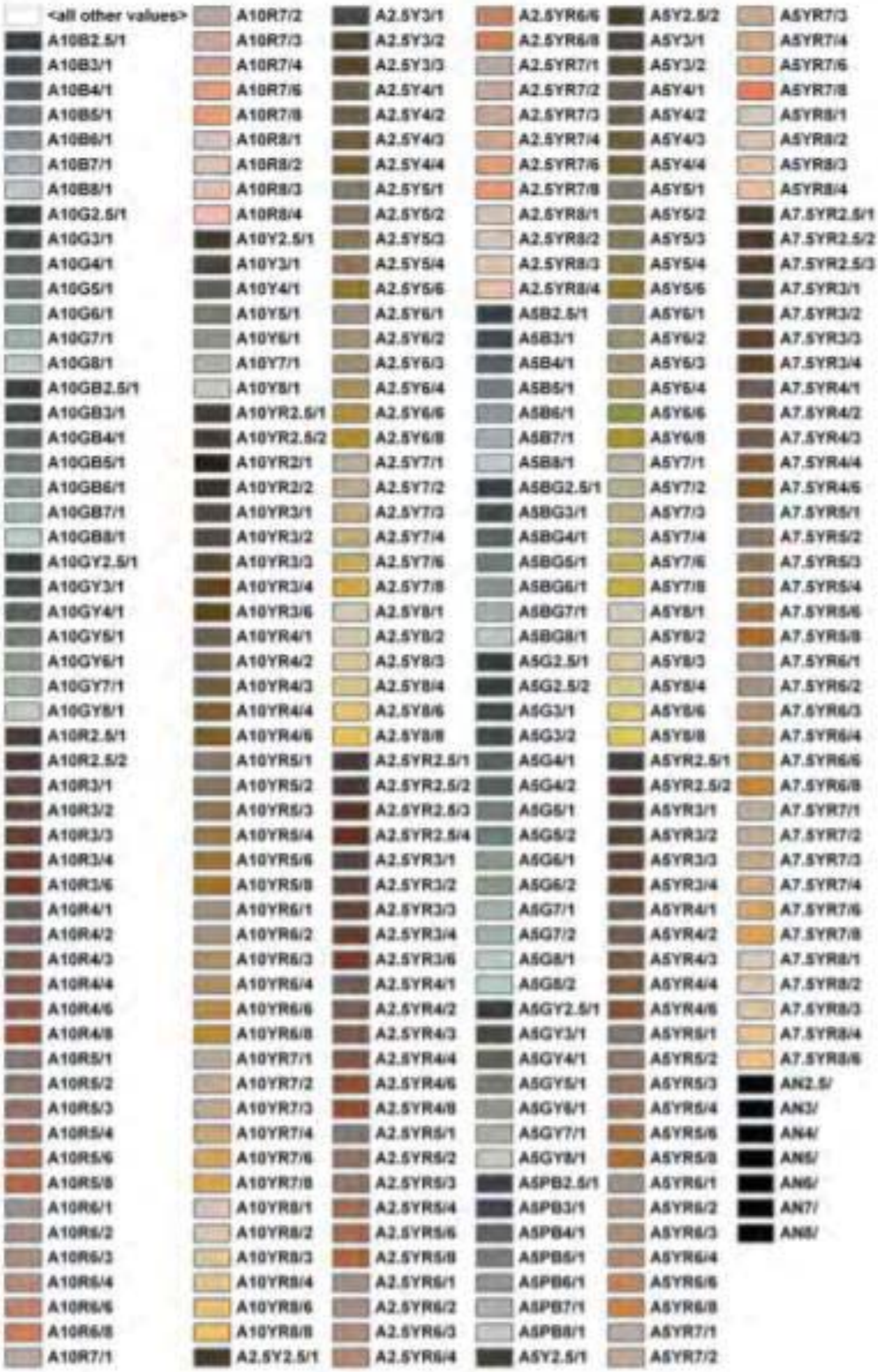
Xu, J., Morris, P. J., Liu, J. & Holden, J. (2018). PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*, 160: 134-140.

Yeloff, D. & Mauquoy, D. (2006). The influence of vegetation composition on peat humification: implications for palaeoclimatic studies. *Boreas*, 35 (4): 662-673.

Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W. & Hunt, S. J. (2010). Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, 37 (13).

Appendix A

Munsell soil colour chart. Taken from Cooper et al. (2010)



Appendix B

Results from Munsell colour assessment.

MM1		MM2		MM3		MM4	
Depth (cm)	Munsell colour code	Depth (cm)	Munsell colour code	Depth (cm)	Munsell colour code	Depth (cm)	Munsell colour code
0-7	5Y: 4/4	0-3	5Y: 6/6	0-5		0-2	5YR: 4/4
7-12	10YR: 4/3	0-23	10YR: 5/4	5-25	10YR: 3/3	2-10	7.5YR: 2/0
12-28	5YR: 3/2	23-31	10 YR: 3/3	25-42	10YR: 3/1	10-33	5YR: 3/2
28-50	5YR: 2.5/2	31-50	10YR: 2/1	42-50	10YR: 2/1	33-50	5YR: 2.5/2
50-90	5YR: 3/2	50-80	5YR: 2.5/1	50-85	5YR: 2.5/1	50-85	5YR: 3/2
90-100	5YR: 2.5/2	80-100	5YR: 2.5/1	85-100	5YR: 2.5/2	85-100	5YR: 2.5/2
100-150	5YR: 2.5/1	100-150	5YR: 2.5/1	100-120	5YR: 2.5/1		
150-200	5YR: 2.5/1	150-200	5YR: 2.5/2	120-150	5YR: 2.5/1		
200-250	5YR: 2.5/1	190-220	7.5YR: 2/0	107-150	5YR: 2.5/1		
250-282	5YR: 2.5/1	220-240	5YR: 2.5/1	150-157	5YR: 2.5/1		
282-300	5YR: 2.5/1						
300-350	7.5 YR: 2/0						
350-375	7.5 YR: 2/0						
375-400	5 YR: 2.5/1						
375-402	5 YR: 2.5/1						
402-418	5 YR: 2.5/2						
418-425	7.5 YR: 4/0						

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway