Høgskulen på Vestlandet

MASTER'S THESIS

Assessing the impact of land-use on soil carbon stored in deep peat

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Master Thesis in Climate Change Management

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This thesis is a part of the master's program in Climate Change Management (Planlegging for klimaendringer) at the Department of Environmental Sciences, Faculty of Engineering and Science at the Western Norway University of Applied Sciences. The author(s) is responsible for the methods used, the results that are presented and the conclusions in the thesis.

Preface

The work on this thesis stretched over many months and I have several people to acknowledge for its smooth execution.

My study originated from the REPEAT project at HVL – REthinking sustainable land use of PEATlands. Thank you to my supervisors, Knut Rydgren and Stein Joar Hegland, for initiating the concept of my study and giving me space to make it my own. Your dedication and patience started in the field and supported me the whole way through.

The methods involved in assembling a field project are often as valuable as the result, and I drew on a large pool of knowledge to learn the necessary skills. Many thanks to Stein Joar Hegland for teaching me proper field and sampling technique. Thank you to Mark Gillespie for technical help with statistics, and for identifying large flaws in my analysis while I still had time to correct them. My gratitude to Knut Rydgren for expertise in the lab and in R, and to Julian Vollering for showing me what professional peat analysis looks like.

Field data formed the backbone of this project, the collection of which would not have been possible alone. My thanks to De Heibergske Samlinger - Sogn Folkemuseum for allowing me access to their fields and letting me climb their fences. Thank you to Maike van der Berg and Clara Edwards, for their energy and tenacity in the mud, and especially to Jochem van Schaick, without whom this would be a literature review.

Lastly, thank you to Ducks Unlimited for inspiring my love of wetlands, and to all those at home who emboldened me to come to Norway to write a Master's.

Abstract

Peatlands accumulate organic material in waterlogged soil and provide stable, long-term storage for carbon. However, peatland carbon stocks are sensitive to disturbance from land-use change and the increase in vascular plant cover. Peat below 0.5 meters is rarely investigated in peatland research but is generally assumed to be recalcitrant and resistant to decomposition, while representing the largest source of potential carbon loss.

In this study I measured peat depth and sampled peat from 0.5, 1.5, and 3 m across varying levels of land-use change within Vestreimsmyrane peatland complex in Kaupanger, Sogndal municipality, western Norway. In total I collected 36 peat cores and 68 depths with vegetation surveys, from 6 sites ranging from intact to drained and cultivated. I calculated soil organic matter (SOM) and bulk density in the lab to estimate carbon density and stocks. I identified patterns of soil carbon loss at depth by using mixed-effect linear modelling to examine the relationships of land-use and vegetation on SOM and bulk density.

The study area had a mean depth of 2.3 m, and the deepest spot was over 9 m. SOM (36.1–97.8%) was 34.6% lower in drained and cultivated sites than intact, while bulk density (0.04–0.32 g/cm^3) was higher, together indicating carbon loss down to 3 m. Vegetation composition was associated with bulk density at 0.5 and 1.5 m, but with SOM only at 1.5 m. Carbon density ranged from a mean of 143 kg/m^2 up to 360 kg/m^2 and closely reflected the depth of the peat. Of the plant types surveyed, only the presence of *Sphagnum* species was an indicator of relative depth, but did not preclude large depths in its absence.

My results show that the impacts of land-use on soil carbon in peatlands extends down to at least 3 m, and that the depth of a peatland is critical to carbon stocks or losses. As *Sphagnum* cannot reliably indicate depth, carbon stock estimates should measure depth when making calculations. Peatland carbon and emissions are likely underestimated in Norway, and a thorough assessment of peatland characteristics is needed to support nature management and planning.

Samandrag på norsk

Torvmark akkumulerer organisk material i vassmetta jord med lite nedbryting, og er deifor eit stabilt og langsiktig lager for karbon. Karbon lagra i torv er likevel sensitivt for forstyrring frå arealbruksendringar og endringar i vegetasjonsdekket. Torv under ein halv meters djupn, som blir rekna for å vera stabil og motstandsdyktig mot nedbrytning, blir sjeldan undersøkt sjølv om den utgjer ei stor kjelde for karbontap.

I dette studiet har eg målt myr djupn og tatt myrprøver frå ein halv, ein og tre meters djupn i myrer som er utsatt for ulike areabruksendringar i myrkomplekset Vestreimsmyrane i Kaupanger, Sogndal kommune, på Vestlandet. Totalt tok eg ut 36 torvkjerner og utførte 68 djupne- og vegetasjonsmålingar i seks lokalitetar som varierter frå intakt myr til drenert myr. Eg analyserte innholdet av organisk material i jorda (SOM) og volumvekt for å kunne berekne karbontettheit og -lager. Påverknaden frå areabruk og vegetasjonsdekke på SOM, volumvekt og karbonlager på ulike djupn blei gjennomført ved bruk av lineær miksa-effekt modellering.

Studieområdet had ein gjennomsnittleg djupn på 2,3 m og det djupaste målepunktet var 9 m. SOM (36.1–97.8%) var 34.6% lågare i drenerte og kultiverte lokalitetar medan volumvekta (0.04–0.32 g/cm^3) var høgare enn i intakt myr, ein indikasjon på karbontap ned til 3 m. Vegetasjonssamansetning, gjennom lyng og tredekke, påverka volumvekta til torv på 1,5 m djupn. Karbontettheit varierte opp til 360 kg/m^2 og var avhengig av myrdybde. Førekomsten av *Sphagnum* artar var den einaste vegetasjonsindikatoren som kunne forklare torvdjupn, sjølv om det også var fråver av *Sphagnum* på djupe målepunkt i mitt studieområde.

Mitt studie viste at både torvdjupn og arealbruksendringar har stor effekt på karbonlageret i myr, og at effekten av arealbruksendringar kan gå langt ned. Vegetasjonsdekke gir ikkje alltid ein indikasjon på djupn og difor heller ikkje karbonlageret i torvmark, og myrdjupn bør målast når ein skal utføre berekningar. Karbontap frå myr er sannsynlegvis underestimert i Norge og ein meir grundig vurdering av torvmark sine eigenskapar er nødvendig for å kunne støtte opp om fornuftig forvaltning av desse vikitge økosystema.

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1 Introduction

Globally, over 2300 Gt of carbon is stored in the top three meters of soil from deposition of plants and dead organisms, more than stored in living biomass and the atmosphere combined (Stockmann et al., 2013). Although soil carbon is in constant flux to the atmosphere, in appropriate conditions the rate of carbon accumulation is greater than respiration and stocks increase over time (Loisel et al., 2017). Peatlands have been accumulating soil organic carbon (SOC) in cool, wet climates across the northern hemisphere since the last ice age due to waterlogged soils that limit decomposition rates (Harris et al., 2022; Hu et al., 2017; Yu, 2012). SOC is contained in soil organic matter (SOM), plant material that has been weakly decomposed and incorporated into the soil. Peatlands by definition contain a minimum 30 cm thick layer of soil which is more than 30% organic content (Joosten, 2009; Loisel et al., 2017). Consequently, peatlands contain a disproportionate amount of SOC per hectare compared to other ecosystems (Bartlett et al., 2020; Harris et al., 2022), storing around 30% of SOC on just 3% of land area (Yu et al., 2021). Most decomposition occurs in the top 0.5 meters (m), where labile carbon is mineralized and returned to the atmosphere (Bader et al., 2018). Below 0.5 m, SOC is recalcitrant and much more resistant to decomposition, comprising a reservoir that can remain intact for many thousand years (Bader et al., 2018; Simo et al., 2019).

However, SOC storage in peatlands is sensitive to changes in moisture regime induced by a lowered water table (Kasimir-Klemedtsson et al., 1997; Liu et al., 2016; Moore & Knowles, 1989). When exposed to the air, peat dries and decomposes, transforming its vast SOC stocks into an enduring source of CO_2. Post drainage, peatlands continue to emit for many decades; degraded peatlands are currently responsible for an estimated 5% of global CO_2-eq emissions contributing to climate change (Leifeld et al., 2019). The main cause of peatland disturbance over the last centuries is drainage for forestry and agricultural use by installing ditches (Qiu et al., 2021). Agriculture has a particularly strong impact on SOC by not only lowering the water table, but also continuously aerating the topsoil, promoting mineralization, and removing plant litter (Bader et al., 2018; Qiu et al., 2021). The response of SOC to revegetation following abandonment or afforestation is more ambiguous; studies show affected peatlands ranging from strong sources to weak sinks of carbon (Hargreaves et al., 2003; Lohila et al., 2011; Ojanen et al., 2014; Strand et al., 2021; Wang et al., 2018). Nevertheless, shifting a peatland from its intact state can have long-lasting and long-reaching effects on local and global carbon storage (Qiu et al., 2021).

Globally over a third of peatland area has been disturbed, most intensely in the northern hemisphere (Hu et al., 2017; Qiu et al., 2021). In Norway, approximately 8.9% of land cover is classified as peatland (Bryn et al., 2018), although this may be a low estimate and be as high as 12.7% in southern Norway (Bakkestuen et al., 2023). Due to historic ditching for agriculture and more recent infrastructure development an estimated 7000 km^2 of Norwegian peatland is currently drained or permanently lost (Øien et al., 2015). Even with these losses, Norway's high proportion of peatland makes the relatively small country a disproportionate store of global carbon (Bartlett et al., 2020). Consequently, understanding and managing peatland SOC content in Norway is an important tool for planning development and conservation projects (Harris et al., 2022; Joosten, 2009; Shukla et al., 2022) as well as a potent strategy for mitigating climate change.

Three key parameters are necessary to measure SOC density in a peatland: peat depth (m), bulk density (g/cm^3) and SOM (% mass) (Yu, 2012). All three can vary considerably, and inaccurate approximations are responsible for over-and under estimations of peatland carbon storage (Bauer et al., 2006; Loisel et al., 2017; Yu, 2012). While the technology for remote depth and extent mapping is advancing rapidly (Gatis et al., 2019), collecting field data for SOC remains time consuming and very few peatlands in Norway have been assessed this way. Instead, estimations of SOC in Norwegian peatlands have used generalized parameters based on ecosystem type to calculate carbon stocks (Grønlund et al., 2010). On a smaller scale, vegetation indicators are used to assess whether degraded and/or restored peatland are currently sequestering carbon, or if an area is a peatland at all (Kyrkjeeide et al., 2018). However, in many mixed-use and abandoned peatlands the effects of disturbance on SOM are not well understood and vegetation indicators can be misleading (Bauer et al., 2006; Lohila et al., 2011; Strand et al., 2021), leaving SOC inventories and management strategies inconclusive.

Following initial losses from drainage, emergent vegetation can create feedbacks that exacerbate or reverse SOC losses (Lohila et al., 2011; Strand et al., 2021). Certain plant types regulate conditions in peatlands; notably, *Sphagnum* moss has an upward effect on the water table, acidity, and SOM compared to trees and other vascular plants (Maanavilja et al., 2014; Palozzi & Lindo, 2017; Uhelski et al., 2022). Trees and graminoids have both been shown to limit the height of the peatland water table, with as comparable effects on peat properties as latitude (Uhelski et al., 2022). Vascular plants can raise SOM by inputting carbon through their roots (Lohila et al., 2011), however the direction of this relationship may depend on nutrient availability (Liu et al., 2022). The addition of plant carbon through the roots of vascular plants can stimulate decomposition in nutrient poor soil, exacerbating the release of SOC in drained peatlands (Liu et al., 2022; Robroek et al., 2016). This effect is strongest in highly decomposed peat or where nutrient cycling is limited by low pH, both characteristic of deeper peat layers (Bader et al., 2018). Extending as far as 10 m below the surface, deep peat is sensitive to large SOC loss when conditions become oxic and vascular plants are introduced (Liu et al., 2022; Liu et al., 2016). Despite this, few studies (Lorenz & Lal, 2005; Uhelski et al., 2022; Wellock et al., 2011) have tested the effect of land-use change on peat SOM below 1 m.

Peat structure also undergoes changes following drainage and shift in plant species composition with notable impacts on bulk density (Palozzi & Lindo, 2017; Wellock et al., 2011). In intact peatlands low bulk density represents high moisture and SOM, often decreasing with depth (Frogbrook et al., 2009; Parry & Charman, 2013; Strand et al., 2021). Following peatland drainage and subsequent loss in moisture and SOM, subsidence of the soil column results in greater bulk density, indicating degradation (Kasimir-Klemedtsson et al., 1997; Pitkänen et al., 2013; Sloan et al., 2019). Compaction and evapotranspiration from vascular plants typically increase bulk density at the surface (Bader et al., 2018), causing SOC loss and lower overall SOC content (Uhelski et al., 2022; Wellock et al., 2011; Wüst-Galley et al., 2016). However, humification at the surface may protect peat at lower layers from oxidation, preserving structure. Therefore, the presence of ditches alone is not enough to predict how a peatland has responded to land-use change, or how SOC has been affected throughout 3-dimensional space.

Although interactions and properties of the top 0.5 m of peat are a growing research topic, little knowledge has been gathered on the extent that these findings extend into deeper reservoirs of peat. As deep peat constitutes a substantial amount of SOC that may be at risk of loss, understanding its properties is important for climate mitigation strategies. To fill this gap, I analyzed the effects of drainage and vegetation on deep peat SOC at the site and point level in a typical peatland complex in western Norway. I collected field data across three levels of land-use to a) determine the extent that SOC at depth depends on the historical use of drains and agriculture; and b) assess the relationships between vegetation, peat degradation, and peat depth. Understanding how these surface characteristics relate to peatland properties may assist in evaluating and managing peatland sites.

As SOC is a product of bulk density and SOM over the depth profile, I examined these factors separately before evaluating their aggregate effect on SOC. I used an ecosystem approach of a small peatland complex that has undergone various levels of drainage, cultivation, and subsequent abandonment. I also characterized the peatland and its carbon stock.

2 Methods

2.1 Study Area

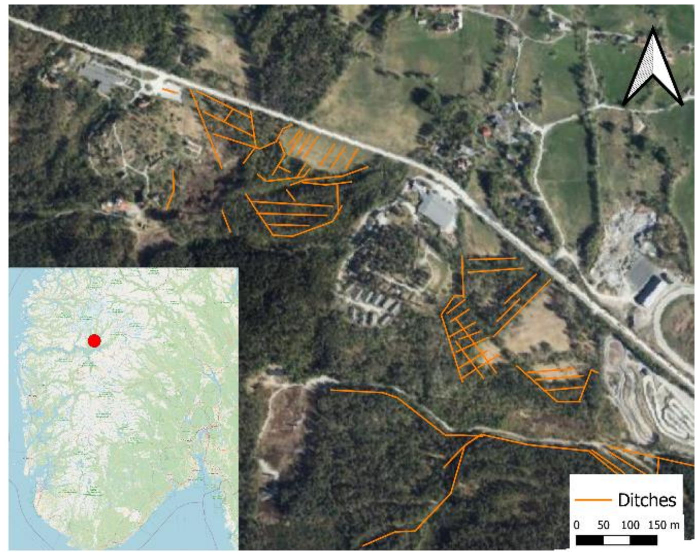

Figure 1. The study area near Kaupanger in Sogndal municipality, Vestland county, Norway. Ditches (orange) were traced from a lidar scan (Danailov, 2019) and formed the basis of the study sites.

The peatland complex used in this study is in Vestreimsmyrane near Kaupanger, Sogndal municipality, western Norway, (61.20491°N, 7.19202°W) covering 0.15 km^2 at ca. 190 meters (m) above sea level (Fig. 1). Mean annual temperature is 4.5°C, mean July temperature is 15°C, and mean total annual precipitation is 750–1000 mm (senorge.no). The area has gentle topography sloping down to the southwest, and is bisected by fences, streams, and an upland development in the middle. The study area is delimited by a museum to the west (De Heibergske Samlinger - Sogn Folkemuseum), to the north a highway, and the east a dog park. The southern edge is bordered by a steep bank and transition to forest.

Although the area is categorized as mire, parts of the complex were ditched in the last century and have developed along several trajectories, divided here into 6 sites (Fig. 2). The intact part of the peatland can be characterized as a fen due to flowing groundwater. The ditched sites consist of pine and birch forested areas (Table 1), and pasture that has been tilled and fertilized in the past and is currently only harvested once a year. Based on observed changes in land-use from historical satellite photos, the sites were assigned to one of three land-use intensities: Intact, no drains (Intact); Drains, no agriculture (Drained); drains, past or present agriculture (Cultivated) (Table 1).

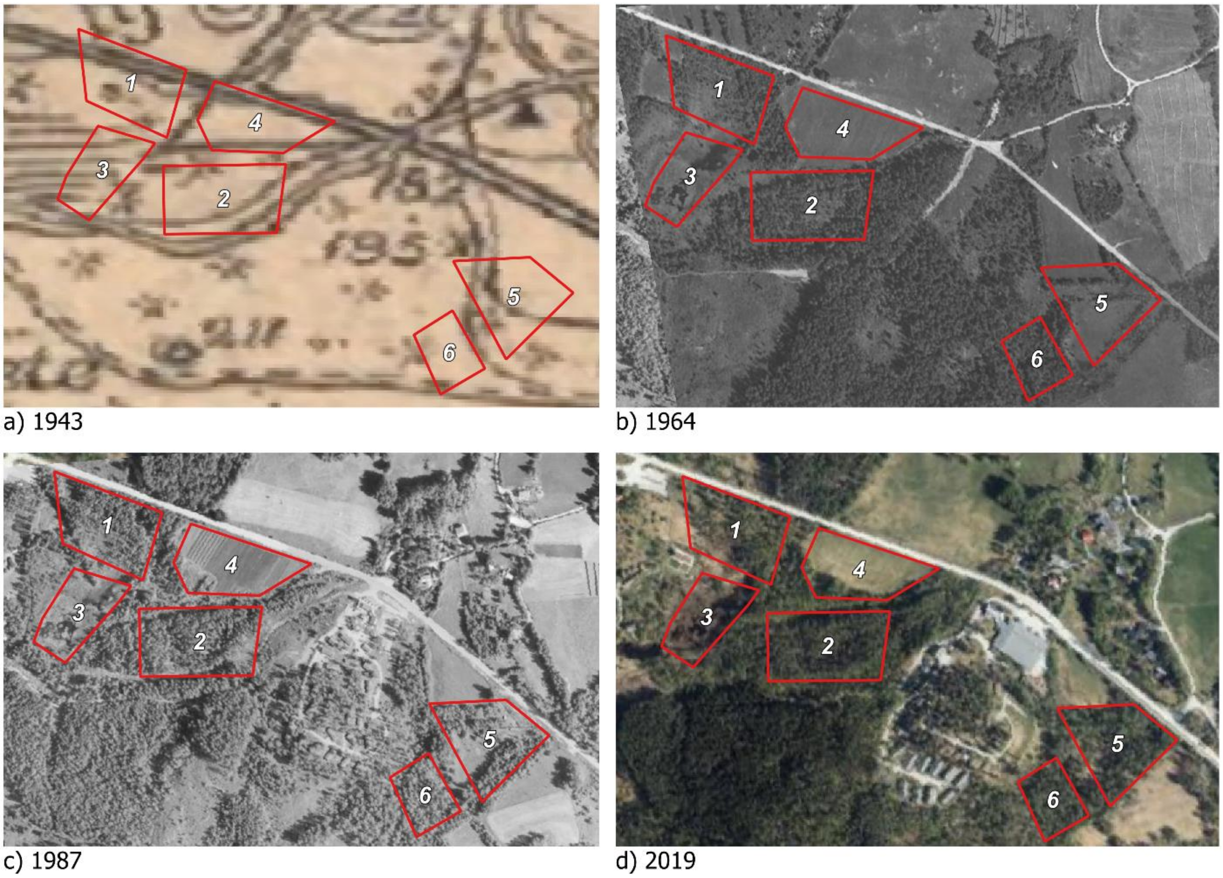

Figure 2. Overview maps of the study sites showing change over time: 1943 (drawn), 1964, 1987, 2019 (Geovekst, 2017). Red outlined sites are described in Table 1. Signs of agriculture were already present in 1943, indicating that drains may have been established by then. Agriculture appears to be most intense in 1964 and 1987, although section 3 is never affected. By 2019 only site 4 is actively used, as pasture.

Table 1. Study site classification based on land-use since 1943.

Site	Description	Land-use
1	Partial forest and horse pasture that appears to have decreased in tree cover since 1964.	Drained
2	Deeply hummocked bilberry-pine forest, that may have contained an open meadow in 1964	Drained
3	Intact fen with a stream that was marked in 1943 and has changed little since 1964	Intact
4	Field used as pasture. It appears to have been cultivated in 1943, and downgraded to pasture sometime after 1987	Cultivated
5	Grassy meadow, cultivated in 1964 or earlier but abandoned sometime after and gradually encroached by shrubs and trees	Cultivated
6	Hummocky bilberry-pine forest that has remained unchanged since 1964	Drained

This peatland is one of many in the Kaupangerskogen valley observable from maps and arial photos, although one of the few that has not been built over and destroyed. My study site then likely once belonged to a larger peatland complex, and is now the remaining area left to peatland in the vicinity. Characterics measured here can be assumed to represent past peatland over the entire area that can no longer be observed directly.

2.2 Data Collection

2.1.1 Site Analysis

I obtained lidar data from hoydedata.no (Danailov, 2019) and processed it in QGIS 3.30.0 (QGIS.org, 2022). Inspecting the slope revealed ditches by their contrast to the otherwise relatively flat area. I established my 6 sites by tracing the most apparent ditches and grouping them by proximity and dominant vegetation. To create a representation of the entire site and avoid geometric inaccuracy (Loisel et al., 2017) I objectively placed 10–15 sample points in a spiral pattern starting at the edges and ending in the centre (Fig. 3). Points were approximately 20 m apart from each other and placed in-between rather than on the ditches. I then located points in the field with +-4 m accuracy during September and October 2023.

Figure 3. Depth points were placed objectively in a rough spiral pattern within each site and adjusted for topography in the field. Peat samples were taken at select points to represent the site.

2.1.2 Depth Measurements

I measured soil depth with a peat spear at all sample points to the nearest possible accuracy (Fig. 3), adjusting when the point fell within 1.5 m of a tree, in a ditch, in deep water, or on a raised slope that was clearly outside the limits of the peatland. In these cases, the point was relocated to the nearest appropriate spot and the coordinates were updated. I assessed the bottom of the peat as the transition from compressible material to hard substrate. The height of the rod above ground was measured from the bottom of the vegetation up to the next 1 m joint with 1 cm accuracy, thereby calculating depth (Table 2). In instances where multiple depths were taken at the same point due to rocks, roots, or uncertainty, only the largest depth was used. All measurements were taken by myself or under my supervision to ensure consistency.

2.1.3 Vegetation Index

I performed a vegetation survey of plant type composition surveyed at each point following the depth measurement. I estimated the proportion of cover of each plant type within a 1 m radius circle around the depth point within the following seven categories: *Sphagnum*, other mosses, graminoids, herbs, shrubs, trees, or litter. Proportions were recorded in 1/10s or 1/20s, and sum to 1.

Figure 4. Peat was measured with a peat spear and meter stick (A). Peat cores were brought up by the Russian Corer (B). After loss-on-ignition only ash was remaining in the crucibles (C).

2.1.4 Peat sampling

I took samples of peat with a Russian corer at three points per site, selected to represent variation in the area and depth of the site. The target depths were 0.5 m, 1.5 m, and 3 m, measured from the mid-point of the corer, representing upper, mid, and lower layers of peat. Sampling below 3 m requires equipment not accessible for this study. At points where the depth was less than 3 m, only 0.5 and 1.5 m were sampled, and in shallower than 1.5 m only the 0.5 m layer. Points with less than 0.5 m depth were removed from sampling and another point was chosen. Of the 50 cm length of the peat core, I took a 10 cm section in the bottom third to be bagged in plastic, labelled, and transported to the drying cabinet within 6 hours (Fig. 4). Few samples contained large pieces of plant matter, but when they occurred they were not removed. In total, I analyzed 38 peat samples from 18 collection points (Table 2). Thirteen points were deep enough to take a 1.5 m sample, and 6 were deep enough for a 3 m sample. I weighed the wet samples and transferred them to a paper bag, then placed them in a 40° C drying cabinet to remove moisture over several days. I re-weighed the dry samples and stored them at room temperature until further analysis.

2.1.5 Loss-on-ignition

I determined soil organic material (SOM) through loss-on-ignition following Krogstad (1992). I first prepared the crucibles by burning them in the oven at 550° C for five hours before recording the mass of each (W1). I filled each crucible with a portion of dried sample and re-dried them in a 105° C oven for 12+ hours to remove all moisture. I then took the mass of the dried sample and crucible (W2) and burned them at 550° for 5 hours (Fig. 4). After cooling in the exicator for a minimum of 12 hours I recorded the final mass of the crucible and burned sample (W3). With my three recorded masses I used the following formula (1) to calculate % SOM:

1) $$SOM\% = [(W3 - W1) / (W2 - W1)] * 100$$

Only SOM over 30% is considered organic matter and qualifies as peat (Yu, 2012), but all samples were included in further analysis for completeness.

Soil organic carbon (SOC) (%) was found from SOM by multiplying with a conservative carbon proportion factor of 0.5 (Yu, 2012). The volume of the core samples was calculated as 98.17 cm^3 from the radius of the Russian Corer (2.5 cm) and the length of the sample (10 cm) according to the following formula (2):

2) $$V = \frac{1}{2} * \pi * r^2 * h$$

Bulk density (g/cm^3) was calculated as the mass of dry peat divided by volume, and carbon density (kg/m^2) was calculated as the product of bulk density, SOC, and depth (Table 2).

2.1.6 pH

To characterize the nutrient availability of the peat I performed pH analysis on each of the peat samples following Krogstad (1992), using a SenTix® pH meter calibrated with 4, 7, and 10 pH solution. I prepared samples from the remaining peat by first crushing it with a mortar and pestle, then mixing a 2:5 ratio of 20 ml dried peat to 50 ml distilled water in a tube. The tubes were shaken vigorously by hand to combine and left for 12+ hours, then shaken again. For each sample, I inserted the rod into the liquid above the sediment and recorded the reading and temperature when the measurement had stabilized (Table 2). One sample did not contain enough fresh peat to test pH and was removed from analysis.

Table 2. Descriptive statistics of variables recorded in the peatland complex of Vestreimsmyrane.

Data	N	Unit	Range	Mean	Measurement
Depth	68	m +- 0.01	0.09–9	2.34	Peat spear
Vegetation Survey	68	% cover	0–100	-	Visual in field
Core Layer	18	m +- 0.25	0.5, 1.5,	-	Russian Corer
Moisture	37	% mass	45–94	86%	[Wet weight (g) – dry weight (g)] / wet weight
Soil organic matter	37	% mass	36.1–97.8	87.7%	Loss on Ignition (Krogstad 1992)
pH	36	pH	4.1–5.7	5.1	Lab measurement (Krogstad 1992)
Bulk density	37	g/cm^3	0.04–0.32	0.125	Dry weight (g) / volume (cm^3)
Carbon density	37	kg/m^2	34.5–360.8	143.3	SOM (%) * bulk density (g/cm^3) * 0.5 * depth (m)
Site history	-	Use	1, 2, 3	-	Satellite photos, field observation

2.2 Data Analysis

All statistical analysis was completed in R 4.1.1 (R.Core.Team, 2023) with “vegan” and “lme4” packages. SOM was logit-transformed prior to analysis (Warton & Hui, 2011) to overcome its bounded, non-binomial properties, and the 3 m layer was removed from layer analysis to remove rank deficiency. For tests with bulk density three outliers were removed due to sand content and lab error.

I created mixed-effect linear (LME) models with random factors to test the response of SOM and bulk density to individual site differences (‘Site’) and land-use intensity (‘Use’) across layers (‘Layer’). As peat samples were taken from multiple layers at the same point, ‘Layer’ is nested within sample point to account for pseudospatial replication (formulas 3 & 4). I simplified the model to find the minimum adequate model, comparing models with ANOVA to test likelihood ratio (Crawley, 2012). Relationships were considered significant when $p<0.05$.

3) SOM ~ Site * Layer + 1|samplepoint
4) SOM ~ Use * Layer + 1|samplepoint

I tested the effects of 'Site' and 'Use' again with bulk density as a response variable in additional LME models (formulas 5 & 6) to find the effect of land-use on peat compaction.

5) Bulk Density ~ Site * Layer + 1|samplepoint
6) Bulk Density ~ Use * Layer + 1|samplepoint

Vegetation and depth analysis demanded further synthesis of the measured variables. To represent average SOM throughout each entire point column I created a weighted average of SOM for each point (LW) and transformed it by logit. An ANOVA confirmed that sample point was a significant predictor of SOM, justifying aggregation. I used weighted SOM (LW) to compare against depth at each sample point. I analysed Depth in Drained and Cultivated sites separately to isolate relationships in each land-use (formula 7).

7) $SOM_{Drained,\ Cultivated}$ ~ Depth + 1|Site

To create a single variable representing plant type cover values, I used a principle component analysis (PCA on a correlation matrix) of the vegetation survey matrix and used the primary axis in further analysis. I created a LME model to test the response of LW to PCA with 'Site' as a random factor, and further compared SOM at 0.5 and 1.5 m to PCA separately (formula 8). I compared Bulk Density in all layers to PCA using both 'Site' and 'samplepoint' as random factors (formula 9).

8) $SOM_{LW,\ 0.5,\ 1.5}$ ~ PCA + 1|Site
9) Bulk Density ~ PCA + 1|Site + 1|samplepoint

I tested the effect of individual plant cover on bulk density and SOM using LME modeling (formulas 10 & 11). Tree, *Sphagnum*, Graminoid, and Shrub cover were each transformed by logit to create additional indexes for individual plant types.

10) $SOM_{LW,\ 0.5,\ 1.5}$ ~ $Plant_{tree,\ sphm,\ graminoid,\ shrub}$ + 1|Site
11) Bulk $Density_{0.5,\ 1.5}$ ~ $Plant_{tree,\ sphm,\ graminoid,\ shrub}$ + 1|Site

To test the strength of vegetation as a predictor of depth, I again aggregated the vegetation survey matrix of the entire point dataset by PCA, and compared the first and second axes to depth with a LME model (formula 12). I further compared depths in the absence and presence of individual plant types (formula 13).

$$12)\ \text{Depth} \sim \text{PCA}_{1,2} + 1|\text{Site}$$
$$13)\ \text{Depth} \sim \text{Logit Plant}_{\text{tree, sphm, graminoid, shrub}} + 1|\text{Site}$$

For visualization, logit-transformed variables were back-transformed with “visreg” package following Breheny and Burchett (2017). I checked residual distributions with the DHARMa package to confirm model validity (Hartig, 2022) and discounted results that did not conform to distribution assumptions.

I estimated the carbon content of the study area in QGIS 3.30.0 (QGIS.org, 2022). Overall depth and carbon density for each layer were interpolated with the triangular irregular network method to fill the study sites in a 1x1 m raster. I calculated the surface carbon density (kg carbon/m^2) by multiplying layer depth (m) and carbon density (kg/m^3) for each layer separately, and added them together to find the total surface density, following Simo et al. (2019). Where depth was over 3 m, I used the 3 m measurements for the remaining depth. I then found cumulative carbon content in each site with the zonal statistics tool in GQIS.

3 Results

I measured peat depth at 68 points, ranging from 0.09 meters (m) in site 1 to over 9 m in site 3. Two-thirds of the points measured were < 2 m in depth, and all depths > 5 m were found in site 3 (Fig. 5). SOM ranged from 8.6–97.8% and bulk density from 0.04–0.32 g/cm^3. Peat pH was lowest in site 1 but showed large variation within each site, with the most acidic conditions found in the top layers.

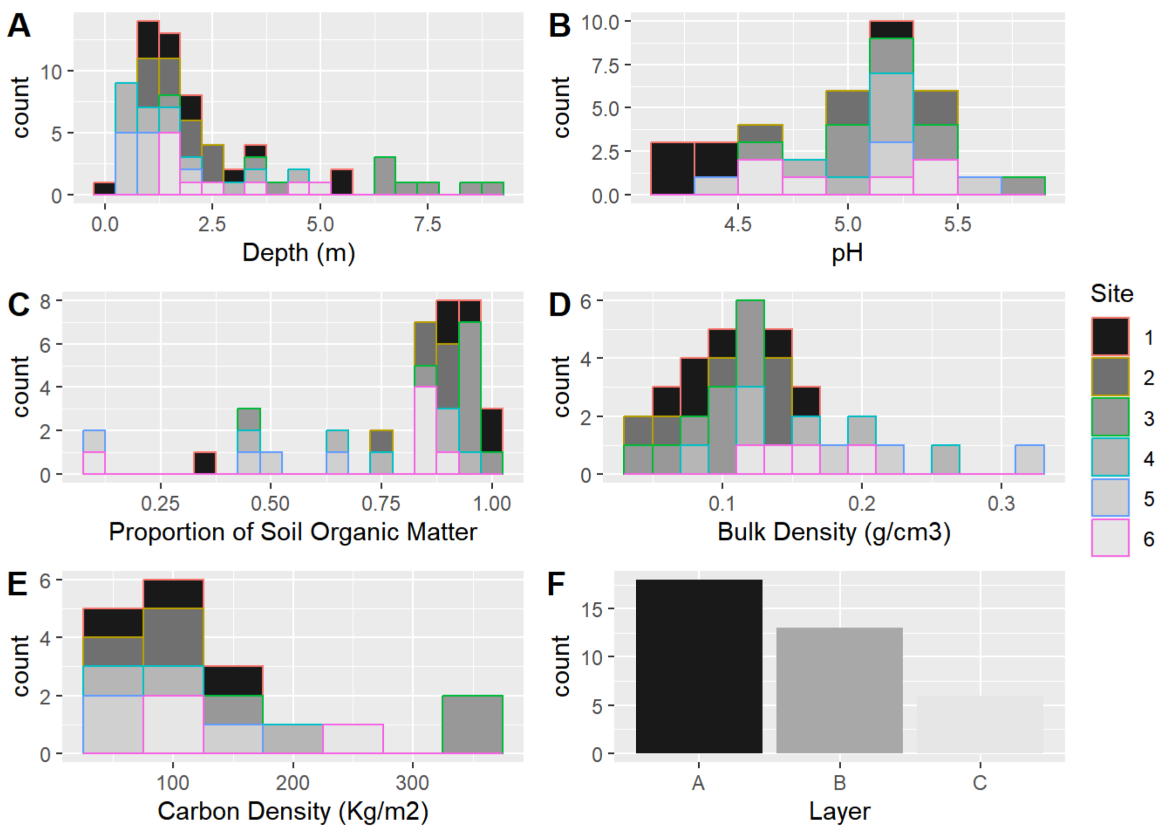

Figure 5. Histograms of data collected in Vestreimsmyrane, Kaupanger, Western Norway. Values are coloured according to site. Two outliers were removed from bulk density (D) for optimal scaling. Carbon density (E) is a composite of depth, soil organic matter, and bulk density. Layer count (F) shows how many samples were taken from each layer.

3.1 Effect of land-use changes on organic matter and soil density

Average SOM roughly halved between the highest site (site 1) and the lowest (site 5) at 0.5 and 1.5 m (Fig. 6a). Sites 1 and 3 together constituted the highest SOM values in the minimum adequate model, while site 5 by itself had the lowest and sites 2, 4, and 6 had similar values together in the middle (Table 3). When grouped by land-use SOM decreased significantly as intensity increased (Fig. 6b); Cultivated sites had a median SOM (66.2) 34.6% lower than the Intact site (93.9), whereas Drained sites had SOM values in-between the other land-uses (median 86.8). Bulk density also varied by site and land-use (Fig. 6c): lowest in the intact site and highest in drained sites with agriculture; bulk density was highly negatively associated with SOM ($p<0.05$). Neither SOM or bulk density differed between layers and the interaction effect of layer between sites was also non-significant ($p>0.05$).

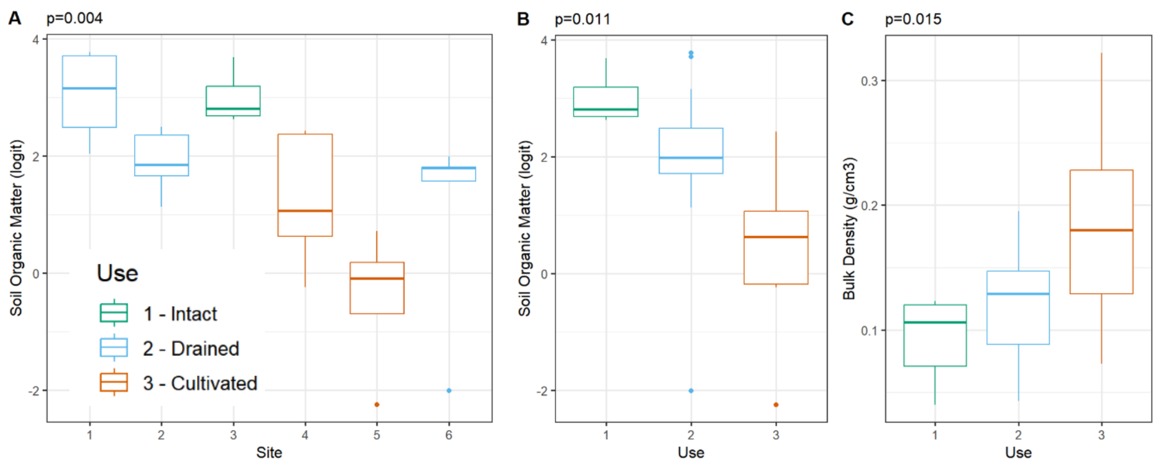

Figure 6. Soil organic matter across sites at 0.5 and 1.5 m depths in a peatland complex, western Norway (A). LME modeling (B) showed significant differences when grouped by Use. Bulk Density (C) also had significant differences between Use classes. Compared to the intact site, Cultivated sites showed the largest change in both properties

Table 3. Results of linear mixed-effect modelling showing the effect of site and land-use on SOM and bulk density.

	SOM					Bulk Density				
Fixed Factor	**Estimate**	**SE**	**df**	**t value**	**p value**	**Estimate**	**SE**	**df**	**t value**	**p value**
Site 1_3 (intercept)	3.03	0.34	12.4	8.73	-	0.1	0.02	8.7	4.82	-
Site 2_4_6	-1.62	0.45	12.5	-3.61	**0.003**	0.06	0.03	8.7	2.12	**0.064**
Site 5	-3.55	0.65	16.2	-5.5	**<0.001**	0.14	0.04	11.3	4.15	**0.001**
Intact (intercept)	2.98	0.65	12.3	4.56	-	0.09	0.02	8.4	3.68	-
Drained	-0.95	0.76	12.6	-1.26	0.232	0.02	0.03	9.2	0.67	0.520
Cultivated	-2.69	0.82	13.4	-3.29	**0.006**	0.11	0.03	9.8	3.15	**0.011**

Note: The minimum adequate model grouped the sites into 1 and 3; 2, 4 and 6; and 5. Each group showed significant difference from each other from both p value <0.05 and more than 2 SE difference in estimate. When grouped by use intensity Intact and Cultivated are significantly different by p value, and Drained is more than 2 SE difference in estimate. Bold indicates significance.

The intact site was on average more than twice as deep as the median depth, while Cultivated sites had the smallest average depth. However, depth had no relationship with weighted SOM overall (Table 4). Only within Cultivated sites did SOM formed a weak positive relationship with Depth (Fig. 7).

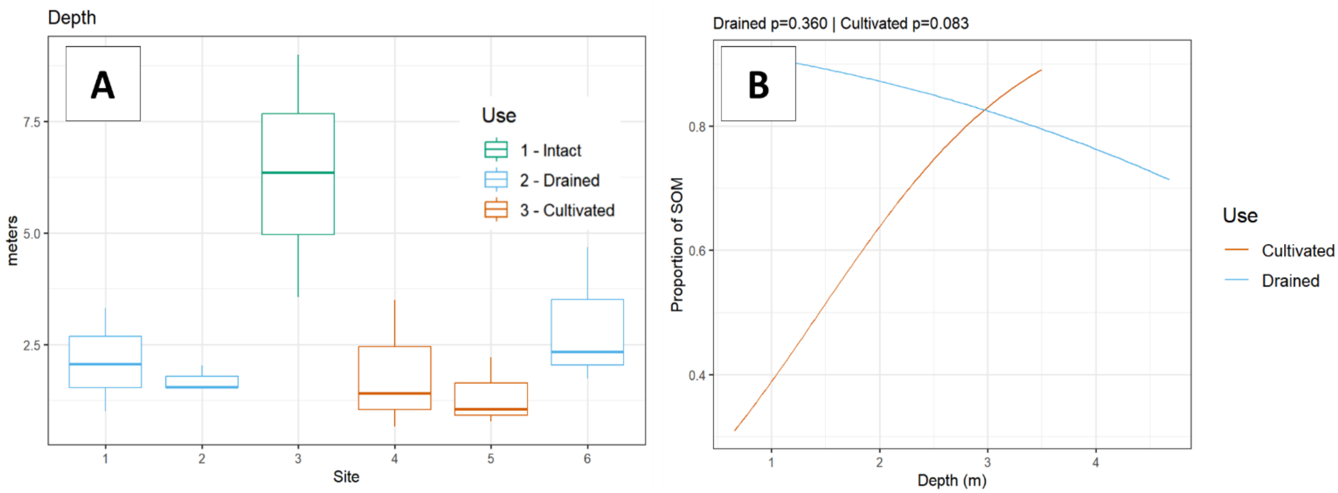

Figure 7. Depth across sites (A) and in relationship to SOM (B). Within Cultivated sites, which were also the shallowest, shallower points had significantly lower average SOM.

Table 4. Fixed effects of Mixed-Effect Linear Modeling between average SOM and depth, separated by land-use type.

Fixed Factor	N	Estimate	SE	df	t value	p value
Depth (all land-uses)	18	0.23	0.17	14.9	1.32	0.206
Depth (Drained)	9	-0.38	0.38	6.9	-0.98	0.360
Depth (Cultivated)	6	1.02	0.41	3.2	2.51	*0.083*

Note: *Only within the highest Use intensity (Cultivated) does depth elicit a corresponding change in SOM. Although p value is between 0.05 and 0.1, the estimate is more than 2 SE from the intercept (0). N refers to the number of points in each land-use type. When depth is compared to SOM in Drained sites, or across all land-uses, no relationship is apparent.*

3.2 Relationships between peat characteristics and vegetation composition

Principle component analysis (PCA) of the vegetation survey created an index of variation in vegetation cover represented along two axis (appendix). SOM was mostly independent of vegetation composition, only correlating with the first axis of the PCA at 1.5 m (appendix). When assessed individually, shrub cover was exclusive in eliciting a relationship (positive) with SOM, and again only at 1.5 m (Table 4).

Table 1. Results of linear mixed-effect modelling showing the relationships between SOM and bulk density and vegetation cover, at 0.5 and 1.5 m.

	SOM					Bulk Density				
Fixed Factor	**Estimate**	**SE**	**df**	**t value**	**p value**	**Estimate**	**SE**	**df**	**t value**	**p value**

PCA (all layers)	0.83	0.41	7.2	1.99	*0.086*	-0.05	0.01	9.1	-2.9	**0.017**
PCA (0.5 m)	0.39	0.43	15.9	0.91	0.377	-0.05	0.02	14	-2.4	**0.031**
PCA (1.5 m)	1.28	0.41	11	3.14	**0.009**	-0.05	0.02	5.9	-3.45	**0.014**
Shrub (0.5 m)	0.05	0.22	14.4	0.23	0.822	-0.03	0.01	14	-2.15	**0.049**
Shrub (1.5 m)	0.62	0.28	11	2.21	**0.049**	-0.02	0.01	4.3	-2.15	*0.093*
Tree (0.5 m)	-0.02	0.27	12.5	-0.09	0.924	-0.02	0.01	9.6	-2.48	**0.033**
Tree (1.5 m)	-0.21	0.37	10.7	-0.57	0.581	0.03	0.01	9.6	2.59	**0.028**
Grass (0.5 m)	0.03	0.24	15.5	0.16	0.879	0.02	0.01	2.9	2.31	0.106
Grass (1.5 m)	-0.41	0.29	10.7	-1.42	0.183	0.01	0.01	5.1	1.2	0.282
Sphagnum (0.5 m)	0.11	0.25	15.6	0.44	0.662	0	0.01	0.1	0	0.990
Sphagnum (1.5 m)	0.45	0.28	7.2	1.61	0.151	-0.03	0.01	6.6	-4.11	0.005*

Note: *Vegetation cover was first compared to SOM and bulk density as the first axis of a principle component analysis (appendix), then as the cover of individual plants. Bold indicates significance, * denotes un-uniform residuals and is discounted.*

Bulk density had a negative relationship with the first axis of the PCA in all layers ($p<0.05$), but most pronounced at 1.5 m (appendix). Certain plant types related to bulk density when assessed individually ($p<0.05$), though not consistently between layers. Increased shrub cover was associated with lower bulk density in both layers (Fig. 8) while tree cover was found with lower density at 0.5 m, but higher density at 1.5 m. pH did not have a relationship with any other variable, at any depth.

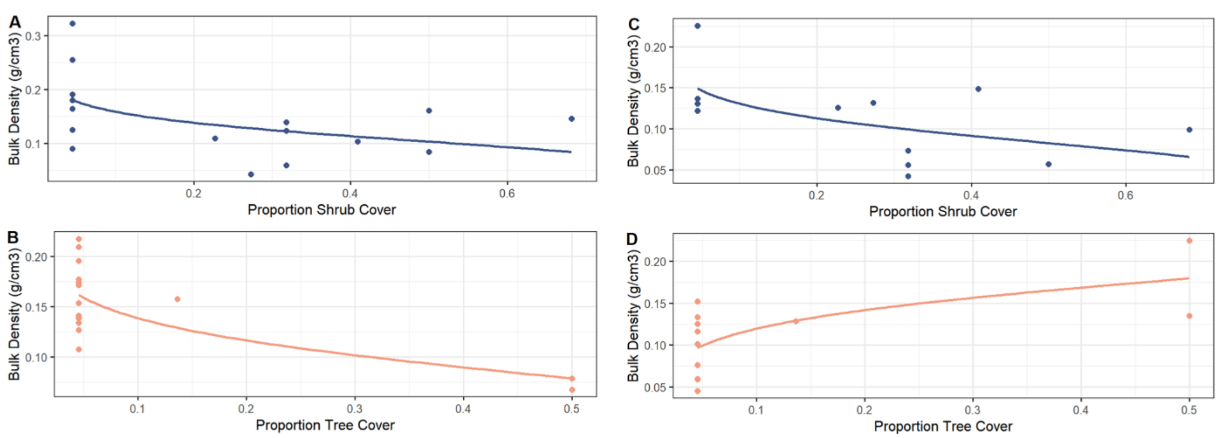

Figure 8. Shrub and tree cover correlated with variation in bulk density at both 0.5 and 1.5 m. At 0.5 m layer shrub cover predicted lower bulk density (A), as did tree cover (B). At 1.5 m shrub cover still predicted lower bulk density (C), but tree cover predicted higher bulk density (D). Residuals were evenly distributed.

3.3 Vegetation composition as an indicator of peat depth

Principle component analysis on the entire vegetation dataset represented 30.7% and 20% of variation on the principle and secondary axis respectively (Fig. 9). Depth had no relationship with PCA 1 and a marginal ($p=0.09$) relationship with PCA 2 (Fig. 10, Table 6). The presence of *Sphagnum* predicted larger relative depths compared to absence of *Sphagnum* ($p<0.05$), but large depths still occurred where *Sphagnum* was not present. No other individual plant type had a relationship with depth.

Table 6. Fixed effects of Mixed-Effect Linear Modeling between Depth and Vegetation Cover.					
Fixed Effect	**Estimate**	**SE**	**df**	**t value**	**p value**
PCA1	0.19	0.44	65.8	0.43	0.671
PCA2	-0.79	0.46	63.6	-1.72	***0.091***
Shrub	-0.16	0.35	65.5	-0.46	0.649
Tree	-2.38	1.89	64.4	-1.25	0.214
Grass	-0.37	0.29	65.4	-1.24	0.217
Sphagnum	1.34	0.36	63.8	3.67	**0.002**

Note: *Vegetation cover was first compared to depth as the first and second axes of a principle component analysis, then as the cover of individual plants. Although PCA2 has a p value <0.1, it is not more than 2 SE difference from the intercept. Only Sphagnum is an indicator of relative depth. Bold indicates significance.*

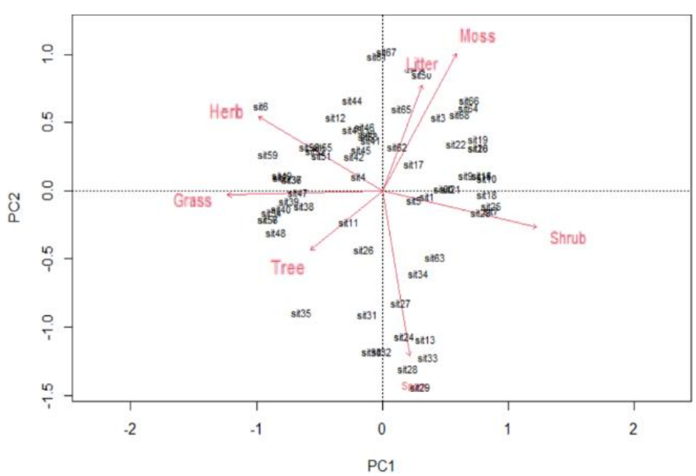

Figure 10. Principle component analysis of the vegetation survey on all depth points shows variation in vegetation cover. The first and second axis together represented 50.7% of variation. Each point (n=68) represents a matrix of plant type cover.

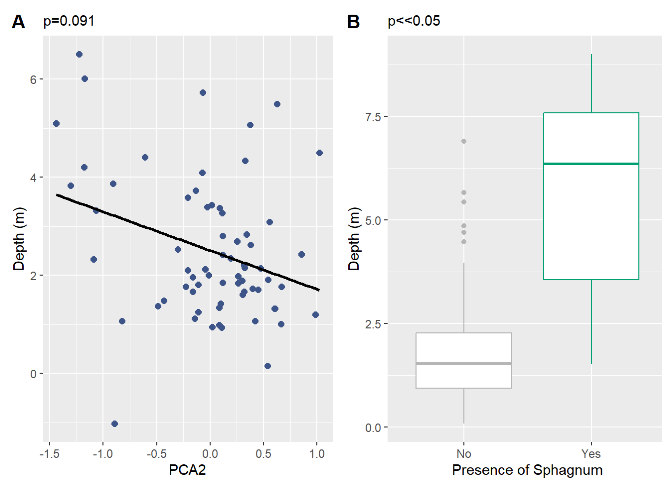

Figure 10. Depth has a slight relationship with PCA 2(A), becoming shallow as other moss takes over from Sphagnum. Sphagnum indicates greater relative depth (B). Residuals are back transformed and do not represent real data.

3.4 Estimation of carbon stock contained in Vestreimsmyrane

I calculated that slightly over 7200 tonnes of carbon was stored in the study area of Vestreimsmyrane with surface density ranging from 34.5–360.8 kg/m^2 (Fig. 11). Site 3 (Intact) had the highest carbon density (tonnes C/Ha), whereas site 5 had the lowest. Carbon density was more closely related to depth than other factors, (Table 7), with an average 38% of carbon stored below 1 m.

Table 7. Carbon stock and density in the study area, interpolated in QGIS as the product of bulk density, SOM, and depth.

Site	Area (m2)	Mean depth (m)	Tonne (C)	C t/Ha
1	12329	2.39	1286	1043
2	14562	1.77	1282	881
3	8272	5.80	2065	2497
4	10831	1.87	1218	1125
5	11787	0.94	585	497
6	5762	2.37	783	1360

Note: *Carbon density was interpolated to a resolution of 1x1 m at each layer before being combined with depth. Carbon stocks are the product of carbon density and area.*

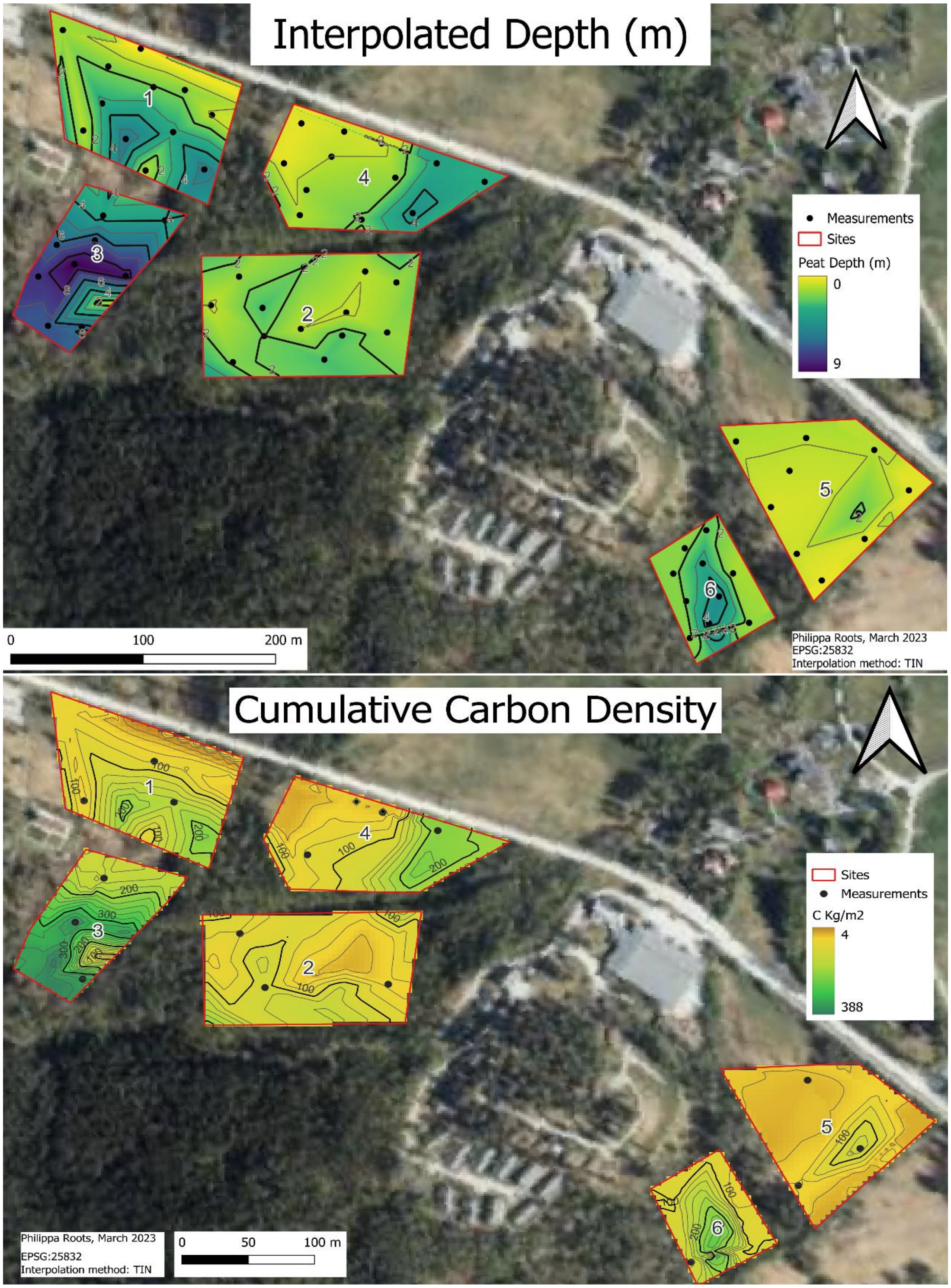

Figure 11. Interpolated depth (top) and surface carbon density (bottom) in Vestreimsmyrane, Norway, created in QGIS from field measurements. Surface density was calculated separately for each layer and added together. Greater depth is always associated with greater carbon density.

4 Discussion

I measured soil organic matter (SOM) and bulk density across levels of land-use in a western Norway peatland complex to understand how past land-use affected factors of soil carbon storage in peat. I further assessed relationships with vegetation composition to examine how vegetation can be used to manage degraded peatlands. I found that carbon losses from land-use change can occur at depth, and that depth is not easily predicted by vegetation.

4.1 Soil organic matter is affected by land-use

The pattern of decline in SOM as land-use intensity increased was apparent at 1.5 m, suggesting losses occurred from this depth and possibly deeper. SOM values in all 6 peatland sites were within line with estimates reported in the literature (Howson et al., 2023; Wellock et al., 2011), and as all but two samples were greater than 30% SOM the whole study area can still be considered peatland. Average pH of 5.1 confirms that the peatland can be classified as a nutrient-poor fen (ESRD, 2015). Using the intact site as a reference median SOM declined by 7.8% in drained sites, and 34.6% in drained and cultivated sites. This is comparable to other studies of managed peatland which find consistent reduction in carbon stocks when the water table drops (Evans et al., 2021; Howson et al., 2023; Qiu et al., 2021). The direct effect of drainage on SOM is increased oxidation; in the absence of high moisture levels micro-organisms are able to decompose organic material and mineralize the soil organic carbon (SOC) (Kasimir-Klemedtsson et al., 1997). Although water table measurements were not included in this study, it can be surmised that the water table occupies different levels between the intact and drained sites.

In Cultivated sites, the highest SOM value was less than the lowest SOM value in the Intact site, implying that at least half of original organic matter by weight may have been lost due to land-use. The difference in SOM between Drained and Cultivated was more moderate, but the addition of agriculture was still observable. This is expected, as agricultural management exacerbates the effect of peat drainage by mixing additional oxygen into the soil by tilling and introducing fresh labile carbon though vascular plant roots, further stimulating microbial activity

(Nelson et al., 2008). That SOM decreased with land-use (Use) intensity is consistent with other studies (Bader et al., 2018; Hatano, 2019; Leifeld et al., 2019; Wüst-Galley et al., 2016), but my results add that the effect on decomposition of organic matter extends below 1 m, and potentially throughout the entire depth, indicating that peatland emissions from land-use change are relative to the depth of the peatland.

4.2 Change in bulk density indicated loss of soil carbon

Bulk density (0.07-0.32 g/cm^3) was lowest in the Intact site and highest in the Cultivated sites where it approached values consistent with pasture (Strand et al., 2021). Bulk density is typically negatively correlated with SOM (Loisel et al., 2017), a relationship repeated in this study. High bulk density implies degraded peat, as it is the loss of organic matter and moisture that compresses peat reduces hydraulic conductivity. However, degradation of the peat may not aways be apparent, as high bulk density can obscure soil carbon loss by raising the carbon density per volume (g/cm^3) of oxidized peat (Sloan et al., 2019). This highlights the importance of measuring factors of SOC separately to observe relative changes.

The association between depth and weighted SOM in the Cultivated sites is a demonstration of the relationship between bulk density and SOC loss. In these sites, where average depth is around 1 m, lower average SOM was found where depth was also lower, and bulk density was higher. This inter-relationship suggests that compaction from agricultural equipment, together with the loss of organic matter, has degraded the quality of the peat and resulted in lower overall depth. Berglund (1998) estimated a subsidence rate of 0.5 cm/year on drained peat soils used as pasture, implying that some of my study sites may have lost up to 30 cm up depth since their cultivation in 1964 with an associated loss of SOC. Although this study lacks data to confirm the trajectory of degradation, subsidence from cultivation has been recorded in comparable sites elsewhere in Norway with associated SOC losses of 0.86 kg C/m^2/year (Grønlund et al., 2008). The depth-SOM-bulk density relationship was only apparent in Cultivated sites, but it is possible that the process has occurred in Drained sites as well where the effects were less severe or obscured by greater variation in depth.

Neither SOM nor bulk density followed an obvious trend between layers; this is contrary to studies of degraded peatlands down to 1 m that observed increasing bulk density with depth (Bader et al., 2018; Wüst-Galley et al., 2016) although not entirely unusual (Wellock et al., 2011). If the study area is compared to intact peatlands that show decreasing bulk density with depth (Frogbrook et al., 2009; Howson et al., 2023; Parry & Charman, 2013), it can be hypothesized that peat quality has degraded equally or more at depth than near the surface, obscuring the original depth relationship. I did not measure the depths of the ditches in the study area, but ditches created in the same time period were standardized and rarely deeper than 1 m (Stoeckeler, 1963). Changes in peat quality below the ditch depth may then be a result of secondary effects, such as vegetation.

4.3 Variation in peat degradation at depth was reflected in vegetation

Tree and shrub cover were associated with variation in peat degradation, particularly at 1.5 m, and although causal relationships were unproven several mechanisms could explain this finding. Most shrub cover was found in Drained sites, where it is frequently the dominant plant type and was associated with less degraded peat at all layers. Shrubs have been recorded to take over from wet-and-low-nutrient adapted species such as *Sphagnum* as nutrients become more available (Bartsch & Schwintzer, 1994; Robroek et al., 2016), as they would in aerobic conditions. Shrub cover may then simply be an indication of the transition of healthy peat into a more nutrient-rich ecosystem. Tree cover in this study only includes the few instances where trees grew within 1 m of the peat sample point and doesn’t reflect the broader tree cover found in sites 2 and 6. The associations with bulk density at 0.5 m (negative) and 1.5 m (positive), though significant, must then be taken with caution. Nevertheless, surface humification from trees has been hypothesized to protect peat beneath it (Uhelski et al., 2022), while the weight of large trees can compact peat at depth (Sloan et al., 2019), together reflecting associations found in this study.

Conversely, shrub and tree cover may simply represent a lack of other plant types or conditions which cause greater oxidation and organic matter loss. Bader (2018) found that afforested peatlands were less degraded than peat under grass; graminoids are generally considered to have adverse effects on peat (Palozzi & Lindo, 2017; Robroek et al., 2016). It was notable then that graminoids in this study showed no relationships with SOM or bulk density at any layer, possibly due to competing processes.

Variation in vegetation composition closely followed land-use classification, so that plants associated with higher quality peat were found in less degraded sites. It is then difficult to distinguish whether peat degradation from land-use intensities has been augmented by vegetation, or if vegetation is simply an indication of the conditions below. The water table has been established as the governing control on SOC losses (Evans et al., 2021), but certain plant types are also well documented to affect peat quality, particularly in deep peat (Fontaine et al., 2007; Liu et al., 2022). Carbon stored in recalcitrant peat – deep peat which has stabilized after initial decomposition – is hypothesized to be controlled by chemical conditions more than hydrological ones, typically caused by the increasing dominance of vascular plants (Lorenz & Lal, 2005). Extrapolating the vegetation relationships discovered in this study into other climatic areas may prove ineffective, but their existence supports the body of research suggesting that surface vegetation can serve as a tool in diagnosing and managing degraded sites (Maanavilja et al., 2014; Palozzi & Lindo, 2017; Robroek et al., 2016; Uhelski et al., 2022).

4.4 Vegetation is a poor indicator of peatland carbon storage

Although the composition of vegetation in combination with site history predicted factors of soil carbon between points, the vegetation index was not a good indicator of the depth of the peatland. Only the presence of *Sphagnum* made any prediction of depth, and large depths were found in the absence of *Sphagnum* as well. *Sphagnum* is the building block of peatlands and indicates where new peat is forming, but in my study area and others deep reserves of peat are contained in degraded peatlands covered by upland vegetation (Gatis et al., 2019; Weissert & Disney, 2013). Without an obvious decrease in carbon density between layers it appears that depth was the largest single contributing factor to carbon stock (Fig. 11), a conclusion echoed in larger studies (Fyfe et al., 2014). Considering this relation, carbon stock in degraded peatlands is then inconclusive from visual observation of vegetation alone.

As vegetation fails to predict peat depth, without prior knowledge of historical land changes it would be possible to overlook some degraded peatlands altogether based on current plant cover. Most peatland in my study area was apparent from ditches visible on a lidar image, but in the case of Site 4 (pasture) repeated tilling had all but erased evidence of ditches and vegetation cover was almost entirely grass. Many thousand hectares of peatland in Norway and beyond have been transformed to agricultural land and no longer carry signs of their past on the surface (Grønlund et al., 2008). If the results of this study can be transferred those fields may have several meters of peat below the surface, and still contain enough SOC to be considered a peatland, therefore retaining value in restoring.

4.5 Management Implications

The combined findings that carbon released up to 1.5 m depth within a peatland complex following land-use change, and that depth could not be determined without direct measurement has severe implications for carbon accounting, land-use planning, and restoration. Past and present peatland area is under-estimated in Norway (Bakkestuen et al., 2023; Bartlett et al., 2020; Bryn et al., 2018), largely due to the considerable amount of peatland that has been converted to agricultural land (Grønlund et al., 2008). Within these estimates, the depth of peatlands is even more rarely measured and thus constitutes a large source of uncertainty in Norwegian peatland reservoirs. Mapping efforts using ariel photos may miss covered peat reservoirs and, due to the importance of depth in carbon stock, understate the significance of peatlands for carbon storage in Norway. My findings indicated that failing to estimate soil carbon with tools other than vegetation assessments could result in developments with higher-than-expected emissions on land that has value in conserving for climate change mitigation.

Efforts to quantify CO_2 emissions from land-use changes involving peatlands are not accounting for a bulk of emissions if they do not first measure peat depth. My results indicated that peatlands risk releasing carbon from along their depth profile, and that proposed land-use changes should take peat depth into account to limit Norway's contribution to global climate change. Depth is not explicitly mentioned in the IPCC guidelines for accounting greenhouse gas emissions from managed peat (IPCC, 2006), and without guidelines a single parameter is often used, resulting in miscalculations (Yu, 2012; Yu et al., 2010). Although peatland drainage for cultivation recently has been prohibited in Norway, exemptions are still allowed and roughly 8% of planned developments are on existing peatland (Miljødirektoratet, 2021). For the rest of the peatlands in Vestreimsmyrane which have been paved over or permanently developed, my estimations of carbon density could be assumed to represent past storage over the wider area. Emissions from land-use change in this valley and others across Norway are likely very high and unreported. To date Norway does not account for emissions from disturbed peat - The Norwegian National Inventory report of greenhouse gases has no mention of peatland (Miljødirektoratet, 2022). When Norway joins other peat-rich countries in reporting induced peatland emissions, it is imperative that the peat depths of historical and planned disturbances are taken into consideration.

Lastly, restoration efforts may be able to use vegetation cover to determine the state of degradation and potential for restoration success. Currently peatland restoration monitoring in Norway uses *Sphagnum* as an indicator to determine if restoration is succeeding in raising the water table (P.M. Eid, pers comm) but may want to consider the additional vegetation relationships found in this study. Shrub type plants may indicate that a peatland is less degraded and is a good candidate for recovery, while peat reservoirs under grass cover should not be discounted. Where full hydrological restoration is not possible, managing dominant plant types may mitigate further degradation of peatlands. This information may prove useful when Norway begins restoring agriculturally drained peat.

Future research analysing the impact of land-use and vegetation in peatlands should measure SOC throughout multiple depths greater than 0.5 m to confirm the results of this study. It is highly recommended that Norway measures depth when mapping peatlands and uses these findings to plan around carbon dense soils when building new developments.

5 Conclusion

I analysed peat properties in a partially ditched peatland complex in western Norway at 0.5, 1.5, and 3 meters depth to test the impact of land-use on soil carbon. Carbon storage in peatlands is of great importance to climate change mitigation, and my study shows that deep peat, generally assumed to be stable, long-term storage, is not immune to the effects of drainage and cultivation. Depth is a large determinant of the amount of carbon at risk, and without a vegetation indicator of depth, carbon density is imperceptible from casual observation. Proposed land-use changes in peatlands should first take accurate depth measurements and calculate the entire carbon stock at risk before proceeding. Dominant plant type may signal or augment peat degradation caused by land-use change, suggesting that following land-use changes, in particular in peatlands that cannot be fully restored, vegetation management may help alleviate soil carbon losses. Degraded peatlands are a substantial source of greenhouse gas emissions in Norway, and better management is needed to mitigate current and future soil carbon losses.

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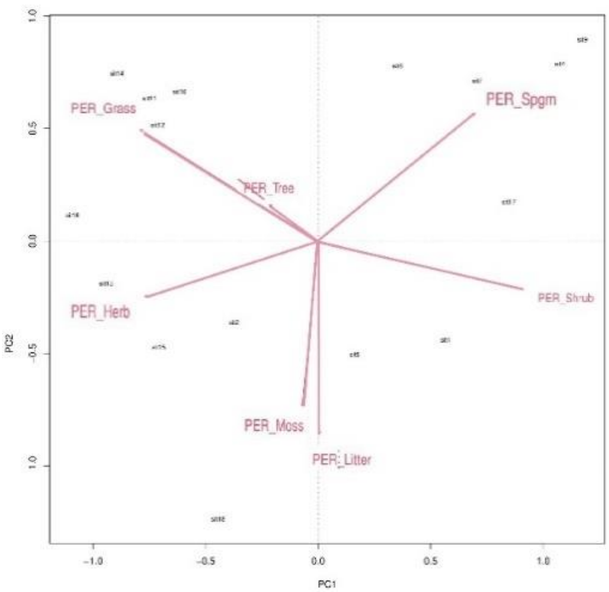
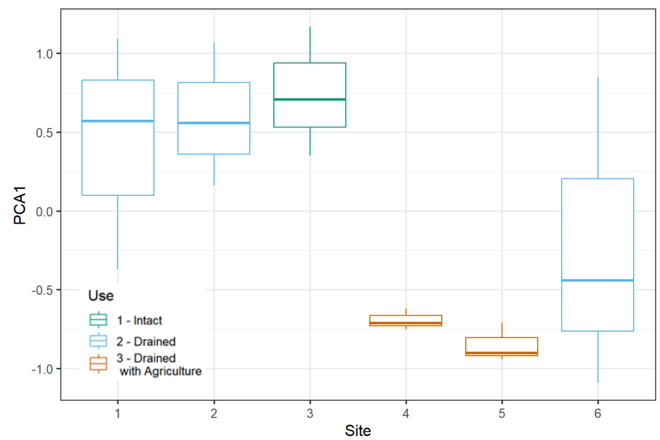
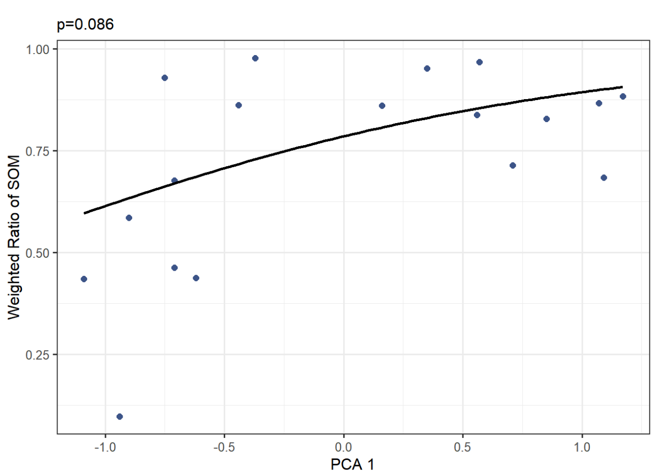
7 Appendix

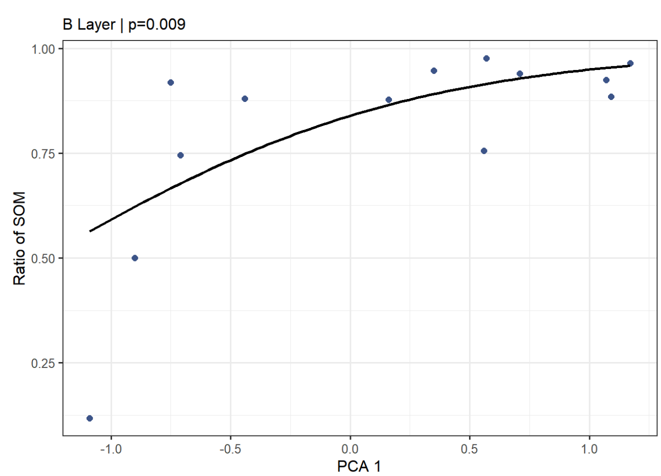
Principle component analysis of the vegetation survey on peat sample points explained 58.5% of variation in plant cover between the two main axes and showed a distribution from Graminoid to Shrub (PCA1) and from Moss to Sphagnum (PCA2) (Fig. 12).



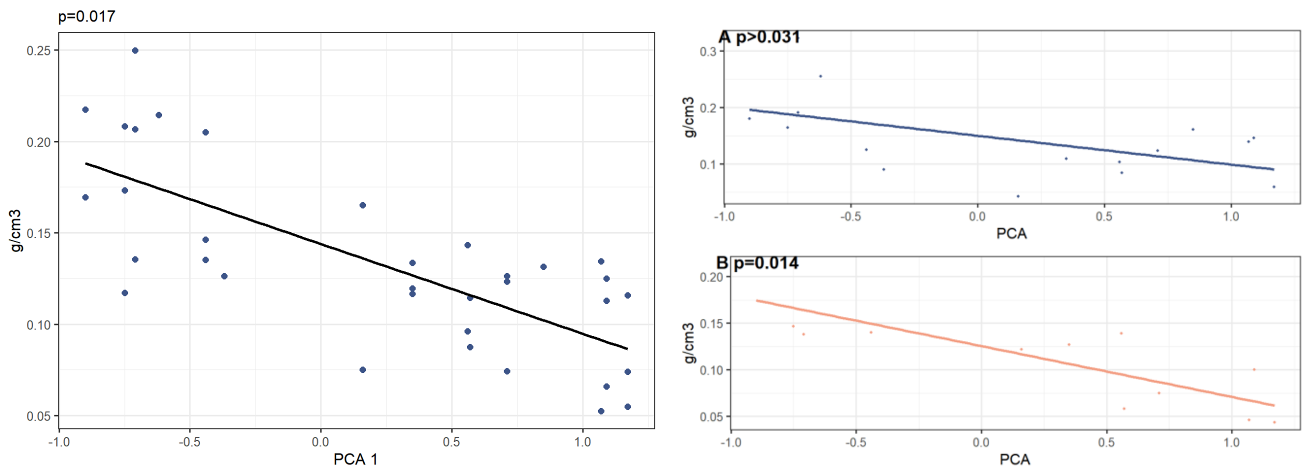


SOM had a weak relationship with PCA1 (p=0.086), as Sphagnum and Shrub cover took over from Graminoid and Herb. The relationship was most pronounced at 1.5 m ($p<0.05$) and insignificant at 0.5 m by itself. Bulk density also correlated with PCA1, again strongest at 1.5 m.





SOM against PCA 1 at all (left) and 1.5 (right) layers.



Bulk density against PCA 1 at all layers (left) and at 0.5 and 1.5 m (right).