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Abstract

Peatlands in their natural state are in general considered as net sinks of greenhouse gases over time, with the accumulation of dead organic matter as peat. Drained organic soils have been of importance for Swedish agriculture for more than a century. On the island Gotland, drained organic soils are in general fertile and are used to grow high value crops such as carrots and are important in fodder production due to their higher resistance to summer droughts. Decomposition of the organic material and release of greenhouse gas occur when organic soils are drained, but there is a considerable variation in emissions and subsidence rate between different organic soils. The knowledge about drained organic soils with high marl and calcium carbonate content is limited. The aim of this work is to examine if there is a variation in CO_2 emissions from different types of organic soils with a high calcareous content. The aim is also to study if the CO_2 emissions rate can be correlated with any soil properties. Undisturbed soil samples were collected from three sites at the Mästermyr peatland area both from the topsoil and the subsoil. The different topsoil types were fen peat, marly peat and peaty marl. Four conclusions that could be made in this work are (1) the CO_2 emissions vary between different soil types. (2) That all soils increase their CO_2 emissions when they are drained but at a different degree and they reach a maximum between 25 cm and 75 cm drainage depth. (3) An increase of air filled pore space was positively correlated with CO_2 emissions in the subsoil but not in the topsoil. (4) There was a positive correlation between loss on ignition and CO_2 emissions for all soils in this study.

Keywords: peatlands, peat, marl, Gotland

Sammanfattning

Myrar i naturligt tillstånd är i allmänhet en sänka för kol över tid när ofullständig nedbrytning av organiskt material sker på grund av begränsad syretillgång, vattenmättnad eller låga temperaturer. Dränerade organogena jordar har varit av stor betydelse för det svenska lantbruket i över ett århundrade. På Gotland är de dränerade torvjordarna ofta mycket bördiga och lämpliga för odling av rotfrukter. Torvjordarna är också viktiga för grovfoderproduktionen då de är vattenhållande även under de torra sommarmånaderna. Nedbrytningen av det organiska materialet och koldioxidavgången ökar när organogena jordar dräneras och syresättningen ökar. Variation mellan de organogena jordarna avseende markytesjunkning och växthusgasavgång är stor. Kunskapen om dränerade organogena jordar med högt innehåll av bleke och kalciumkarbonat är begränsad. Syftet med arbetet var att undersöka om det är någon variation i avgång av CO_2 från olika typer av organogena jordar med högt innehåll av kalk. Syftet var också att undersöka om CO_2-avgången kan korreleras med några kemiska eller fysikaliska egenskaper hos jorden. Ostörda jordprover togs ut i stålcylindrar från tre platser på Mästermyr, både från matjorden och från alven. De olika jordtyperna var torv, blekeblandad torv och torvblandad bleke. Fyra slutsatser kunde dras från detta arbete. (1) CO_2-avgången varierar mellan olika jordtyper. (2) CO_2-avgången ökar initialt med intensivare dränering och maximal CO_2-avgång uppnås i en del jordar redan vid 25 cm dräneringsdjup medan andra behöver dräneras till 75 cm djup för att nå maximal CO_2-avgång. (3) Andelen stora porer, som är luftfyllda vid dränering (AFPS) var större i de kalkrika alvjordarna (bleke) jämfört med de torvrika matjordarna. (4) Ökad organisk halt (loss on ignition) ledde till ökad CO_2-avgång.

Nyckelord: Torvjordar, torv, myr, bleke, kalk, koldioxid, växthusgaser

Populärvetenskaplig sammanfattning

En myr är ett samlingsnamn för våtmarker som innefattar allt från öppna vattenytor till kärrtorv och mossar. Myrar i naturligt tillstånd är i allmänhet en sänka för kol över tid när ofullständig nedbrytning av organiskt material sker på grund av begränsad syretillgång, vattenmättnad eller låga temperaturer. Dränerade torvjordar och gyttjejordar har varit av stor betydelse för det svenska lantbruket i över ett århundrade. På Gotland är de dränerade torvjordarna ofta mycket bördiga och lämpliga för odling av rotfrukter. Torvjordarna är också viktiga för grovfoderproduktionen då de är vattenhållande även under de torra sommarmånaderna. Nedbrytningen av det organiska materialet och koldioxidavgången ökar när torvjordar dräneras och syresättningen ökar. När torvjordar dräneras sjunker markytan på grund av en sättning av torven när stödet av vattnet försvinner. Det är dock en stor variation mellan olika typer av torvjordar och gyttjejordar vad gäller koldioxidavgång och hur mycket markytan sjunker.

Syftet med arbetet var att undersöka om det är någon variation i avgång av koldioxid från olika typer av torvjordar och gyttjejordar med högt innehåll av kalk. Syftet var också att undersöka om koldioxidavgången kan korreleras med särskilda egenskaper hos jorden, så som pH eller mängd organiskt material i jorden. Jordprover togs vid tre platser i Mästermyrområdet på södra Gotland, från olika djup i marken. De olika jordtyperna var torv, blekeblandad torv och torvblandad bleke (bleke är gyttja med ett stort inslag av kalk).

Egenskaperna hos de olika jordarna varierar vilket påverkar koldioxidavgången på olika sätt. Jordproverna vattenmättades och dränerades till olika djup där koldioxidavgången mättes. Vissa jordar nådde maximalt koldioxidutsläpp vi 25 cm dränering men några jordar nådde maximalt koldioxidutsläpp vid 75 cm dränering. Djupare dränering gav inte ett högre koldioxidutsläpp. En egenskap med stor betydelse för koldioxidavgången är halten organiskt material i jorden, där en högre halt organiskt material ger en högre koldioxidavgång vid alla dräneringsdjup.

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1 Introduction

Northern peatlands cover 4 % of the world surface and contain approximately 30% of the soil carbon in the world, (Laiho, 2006, Aurela et al., 2009). Northern boreal and subarctic peatlands store about 455 Pg or 455 000 000 000 ton carbon (Gorham, 1991). Peatlands in their natural state are in general considered as net sinks of greenhouse gases over time, when the accumulation of carbon dioxide (CO_2) is greater than the emissions of methane (CH_4) (Whiting and Chanton, 2001, Berglund and Berglund, 2010, Laiho, 2006).

Peat soils are formed when the organic matter from dead plant remains are accumulated on the ground, due to incomplete degradation of the organic matter usually because of water logging. Gyttja soils on the other hand are deposited in open waters and are a mixture of organic and minerogenic materials. Peat soils are often underlayered by gyttja soils. It is common that the formation of a peat soil is the endpoint of an overgrowing of a shallow lake (Osvald, 1937).

Drained organic soils have been of importance for Swedish agriculture for over a century. On the Swedish island Gotland, drained organic soils are in general fertile and are used to grow high value crops such as carrots and are important in fodder production due to their higher resistance to summer droughts (Osvald, 1937, Berglund, 1982).

Decomposition of the organic matter and release of greenhouse gases occur when organic soils are drained. But there is a considerable variation in emissions and subsidence rate between different organic soils (Norberg et al., 2016b, Beetz et al., 2013). The knowledge about drained organic soils with high marl and calcium carbonate content is limited.

The aim of this work is to examine if there is a variation in CO_2 emissions from different types of organic soils with a high calcareous content. The aim is also to study if the CO_2 emissions rate can be correlated with any soil properties. In this work, three sites from the Mästermyr area on Gotland are examined. This area is attributed with a high pH and a high calcium content. The organic matter varies between the sites, with varying properties correlated with it such as hydraulic conductivity.

2 Literature review

2.1 Organic soils

In Sweden, the term organic soils include both peat soils and different types of gyttja soils (Osvald, 1937). The organic soils are generally porous and have a low dry bulk density (Kasimir-Klemedtsson et al., 1997). When an organic soil is drained it shrinks and the pore volume decreases, often irreversible. The water filled pores in peat can collapse when they are drained and with a higher decomposition rate the organic particle gets smaller and form smaller pores (Kasimir-Klemedtsson et al., 1997). When the porosity decreases, the permeability of air and water decreases as well (Kasimir-Klemedtsson et al., 1997).

Within the term peat soil, both fen and moss peat are included. A fen peat is more nutritious than a moss peat. The fen peat is formed in shallow waters such as sinks, lakes or streams, where the ground water supplies the area with a flow of nutritious water. A moss peat is supplied with water mainly from rainfall and is therefore less nutritious (Osvald, 1937). According to the Swedish classification criteria, an organic soil must contain ≥ 30 % organic matter. The criteria for gyttja soil is slightly different. A gyttja should contain ≥ 30 % organic matter and clay gyttja 6 % to 30 % organic matter. Gyttja clay that is not classified as an organic soil contains 1 % to 6 % organic matter. The low gyttja content in gyttja clay gives it properties similar to gyttja even in low concentrations, but is not defined as an organic soil (Berglund, 1996). Swedish gyttja soils are young in a geological perspective and have been deposit during the last 10 000 years. Gyttja soils form when residues from plant and animal life (detritus) sediment together with minerals in nutrient rich lakes and other waters with low depths (Berglund, 1995).

2.1.1 Peat soils

Peat soils are formed when organic substrates accumulate under waterlogged conditions with a low occurrence of oxygen (Kasimir-Klemedtsson et al., 1997). The water saturated conditions gives a 1000 times slower diffusion of oxygen than in dry soil, which inhibits the oxidation of the organic material. Another factor that inhibits the decomposition of the organic matter is low temperatures (Whiting and Chanton, 2001).

The mean depth of the world's peat soils is 2.3 m and the annual mean growth rate in height is between 0.2 mm to 0.8 mm for boreal and subarctic peatlands. Peatlands grow horizontal at some stage. The main period of peatland spreading was 5000 to 2000 years before present. Bakchar Bog in Westerns Siberia is an example of a peat still expanding (Gorham, 1991).

2.1.2 Gyttja soils

General characteristics for gyttja soils are the gelatine consistency, the grey to greenish colour and the chemical and physical properties. It is mostly dependent on the domination of algae in the detritus. Algae with organic cell walls have an almost complete decomposition and will dissolve. Diatom (kiselalger) cell walls consist of biogenic silica which makes the algae resistant to decomposition (Berglund, 1995, Berglund et al., 1989). The diatoms are mostly in the same size as silt particles but have a very porous structure which give them a "clay-like behaviour" (Berglund, 1995). The organic matter content in gyttja can vary between some few per cent up to over 30 %. The gyttja content is not equal to the organic matter content when the detritus consist of a large part of diatoms (Berglund, 1995).

2.1.3 Marl and calcareous gyttja

Marl is a dense and loose, white to yellow soil. The main component in this soil type is calcareous sludge (calcium carbonate). Marl and calcareous gyttja are through numerous transitions interspersed. The calcareous gyttja differs from marl in the way it is interlayered with calcareous sludge together with algae gyttja. The colour is commonly yellow to white but can have a tendency to read, brown and green (Osvald, 1937).

The most important factor for crack formation in marl and calcareous gyttja is due to the content of gyttja. The marl is often overlayered by peat that falls down in the crack, which makes the crack irreversible and a favourable environment for root growth (Olofsson, 1954, Hallgren, 1965, Berglund, 1982). The elasticity differs between marl that has no elasticity to calcareous gyttja that has some elasticity similar to gyttja (Nilsson, 1961).

2.2 Farmed organic soils in Sweden and Gotland

Of the total Swedish land area, 15,2 % are organic soils (Pahkakangas et al., 2016). The total area of farmland according to the agricultural blocks (blockareal) in Sweden, was 3 525 259 ha in 2008 (Table 1). The agricultural blocks are according to the database Integrated Agricultural Control System (IACS), which contain the registered agricultural areal at the Swedish Board of Agriculture. It includes arable land, pasture and mown meadows. Farmland not registered in the database is negligible (Berglund et al., 2009). In Table 1 and 3 the data from Berglund et al. (2009) is used instead of the latest inventory by Pahkakangas et al. (2016), due to its more detailed descriptions of the different soil types and the crop distribution.

Table 1. *Area (ha) of organic soils and the area of the total farmland on Gotland in comparison with the mean value for Sweden. Sallow peat is <50 cm. Data from 2008 (Berglund et al., 2009)*

	Peat	Sallow peat	Total peat	Gyttja*	Organic soils	Total farmland
Gotland	4 347	2 214	6 561	6 889	13 450	134 121
Sweden	160 020	38 244	198 264	69 726	267 990	3 525 259

* Gyttja, marl, calcareous gyttja, clay gyttja, gyttja clay

The area of farmed organic soil in Sweden has decreased since 2003 (Table 2). It is also a decrease from 1945, when approximately 705 000 ha organic soils were farmed in Sweden (Hjertstedt, 1946).

Table 2. *Description of how the agricultural blocks (AB) has changed during the three latest inventories in Sweden and on Gotland. The area of arable organic soils (AOS) shown in comparison between Sweden and Gotland (Berglund and Berglund, 2008, Berglund et al., 2009, Pahkakangas et al., 2016). All area is given in ha*

Year	AB, Gotland	AB, Sweden	AOS Gotland	AOS Sweden
2003	126 810	3 496 665	12 905	301 487
2008	134 121	3 525 259	13 450	267 990
2015	121 196	3 232 039	12 687	225 722

The farming intensity varies between regions in Sweden (Table 3). The intensity of the cultivation affects the subsidence rate of the organic substrate. Row crops (carrots, potatoes and similar crops) with the most intensive cultivation has the highest subsidence, followed by annual crops (Berglund, 1989). Only Blekinge landscape has a larger part row crops (8,0 %) on organic soils than Gotland, but less annual crops (22 %) (Berglund et al., 2009).

Table 3. *Crop distribution (% of area) for organic soils for Gotland and the mean value for Sweden (Berglund et al., 2009)*

	Pasture	Annual crops	Row crops	Fallow	Tree plantation	Ley	Wetland	Other
Gotland	4.4	37.7	5.2	2.6	0.1	49.0	1.0	0.0
Sweden	22.1	27.8	1.7	7.1	0.8	39.5	1.1	0.1

2.3 Soil properties of organic soils

In contrast to mineral soils, organic soils have a high porosity, low compact density and low dry bulk density (Table 4). The degree of decompensation in a peat soil is negatively correlated with the dry bulk density and porosity, which gives a lower hydraulic conductivity for a more decomposed peat. There is also a difference between moss and fen peat, where fen peat has a higher hydraulic conductivity at the same decomposing stage (Berglund, 1996).

Gyttja, clay gyttja and gyttja clay have a high porosity despite their relatively high compact density (Table 4). Permanent cracks occur in gyttja soils after they are drained. Iron oxides precipitate and stabilise the structure. The initial drainage rate determines the size of the cracks. Faster initial drainage rate gives larger cracks and a lower drainage rate gives smaller cracks. Well-developed cracks can form pillar like structures which give high hydraulic conductivity. This crack system can be damaged by freezing and cultivation, which leads to formation of small prismatic aggregates (Berglund et al., 1989, Berglund, 1995).

Table 4. *Compact density, dry bulk density and porosity. Comparison between organic soils and mineral soils. Values are taken from Berglund (1996) and Berglund (1995)*

Soil type	Compact density g/cm^3	Dry bulk density g/cm^3	Porosity % of volume
Moss peat	1.1 – 1.8	0.07 – 0.2	85 – 95
Fen peat	1.4 – 1.8	0.1 – 0.6	70 – 91
Gyttja	1.9 – 2.0	0.2 – 0.4	81 – 89
Clay gyttja	1.9 – 2.5	0.3 – 0.8	69 – 84
Gyttja clay	2.3 – 2.8	0.5 – 1.1	60 – 78
Mineral soils	2.5 – 2.8	1.0 – 1.7	40 – 60
Marl gyttja	2.4 – 2.5	0.5 – 0.7	71 – 81

The nitrogen content in peat soils varies between moss and fen peats. Generally, moss peats have low nutrient levels and a low ash content. C/N ratios can be between 20 and 100 depending on how decomposed the material is. In contrast, fen peats have a higher content of nitrogen, even at low ash contents. Nitrogen can be bound to organic substrates that decreases the availability, but cultivation of the soil stimulates mineralisation of the nutrients.

All peat soils have low levels of phosphorus and potassium, due to the low ash content (Hjertstedt, 1946, Berglund, 1996). C/N ratio for gyttja soils are 10 and in some cases somewhat higher (Berglund, 1996). Gyttja has a higher compact density than peat soils but similar porosity (Table 4). pH and calcium content do not have a linear relationship in organic soils, especially when the soil contains sulfuric acid (Hjertstedt, 1946). In gyttja soils, the root depth can be limited by aluminium toxicity due to low pH. In peat soils with low mineral content this problem does not occur (Berglund, 1996).

2.4 Soil properties of calcareous organic soils on Gotland

The organic soils on Gotland are mostly fen peats formed in old lakes (Berglund, 1982). The soil profiles vary between the different peatland areas, from thick peat layers to marl and calcareous gyttja as described by Berglund (1982). Mästermyr is a peatland located west of Hemse on the south of Gotland. Mästermyr peatland area was drained at the beginning of the 20^{th} century and the area was estimated to 2670 ha in total (Berglund, 1982). In 1925 the estimated area was 1740 ha of peat, 275 ha of bleke soil and the rest, 655 ha was moraine soils (Berglund, 1982). In Table 5 and 6, properties from a soil profile from the Mästermyr area is described.

Table 5. Loss on ignition and calcium carbonate for a Mästermyr profile according to Berglund (1982)

Depth in the profile (cm)	Loss on ignition %	Corrected loss on ignition* due to calcium weight %	Weight of calcium carbonates %
0-10	18	13	49
10-20	17	12	50
20-30	9	4	54
30-40	2	2	55
40-50	15	10	49

*Corrected loss of ignition due to calcium content according to (Ekström, 1927)

The loss on ignition cannot be directly translated into organic matter content if the soil contains calcium carbonate (Ekström, 1927). In Table 5, Berglund (1982) corrected the loss on ignition values with 1 % for every 10 % of calcium carbonate.

The correction is due to loss of crystal water from the calcium carbonate and from clay particles. Berglund (1982) determined the loss of ignition at 600 °C. In Table 6, pH, dry bulk density, compact density and hydraulic conductivity is shown for the Mästermyr profile according to Berglund (1982).

Table 6. pH, dry bulk density, compact density and hydraulic conductivity for a Mästermyr profile according to Berglund (1982). It was not possible to take cylinder samples in the horizon 90-100 cm due to the moraine

Depth	pH	Dry bulk density, g/cm^3	Compact density, g/cm^3	Hydraulic conductivity after 1 h, cm/h	Hydraulic conductivity after 24 h, cm/h
0-10	7.2	0.86	2.32	0.7	2.1
10-20	7.4	0.85	2.34	3.2	4.0
20-30	7.7	0.82	2.40	35.1*	14.6*
30-40	7.8	0.70	2.44	127.4*	51.0*
40-50	7.6	0.48	2.29	53.6	40.7
50-60	7.9	0.50	2.51	109.3*	44.9*
60-70	7.8	0.56	2.51	55.0	33.1
70-80	7.7	0.66	2.51	12.6	7.7
80-90	7.6	0.57	2.57	31.7	23.5
90-100	7.6	-	-	-	-

*Large variations between replicates.

In the report by Berglund (1982), a marl profile from the Elinghem peatland area located 25 km north-west of the city Visby, is described. When the area was drained in the middle of the 19th century the area was estimated to be 1077 ha. The soil profile from Elinghem is similar to the Mästermyr profile but has lower loss on ignition value in the topsoil than Mästermyr, 7 % and 17 %, the corrected value is 2 % and 12 %. The described soil profile at Elinghem is from a part of the area where the marl is not covered by a fen peat layer.

Stångmyr is a peatland area north-west of Hemse and is one of the smallest areas with only 425 ha. The soil profile from Stångmyr represents profiles with a deeper peatlayer remaining at the top of the profile. The pH in the soil profile is somewhat lower than at the Mästermyr profile. The dry bulk density is lower in the topsoil and higher in the subsoil than for the Mästermyr profile.

2.5 Greenhouse gas emissions

Cultivated organic soils are a small part of the European arable land, but contributes to a large part of the CO_2 emissions from European agriculture (Kasimir-Klemedtsson et al., 1997). In Sweden it has been estimated that farmed organic soils contribute with approximately 6 % to 8 % of total anthropogenic greenhouse gas emissions (Berglund and Berglund, 2010).

Peatlands in their natural state are considered a net sink of greenhouse gases, due to their accumulation of dead organic matter as peat (Whiting and Chanton, 2001). The main three factors that control CO_2 emissions from drained organic soils are (1) temperature, (2) aeration (and soil moisture) and (3) type of organic matter (Moore and Dalva, 1993, Koizumi et al., 1999, Fang and Moncrieff, 2001, Maljanen et al., 2001, Laiho, 2006, Aurela et al., 2009). The microorganisms that are present in a soil are often adapted to the general water content in the soil. The activity of the microorganisms increases when the temperature increases, and therefore gives rise to higher CO_2 emissions. Soil moisture may limit the microbial community either through high water content that inhibits aeration or through a dry soil that causes osmotic stress for the microorganisms (Schaufler et al., 2010). Fresh organic matter is general more attractive for microbial decomposers than older organic material where it is a higher proportion of lignin left in the organic matter (Laiho, 2006).

Berglund and Berglund (2011) investigated the influence of water table depth and some soil properties on greenhouse gas emissions from cultivated peat soils. In the experiment, they used undisturbed soil samples in a lysimeter from two different peat soils. The CO_2 emissions were low during the spring and increased during the vegetation period due to higher temperatures. There were greater CO_2 emissions from the lysimeters with a water table depth at 40 cm from the surface, than from water table depth at 80 cm from the surface (Berglund and Berglund, 2011). In the opposite Wessolek et al. (2002) have found higher CO_2 emissions with a lowering of the ground water table in peat soils. The temperature is only positively correlated with degradation when moisture is not limiting (Laiho, 2006). In natural peatlands there is a lower carbon uptake when warm and dry due to limitations in the plant growth on site (Aurela et al., 2009). During warm and dry summers with low water table in subarctic and boreal peat soils, loss of carbon has been reported (Laiho, 2006).

Norberg (2017) shows that a higher organic matter content (loss on ignition) gives a higher CO_2 emission from the soil, but the correlation between CO_2 emissions and drainage depth (air filled pore space) from organic soils differ between soil types. The study could not find any correlation between water content and CO_2 emissions.

This study focuses on CO_2 emissions from drained organic soils. Nitrogen dioxide (N_2O) is more difficult to measure and constitute a small part of the global warming potential in comparison to the CO_2 emissions. Therefore, N_2O emissions will not be addressed. Drained peat soils are generally a small sink of CH_4 and were therefore not measured (Berglund and Berglund, 2011, Norberg et al., 2016a, Norberg et al., 2016b).

3 Materials and Methods

3.1 Sampling sites

Soil samples were collected from three sites at Mästermyr, on the 25th and 26th of October 2016. Ten undisturbed soil samples were collected from each topsoil and from each subsoil, in total sixty cylinders. The soil cylinder that was used is 100 mm high and had a diameter of 72 mm. Samples of loose soil were taken at the same time from both topsoil and subsoil at all sites.

The three sampling sites were selected both from knowledge about how the different soils looked in reality and after examination of web based (Google maps) maps and maps from Berglund (1982). The aim was to sample three different soils with various amount of marl in the topsoil (Table 7). The sample from the topsoil was taken within the ploughing depth (5-15 cm) and in the upper part of the subsoil. After extraction, the cylinders were sealed with plastic lids and stored in wooden boxes for transportation to the lab for storage at 4 °C together with the loose soil samples.

There had been a heavy rainfall the previous days after a long dry period. In Alveskogs the upper part of the profile was wetter than the other profiles. In the Stenstugu and Hägsarve profile it was not noticed, it can depend on the fact that Alveskogs was excavated first.

Table 7. *Names of the different farms, sampling depth and coordinates*

Farm	Topsoil type	Sampling depth	Subsoil type	Sampling depth	Coordinates
Alveskogs	Fen peat	5-15	Marl	30-40	57°13'25.2"N 18°18'51.0"E
Stenstugu	Marly peat	5-15	Marl	30-40	57°14'30.4"N 18°17'56.4"E
Hägsarve	Peaty marl	8-18	Marl	35-45	57°13'56.6"N 18°17'27.8"E

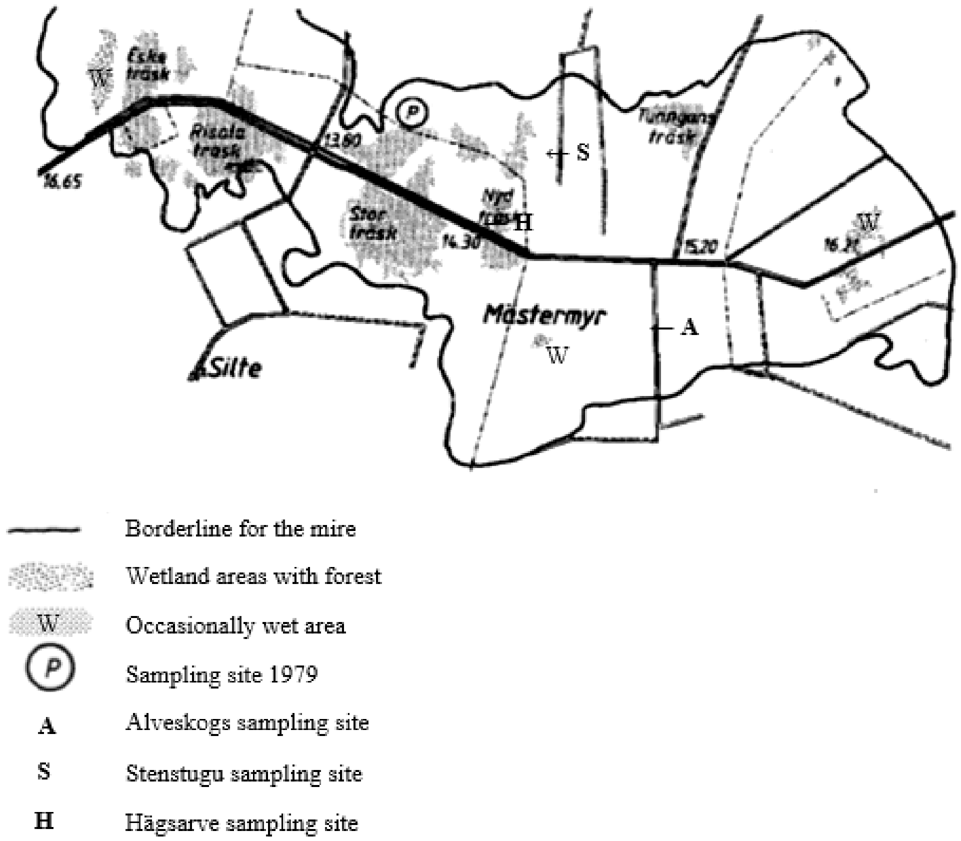

Figure 1. Map of Mästermyr from Berglund (1982). Updated text and added sampling sites. Scale 1:70 000. The map also shows height above sea level (m)

3.1.1 Alveskogs site

Alveskogs is the profile of these three soils with the highest organic matter content in the topsoil and it is defined as a fen peat (Table 7). There were no worms in the soil profile during the excavation but there were traces such as wormholes. The peat layer is 30 cm thick and some aggregates of marl is present, supposedly formed in a part of the field were the topsoil is thinner and has been ploughed up and distributed over the field. Winter wheat was planted at Alveskogs and the field had been ploughed more than one month before. The previous crop was also winter wheat but there was no straw that affected the sampling. There were some rape seed residues from year 2015 that was not completely degraded. The layering of marl, shell sand

and calcareous gyttja in the subsoil was distinguised than in the other profiles (Figure 2, 5 and 6). In the subsoil, there were some cracks that had to be avoided when the cylinders were inserted. In figure 3 and 4 crack formation is visible and the deepest crack measured 30 cm depth. The cracks were not widest at the top of the subsoil, due to marl and peat that has fallen down in the cracks.

Figure 2. Profile picture from Alveskogs. The peat layer is 30 cm thick and well decomposed. The subsoil has layers of marl, shell sand and calcareous gyttja (Photo: Erik Siggelin)

Figure 3. Visual cracks at Alveskogs subsoil, seen from above (Photo: Erik Siggelin)

Figure 4. Roots, cracks and layering at Alveskogs (Photo: Erik Siggelin)

3.1.2 Stenstugu site

The high marl content gives a grey tone to the peat layer which is defined as marly peat (Table 7). In the profile picture (Figure 5) some marl aggregates are visible in the topsoil. The layers in the Stenstugu subsoil are not as clear as in the Alveskogs and Hägsarve subsoil. At Stenstugu the spring wheat stubble was still untouched. But there was some straw within the ploughing depth that affected the sampling and some samples had to be remade. In the subsoil there was one large (10 cm wide) crack filled with peat that had to be avoided at the sampling, in order to get a representative sample.

Figure 5. Profile picture of Stenstugu. The straw that is incorporated in the topsoil is assumed to be from the cereals form the year before, thus it is in the plough furrow. The peat layer is 30 cm thick. The picture is taken with the sun standing lower than on the other profile pictures and is therefore shadowed with sunshine in the upper right corner (Photo: Erik Siggelin)

3.1.3 Hägsarve site

The Hägsarve topsoil has the lowest organic matter content of the three profiles. The peat layer is 35 cm thick and defined as a peaty marl (Table 7). The peat layer has a grey tone due to its lower organic matter content than the other soil profiles (Figure 6). Hägsarve was the only place that was cultivated a short while before. Therefore the samples in the topsoil were needed to be taken a little bit deeper than in the other places (8-18 cm).

Figure 6. Profile picture of Hägsarve. The peat and marl layer is 35 cm thick over the subsoil. The soil had recently been tilled to a depth of 8 cm. Some root and worm channels are visible in the subsoil. The layering is clearer than in the Stenstugu profile (Photo: Erik Siggelin)

3.2 Laboratory methods

The measurements were made in Soil physics lab at SLU, Department of Soil and Environment. All cylinders were water saturated before the start of the measuring. It was made through an increase of the water table until the water was in line with the top of the cylinders. The temperature in the lab was constant at 20 °C.

3.2.1 EC and pH

For measuring of electric conductivity (EC) and pH, soil from the loose soil samples were air dried at ≤ 40 °C. The soil samples were then grinded and sieved through a < 2 mm screen. One part soil and five parts deionized water by volume were added to a test tube with a lid and then shaken for 30 minutes. Before measuring of the EC and pH, the samples rested for two hours for sedimentation. EC was measured first and then pH. After 24 hours pH was measured again in the same sample. EC were measured at two occasions with new soil at the second occasion. The pH electrode was calibrated at pH 7, pH 4 and pH 9. All samples had one duplicate at each measuring.

3.2.2 Measurements of soil physical properties

The measuring of hydraulic conductivity was done with the constant-head method. For determination of loss on ignition, the soil samples were pre-dried at 105 °C in 24 hours and for the dry combustion the soil samples were heated for another 24 hours at 550 °C.

3.2.3 CO_2-measurments

For measuring of the CO_2 emissions eight cylinders from each site were selected that had no disturbance of worms, four from the topsoil and subsoil respectively. Measuring of CO_2 was done at five drainage steps. Drainage of the soil samples was done by placing them on a sand bed (Figure 7) and then gradually increasing the drainage, water saturated, to 25 cm, 50 cm, 75 cm and 100 cm drainage (Figure 7). The first drainage step (25 cm) took about one week to reach equilibrium. For the other drainage steps, it took about two weeks to reach equilibrium. For measuring of the CO_2 emissions of each cylinder it was placed in a plastic jar with an air tight lid. The jar was connected to a portable infrared CO_2 analyser (Carbocap CO_2 Probe

GMP343, Vaisala Ltd, Vantaa, Finland) (Figure 8). The air in the jar was circulated between the jar and the analyser by an air pump.

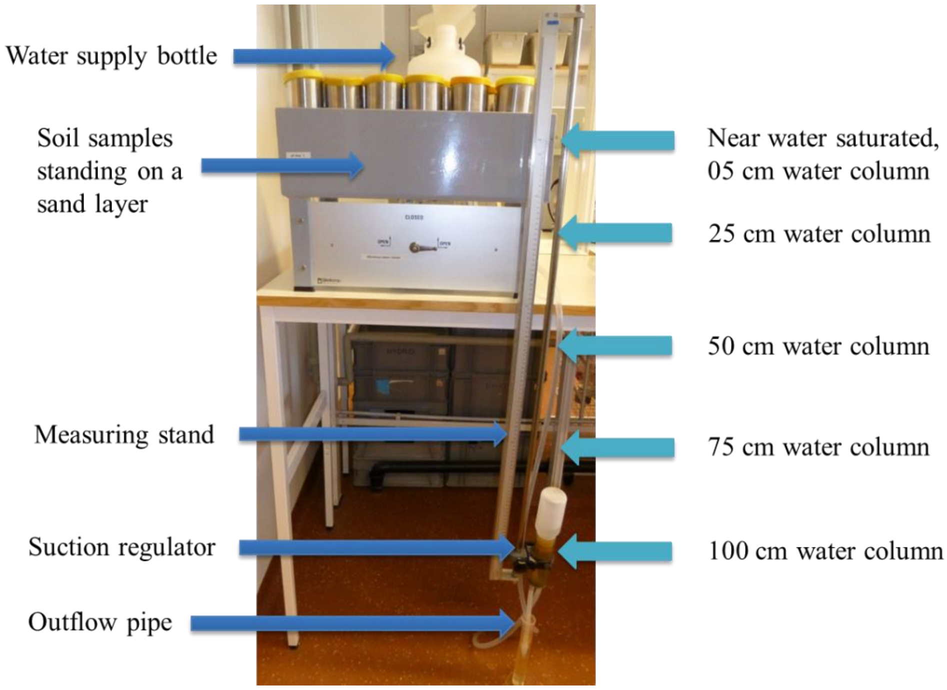

Figure 7. A simplified description of a sand bed for drainage of the soil cylinders. The suction regulator controls the drainage depth which is measured from the middle of the soil cylinder. The figure is modified from Norberg (2017)

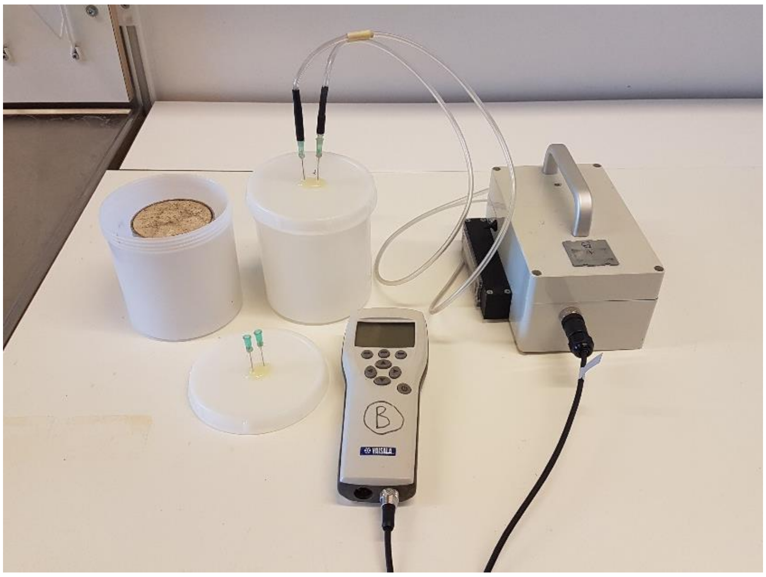

Figure 8. Set up of the infrared CO_2 analyser, plastic jars with soil samples and an air pump (Photo: Erik Siggelin)

The increase of CO_2 concentration was measured during 15 minutes with a 30 second interval. The samples were only measured once at each drainage level. The emissions were calculated from the linear increase of CO_2 concentration in the jar. Samples with a linearity lower than $r^2 = 0.85$ were analysed visually to determine if the measurements should be rejected or not. If there was no obvious error, the measurement was included. The slope of the concentration increase of CO_2 in the jar was calculated with eq. 1, which is described in more detail by Kainiemi et al. (2015). It was then divided with the soil dry weight.

$$\mathrm{m} = \frac{res * P * V * M}{R * T} \qquad \text{(Eq. 1.)}$$

m = mg CO_2, res = ppm CO_2 min^{-1}, P = atmospheric pressure = 101325 Pa, V = volume of air in the jar (L), M = molecular mass of CO_2 (g mol^{-1}), R = gas constant (8.3145 J mol^{-1} K^{-1}) and T = temperature (K^{o}).

3.3 Statistical analysis

An average value of the CO_2 emissions from four measured soil samples for the topsoil and subsoil respectively were calculated for all sampling sites at each drainage depth. Standard deviation for the measured CO_2 emissions were calculated with Excel (Microsoft Office). The increase of CO_2 emissions was analyzed with One Way Anova and compared the means at each drainage step with students t-test using JMP Pro 12.2.0.

4 Results

4.1 Soil properties

The topsoil at Alveskogs had the highest Electric Conductivity (EC) and the highest loss of ignition (Table 8). The second highest EC value was in Stenstugu subsoil, which had the lowest loss on ignition. There was no difference in pH between the topsoils and the subsoils (Table 8). The pH measurement, 24 hours after shaking, showed lower values than the pH measurement 2 hours after shaking (Table 8). The values for loss of ignition cannot be directly translated to organic matter if the soil contains calcium carbonates. The correction factor for organic matter is 1 % unit lower for every 10 % calcium carbonates the soil contains (Ekström, 1927). No measurement of calcium carbonates was done for these soils due to its complexity. Alveskogs topsoil had the highest loss on ignition value (Table 7) which could be expected by profile morphology, Figure 2, 5 and 6.

Table 8. *Electric conductivity (EC) 4 replicates, pH 2 replicates and loss on ignition 2 replicates. The loss on ignition cannot be directly translated to organic matter when there is a high calcium content in the soil*

	EC µS/cm	pH*	pH**	Loss on ignition % of wheigt
Alveskogs topsoil	376	8.1	7.6	37.3
Alveskogs subsoil	342	8.2	7.7	9.3
Stenstugu topsoil	313	8.2	7.6	20.9
Stenstugu subsoil	361	8.0	7.8	6.1
Hägsarve topsoil	260	8.4	7.8	7.5
Hägsarve subsoil	262	8.4	8.0	6.4

*pH measuerd within 2 hours after shaking **pH measuerd within 24 hours after shaking

Alveskogs topsoil had the lowest compact density, 2.07 g/cm^3 (Table 9). Stenstugu and Hägsarve topsoil had a compact density at 2.33 g/cm^3 and 2.52 g/cm^3 respectively. The subsoils do not differ much between the sites. Alveskogs subsoil had the lowest compact density value at 2.50 g/cm^3 compared to Stenstugu and Hägsarve at 2.55 g/cm^3 and 2.53 g/cm^3, respectively. The porosity is similar between the sites, except for Hägsarve topsoil where it was 60.5 %, which is around 10 % units lower than the other sampling sites (Table 9).

Table 9. *Compact density, dry bulk density and porosity for all soil profiles. The porosity value is an average value from four soil samples with individual values for dry bulk density*

	Compact density g/cm^3	Dry bulk density g/cm^3	Porosity %
Alveskogs topsoil	2.07	0.58	71.8
Alveskogs subsoil	2.50	0.72	71.2
Stenstugu topsoil	2.33	0.72	69.2
Stenstugu subsoil	2.55	0.71	72.2
Hägsarve topsoil	2.52	1.00	60.5
Hägsarve subsoil	2.53	0.73	71.3

Alveskogs topsoil with the lowest compact density and a porosity similar to the other sites, had the lowest hydraulic conductivity (Table 9 and 10). The variation is large between the samples and between the sampling sites. Generally, the topsoil has lower values for the hydraulic conductivity than the subsoil (Table 10).

Table 10. *Hydraulic conductivity for all sampling sites. All measurements <1 is shown with two decimals*

Hydraulic conductivity	Average m/day	Min m/day	Max m/day	Median m/day
Alveskogs topsoil	0.09	0.07	0.11	0.08
Alveskogs subsoil	8.0	1.6	20.4	2.0
Stenstugu topsoil	2.1	0.00	4.5	1.9
Stenstugu subsoil	4.9	0.31	7.8	6.7
Hägsarve topsoil	1.1	0.01	2.4	0.87
Hägsarve subsoil	13.7	5.8	24.3	11.1

Alveskogs topsoil had the highest water content at all drainage depths, it ranged from 71 % at 5 cm drainage depth down to 58 % at 100 cm drainage depth. The other soil samples decreased in water content at lower drainage depth than Alveskogs topsoil (Figure 9). At 5 cm drainage depth all soils had a similar water content between 68 % to 71 %, except for Hägsarve topsoil that had a water content of 61 % at 5 cm drainage depth. Hägsarve topsoil have the lowest water content at all drainage depths (Figure 9). When plotting the distribution of the air filled pore space (AFPS) together with the drainage depth, the topsoil and subsoil conditions divides clearly into two groups were the subsoil had a higher AFPS than the topsoil (Figure 10).

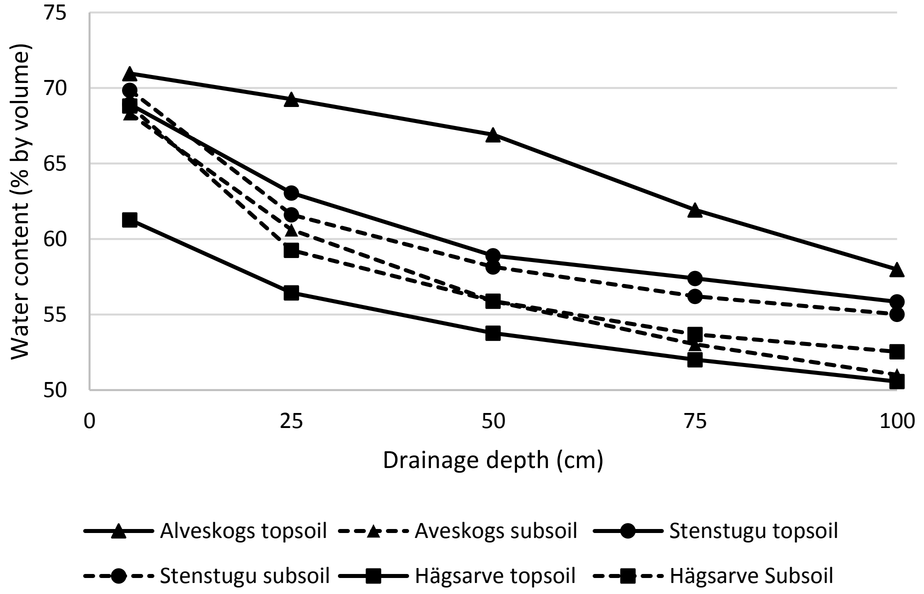

Figure 9. Water content for the different soils at all drainage depth

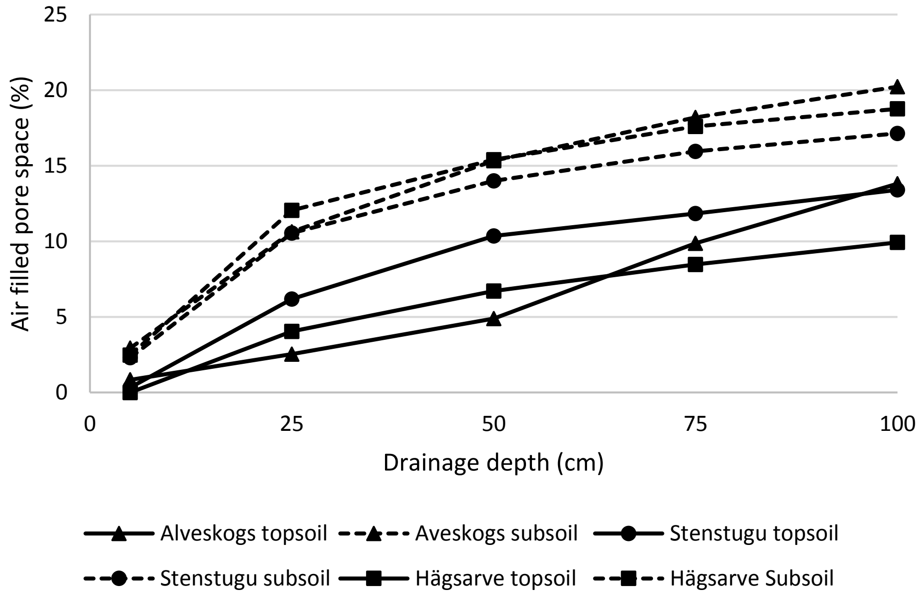

Figure 10. Percent air filled pore space (AFPS) at all drainage depth

4.2 CO_2 emissions

Alveskogs topsoil had the highest CO_2 emissions at all drainage depths. At the drainage depths 50 cm, 75 cm and 100 cm, CO_2 emissions were more than two times higher than the Alveskogs subsoil and Stenstugu topsoil that had the second highest CO_2 emissions (Figure 11). At 5 cm drainage depth both Hägsarve topsoil and subsoil had a CO_2 emissions rate of 3 mg g^{-1} dry soil min^{-1} and Alveskogs topsoil had CO_2 emissions of 26 mg g^{-1} dry soil min^{-1} (Figure 11). At 25 cm drainage depth Alveskogs and Stenstugu topsoil had a CO_2 emissions rate of 96 mg g^{-1} dry soil min^{-1} and 77 mg g^{-1} dry soil min^{-1} respectively, which is more than two times higher than the CO_2 emissions rate from the other soils (Figure 11). Alveskogs and Hägsarve topsoil and Stenstugu subsoil had a significant increase of the CO_2 emissions until 50 cm drainage depth. Stenstugu topsoil had a significant increase of the CO_2 emissions until 25 cm drainage depth. Alveskogs and Hägsarve subsoil had a significant increase of the CO_2 emissions until 75 cm drainage depth (Figure 11).

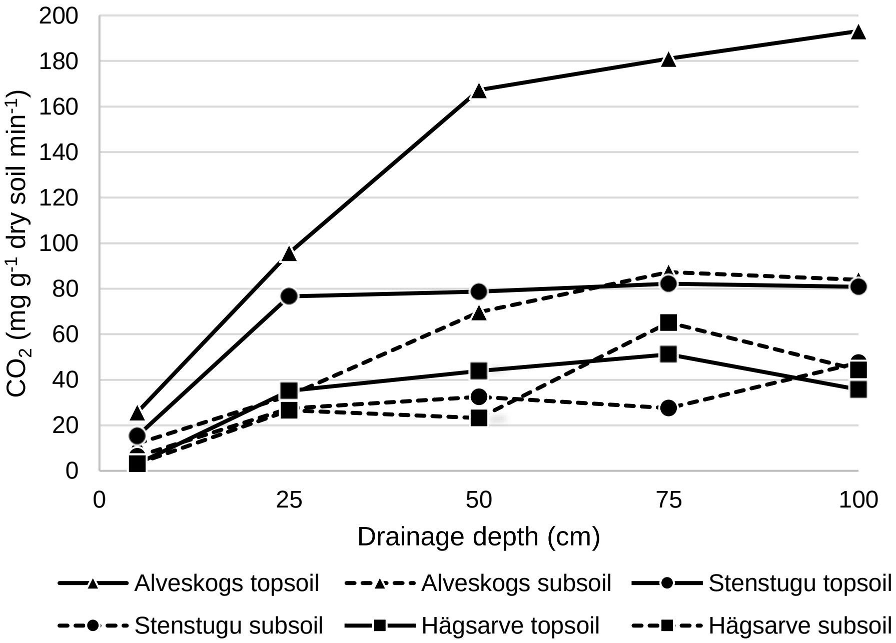

Figure 11. Average CO_2 emissions (mg g^{-1} dry soil min^{-1}) from the different soils at five drainage depths

Out of 120 measurements, 7 hade slightly negative slope in the calculations (Eq. 1) and was therefore set as 0 slope, which means there were no emissions. Negative values were not used, the emissions fluctuated around 0 and happened to end at a negative value. Of the 7 measurements set as 0 value, six originated from Hägsarve and one from Stenstugu subsoil. Both Alveskogs and Stenstugu had a significant difference in the CO_2 emissions between the topsoil and the subsoil (Figure 12 and 13). At the drainage depth of 5 cm the standard deviation at the Hägsarve profile was greater than the average value of CO_2 emissions (Figure 14).

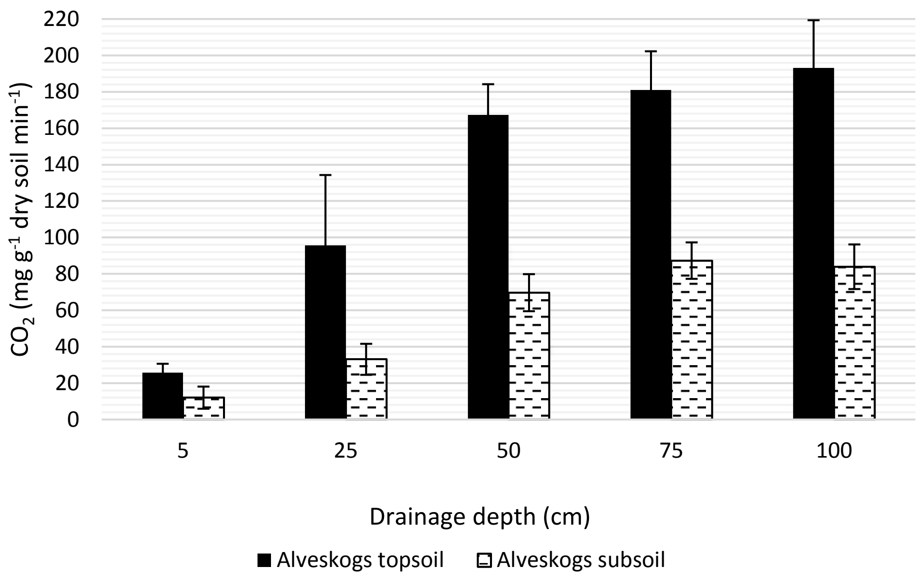

Figure 12. Average CO_2 emissions (mg g^{-1} dry soil min^{-1}) from the Alveskogs topsoil and subsoil

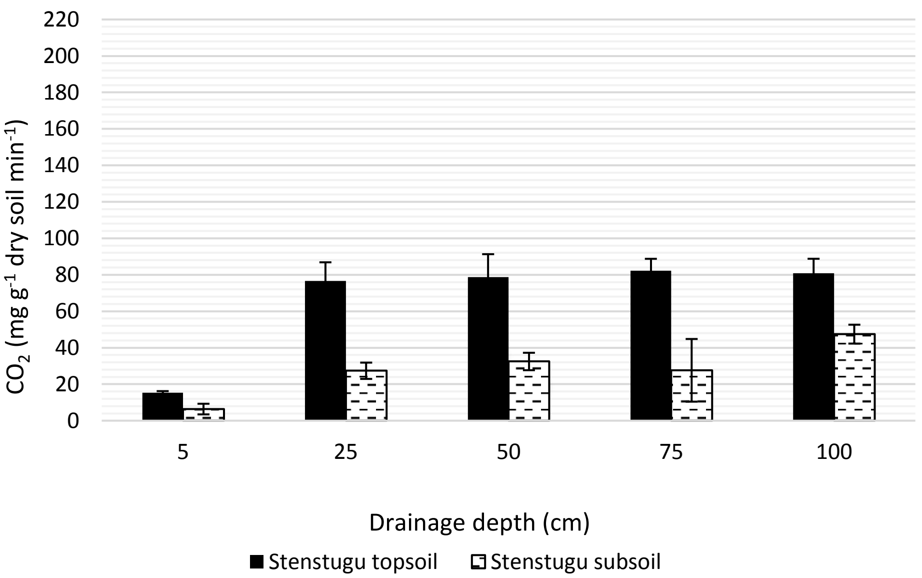

Figure 13. Average CO_2 emissions (mg g^{-1} dry soil min^{-1}) from the Stenstugu topsoil and subsoil

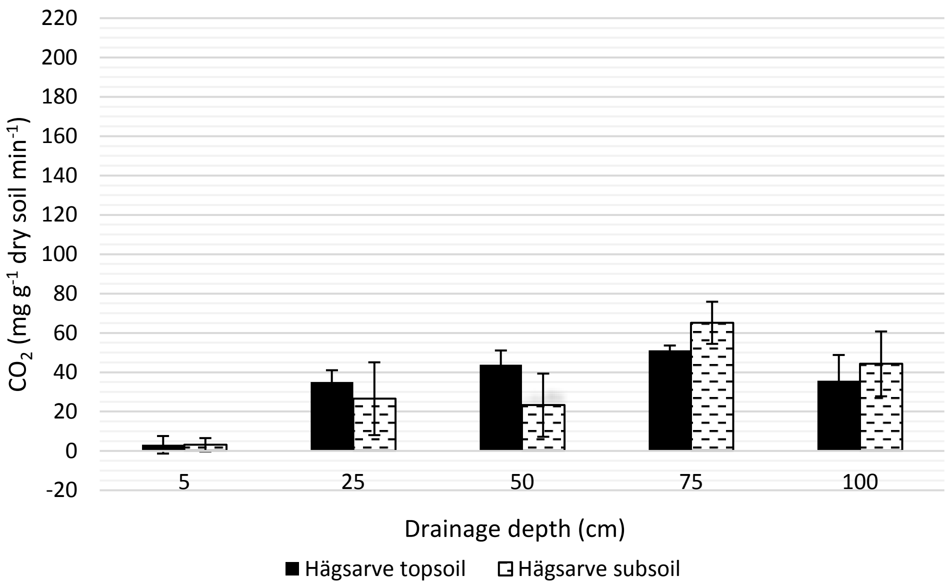

Figure 14. Average CO_2 emissions (mg g^{-1} dry soil min^{-1}) from the Hägsarve topsoil and subsoil

The CO_2 emissions correlates with increased AFPS in the subsoil. In the topsoil there is a larger spread of the data points and no correlation can be seen between the CO_2 emissions and AFPS (Figure 15). At 50 cm drainage depth the CO_2 emissions from all six samples has a linear correlation with the loss on ignition (Figure 16).

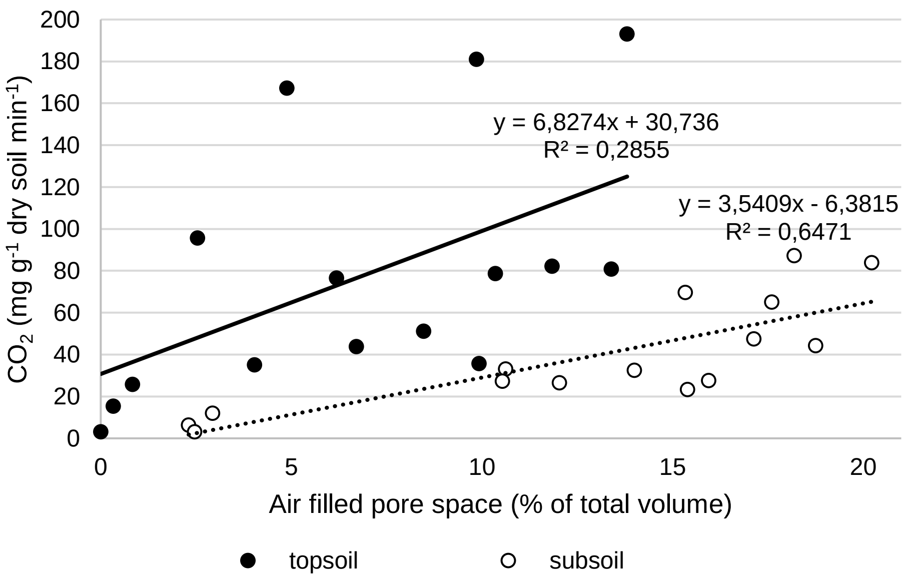

Figure 15. CO_2 emissions correlated with air filled pore space (AFPS) in topsoil and in subsoil

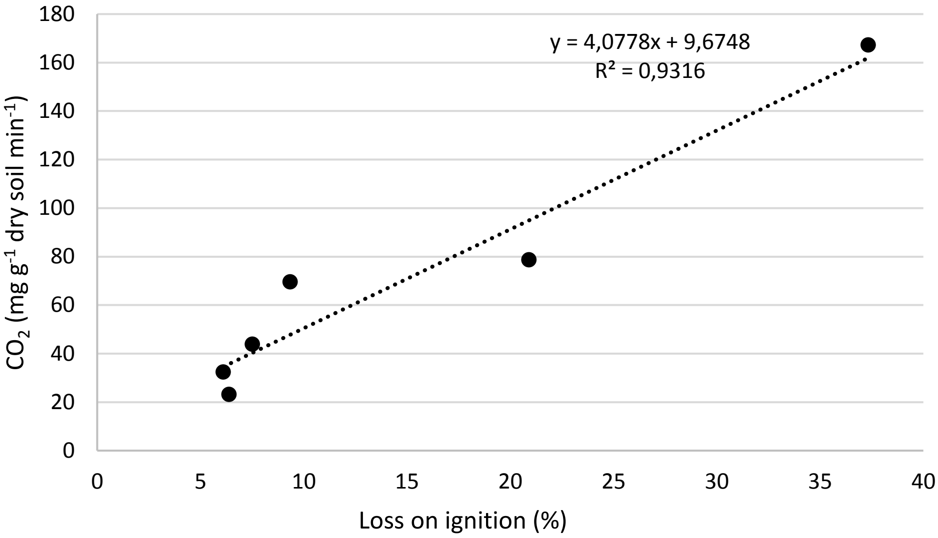

Figure 16. CO_2 emissions correlated with loss on ignition at 50 cm drainage depth

5 Discussion

Despite the relatively close range between the three sampling sites, there are large differences of the soil properties (Table 8, 9 and 10). The soil sampling made by Berglund (1982) of various soil profiles from the peatland areas on Gotland also show a large variation of the soil properties. Berglund (1982) described three soil profiles that in many ways resemble the soil profiles studied in this project. The pH values of the soil profiles vary similar, 7.6-8.0 in this study and 7.0-8.1 for the soil profiles in the older study. Stenstugu is the profile most similar to the Mästermyr profile described in Table 5 and 6. The topsoil has similar loss on ignition value before the correction due to the calcium carbonate content. Hägsarve soil profile is similar to the soil profile from Elinghems peatland area, where the topsoil is similar in loss of ignition but has somewhat lower compact density and higher porosity. The subsoil also has higher porosity but similar compact density (Berglund, 1982). Alveskogs is more similar to a soil profile from Stångmyr, that also has a well-decomposed fen peat in the topsoil and layers of different types of calcareous soils in the subsoil (Berglund, 1982).

When comparing loss on ignition values in this study with those in the study by Berglund (1982) you have to bear in mind that the loss on ignition values haven't been corrected for the calcium carbonate content as they were in the study by (Berglund, 1982). The calcium carbonate content in the Mästermyr and Elinghems soil profile is around 50 %, which would give a correction factor at 5 % unit lover loss on ignition value for the Stenstugu and Hägsarve soil profiles. The difference in the method to determine the loss on ignition is that the values in this paper was done at 550 °C instead of 600 °C as Ekström (1927) describes. Which mean that a smaller amount of crystal water will vaporize, than with the higher temperature.

Most soils are easily drained (Figure 9) and already at small drainage depths, a considerable amount of air has entered the soil (Figure 10). Alveskogs topsoil has a higher proportion of micro pores and is slowly drained until 50 cm drainage depth and then drains quickly. The well-decomposed peat gives a narrow distribution of the pores sizes. The pours marl subsoils were in general more easily aerated than the more peaty topsoils (figure 10). The hydraulic conductivity differs between the topsoils and the subsoil, were the subsoils have a higher hydraulic conductivity than the topsoils (Table 10). This indicates that the subsoils has larger proportion of macro pores. Alveskogs has the lowest hydraulic conductivity, because of the lack of macro pores in the peat layer.

There was a great variation in CO_2 emissions between the different soil profiles (Figure 9, 10, 11 and 12). The variation of the results is similar to results by Norberg et al. (2016b). Norberg (2017) has shown similar results from nine organic soils, three were from Gotland and had similar soil properties, two peat soils (65 % loss of ignition) and one marly peat soil (17 % loss of ignition, Norberg (2017) defines the soil as marl). The two peat soils had the highest CO_2 emissions and the peaty marl soil had the lowest CO_2 emissions. The three soils had its highest emissions at 75 cm drainage depth as well. The CO_2 emissions from the peaty marl soil did not differ much between the drainage depths 50, 75 and 100 cm, as for the Stenstugu topsoil. There was no measuring of CO_2 emissions at 25 cm drainage depth. Berglund and Berglund (2011) had higher CO_2 emissions from a peat soil at 40 cm drainage depth than at 80 cm drainage depth because of the soil got to dry. Wessolek et al. (2002) reports higher CO_2 emissions at lower drainage depth.

The correlation between loss on ignition (Table 8) with CO_2 emissions from all soils at 50 cm drainage depth is strong (Figure 14). There is some uncertainty when it is only a few data points. The samples with low loss of ignition value could be questioned if they should be considered as organic soils. Norberg (2017) also shows a correlation between CO_2 emissions and loss on ignition. The correlation between loss of ignition and CO_2 emissions without the marl and gyttja soils would not be that clear, neither in this study or in Norberg (2017).

In the subsoil there is a correlation between AFPS and CO_2 emission. The same correlation cannot be seen for the topsoil (Figure 13). For all soils except Alveskogs topsoil the availability of organic matter can be one limiting factor for CO_2 emissions. For Stenstugu and Hägsarve subsoil it is unclear if they have reach their maximum CO_2 emissions because of the fluctuation between all drainage depths (Figure 9). The deviation for each average CO_2 emission value is larger for the Hägsarve soils in relation to the CO_2 emission.

All measuring in the lab was done at 20 °C which is higher than the soil temperature in the field under a large part of the year. Norberg (2017) found an increase of CO_2 emissions at higher temperatures. Moore and Dalva (1993) had an increase in CO_2 emissions between 2.4 and 6.6 times when the temperature increased from 10 °C to 23 °C. Due to the high temperatures in the soil samples, the microbial community could have a higher activity and therefore increase the CO_2 emissions rate at lower drainage depths than what could be expected in field conditions. Norberg (2017) found a correlation in CO_2 emissions between lab measurements and field measurements. Which means that the lab measurements can be used to identify organic soils with high risk of greenhouse gas emissions, even due to different conditions between the lab and the field in terms of soil moisture and temperature.

An amelioration action for the mires at Gotland could be too deep plough the soil profile. The mixing of the peat layer with underlaying marl and calcareous gyttja would decrease the loss of ignition value and decrease the CO_2 emissions. Mixing of the peat layer with the underlaying subsoils would also increase the thermal conductivity. The risk of frost damage on crops is high on organic soils in the spring due to the insulating effect of the dry peat which prevents transport of heat from the soil to the air around the crop during cold nights (Berglund, 1996). In general, annual crops is spring seeded on organic soils. If the soil has a higher thermal conductivity a larger proportion of the mires could be autumn sown and have a plant cover for a larger part of the year.

6 Conclusion

The soil profiles in this study differ in many ways between the sites. There can be many factors that limit the CO_2 emissions from drained organic soils. For these six groups of soil samples there are different factors that are limiting the CO_2 emissions from each group.

There are four conclusions that can be drawn from this study:

- The CO_2 emissions vary between different soil types.
- All soils increase their CO_2 emissions when drained, but in different degrees. The soils reach a maximum at drainage depth between 25 cm and 75 cm.
- There is a positive correlation between AFPS and CO_2 emissions in the subsoil but not in the topsoil.
- There is a positive correlation between loss of ignition and CO_2 emissions for all soils in this study.

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References

AURELA, M., LOHILA, A., TUOVINEN, J.-P., HATAKKA, J., RIUTTA, T. & LAURILA, T. 2009. Carbon dioxide exchange on a northern boreal fen. *Boreal Environ. Res,* 14**,** 699-710.

BEETZ, S., LIEBERSBACH, H., GLATZEL, S., JURASINSKI, G., BUCZKO, U. & HÖPER, H. 2013. Effects of land use intensity on the full greenhouse gas balance in an Atlantic peat bog. *Biogeosciences,* 10**,** 1067-1082.

BERGLUND, K. 1982. Beskrivning av fem myrjordsprofiler från Gotland Gotland (Description of five peat soil profiles from Gotland). Rapport 125. Sveriges Lantbruksuniversitet, Uppsala.

BERGLUND, K. 1989. Ytsänkning på mosstrovjord. Sammanställning av material från Lidhult, Jönköpings län. *Avdelningsmeddelande* Svergies lantbruksuniversitet: Instutitionen för markvetenskap, Avdelningen för lantbrukets hydroteknik.

BERGLUND, K. 1995. Properties of cultivated gyttja soils. *Int. Peat J,* 6**,** 5-23.

BERGLUND, K. 1996. Cultivated Organic Soils in Sweden: Properties and Amelioration. *Reports and Dissertations.* Uppsala: Department of Soil Sciences.

BERGLUND, K., MILLER, U. & PERSSON, J. 1989. Gyttjejordar, deras sammansättning och egenskaper. Uppsala: Rapport 160. Instiutionen för markvetenskap, Uppsala

BERGLUND, Ö. & BERGLUND, K. 2008. Odlad organogen jord i Sverige 2003: areal och grödfördelning uppskattad med hjälp av digitaliserade databaser. Institutionen för mark och miljö, Avdelningen för hydroteknik, Sveriges lantbruksuniversitet.

BERGLUND, Ö. & BERGLUND, K. 2010. Distribution and cultivation intensity of agricultural peat and gyttja soils in Sweden and estimation of greenhouse gas emissions from cultivated peat soils. *Geoderma,* 154**,** 173-180.

BERGLUND, Ö. & BERGLUND, K. 2011. Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil. *Soil Biology and Biochemistry,* 43**,** 923-931.

BERGLUND, Ö., BERGLUND, K. & KLEMEDTSSON, L. 2011. Plant-derived CO2 flux from cultivated peat soils*. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science,* 61**,** 508-513.

BERGLUND, Ö., BERGLUND, K. & SOLHENIUS, G. 2009. Organogen jordbruksmark i Sverige 1999-2008. Uppsala.

EKSTRÖM, G. 1927. Klassifikation av svenska åkerjordar. Sveriges Geologiska undersökning. *Serie C.* 345 ed.

FANG, C. & MONCRIEFF, J. B. 2001. The dependence of soil CO2 efflux on temperature. *Soil Biology and Biochemistry,* 33**,** 155-165.

GORHAM, E. 1991. Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming. *Ecological Applications,* 1**,** 182-195.

HALLGREN, G. N., OLOV; WIKLERT, PAUL 1965. Undersökningar rörande grundvattenuppdäning i blekejord på Gotland åren 1942-1961. *In:* HALLGREN, G. (ed.) *Grundförbättring (särtryck).* Uppsala: Institutionen för lantbrukets hydroteknik.

HJERTSTEDT, H. 1946. De organogena odlingsjordarnas beskaffenhet i olika län med avseende på torvslag, förmultningsgrad och reaktion samt innehåll av kalk och kväve, kali och

fosforsyra organisk substans, seskvioxider och svavelsyra. *Svenska vall- och mosskulturföreningens kvartalsskrift,* 8**,** 255-277.
KAINIEMI, V., ARVIDSSON, J. & KÄTTERER, T. 2015. Effects of autumn tillage and residue management on soil respiration in a long-term field experiment in Sweden. *Journal of Plant Nutrition and Soil Science,* 178**,** 189-198.
KASIMIR-KLEMEDTSSON, Å., KLEMEDTSSON, L., BERGLUND, K., MARTIKAINEN, P., SILVOLA, J. & OENEMA, O. 1997. Greenhouse gas emissions from farmed organic soils: a review. *Soil Use and Management,* 13**,** 245-250.
KOIZUMI, H., KONTTURI, M., MARIKO, S., NAKADAI, T., BEKKU, Y. & MELA, T. 1999. Soil Respiration in Three Soil Types in Agricultural Ecosystems in Finland. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science,* 49**,** 65-74.
LAIHO, R. 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology and Biochemistry,* 38**,** 2011-2024.
MALJANEN, M., MARTIKAINEN, P. J., WALDEN, J. & SILVOLA, J. 2001. CO2 exchange in an organic field growing barley or grass in eastern Finland. *Global Change Biology,* 7**,** 679-692.
MOORE, T. R. & DALVA, M. 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. *Journal of Soil Science,* 44**,** 651-664.
NILSSON, T. 1961. Kompendium i kvartärpaleontologi och kvartärpaleontologiska undersökningsmetoder. Lunds universitet.
NORBERG, L. 2017. *Greenhouse Gas Emissions from Cultivated Organic Soils,* Uppsala, Acta Universitatis agriculturare Sueciae.
NORBERG, L., BERGLUND, Ö. & BERGLUND, K. 2016a. Nitrous oxide and methane fluxes during the growing season from cultivated peat soils, peaty marl and gyttja clay under different cropping systems. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science,* 66**,** 602-612.
NORBERG, L., BERGLUND, Ö. & BERGLUND, K. 2016b. Seasonal CO2 emission under different cropping systems on Histosols in southern Sweden. *Geoderma Regional,* 7**,** 338-345.
OLOFSSON, S. B., SVEN O. 1954. Grundvattenstånd inom myrområden på Gotland samt förekomsten av gyttja i blekebildningar. *Kungliga Lantbruksakademins tidsskrift***,** 149-178.
OSVALD, H. 1937. *Myrar och myrodling (Mire and mire cultivation),* Stockholm, Kooperativa förbundets bokförlag.
PAHKAKANGAS, S., BERGLUND, Ö., LUNDBLAD, M. & KARLTUN, E. 2016. Markanvändning på organogena jordar i Sverige.
SCHAUFLER, G., KITZLER, B., SCHINDLBACHER, A., SKIBA, U., SUTTON, M. A. & ZECHMEISTER-BOLTENSTERN, S. 2010. Greenhouse gas emissions from European soils under different land use: effects of soil moisture and temperature. *European Journal of Soil Science,* 61**,** 683-696.
WESSOLEK, G., SCHWARZEL, K., RENGER, M., SAUERBREY, R. & SIEWERT, C. 2002. Soil hydrology and CO2 release of peat soils. *Journal of Plant Nutrition and Soil Science,* 165**,** 494.
WHITING, G. J. & CHANTON, J. P. 2001. Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration. *Tellus B,* 53**,** 521-528.