Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Soil and Environment

Liming and deep cultivation as long term mitigation actions to lower the rate of peat decomposition and CO_2 emissions from peat soils

Joakim Hermansson

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Kalkning och djupkultivering som behandlingar med långtidseffekt för att minska nedbrytningshastigheten hos torv och minska CO_2-avgången från torvjordar

Joakim Hermansson

Supervisor: Örjan Berglund, Department of Soil and Environment, SLU
Assistant supervisor: Kerstin Berglund, Department of Soil and Environment, SLU
Examiner: Lars Lundin, Department of Soil and Environment, SLU

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Abstract

Cultivated drained peat soils have a complex relationship towards CO_2 emissions and the contribution to global warming. Many people are unaware that the CO_2 emissions from peat soils, also known as organic soils, vary a lot within, and between, the fields. Permanent grassland may not always be the best mitigating action for lowering CO_2 emissions.

My research was done to provide a wider view on cultivated peat soils and the effects of long-term mitigating treatment towards slowing down the rate of peat decomposition and thus lowering CO_2 emissions. The decisions regarding future use of cultivated peat soils should not be limited by incorrect information on the impact on climate change. The study was done by reviewing the literature together with lab-experiments that measured the CO_2 emissions from samples that had different treatments. The samples' physical and chemical properties were examined as well.

CO_2 emissions were measured from undisturbed soil cores representing different treatments. The soil cores were collected in big lysimeters and small steel cylinders. The variables were differences in water content (lysimeter experiment) and altering water retentions (steel cylinders).

I had too few samples and data for any statistically significant findings. But I observed differences between the samples and the treatments. The observations were brought to discussion and compared with findings in the literature to provide possible explanations as to how the CO_2 emission could be affected.

The water content is one of the main driving factors regulating the peat decomposition. Water content has a complex relationship to the physical and chemical properties of the peat soils and the effect on CO_2 emissions. It affects temperature response towards microbial degradation as well as structure and abundance of microbial communities that are responsible for the degradation (CO_2 emissions) of peat soil. This creates varying rates of peat decomposition and differences in CO_2 emissions.

I hope that this research provides more general information and wider views on the rate of peat decomposition and CO_2 emissions from cultivated peat soils.

Keywords: Peat soil, organic soil, decomposition, CO_2 emission, water retention

Sammanfattning

Odlade dränerade torvjordar har ett komplext förhållande till koldioxidutsläpp dess bidrag till den globala uppvärmningen. Många människor är inte medvetna om att koldioxidutsläppen från torvjordar, även kallade organogena jordar, varierar mycket inom och mellan fälten. Permanent betesmark behöver inte alltid vara den bästa strategin för att sänka koldioxidutsläppen.

Min forskning gjordes för att ge en bredare bild av odlade torvjordar och effekterna av behandlingar för att långsiktigt minska nedbrytningen av torv och därmed minska koldioxidutsläppen. Beslut om framtida användning av odlade torvjordar bör inte begränsas av felaktig information om klimatpåverkan. Studien gjordes som en kombinerad litteraturstudie och laboratoriestudie där mätningar av koldioxidutsläpp gjordes från prover som hade olika behandlingar. Provernas fysikaliska och kemiska egenskaper undersöktes också.

Koldioxid mättes från ostörda jordprov som representerar olika behandlingar. Jordproven togs ut i lysimetrar och i stålcylindrar. Variablerna var skillnader i vattenhalt (lysimetrarna) och förändring av vattenavförande tryck (stålcylindrarna).

Jag hade för få upprepningar för att erhålla statistiskt signifikanta resultat. Men jag kunde skönja vissa tendenser mellan prover och behandlingar. Observationerna diskuterades i relation till litteraturens resultat för att ge möjliga förklaringar om hur koldioxidemissionerna skulle kunna påverkas.

Vattenhalten är en av de viktigaste parametrarna som styr nedbrytningen av torv, och har ett komplicerat förhållande till torvjordens fysikaliska och kemiska egenskaper och effekterna på koldioxidemissioner. Vattenhalten påverkar med andra ord temperatur och respons för mikrobernas nedbrytningar och struktur samt de mikrobiella samhällen som är ansvariga för nedbrytningen från torvjord. Detta skapar varierande hastigheter för nedbrytning av torv och skillnader i koldioxidemissioner.

Min förhoppning är att denna forskning ger ökad information och bredare syn på koldioxidemissionerna från odlade torvjordar.

Keywords: Torv, organogen jord, nedbrytning, CO_2 avgång, vattenretention

Populärvetenskaplig sammanfattning

Lantbrukare har sedan länge nyttjat dränerade torvmarker för odling. Det senaste decenniet har forskare och media diskuterat ingående de klimatförändraringarna som den mänskliga påverkan har på det globala klimatet och den rollen som dessa uppodlade torvmarker har i sammanhanget.

Torvjordar täcker 400 miljoner hektar av jordens yta (varav ca 270 000 ha utgörs av odlade torvjordar i Sverige) och innehåller väldiga mängder lagrat organiskt material. Ungefär 80 % av jordens torvmarker hittar man på det norra halvklotet. Detta organiska material har under tusentals år fått byggas upp ostört under syrefria miljöer med väldigt liten nedbrytning, och detta material är växternas in-bundna koldioxid. Med hjälp av denna anaeroba process har torvmarker ka-tegoriserats som kolsänkor i och med att de lagrar in mer kol än vad de avger. På det norra halvklotets torvmarker ligger det lagrat en tredjedel av markens kolinlagringar och i och med den ökade temperaturen och ett vidare utnyttjande och uppodlande av torvmarkerna så börjar dessa torvmarker att ses som en kolkälla som istället avger mer kol än vad den binder in.

Under våren 2017 gjordes mätningar av koldioxidemissioner ifrån prover som hade under 70-talet genomgått olika behandlingar så som; djupplöjning, omgrävning av jordprofilen samt kalkning. Inga signifikanta resultat kunde erhållas ifrån experimentet men tendenser kunde skönjas att kalkning kombi-nerat med total omgrävning av jordprofilen kunde långsiktigt minska koldioxidemissionerna från den uppodlade torvjorden.

Denna rapport gjordes för att ge en bredare bild av odlade torvjordar och for att ta reda på om olika behandlingar kunde göras för att långsiktigt minska nedbrytningen av torv och därmed minska koldioxidutsläppen. Det finns ett behov för att komma fram till gemensams hanteringsvägar för att minska koldioxidavgången för att på ett enkelt sätt kunna applicera minskande åtgärder över större områden. Detta är problematiskt dock då torvens organiska sam-mansättning och egenskaper kan variera stort inom fältet.

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1 Introduction

Worldwide, peatlands cover over 400 million hectares which is about 3% of the earth land area (Limpens et al. 2008). Peatlands consist of thousands of years of deposited organic material and are defined as having at least a 30 cm thick organic layer. Peatlands are big carbon storages and if left undisturbed they act as huge carbon sinks (Turunen 2002). 80% of the world's peatlands are located in the northern hemisphere (Limpens et al. 2008) and roughly one-third of the total pool of soil carbon is stored there (Turunen 2002). With the climate change and the change in temperature, the utilization of peatlands is viewed as a source of CO_2 (Charman et al. 2013) and research on long-term effects to stabilize carbon flux and reduce CO_2 emissions is valuable.

In Sweden the use of peatlands has a long history. Before the 18th-century they were considered undesirable and no good for using as either fuel resources or crop-/graze- land which historically have been the main use in Sweden (Runefelt 2008[1]). Educated people at the time knew that the peatlands could be perfectly fine to grow crops on when properly drained and maintained. In the 19th-century Sweden's economy and population started to grow rapidly and the need for agricultural land got bigger. Subsidies were given for extensive drainage projects and claiming of new agricultural land and the sight was set on the vast peatlands covering a large part of Sweden (Runefelt 2008[1]).

In 1886 the Swedish Peat Society (Svenska Mosskulturföreningen) was founded that performed and constructed trials, advisory services, research and instructing on how to best transform Sweden's peatlands into rich agricultural land. The use of peatlands for agricultural purposes was at its maximum areal amount in the 1940's when around 700 000 hectares had been drained and put to use. After that it has been constantly decreasing since no new drainage projects have been undertaken on most of the land (Runefelt 2008[2]).

The total area of peatlands in Sweden today is around 6.3 million hectares and roughly 2.1 million hectares is used for agricultural purposes, forestry or peat cutting (Runefelt 2008[3]). Peat belongs to the organic soil type which includes the gyttja soil (partially decayed peat), and marl. The cultivated organic soils make up roughly 270 000 hectares. Common uses of the organic soils today are mainly managed grass land, pastures and forestry, but some of the soils are well suitable for crop growth such as oats, barley, rye, potatoes or carrots (Berglund 2008).

Modern views on nutrient leeching and carbon fluxes put the peatlands in a questionable situation whether to be a long-term renewable resource that is worth maintaining in modern times. New legislations with purpose to restore and protect peatlands/wetlands as wild life natural environment make it almost impossible to update or renew the drainage systems on these soils. Unfortunately the use of the ever decreasing agricultural purposes suffers. All effort and research data that can contribute to knowledge about peatlands and its varying properties is valuable when it comes to decide the future uses of this natural resource.

2 Background & literature review

2.1 The formation of peat

The formation of peat in the landscape is ongoing and has been a century or millennia long process. Peat normally forms from overgrown waters and followed by partial or low degradation of organic material through anaerobic conditions. The anaerobic conditions are usually due to waterlogging. Low temperatures can also be a cause of partial or low degradation. Gyttja is an organic material that has partially been decayed by water living organisms through anaerobic conditions and has formed as sediment in cold temperature lakes (Berglund 2008). The alternating and varying original organic material has contributed to the vast dynamics that the peat soil inherited. The original material can either consist of nutrient rich fen peat or nutrient poor bog (Berglund 2008).

2.2 Water content in peat soil

The peat soil and its characteristics are categorized based on the originating material and can have great physical and chemical variations, but all peat soils often share characteristics of high porosity and low dry bulk density. The high porosity gives high water holding capacity in the soil profile, but the topsoil of the peat soils usually have problems of low permeability. The low permeability expresses itself during conditions of low water content, typically within the range of 20-30% (Berglund G. 1982). Low water content can occur numerous times during the growing season in the topsoil, especially during the first part. Cultivated peat soils can get a special structure that is characterized by hydrophobicity from years of intensive cultivation. This typical structure in combination with drought has a significantly negative effect to the permeability (Berglund G. 1982).

The peat soils are relative young soils with high organic content and they all share common problems: subsidence and loss of carbon through CO_2 emissions. These two problems are the basis of the greenhouse gas emissions that the drained cultivated peat soils bring with them. Four factors are major in lowering the soil level (subsidence) after draining the soil; initial setting of soil, consolidation, shrinking and carbon efflux (Berglund 2008).

The initial setting above the groundwater table is caused by collapsing of the larger pores when the mechanical support of the water disappears. Consolidation of the soil below the groundwater table occurs when the hydrostatic pressure drops but the weight of the soil, with still some water left in the pores, is almost the same. Shrinking affect the soil above the groundwater table in the long-term and is caused by drought (Berglund 2008).

Carbon efflux (loss of carbon through CO_2 emissions) is the degradation and oxidation of peat through respiration by the microbial communities that make up the degraders in the soil. Loss of carbon occurs when the groundwater table drops and the soil gets aerated (Berglund 1989). This allows for increase in gaseous exchange in the soil and an increase in oxygen level. There is a high demand for oxygen by heterotrophic decomposing microorganisms. When they come in contact with the oxygen in the soil their activity increase and decomposing processes like mineralization and oxidation of Soil Organic Matter (SOM) increase. Carbon is emitted as CO_2 from respiration by the heterotrophic microorganism. Figure 1 displays an illustrated timeline of the creation and shrinkage of drained peatland. Degradation processes are often significant in the relative young organic soils because of the high SOM availability for the microbial communities (Berglund 1996).

There is a minimal and maximum level of water content availability for optimum decomposition and oxidization of the SOM in peat. This is varying greatly from different peat soils due to their complexity of content from different originating material and alternating soil profiles in the landscape. Too much water results in oxygen becoming a limiting factor for soil organisms. Too little water and the result is that mobility of enzymes and substrates becomes limited and never reach soil organisms (German & Allison 2015; Norberg et al. 2016).

In a wider perspective an altering water level cause greater aeration in the soil profile and stimulates denitrification bacteria. This raises N_2O emissions to the atmosphere. N_2O is a more effective greenhouse gas than CO_2 (Jordan 2016).

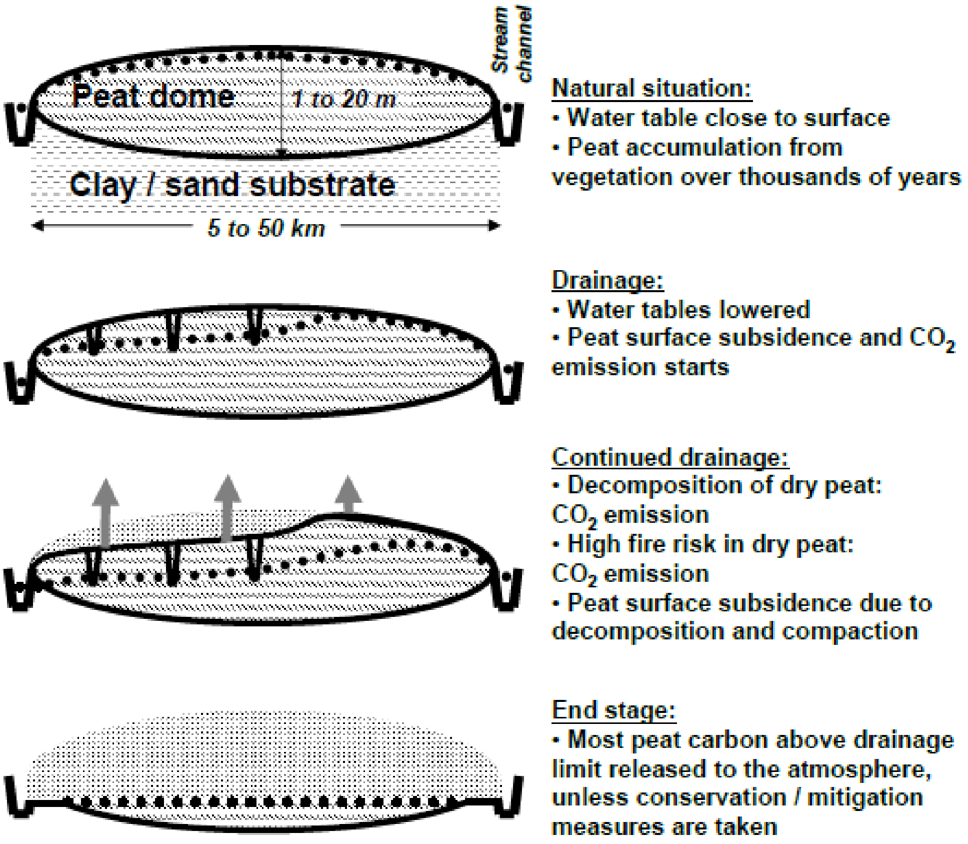

Figure 1. "Schematic illustration of progressive subsidence of the peat surface in drained peatland, due to peat decomposition resulting in CO_2 emission as well as compaction." From: Hooijer et al. 2010.

2.3 CO_2 flux

With increased microbial degradation and respiration, oxidation turns the peat soil from net accumulation of carbon to respiration and increased emissions of CO_2. The soil goes from acting as a carbon sink, to acting as a carbon source. This makes the peat soils contribute to the greenhouse effect. The amount of carbon stored in northern boreal and subarctic peatlands is 220-460 x1015 g carbon (Turunen 2002).

Cultivated peatlands dominate the CO_2 emissions from agricultural land in Sweden and they can subside 2-20 mm per year due to oxidization and respiration caused by microbial degraders (Berglund 2011). Measured CO_2 emissions from drained cultivated peat soils have different origin. It can be SOM-derived CO_2 or CO_2 from plant and root respiration. There is a need to distinguish between these two on cultivated peat soils in order to grasp the problem of (carbon) CO_2 emissions that contribute to the greenhouse effect. Growing vegetation contributes to short-term carbon efflux by root and rhizomicrobial respiration. Short-term carbon is stored by plants in the beginning of the growing season and has a high turnover rate (Figure 2) while possible plant debris and organic matter that are later left in the soil have a high residence time and add to the long-term storage of SOM (Kuzyakov 2006). This short-term storage compared to long-term storage of carbon is what distinguishes the two sources and their future role in the ecosystem as either a source or a sink (Kuzyakov 2006; Berglund et al. 2011). CO_2 emissions is commonly measured as the total of the two general sources which are plant-derived CO_2 and SOM-derived CO2 (Figure 2). Excluded in Figure 2 is the abiotic derived CO_2 flux from liming of acidic peat soils (Biasi et al. 2008).

2.4 Liming & tillage

Liming is a collective term that consists of spreading usually one of four different calcium (Ca) chemical compositions: CaO, $Ca(OH)_2$, $CaCO_3$, $CaMg(CO_3)_2$. Liming has a positive soil structural effect on clay soils and neutralizing effect on soil acidity, raising the pH towards an optimum for plant growth (Berglund K. 2015). One product which historically was used on peatsoils was tetracalcium phosphate $(CaO)_4P_2O_5$), commonly called Thomas-phosphate or Thomas slag. It had the primary purpose of fertilization (phosphorous) but also had liming effects (pH regulating and structural), although not enough to cover the need in most soils. It has long

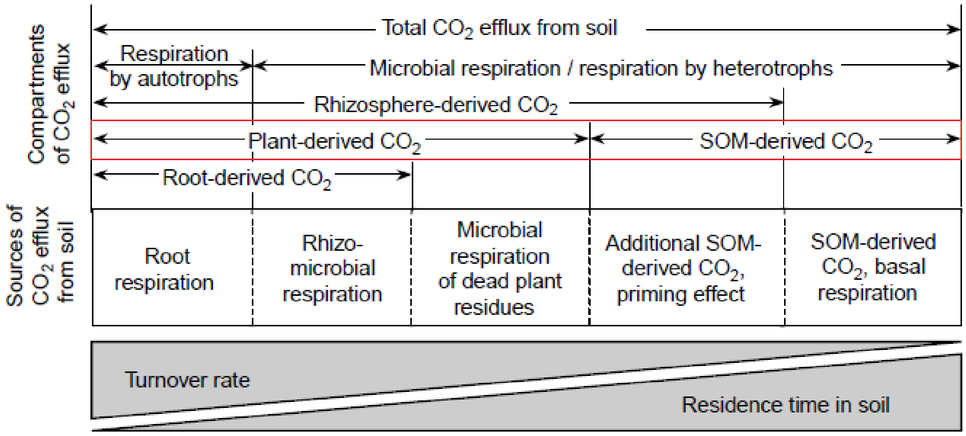

Figure 2. Illustrated in the figure is the sources of CO_2 emission that can be distinguished from the total soil respiration. Turnover rates and mean residence time of carbon in soil is put in perspective at the bottom. Highlighted in red are the two general CO_2 sources. Modified and taken from: Figure 1 in Kuzyakov (2006).

been known that liming is necessary on peatsoils due to its acidic character (Persson 2008).

There are abiotic aspects contributing to increased CO_2 emissions from liming acidic soils. The first is dissolving carbonates ($CaCO_3$) and gaseous emissions from adding the liming material itself (Biasi et al. 2008). The second is the increase in microbial activity and degradation due to raised pH, neutralizing acidity in soil, and improving soil environment (Fuentes et al. 2006; Kemmit et al. 2006). In addition, there is dissolvable carbonates that are already present in the soil (soils derived from limestone) and its carbon pool (Kuzyakov 2006). There is a risk to overestimate heterotrophic microbial activity in limed soils when not separating abiotic and biotic CO_2 release (Biasi et al. 2008).

Deep cultivation in combination with liming can improve the peat soil stratigraphy and also improve the plants root zone (Berglund 1996). Peat soils that are characterized with a shallow cultivated peat layer as topsoil, usually have an acidic gyttja soil as subsoil. A pH-value below 5.0 has a negative effect and pH below 4.0 is a definitive restriction of root growth. Cultivating and liming to increase pH towards 5.5 throughout the soils stratigraphy provides a better optimum for plant growth on peat soils (Berglund 1996). Cultivating deeper than the upper peat layer consisting of typically 30 cm can also improve the physical aspects of the topsoil from a plant point of view. These improvements could be a more even distribution of pores in the soil and an improved hydraulic conductivity (Berglund 1996; Walczak et al. 2002; Elder et al. 2008[2]).

Deep cultivation and mixing the soils stratigraphy can have an effect on conserving the peat layer by placing it lower down where biological activity and decomposition processes are less (Richardson et al. 1991). In the long-term it can mean that CO_2 emission from SOM is reduced.

2.5 The effect of temperature on Rate of Peat Decomposition

Temperature is one of the major environmental factors that influences the Rate of Peat Decomposition (R_{PD}) and thereby the rate of CO_2 emissions. Mäkiranta et al. (2009), Kluge et al. (2008) and Lefleur et al. (2005) have found a strong correlation between temperature, decomposition rate and CO_2 emissions in their studies. This is in accordance to other studies that have promoted temperature as a main driving factor for R_{PD} (Jordan 2016; Nieveen 2005; Wessolek et al. 2002). In a study made by Kluge et al. (2008) they have results showing CO_2 emissions at increased water retentions (pF-value) and at fixed temperatures ranging from 5-25°C. They found that there is a temperature threshold of >+10°C that significantly increase CO_2 emissions for both top- and subsoil at all water retentions. This provides evidence indicating that temperature is a dominating environmental factor in these soil horizons (Figure 3). Wessolek et al. (2002) also found a threshold at low temperature (+5°C) showing similar results as Kluge et al. (2008) (Figure 4).

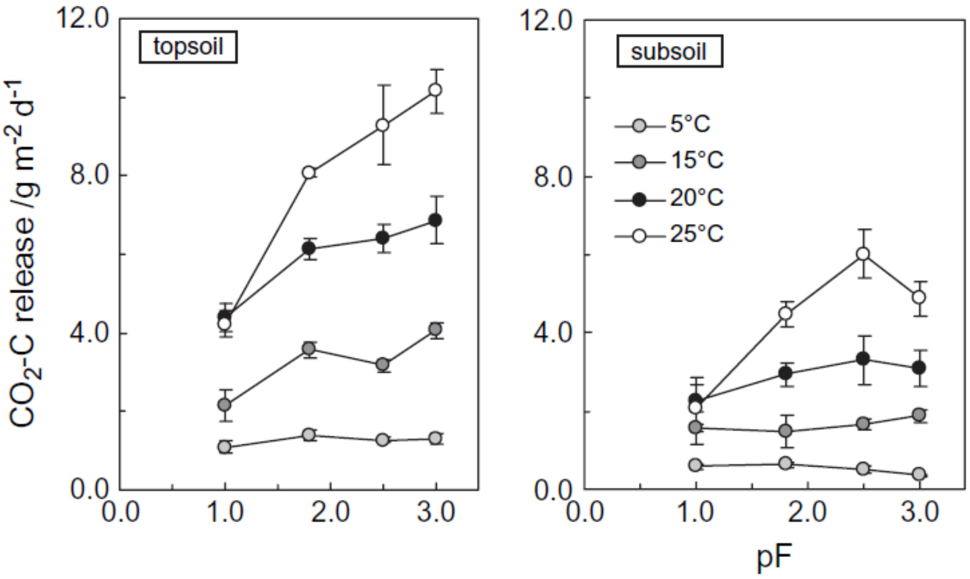

Figure 3. CO_2 emissions as a function of different water retentions and at different temperatures for the top soil and the subsoil. The series representing temperatures >+10°C show a great increase in CO_2 emissions at all water retentions. From: Kluge et al. (2008).

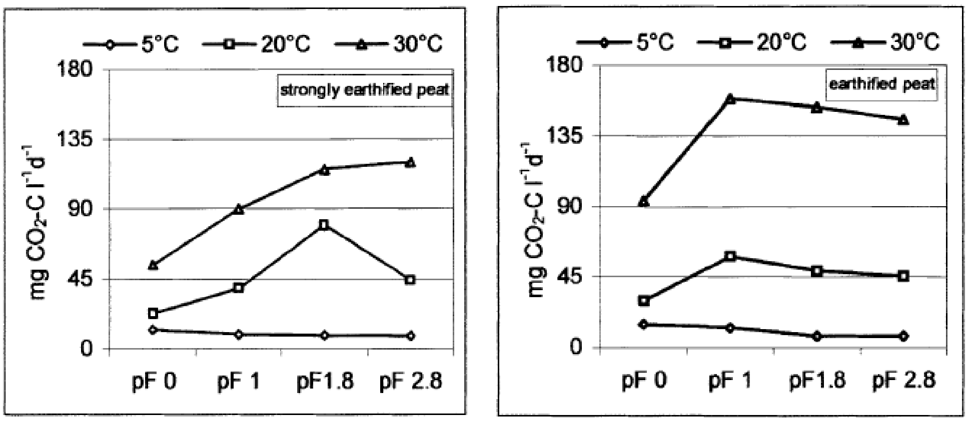

Figure 4. CO_2 emissions as a function of different water retentions and at different temperatures "Results are shown for two peat substrates with low (left side) and strong degradation (right side)". The series representing temperatures $>+5°C$ show an increase in CO_2 emissions at water retentions $>$pF 1. From: Wessolek et al. (2002).

2.6 The effects of water content and drainage depth on R_{PD}

Soil moisture content is another major environmental factor to influence the R_{PD} and thereby the rate of CO_2 emissions. Several authors agree on that the varying physical properties of the peat soils result in a complex correlation of decomposition rate and soil moisture content in the profile (Berglund et al. 2011; Mäkiranta et al. 2009; Nieveen 2005; Lefleur et al. 2005; Wessolek et al. 2002). Drainage depth and water table level along with the peat soils physical properties determine properties such as the water retention (pF curve, pF= The common (base 10) logarithm of the head (in centimetres of water) required to produce a suction equal to the capillary potential) and aeration in the peat soil profile (Witkowska-Walczak et al. 2002). Lowering the water table will lower the amount of water filled pores and increase aeration. Berglund et al. (2011) reported a sufficient aerated porosity of 1-8% to achieve high R_{PD} for microbial communities. Mäkiranta et al. (2009) found a Gaussian relationship between CO_2 emissions and water retention with a peak in emissions at around pF 1.8 or 63 cm water column. Other studies confirm this peak in emissions with different pF values (Table 1).

Table 1. Author(s) and their calculated/presented result of optimal water potentials for R_{PD}.

Author(s):	Peak of R_{PD} at pF	cm water column
Berglund et al. (2011)	1.6	40
Mäkiranta et al. (2009)	1.79	61
Witkowska-Walczak et al. (2002)	1.81	65
Wessolek et al. (2002)	1.8	63
Mundel (1976)	2	110
Average	1.8	63

Release functions of CO_2 emission of peat topsoils substrates in various climates and environmental conditions were presented by Wessolek et al. (2002) and Kluge et al. (2008), both including the important variables of soil temperature and soil water pressure head (pF value).

$^1CO_2 = 2.243 + 0.648x - 0.241y - 0.52x^2 - 0.088xy + 0.011y^2$, ($r^2=0.87$) (Wessolek et al. 2002)

$^2CO_2 = 1.314 + 0.853x - 0.273y - 0.451x^2 + 0.132xy + 0.011y^2$, ($r^2=0.96$) (Kluge et al. 2008)

$^1CO_2$ [mg d^{-1} 100^{-1} m^{-3}]. x = pF. y = temp. [°C].

$^2CO_2$ [g d^{-1} m^{-2}]. x = pF. y = temp. [°C].

The water retention also influences the top soil water content and is important for the thermal conductivity which connects the two most influent factors of R_{PD}: temperature and water. So with an increase in water in the soil profile the thermal conductivity increases and R_{PD} response on shifting temperature goes up (Mäkiranta et al. 2009; Kluge et al. 2008).

2.7 The effect of organic material quality and microbial communities on R_{PD} and CO_2 emissions

Temperature and water content are dominating environmental factors since they affect microbial communities and enzymes in the soil (Donovan et al. 2015; Mäkiranta et al. 2009; Kluge et al. 2008). Microbial communities are important and responsible for degradation and mineralization of SOM and emissions of CO_2. Mäkiranta et al. (2009) highlight and define at least two factors that affect R_{PD}: the first being the amount and quality of soil organic matter substrate available for the microbial communities (degraders), and second is the microbial community structure and number of decomposers present in the soil and in contact with the substrate. Wessolek et al. (2002) found higher emissions of CO_2 in peat undergoing stronger degradation and mineralization (Figure 4). The more rapid degradation of SOM, the more it indicated that established and efficient microbial communities were present, and that favourable environmental conditions have a great effect on R_{PD}.

Kluge et al. (2008) linked their findings of varying CO_2 emissions with temperature and soil water content to material quality and unfavourable life conditions. The SOM in the topsoil had a greater amount of easily available organic carbon to the microbial degraders that gave an increase in mineralization and R_{PD}. The subsoil had the occurrence of muddy horizons with lower substrate quality and unfavourable life conditions for degraders. This caused R_{PD} and mineralization to decrease.

Mäkiranta et al. (2009) found that long-term average water levels had a bigger effect on R_{PD} than instantaneous changes of water levels. This corresponds to Mäkirantas 2nd defining factor mentioned above, that long-term average water levels affect the structure and presence of microbial communities and different decomposers. Direct water fluctuations do have an effect on microbial communities, although of smaller significance than long-term. Direct water fluctuations can transport bacteria or other more mobile decomposers away from substrate or vice versa. Water fluctuations can also have an effect on temperature and other environmental factors such as C/N-ratios. This can lead to inhibiting decomposers and slowing down R_{PD}, causing changes in the microbial communities (Mäkiranta et al. 2009; Kluge et al. 2008; Bishal et al. 1995)

A study made by Donovan et al. (2015) researched what effect the interaction between reduction in soil water content and different substrate concentrations had on decomposition of carbon substrates and the release of CO_2 emissions. They tested two hypotheses: (1) “Rates of decomposition decline at lower substrate concentrations”, and (2) “reductions in soil moisture disproportionately constrain the degradation of low-concentration substrates”. They found that the rate of decomposition did not decrease with declining substrate concentration, and discarded their first hypothesis. For their second hypothesis, the results supported that reducing soil water content led to lower decomposition rates for low substrate concentration and that the physical protection and specific soil microenvironment gave the SOM more stability than chemical recalcitrance of SOM (Donovan et al. 2015).

In the same study, they discussed that low to moderate substrate concentrations increased microbial biomass and the expression of certain enzymes for easily available organic carbon. Their findings indicated that microbial communities handle less diffusive conditions by compensating with an increased enzyme activity and expansion of mass. However this only happened during favourable temperature conditions of >+5-10°C. They conclude that decomposition rate is more dependent on substrate concentration during dry conditions and that somewhat less favourable conditions can lead to an increased enzyme pool and more efficient microbial communities.

2.8 The effects of soil pH and N-fertilization on R_{PD}

In an experiment carried out in the south of Sweden the correlation between different cropping systems and CO_2 emissions from peat soils and peaty marl soils was tested (Norberg et al. 2016). It was an attempt to establish recommendations on mitigating emissions. The authors found a slightly negative correlation between pH and emissions of CO_2 for peaty marl soils. This indicates that higher pH values would lower CO_2 emissions in cases where the topsoil is high in organic material originating from peat, and the rest of the profile is marl (carbon-rich, silty clay similar to gyttja, from precipitation of calcite in swamps or lakes). To put it in a wider greenhouse gas perspective a higher pH can decrease N_2O emission as well (Van den Heuvel 2011).

Additionally, another study made by Murayama and Bakar (1996) where they measured CO_2 emissions on cultivated peatlands in Malaysia, they found a positive correlation between pH and CO_2 emissions. This indicates that the higher the pH values the more CO_2 emissions. The peat soil with higher pH also contained higher percentage of ash and less organic substrate (Murayama & Bakar 1996).

In a Norwegian study about the acidification + N-fertilization effect on decomposition rate in Norwegian pine forest soil (typical Udorthent soil). They found a significant lower decomposition rate and release of CO_2 emissions in acidic soil (pH close to 3.0) (Bishal et al. 1995). A comparison between pH 4.0 and 5.5 gave no significant difference, but both of them gave increased release of CO_2 and increased decomposition rates in relation to pH 3.0. At pH 3.0 neither high (90 kg N ha^{-1}) nor low (0 kg N ha^{-1}) addition of N-fertilizer gave an increase in decomposition and release of CO_2. An explanation why this low pH reduced emissions was provided with the help of their observation results. In the acidified plots there were much smaller communities of bacteria and fungi decomposers. This was because the lower pH gave an increased solubility and release of potentially toxic cations such as Al- and Mn-ions. This created an unfavourable life environment for the degraders and reduced CO_2 emissions (Bishal et al. 1995).

The highest decomposition rate was found for the medium N-fertilization treatment (30kg N ha^{-1}) in soil with a pH-value of 4.0 and they observed reduced CO_2 concentration in soil with the highest N-treatments (90kg N ha^{-1}). It is speculated that the cause is a reduction and inhibition of microbial communities' respiration, possibly due to high C/N-ratios (Bishal et al. 1995).

2.9 The effects of different crop growth on R_{PD}

Long-term effect of grassland management on peat soil conservation and subsidence was examined by Kluge et al. (2008). Their results indicated that extensive grassland was less intense on R_{PD} and thereby showed less CO_2 emissions compared to intense agricultural use. However this does not mean that CO_2 emissions is generally lower from extensive grassland management since it is, according to Kluge et al. (2008), determined by the water table depth, surface aeration and temperature on each individual site. In a study by Norberg et al. (2016) they measured and compared CO_2 emissions from different cropping systems on peat soils from both the same sites and different sites. Managed grassland displayed higher emissions than cereals and row crops. The authors emphasise the complexity of comparing possible mitigating actions on peaty soils that do not share the exact location or physical properties (Norberg et al. 2016). With grassland management follows increased root respiration and increased plant-derived CO_2 emissions that need to be taken into account. In their study the plant-derived CO_2 was estimated to 27% of the total average compared to bare soil and they reported a possible range of up to 63% plant-derived CO_2 (Norberg et al. 2016).

2.10 The effects of tillage, soil physical properties and sand mixtures on R_{PD}

Elder et al. 2008[2] did studies on short-term impact of conversion from intensively tilled organic soil to no-till management. The physical properties of the peat soils were compared and the CO_2 emissions (R_{PD}) were evaluated. No-till cultivation and leaving the soil bare, increased bulk density and decreased total porosity. Bulk density when ploughed remained unchanged, but the ratio between air-filled porosity and total porosity in the topsoil increased. The soil water content also increased. This means that more air and water became present in the topsoil and that the pore size distribution evened out (Elder et al. 2008[1]). The annual mean temperatures were significantly higher at 5 cm depth for bare soil compared to ploughed and no-till. None of the treatments showed difference in R_{PD} and CO_2 emissions (Elder et al. 2008[1]).

Peat soil with a higher SOM has a lower hydraulic conductivity than gyttja soils and mineral soils (Berglund K. 1982). Ploughing deeper than the upper peat layer and mixing possible gyttja soil or other mineral containing soil material from underneath improves the physical properties for growth as well as improves the environment for decomposing microorganisms (Walczak et al. 2002; Elder et al. 2008[1,2]).

As seen in Figure 5 a typical example of the hydraulic conductivity of a peatsoil is very low at certain water contents (Berglund G. 1982). This is due to the distribution of macro-, meso- and micropores in organic soils. The lack of mesopores as an intermediate carrier of the water between micro- and macropores, creates a phenomenon of low water mobility (Walczak et al. 2002). The micropores strong capillary force and the macropores weak capillary force do not allow the water to be transported through the profile in any axis except through larger cracks and bigger pores (Berglund K. 1982).

Richardson et al. (1991) performed experiments that involved mixing the peat soil profile and distributing the higher SOM and the mineral material throughout the whole profile. The long-term result of this was a conservative effect and lowering R_{PD} by moving the organic matter in the profile to a less environmentally favourable place for microbial communities and heterotrophic degraders.

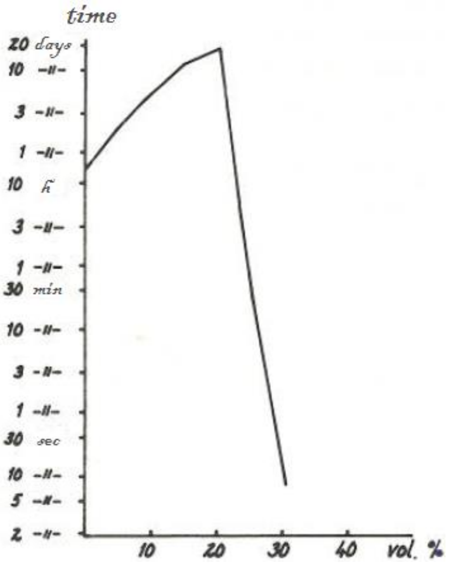

Figure 5. Hydraulic conductivity of a eutrophic fen peat soil in Sweden. The diagram shows the time it takes for the soil to absorb 1 cm^3 of water at different water contents. Note that the low hydraulic conductivity starts off when the soil has dried to a water content of about 30% of total volume. From: (Berglund G. 1982).

Results and conclusions found in a study by Walczak et al. (2002) show that the physical properties of the peat soils (Table 2) are very much dependent on their relation between organic and mineral parts. In terms of increasing total porosity and lowering dry bulk density, a significant change occurs when peat and mineral material is mixed up to a relation consisting of 23% peat (Walczak et al. 2002).

In a later study by Witkowska-Walczak et al. (2002) concerning water-air properties of peat and sand mixtures a significant reduction in water retention capacity at all pF values occurred when >60% sand was mixed in. Mixtures of peat and mineral material at these high ratios significantly increased aeration throughout the whole profile and exposed organic material to heterotrophic microbial degraders (Witkowska-Walczak et al. 2002).

Table 2. Physical properties of peat, sand and their mixtures. With good examples of the pore size distribution in varying peat and mineral (sand) mixtures. From: Walczak et al. 2002.

Sample No.	Composition	Organic matter	Mineral matter	Bulk density (g cm^{-3})	Total porosity (%)	Content of different sizes pores (%, m^{3}m^{-3})		
		Content in % dry matter				Macropores >30 μm	Mezopores 30-0.2 μm	Micropores <0.2 μm
1.	Peat	57.4	42.6	0.33	90	37	9	44
2.	80% of peat + sand	45.9	54.0	0.41	88	37	8	43
3.	60% of peat + sand	34.5	65.5	0.51	87	38	7	42
4.	40% of peat + sand	23.0	77.0	0.68	84	38	7	39
5.	20% of peat + sand	11.6	88.4	1.05	75	40	5	30
6.	5% of peat + sand	3.0	97.0	1.57	55	39	3	13
7.	Sand	0.1	99.9	1.86	38	31	2	5

3 Materials and methods

3.1 Field site and trial design

The soil samples were retrieved from a field near Knutby-Ösby, Sweden, (lat 59.91°, long 18.24°) on the 28th of October 2016. The site was an old trial established in 1975 intended for testing structural improvements and irrigation and their effects on crop yield (Berglund et al. 1978). The site was located and marked out on site using GPS and georeferenced old trial maps on historical orthophotos. The peat layer had a complex structure and high SOM with 20-30 cm of fen peat on top, followed by gyttja soil and gyttja clay with low pH. At a depth, varying across the field, of about 20-35 cm there was a layer of paper gyttja impenetrable to water and root growth. At 75 cm there was a thin layer of sand before an unknown bulky layer dominated by soap clay and this layer was unaffected by cultivation and plant growth (Berglund et al. 1978).

The loss on ignition in percent of total dry weight ranged nonlinear from 3-88% throughout the profile (Table 3) on Ösby trial site at the time of the trial start. At depth of 20-30 cm the layer of paper gyttja appears as a peak in SOM.

Table 3. Depth in cm and loss on ignition (% of total dry weight) throughout the soil profile on the Ösby trial site at the start of the trial in the 70's. From: Berglund et al. 1978.

Depth (cm)	Loss on ignition (weight %)
0-10	72.1
10-20	70.9
20-30	88.1
30-40	30.0
40-50	38.2
50-60	15.1
60-70	14.1
70-80	3.1
80-90	3.8
90-100	4.1

The pH value in the soil profile on the trial site in 1975 ranged from 3.5 in the gyttja layer to 6.5 in the topsoils and in at 1 m (Table 4. (Berglund et al. 1978)). The measurements was taken before the plot treatments. Below 30-40 cm in the profile there is a layer of acidic gyttja soil. At 70-80 cm there is a thin layer of sand and at 80 cm and further downward you find the soap-clay that is unaffected by cultivation. The relative high pH in the topsoil (between 0-20 cm) seen in Table 4 could be explained by the liming effect that the Thomas-phosphate had (as explained in the background section 2.4) on the cultivated soil and previous crop growth on the site (Berglund 1978).

Table 4. Depth and pH in untreated soil profile on trial site at Ösby at the time of trial start. From: Berglund et al. 1978.

Depth (cm)	pH
0-10	6.4
10-20	6.2
20-30	5.8
30-40	4.2
40-50	3.5
50-60	3.5
60-70	3.9
70-80	4.5
80-90	6.1
90-100	6.5

A systemic, non-randomized experimental design was used in this trial (Figure 6), in which five main treatments and their combinations could be tested. The treatments for the trial plots were;

A. Liming. Lime was first of all added to the surface at a rate of 20 ton unslaked lime (CaO) per hectare.

B. Deep-cultivation with an excavator. Deep-cultivation took place by excavating with a digger to 100 cm and thoroughly mixing up the topsoil with the subsoil that is characterized by low pH. By using an excavator a more intense mixing are accomplished and the results appears quicker. The prospect of deep-cultivation is to improve the rooting depth, neutralize acid subsoil and improving ground soil proneness to frost (Berglund et al. 1978).

C. P-fertilizing. Fertilizing was done by adding Thomas-phosphate at a rate of 1 ton per hectare. This was done in order to see what effect a basic fertilization of phosphorus had in combination with the other implements.

D. Irrigation. Irrigation is not taken consideration in this study but was done once in late June 1976. After that there was sufficient rainfall so no further irrigation was needed (Berglund et al. 1978).

E. Deep-ploughing. Deep- ploughing was done to the whole field in the autumn of 1975 and not part of the original trial but represented in this study as treatment (E) (Figure 6). The deep-ploughing was to a depth of 50-60 cm.

O. No treatment.

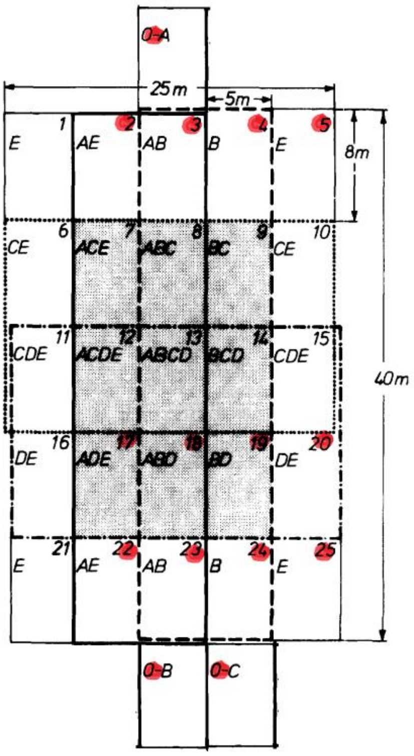

Figure 6. The systemic, non-randomized experimental design of the trial put out in 1975. The red dots indicate the plots were samples was collected for the experiment in this paper.

3.2 Experimental setup

The experiments were based on separate sets of undisturbed soil cores collected from a depth of 10 cm, and loose soil collected in plastic bags. The soil was sampled just below the grass cover (roughly 10 cm) excluding the majority of fine roots and soil held on by friction of the fine roots. There were 15 plots and five different treatments represented by three repetitions (n=3) for each treatment.

One lysimeter (20 cm height, ⌀19 cm) with undisturbed soil core was sampled from each plot and brought into the lab to test CO_2 emissions with varying water content. Water was constantly added from beneath until a few days prior to each measurement allowing the water level to stabilize in the sample. The soil core in the lysimeters was scaled to be the size of the cylinders but with a top soil core edge 15 mm below the cylinders edge to make room for added water pooling on top. This was also to allow the soil core to expand when water was added. Once a week the lysimeters were measured for weight, CO_2 emission and water content.

Total of three small steel cylinders (10 cm height, ⌀7.2 cm) with undisturbed soil cores were sampled from each plot. The soil cores were placed in plastic crates and saturated to 100% water content using water that was boiled and cooled to room temperature.

The lysimeters were kept in storage with low temperatures ranging from -5°C to +10°C during approximately three months. The steel cylinders and loose soil samples were kept refrigerated in 8°C for the same time period as the lysimeters. The climate in lab was constant 20°C and the samples were measures shortly (few days) after they had been brought out from storage.

Figure 7. A lysimeter being sampled at the Ösby trial site. The metal hood was used together with a sledge to press the lysimeter down and collect an undisturbed soil core sample. (Photo: Hermansson 2017)

3.3 Water content, water retention and physical and chemical properties

Water content in the lysimeters was measured with a SM300 moisture sensor (Delta-T Devices Ltd., Cambridge, UK) that puts out a reading in millivolt that can be converted to water content in volumetric percent. Water content was also determined by weighing the samples at each measuring occasion and then finally drying the soil in 105°C for three days to get the dry weight of the soil in each sample. The exact volume of the lysimeters and steel cylinders and the dry weight of the soil was then used for calculating the volumetric water content for each measuring occasion.

After measuring emissions at saturated conditions the steel cylinder with its soil core was placed on a sand bed and water was drained to simulate different drainage levels and water retentions, effectively creating different moisture levels in the soil core sample. The whole process of CO_2 emissions measuring and weighing was repeated with the water retentions (pF); 1.4, 1.7, 1.9 and 2.0 representing drainage levels of 0 cm, 25 cm, 50 cm, 75 cm and 100 cm respectively. The pF value represents log $(-\psi)$ where $-\psi$ is the water pressure potential in cm water or hPa (where 1 cm water = 1hPa) (Berglund et al. 2011). At the end, the drained samples were air dried in room temperature (constant 20°C) for two weeks and measured for CO_2 emission.

3.4 Measuring CO_2 emissions

The CO_2 emissions from the soil in the lysimeters were measured in a closed chamber (Figure 8) that was place on top of the lysimeter a few seconds before the start of the measurement. The chamber had the same dimensions as the lysimeter itself. Air was circulated through the sensor and chamber during 5 minutes and CO_2 concentration was logged every 5 seconds. CO_2 emissions were measured with a Vaisala GMP 323 CO_2-meter. All data measured before 30 seconds was discarded to allow the atmosphere in the closed hood to stabilize.

One small steel cylinder from each plot was selected and weighed after being fully saturated from below with de-oxygenized water. The cylinder with its soil core was then put into an air-tight PVC-container a few seconds before the start of the measurement. The sample was measured for 15 minutes and data collected every 15 seconds. All data measured before 90 seconds was discarded to allow the atmosphere to stabilize in the closed PVC-container.

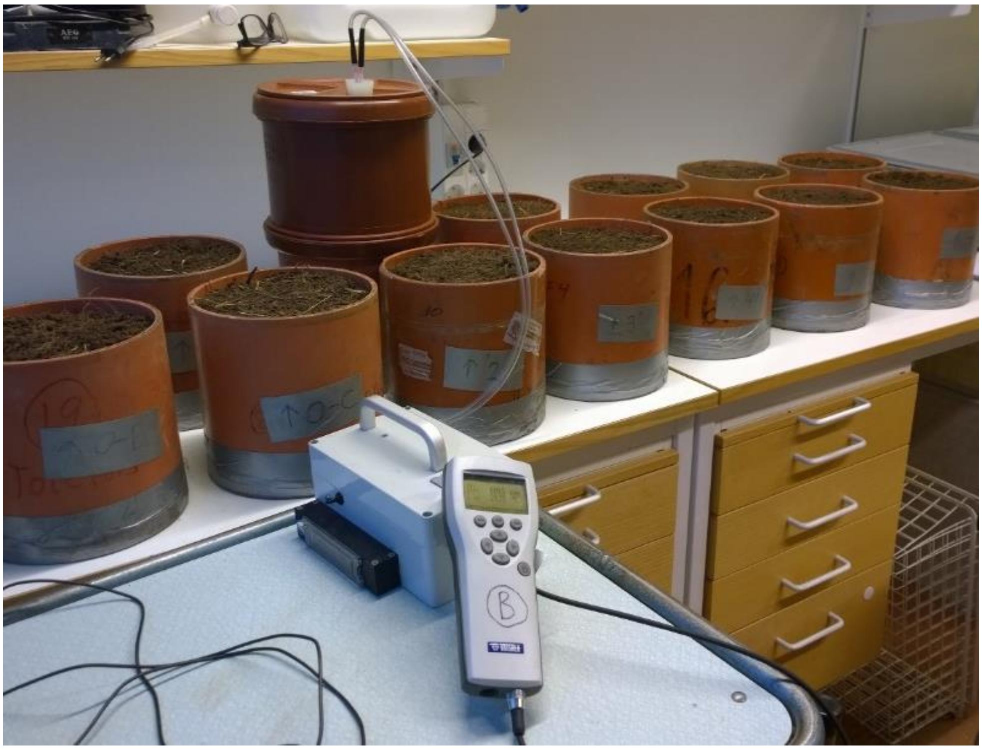

Figure 8. CO_2 emissions being measured in a closed hood on top of the lysimeters. The instrument is a Vaisala GMP 323 CO_2 meter. (Photo: Hermansson 2017)

3.5 Statistics

A linear regression line was added to the accumulated dataset and slope, intersect and R^2-value was calculated.

The measurements for the lysimeters were used when the dataset gave an R^2 above 0.9. The measurements for the steel cylinders were used when the dataset gave an R^2 above 0.8. Soil CO_2 emissions were calculated from the linear increase of CO_2 concentration over time. The formula used for calculating CO_2 emission for the lysimeters and soil cores in the steel cylinders is presented below:

$$F = (\frac{ppm_{CO_2}}{h}) \times \rho \times n_{CO_2} \div R \div T \times V \times 0{,}001$$

F is efflux of CO_2 in milligram per m^2 per hour. $\left(\frac{ppm_{CO_2}}{h}\right)$ is the result from the linear regression from emissions measurements in increasing rate of ppmCO_2 h^{-1}. ρ is the atmospheric pressure at sea level (101325 N/m^2). n_{CO_2} is the molecular weight of CO_2. R is the gaseous constant (8.3145 J/mol·K). T is temperature in Kelvin. V is the volume of the soil core and 0,001 is to present the expression in milligrams CO_2.

Outliers include; the whole O-B series in the lysimeter experiment and one data point from the steel cylinder experiment. There were water leakage problems with the O-B lysimeter cylinder from an early start, which resulted in unpredictable results and it differentiated greatly from the other ‘no-treatments’-samples. There was a mistreatment in the steel cylinder experiment when one sample was placed inside the airtight PVC-container. The sample was placed inside the container too early before the measurement began, raising the initial CO_2 level inside and thereby reducing the calculated slope and giving misleading results.

Both of the CO_2 measurement methods (lysimeters and steel cylinders) showed large variation at the first occasion (31-jan) when they were brought into the lab. They had been kept in cold storage with varying temperatures between -5°C to +10°C for approximately three months. These initial measurements were removed as outliers. The solution in the future could be to reset the samples in lab conditions for two to three weeks before conducting the initial measurement. This way the samples get a chance to acclimatise to a raised, stable temperature.

Dry bulk density, loss on ignition, electrical conductivity, soil pH, hydraulic conductivity, and compact density were measured and details of the methods used are presented in Table 5.

Table 5. Laboratory methods of the soil physical and chemical properties.

Properties	Method
Loss on ignition, /kg^{-1}	24h drying at 105°C and then 24h incineration at 550°C before weighing.
Soil pH	pH electrode. 1:5 soil to deionized water ratio. Shaken for 30 minutes. Measured after 2h and then after 24h
Electrical conductivity, / mS/m	Measured with EC-meter after pH was measured (24h). 1:5 soil to deionized water ratio.
Hydraulic conductivity	The constant-head method was used to measure the saturated hydraulic conductivity of the soil cores.

4 Results

4.1 Physical and chemical properties

In Table 6 the results of the average pH-measurement, electric conductivity, loss on ignition, compact density, dry bulk density and hydraulic conductivity from the treatments are presented. None of the properties for each treatment are different from on another according to the box plot analyses (Figure 19-24). The hydraulic conductivity for treatments AB and O have a high average value due to few repetitions and a wide variation.

Table 6. Soil test results that include: pH, electric conductivity, loss on ignition, compact density, dry bulk density and hydraulic conductivity. The results are averages from the different treatments represented in the trial.

Treatment	pH	Electric conductivity (µS/cm)	Loss on ignition (%)	Compact density (g/cm^3)	Dry bulk density (g/cm^3)	Hydraulic conductivity (m/day)
AB	5.4	116	43.2	2.00	0.52	7.09
AE	5.6	96	48.5	1.93	0.49	0.49
B	5.2	115	43.3	2.00	0.53	0.84
E	5.4	89	47.0	1.96	0.50	0.63
O	5.6	89	49.6	1.94	0.52	5.79
(Subsoil)	5.2	93	20.1	2.30	-	-

4.2 Water retention

Figure 9 shows the volumetric water content in percent at increasing water retentions 0 cm (saturated), 25 cm, 50 cm, 75 cm, 100 cm (pF 0, 1.4, 1.7, 1.9 and 2.0 respectively) and drying at 20°C and 105°C. The curves are following the same paths since none of the soil properties (Table 6) for each treatment are different from each other according to the box plot analyses (Figure 19-24).

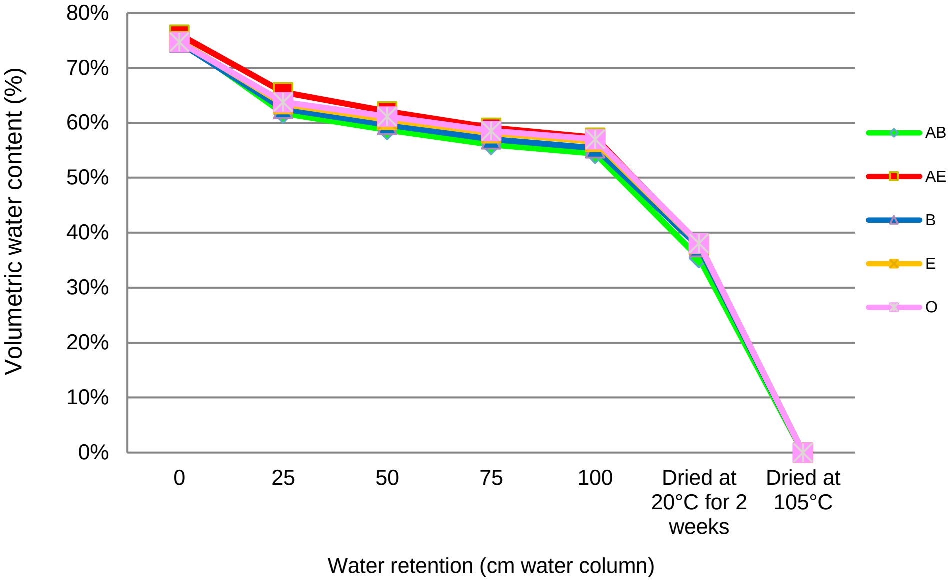

Figure 9. The average volumetric water contents in percent at increasing water retentions 0 cm (saturated), 25 cm, 50 cm, 75 cm, 100 cm (pF 1.4, 1.7, 1.9 and 2.0 respectively) and drying at 20°C and 105°C. The series represent the four different treatments in the trial (Berglund et al. 1978) and a 'no-treatment'.

Figure 10 has the same information as Figure 9 except the axels have interchanged. The x–axis now displays the volumetric water content in percent. The y-axis displays the increasing water retentions pF 1.4, 1.7, 1.9 and 2.0 respectively and drying at 20°C and 105°C. A water content of 60% represents a pF-value of around 1.8.

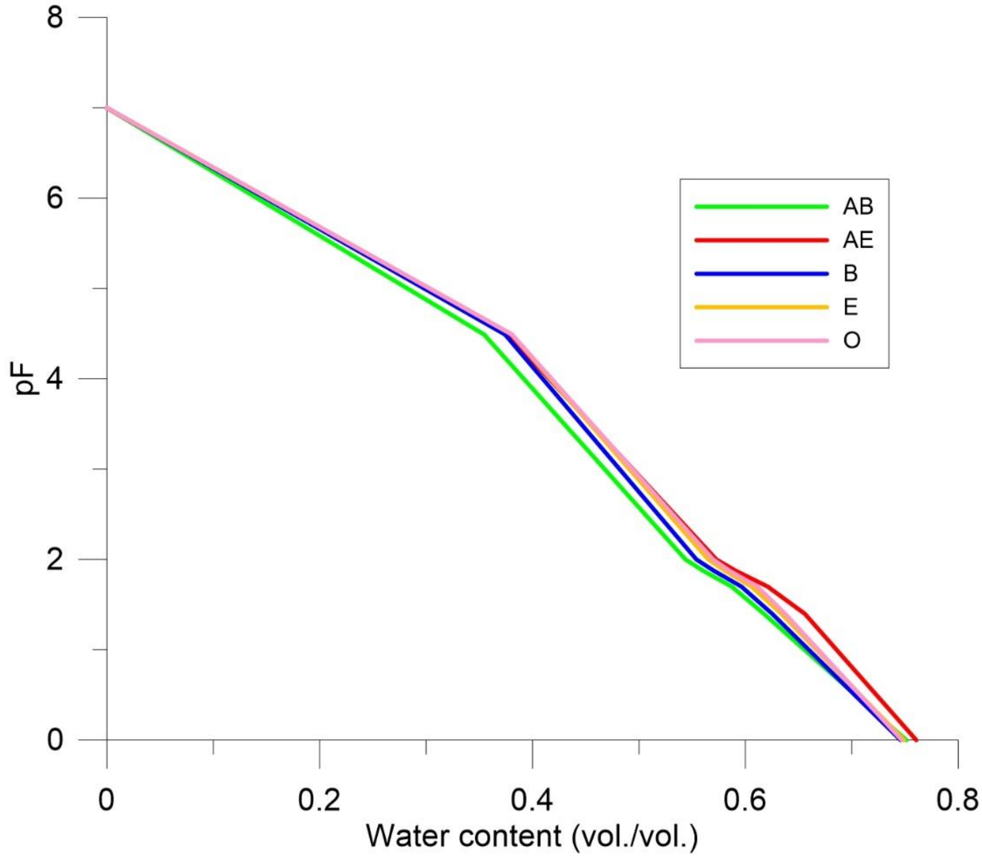

Figure 10. The average volumetric water contents in percent at increasing water retentions pF 1.4, 1.7, 1.9 and 2.0 respectively and drying at 20°C and 105°C. The series represent the four different treatments in the trial (Berglund et al. 1978) and a 'no-treatment'.

4.3 CO_2 emissions from lysimeters

In Figure 11 the CO_2 emissions were plotted for each week representing a different, and increased, water content (Figure 12). All treatments except E (deep ploughing) display a peak (CO_2-emissions) in the beginning (14th-feb) where the water contents are in the range 40-45% (Figure 12). After the 27th of February there is a greater variation. The water content were for the CO_2 measurements after the 27th of February >60% (Figure 14). There was no difference between each treatment when looking at the box plot analysis and taken consideration that the repetitions were so few (Figure 17).

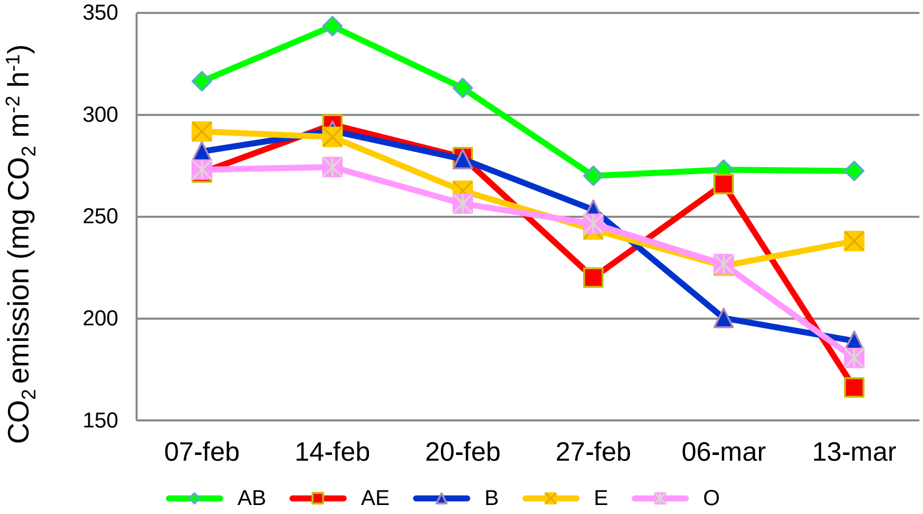

Figure 11. CO_2 emissions from lysimeters with increased water content. The series represent four different averages of treatments in the trial (Berglund et al. 1978) and a 'no-treatment'. The measurements were taken every week with a Vaisala GMP 323 CO_2 meter.

The results of the average volumetric water content of the lysimeters for each week and treatment had a steady incline until the 27th of February where more water was added and the water content raised up over 60% (Figure 12). There were small to no differences observed in the average wetness of the treatment during the period (Figure 12).

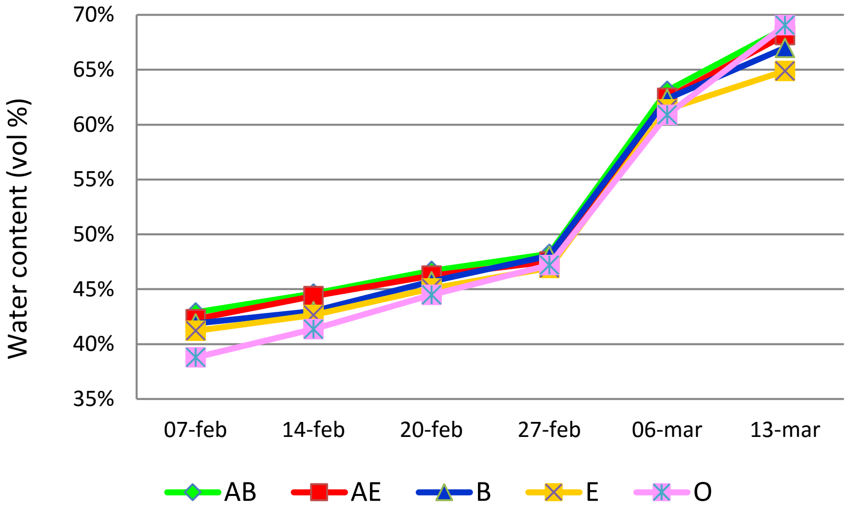

Figure 12. Water content in percent of total volume of the lysimeters determined by weight. The series represent four averages of different treatments in the trial (Berglund et al. 1978) and a 'no-treatment'.

The average water content of the lysimeters for each treatment was also measured with the sensor "SM300 moisture sensor". The output results are displayed in millivolt (Figure 13) and does not show the same steady incline as Figure 12.

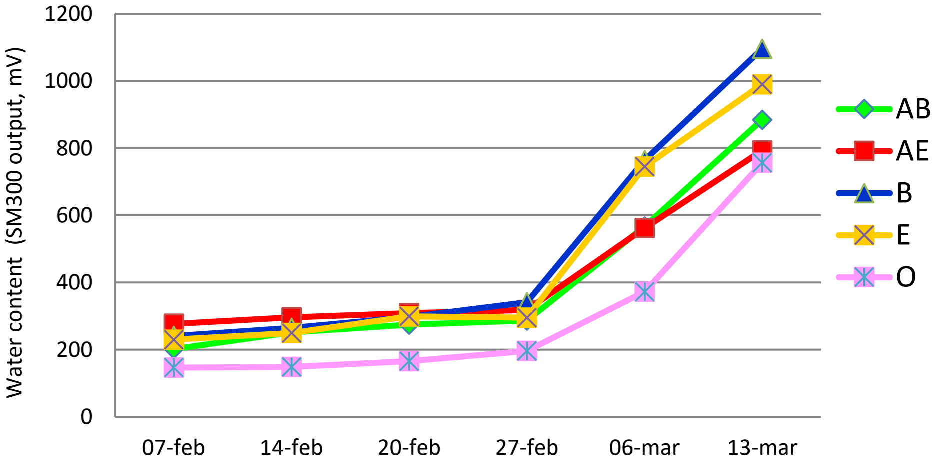

Figure 13. Water content of the lysimeters in millivolt measured with a sensor (SM300 moisture sensor). The series represent four averages of different treatments in the trial (Berglund et al. 1978) and a 'no-treatment'.

The CO_2 emissions from the lysimeters were plotted against the volumetric water content (Figure 14). There is a peak in all curves except E (deep ploughing) when the water content is between 40-45%. At measurements with water content above 60% there is a greater variation in CO_2 emissions.

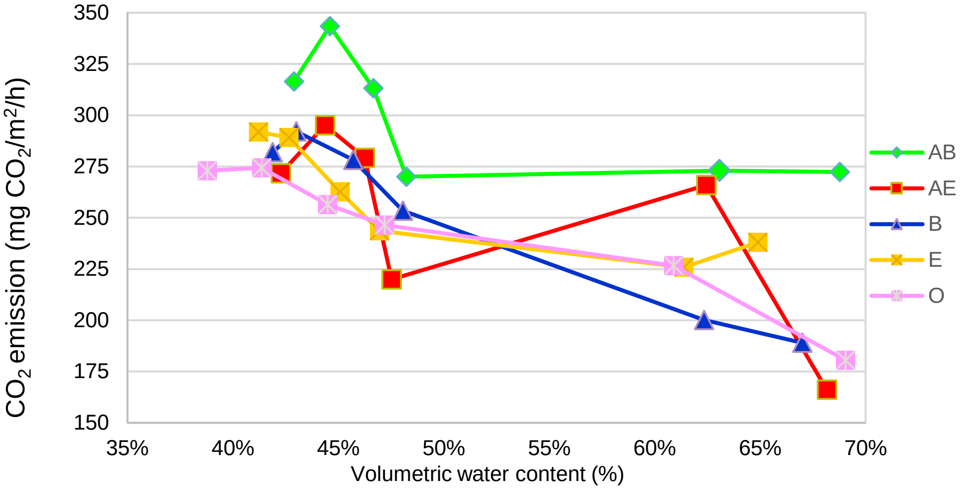

Figure 14. CO_2 emissions from the lysimeters plotted against the volumetric water content measured at the time.

When the results of the water content in the lysimeters (Figure 12) were plotted against the millivolt value measured by the "SM300 moisture sensor" (Figure 13) it resulted in a scatter plot where a curve (polyline) and equation were generated (Figure 15). This equation represents a calibration curve that could be used on this type of peat soil to improve the accuracy of the sensor reading.

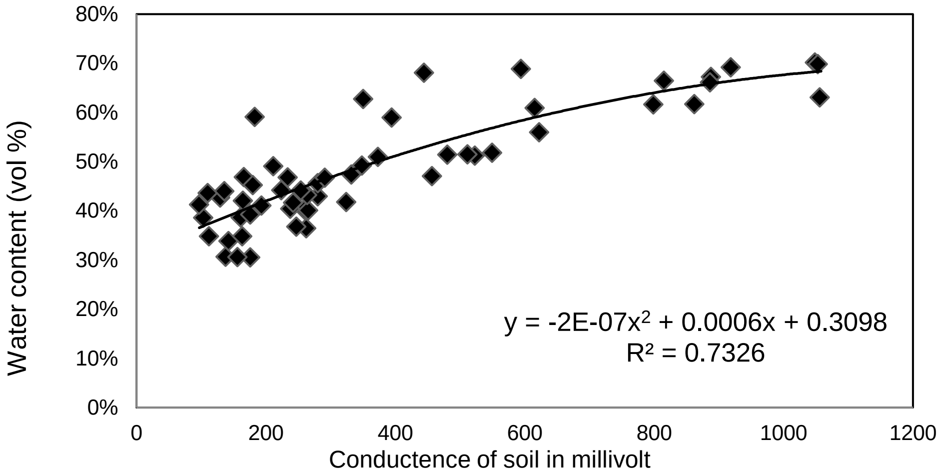

Figure 15. Water content of the lysimeters in millivolt and plotted against the water content measured by weight and displayed by percent of volume. Millivolt is measured with a sensor (SM300 moisture sensor). The function of the polyline curve works as a calibration function for this peat soil.
**All treatments that include deep cultivation was removed since the mineral material effects the measurements.*

4.4 CO_2 emissions from the soil cores in the steel cylinders at different water retention (water- table/level depth)

Figure 16 shows the results of the average CO_2 emissions at increasing water retentions 25 cm, 50 cm, 75 cm, 100 cm (pF 1.4, 1.7, 1.9 and 2.0 respectively) in the steel cylinders for the different treatments. AE, O and AB have a peak in emissions at 50 cm and B has a peak at 75 cm. It is the water retention at 50 cm that has the greatest variation in emission. After the samples had been dried for 2 week at 20°C the emissions dropped significantly. There was no difference between the averages for each treatment when analysing the box plot (Figure 18).

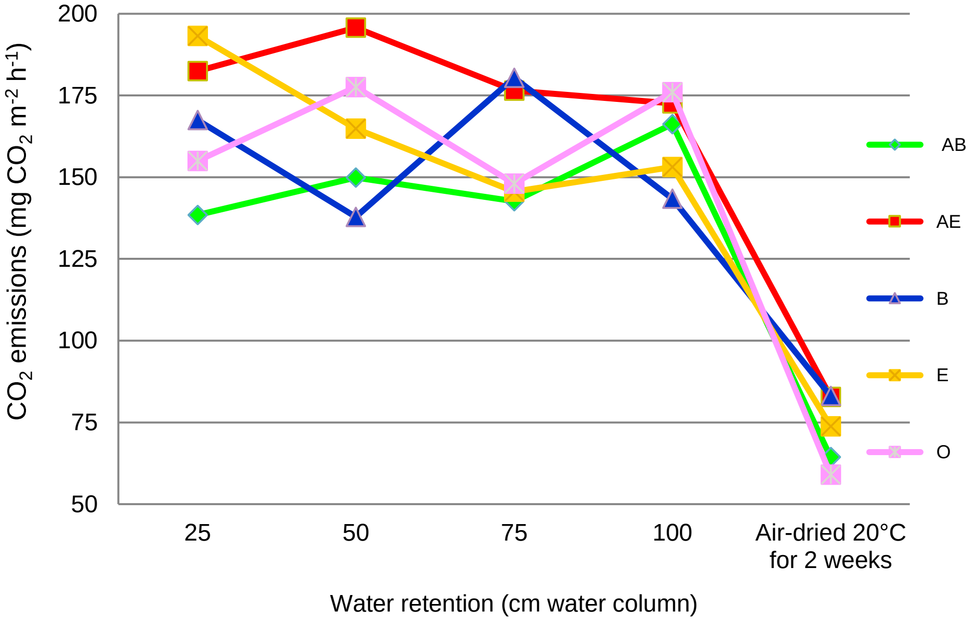

Figure 16. CO_2 emissions from the steel cylinders at increasing water retentions 25, 50, 75, 100 cm (pF 1.4, 1.7, 1.9 and 2.0 respectively) and representing the averages of the four different treatments in the trial (Berglund et al. 1978) and a 'no-treatment'. The measurements were taken every week with a Vaisala GMP 323 CO_2 meter. Lastly CO_2 emissions measured after the samples had been air-dried at 20°C for 2 weeks.

4.5 Box plot analyses

Box plot analysis for CO_2 emissions, physical and chemical properties are presented in Figure 17-24. None of the treatments differs significantly from the ‘no-treatment’ in any of the analyses.

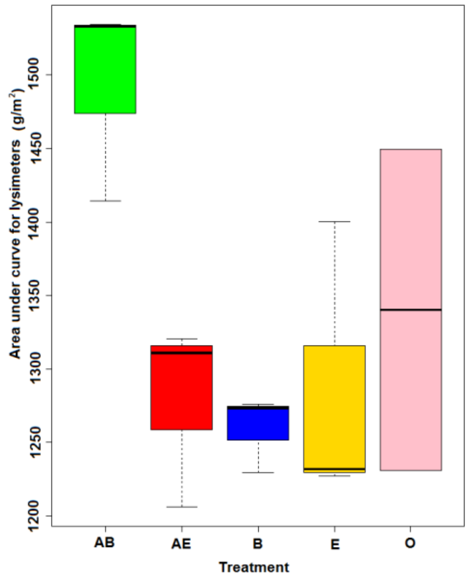

Figure 17. Box plot analysis of the area under the emission curve (lysimeters) for the different treatments.

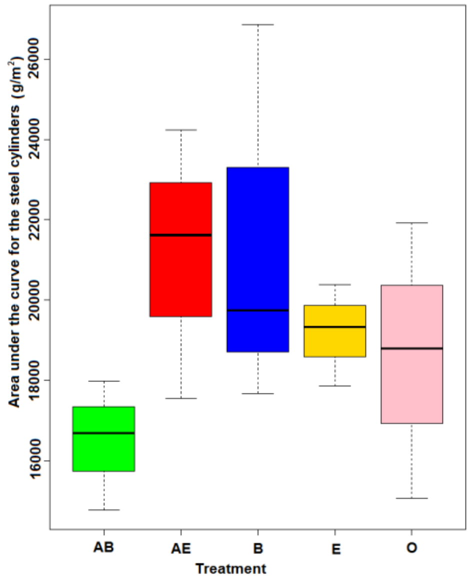

Figure 18. Box plot analysis of the area under the emission curve (steel cylinders) for the different treatments.

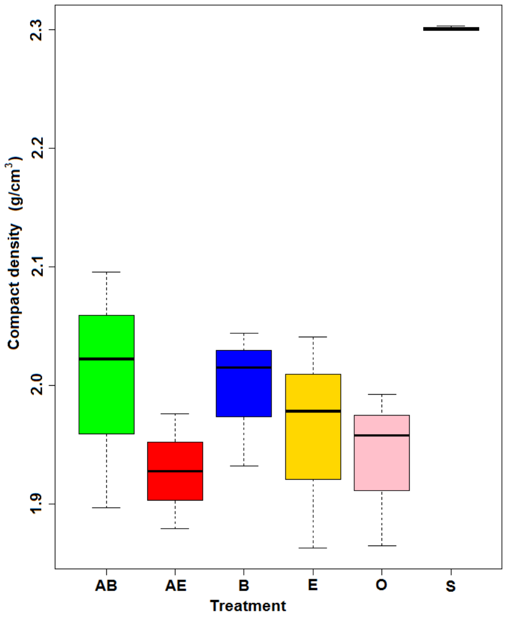

Figure 19. Box plot analysis of the compact density for the different treatments.

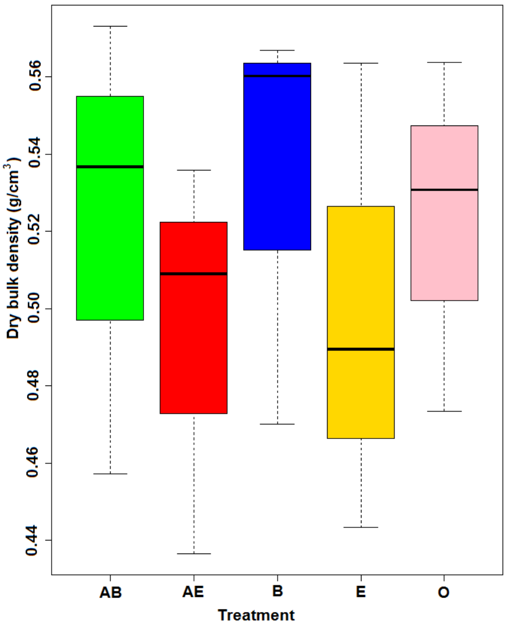

Figure 20. Box plot analysis of the dry bulk density for the different treatments.

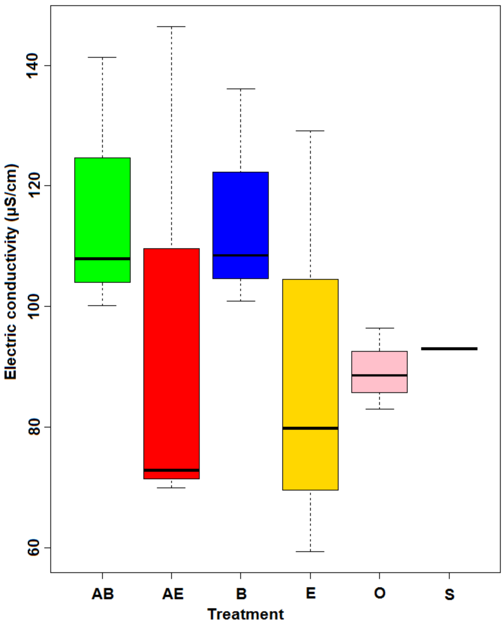

Figure 21. Box plot analysis of the electric conductivity for the different treatments.

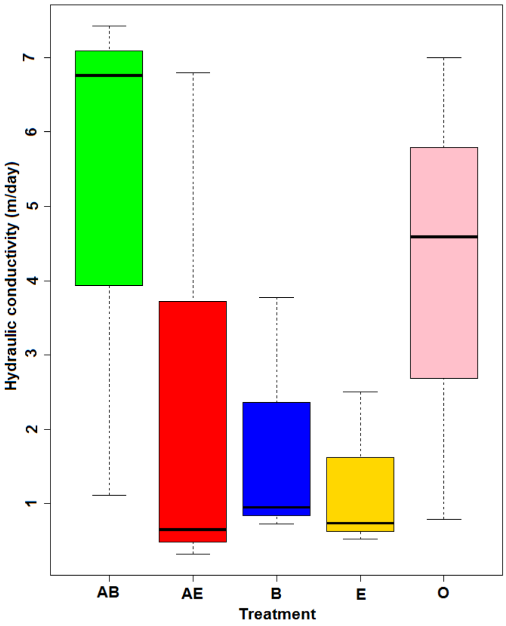

Figure 22. Box plot analysis of the hydraulic conductivity for the different treatments.

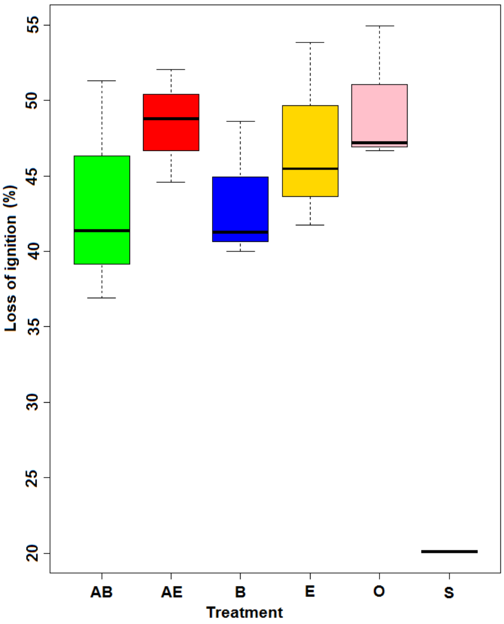

Figure 23. Box plot analysis of the loss on ignition for the different treatments.

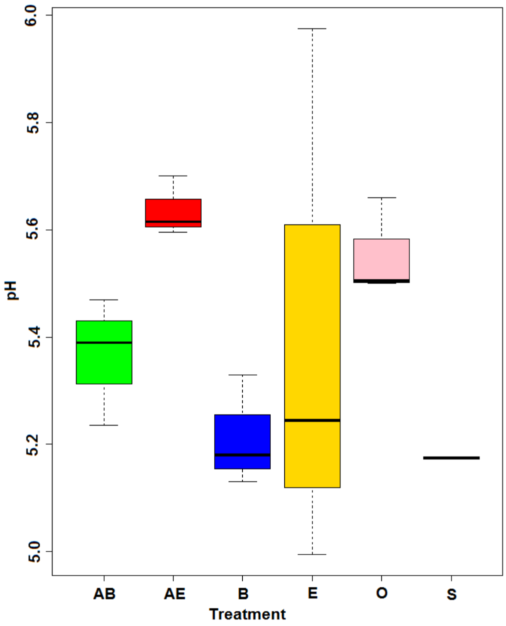

Figure 24. Box plot analysis of the pH for the different treatments.

4.6 Visual observations

Visual observations were made from the soils physical properties represented by the treatments as well a single sample from the subsoil (Figure 25; *a*-*f*). The observations were from the collected loose soil samples. Mineral material could be observed in treatments AB, B, E which all represent some degree of mixing the soil profile.

a. Treatment AB

Black colour with roots and aggregate/granular structure that has low solidity. A low clay content with bits of paper gyttja and minerals/sand present.

b. Treatment AE

Black colour with roots and aggregate/granular structure that has low solidity with bits of paper gyttja present.

c. Treatment B

d. Treatment E

Brown colour with roots and aggregate/granular structure that has low solidity. Bits of paper gyttja and minerals/sand present.

Brown colour with roots and aggregate/granular structure that has medium solidity. Clay content clearly present and also minerals/sand.

e. Treatment O

f. Subsoil

Dark brown colour with roots and woody bits. Aggregate/granular structure that has low solidity and bits of paper gyttja present.

Woody bits and paper gyttja clearly present with very high solidity.

Figure 25. Pictures and visual observations (a-f) of the soils physical properties represented by the treatments (AB, AE, B, E, O, S (subsoil)). (Photos: Hermansson 2017)

5 Discussion

5.1 CO_2 emissions results and soil properties

The results from the lysimeters' CO_2 emissions and from the steel cylinders' CO_2 emissions show that there were no significant differences between treatments in the experiment. However there is an indication that the lysimeters with liming combined with deep-cultivation (mixing of the entire soil profile) gives a higher level of CO_2 emissions (Figure 17). This was not confirmed in the experiment with the steel cylinders (Figure 18). The result of the box plot analysis created over the soils properties (pH, EC, dry bulk density etc., Figure 19-24) also gave mixed results and no certain conclusion or connection can be made. These results confirm the variation that is characteristic to peat soils (Berglund G. 1982; Berglund 2008). This means that results could have been different if they were sampled somewhere else in the field, or from a slightly different profile depth. The in-field variation of CO_2 emission and soil properties is difficult to highlight without numerous samples, repetitions and tests. This however quickly puts restraints on budget and space. One can easily understand this variation when looking back historically on how the peat soil was created and see that local landscape characteristics, such as simply a nearby tree-line inflicting wind, could alter the thickness and composition of the organic layers formed by deposits. In order to make up for these variations in the field and get more accurate results the number of samples and repetitions need to be higher in order to make a statistically significant conclusion. The layout and design for this type of trial presented in this report (Figure 6) is outdated with today's standards (demand for statistically proven data).

5.2 CO_2 emissions and R_{PD} in response to water content

Average water content for the different treatments in the lysimeters has a slow but steady incline each week up until the 6th of March where the added water was increased in volume and the water content rapidly increased (Figure 12). The treatments' response to increased water content was different and showed varying results regarding the CO_2 emissions (peat decomposition) when the water content was around 60%. The reason could be that the water added to the lysimeters collected differently in the soil core, due to difference in pore space and pore-distribution. This could make the whole soil core wetter in some parts of the sample. The overall cause could be due to individual treatment, coincidence or previous handling of the samples. With a wetted soil the sensitivity to temperature response is increased as well as the efficiency to distribute nutrients and minerals (Donovan et al. 2015; Mäkiranta et al. 2009; Kluge et al. 2008). This stimulates microbial activity and increase R_{PD} and CO_2 emissions (Mäkiranta et al. 2009).

5.3 CO_2 emissions in response to water retentions

The water retention curves for the different treatments show no significant difference. There is a tendency that the average of the treatment with liming combined with deep ploughing (AE) is a bit wetter as well as being the treatment that measured the highest average CO_2 emission. Although with not enough data for a statistical conclusion, it can only be speculated that the structural effects and pore-distributions combined with a high organic content in the topsoil for AE (Figure 23) provide better circumstances for microbial communities and increased rates of R_{PD} and CO_2 emission.

The curves in Figure 16 have a tendency to follow the predicted results of a peak in emissions around 50-75 cm water column (pF 1.8). It is displayed in Figure 16 as a slight peak at 50 cm water column in three out of five average treatments. However, instead of the majority of the average measurements showing a consistency in higher emissions, even for 75 cm water column, they dropped in emission. More data is required in this experiment to draw additional conclusions to this hypothesis that a peak-emission occurs at this specific water retention span (water content). It provides information that once again peat soils does not follow a strict linear correlation between water content and CO_2 emissions. Therefore great in-field variation is to be expected.

5.4 Sensors and models in comparison to traditional methods

Budget and space can put restraints on the scale of experiments. Sensors and models are becoming more common as the basis for data collection especially when collecting data from bigger regions or several fields. When it comes to peat soil and R_{PD}, models are struggling to implement the variation of properties and to find significant correlation between results of calculated data and CO_2 emission. A sensor require careful and thorough calibration based on a lot of data and tests. This thorough calibration takes time and resources, but if it is done correctly, it can save just that. This experiment used a SM300 moisture sensor to measure the water content parallel to weighing the lysimeters before each measurement. The SM300 moisture sensor is calibrated for either a high organic soil or a mineral soil. The results from both types of measurements were used to generate a calibration curve and a function for this type of soil (Figure 15). The purpose of the calibration curve was to show the risk of relying directly on this kind of sensor.

$$y = -2E\text{-}07x^2 + 0.0006x + 0.3098 \ (R^2 = 0.73)$$

(y = water content [%], x = conductance in soil [millivolt]), *Deep cultivation samples removed

The function does not include plots where deep cultivation was involved since this higher amount of mineral content and mixing of the whole profile is not representative of the other treatments, when measuring water content in the rest of the field.

Release-functions of CO_2 from peat topsoil are sometimes used as models for whole regions. When comparing a calculated result of the CO_2 emission using the following function provided by Kluge et al. (2008):

$$CO_2 = 1.314 + 0.853x - 0.273y - 0.451x^2 + 0.132xy + 0.011y^2, \ (R^2=0.96)$$

(Kluge et al. 2008)

(CO_2 = [g C m^{-2} d^{-1}]. x = pF. y = temp. [°C])

The result was value for CO_2 emissions at: 226.5 mg $CO_2/m^2/h$ @pF 2.0 (100 cm water column). Comparing this to the average value of the ‘no-treatment’ based on the fact that it is sharing similar soil properties and that it has a high correlation coefficient (R^2=0.96), it was calculated to: 176 mg $CO_2/m^2/h$. It shows that models can be valuable in making predictions but one should be careful when using functions as exact models for specific regions outside the study.

5.5 Microbial communities and their activity related to temperature and moisture

Microbial communities in the soil perform the degrading processes of peat and this is generating emissions of CO_2. It is showed that the physical and chemical properties in peat soil could correlate to CO_2 emissions and that this vary within and between fields.

It is reasonable to conclude that whatever affects the microbial structure and activity also has an effect on R_{PD} and CO_2 emissions. Moisture is highlighted in this study as one of the most influential environmental factors affecting the R_{PD} and CO_2 emission. The literature emphasise that temperature also has a big influence and direct effect on R_{PD}, as well enzyme efficiency. Both long- and short-term water tables and soil water content inflicts greatly on the structure and composition of the microbial communities present as well as the microbial communities' easy access to nutrients and carbon.

To draw any significant conclusions on the effect of microbial communities in the different treatments of the experiment more samples and repetitions are required along with further research on what type of microbes that are present and their level of activity on the specific substrates. It is non-negligible, judging from the visual analysis and the feel of the loose soil samples, that there is a difference between the soils properties and that this affect the microbial communities' structure and thereby R_{PD} and CO_2 emissions. A solution for reducing the R_{PD} and CO_2 emissions requires means on how to negatively inflict on microbial activity and structure by inhibiting the microbes and enzymes.

Since temperature is a main factor (Kluge et al. 2008) and difficult to control, one has to focus on ways to reduce the thermal conductivity and the microbes' response to temperature. Several ways to do this is about means that reduce the chance for microbial communities to build up over time. Unfortunately what might be the least optimum for microbes and R_{PD} might also be the least optimum for plat growth. As a stable water table and long-term water levels inflict greatly on structure and abundance of microbes (Mäkiranta et al. 2009), an altering water table would inflict negatively on R_{PD} and CO_2 emissions. However, an altering water level would increase aeration in the profile and at the same time create periods of waterlogging. In a wider perspective this stimulates denitrification bacteria and raises N_2O emissions which could have equal or worse consequences from a greenhouse gas perspective (Jordan 2016).

The water tables' effect on the soil water content can also affect the thermal conductivity. By raising the water table in times of low temperature (autumn-winter-early spring) and keeping it low during periods of high temperatures (late spring-summer), the microbial community and activity could possibly be kept on a constant low. A practical problem with raising the water table level at times of low temperature would be the availability for the farmers to decide when to cultivate the soil. The ground should not be too soft for the heavy machinery that is used in every day agriculture.

Raising the water table, and other protective implications, is not possible to do with undisturbed permanent grassland. Along with undisturbed permanent grassland follows a higher water table, higher thermal conductivity and higher hydraulic conductivity. A future warmer climate makes the situation worse as water demand and flow from deeper horizons increase with higher evapotranspiration, the process altogether fuels decomposition and CO_2 emission. More extreme weather would probably also mean that precipitation and local climate would correlate more to the soil water table and CO_2 emission. It is possible that it also results in great differences but lack any statistical correlation.

5.6 Practical recommendations

It is difficult to provide recommendations that would be applicable for all farmers. To implement subsidies for long-term mitigating actions would not be easy due to the great variation in- and between fields. It is not possible today, within economic reason, to get the type of data that can adjust the level of implications with the level of emission and it is not safe to say: drain all soils, or cover all soils with water.

6 Conclusions

No significant conclusions can be made from the results of the experiments on long-term mitigating treatments. But observations and literature findings conclude this:

1. The rate of peat decomposition (R_{PD}) and CO_2 emissions is influenced by the soils' water content and water retention.
2. The water content in the soil regulates the structure and abundance of microbial communities present.
3. In-field variation of the soils' physical and chemical properties affects the CO_2 emissions.

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