Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil

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Abstract

A lysimeter method using undisturbed soil columns was used to investigate the effect of water table depth and soil properties on soil organic matter decomposition and greenhouse gas (GHG) emissions from cultivated peat soils. The study was carried out using cultivated organic soils from two locations in Sweden: Örke, a typical cultivated fen peat with low pH and high organic matter content and Majnegården, a more uncommon fen peat type with high pH and low organic matter content. Even though carbon and nitrogen contents differ greatly between the sites, carbon and nitrogen density are quite similar. A drilling method with minimal soil disturbance was used to collect 12 undisturbed soil monoliths (50 cm high, ⌀29.5 cm) per site. They were sown with ryegrass (*Lolium perenne*) after the original vegetation was removed. The lysimeter design allowed the introduction of water at depth so as to maintain a constant water table at either 40 cm or 80 cm below the soil surface. CO_2, CH_4 and N_2O emissions from the lysimeters were measured weekly and complemented with incubation experiments with small undisturbed soil cores subjected to different tensions (5, 40, 80 and 600 cm water column). CO_2 emissions were greater from the treatment with the high water table level (40 cm) compared with the low level (80 cm). N_2O emissions peaked in springtime and CH_4 emissions were very low or negative. Estimated GHG emissions during one year were between 2.70 and 3.55 kg CO_2 equivalents m^{-2}. The results from the incubation experiment were in agreement with emissions results from the lysimeter experiments. We attribute the observed differences in GHG emissions between the soils to the contrasting dry matter liability and soil physical properties. The properties of the different soil layers will determine the effect of water table regulation. Lowering the water table without exposing new layers with easily decomposable material would have a limited effect on emission rates.

Keywords

Peat soils; greenhouse gas emission; groundwater level; agricultural soils; lysimeter; CO_2; organic soils.

1. Introduction

Peatlands are areas of the pedosphere that are particularly active in the flux of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) between soil and the atmosphere. Natural water-saturated peatlands sequester large amounts of CO_2 from the atmosphere and emit CH_4 (Martikainen et al., 1995). Drainage and cultivation of peat soils increase soil aeration and reverses the carbon flux into net CO_2 emissions, while CH_4 emissions decrease and cultivated peat soils may even act as sinks for CH_4 (Maljanen et al., 2003b). Fertile peat soils are potential sources of N_2O when drained (Regina et al., 1996). This change from a carbon sink to a source is a major global environmental concern.

Drained peatlands subside due to consolidation, shrinkage, compaction and oxidation of the organic material (Berglund, 1996). Losses of peat can also occur due to fire or wind and water erosion. Peat soils drained for agriculture have been estimated to subside due to oxidation at a rate between 2 and 20 mm per year (Schothorst, 1977; McAfee, 1985; Berglund, 1996; Wösten et al., 1997; Schipper & McLeod, 2002) and will continue to subside until the water table reaches the soil surface (McAfee, 1985; Reddy et al., 2006) or until all peat is oxidized. This means that a 1 m deep peat profile could be completely gone 50 years after drainage despite carbon input from crop production (Berglund, 2008). This effect is visualized by the Holme post (Hutchinson, 1980) and a concrete monument at the Everglades experiment station (Stephens, 1956). Restoring these soils as carbon sinks while keeping them in production is unlikely (Stephens, 1956; Paustian et al., 1998), we can only slow down or speed up the decomposition process. Contrary to natural peatlands where plant debris is accumulated, the crop produced on these fields is removed from the field and the root material is easily and quickly decomposed (Kirchmann & Bergqvist, 1989). Therefore it is only the decomposition of the parent peat material that is of interest in a GHG emission perspective, not the carbon in- or output originating from the plant. In this study we compared the effect of different agricultural management options on the breakdown of the peat regardless of the above ground carbon input of the plant that is removed every year.

The water table depth in peatlands influences greenhouse gas emission rates but earlier research has given highly contrasting results. This is probably due to the large variation in soil properties. Mundel (1976) reported that CO_2 release peaked at 90 cm drainage depth in lysimeter experiments, whereas Wessolek et al. (2002) recorded peak CO_2 release between matric suction corresponding to drainage depths of 10 and 60 cm in incubation experiments. Mäkiranta (2009) found that the instantaneous effect of water level followed a Gaussian form with the highest respiration with a water level of 61 cm. Renger et al. (2002) showed that CO_2 emissions doubled with the groundwater level at 80 cm depth compared with 30 cm depth. The influence of water table level was questioned by Joosten & Clarke (2002), who found that the highest mineralisation rate was observed with the groundwater level at 80-90 cm depth, but that a groundwater level at 17-60 cm still had 80% of the maximum mineralisation rate. Several authors (Freeman et al., 1996; Aerts and Ludwig, 1997; Maljanen et al., 2001; Campbell et al., 2004; Lafleur et al., 2005; Nieveen et al., 2005) argue that the correlation between groundwater depth (and therefore top soil moisture content) and CO_2 emission is poor.

N_2O emissions from cultivated peat soils show a great variation in time and space (Wessolek et al., 2002) and depend on a number of factors (Regina et al., 2004) such as drainage, peat type, climate and fertilisation. Initial lowering of the water table generally increases the N_2O emission rate but the long-term influence of drainage depth is not as straightforward (Regina et al., 1996; Maljanen et al., 2003c; Klemedtsson et al., 2005)

Many investigations of GHG emissions from peat soils have been conducted under uncontrolled conditions in the field (Nykänen et al., 1995; Freeman et al., 1996; Silvola et al., 1996; Flessa et al., 1998) or on disturbed soil samples (Freeman et al., 1996; Aerts and Ludwig, 1997; Best and Jacobs, 1997; Chapman and Thurlow, 1998) where the original structure of the peat profile and its characteristic hydrological features are lost. Information on the peat soil profile and the properties of the soils has in many cases been lacking or insufficient (Freeman et al., 1996; Koizumi et al., 1999; Regina et al., 2004), which makes interpretation of the results difficult. An essential feature in this study is the emission measurements from intact soil cores together with the collection of associated soil property data.

The main aim of this study were to examine if raising the water table from a normal drainage depth of 80 cm to 40 cm will decrease the greenhouse gas emissions from cultivated peat soils and evaluate how physical soil properties will influence the effect of water table regulation on greenhouse gas emissions.
We studied the effect of water table regulation and peat properties on soil decomposition and emissions of greenhouse gases from two cultivated fen peat soils with contrasting soil properties under a controlled water regime. The study was carried out at the university lysimeter site on undisturbed soil monoliths sown with ryegrass. Incubation experiments on small undisturbed soil cores were carried out to support the lysimeter experiment.

2 Materials and methods

2.1 Study sites and soil types

Twelve undisturbed soil monoliths were extracted from each of two sites, Örke in central Sweden (60.03^{o}N, 17.45^{o}E) and Majnegården in southern Sweden (58.13^o N, 13.54^{o}E). Majnegården was drained in the 1920s and has been used mainly for grass and silage production and cattle grazing (Kasimir-Klemedtsson et al., 2009). Örke was drained 1938 (area B in McAfee (1985)) and is now mainly managed as grassland with hay production. The soils in the lysimeter experiments (Table 1)

Table 1. Soil classification for Majnegården and Örke. H1-10 denotes degree of decomposition (von Post, 1922) in topsoil/subsoil

	Site	
Classification system	Majnegården	Örke
US Soil Taxonomy	Euic Terric Haplofibrist	Euic Typic Haplosaprist
WRB	Rheifibric Histosol (eutric)	Rheisapric Histosol (eutric)
Swedish system	Fen peat H7-8/H1-2	Fen peat H9-10/H8-9

were classified according to American Soil Taxonomy (Soil Survey Staff, 2003), the WRB system (FAO, 2001) and the national classification system of Sweden (Osvald, 1937). The degree of decomposition is indicated from H1 to H10, with classes from H1 to H3 being material undecomposed or with low degrees of decomposition, classes from H4 to H6 were partly decomposed materials, and classes from H7 to H10 well-decomposed peat according to von Post (1922). Örke is dominated by sedge-brown moss peat (*Carex-Amblystegium*) and Majnegården by reed peat (*Phragmites*).

2.2 Soil analysis

Soil sampling at Majnegården was carried out after the last grass cut in the autumn of 2002 and at Örke late in the spring of 2003. Four replicate undisturbed soil cores (7.2 cm diameter, 10 cm high) were taken from five soil layers (0-10, 10-20, 20-30, 30-40 and 40-50 cm) at both sites. These undisturbed soil cores were used for determination of dry bulk density, water content at sampling and water content at matric potential -5, -30, -50, -70, -100 and -600 cm water column (Andersson, 1955). 1 cm water column is ≈ 1 hPa. All soil cores were vacuum-dried at 50-60 ºC before dry bulk density measurements were made. Low temperature was used to avoid any loss of organic matter (OM) during the drying process (Landva et al., 1983). Physical wilting point (water content at matric potential 15000 cm water column) and particle density were determined on disturbed soil samples. Porosity was calculated from particle and dry bulk densities. Shrinkage was not considered when calculating water content at different tensions. Saturated hydraulic conductivity was determined using a constant head method (unit hydraulic gradient) on another set of undisturbed soil cores (4 replicates). Soil pH was measured in deionized water at a soil-solution ratio of 1:2.5 and organic matter content (loss on ignition) was determined by dry combustion at 550 °C for 8 h. Total carbon and nitrogen were analysed by dry-combustion on a LECO CHN-932 analyser (St. Joseph, MI, USA).

2.3 Lysimeter collection, set-up and construction

A drilling method with minimal soil disturbance (Persson and Bergström, 1991) was used to collect 50 cm deep undisturbed soil monoliths. The casings consisted of PVC pipes (29.5 cm inner diameter and 59.8 cm length) that were lidded above and below and transported to the lysimeter site at the Agricultural University where the study was carried out. In lysimeter studies, shrinkage of peat soils on drying can create problems (Schwärzel et al., 2002) such as gas and water flux from the sides of the soil column. To overcome this problem, Cameron et al. (1990, 1992) constructed a special lysimeter where liquefied petroleum was injected into the gap between the lysimeter wall and the soil. In the present study, we constructed a system with an inner wall of 0.5 mm neoprene rubber sheet that was flexible, giving the peat core the opportunity to both shrink and swell. During the growing season, water was supplied from below with a 1-litre flask filled with water connected to an air trap. This flask was continuously filled so the water table level could be kept constant. The construction and set-up of this system are explained in detail in Berglund et al. (2010a).

2.4 Treatments

The effect of water table regulation on GHG emissions was studied using a factorial experimental design with four columns of each peat type. The following treatments were used:

A. Static water table level at 40 cm depth (4+4* lysimeters/site) WT@40 cm
B. Static water table level at 80 cm depth (4 lysimeters/site) WT@80 cm
C. (Originally planned to be a dynamic water table, but was not used. *These lysimeters were transferred to WT@40 cm)

Before the imposition of the above treatments, the lysimeters were saturated from below with water, fertilised (0.25 g P as $Ca(H_2PO_4)_2$, 4 g K as K_2SO_4 and micronutrients including S and Mg) and sown with ryegrass (*Lolium perenne*).

2.5 Lysimeter measurements

Measurements started in spring 2004 and continued until April 2005. Meteorological monitoring was carried out at the lysimeter site during the entire experimental period. Soil moisture was measured in all the lysimeters prior to gas sampling with a Profile Probe PR-1 (Delta-T Devices) (measuring depths 10, 20, 30 and 40 cm) inserted into access tubes installed in the lysimeters. The voltage of the standing wave created by the Profile Probe, which is a measure of the dielectric properties of the soil, was captured with a Moisture Meter HH2 and calibrated for the soils from the two sites. The soil moisture for each depth was calculated from an average of three measurements per lysimeter. Before every reading, the probe was rotated 120 degrees. The grass was cut one day before gas measurements to estimate yield (see section 2.7). Gas flux from the soil was measured by the closed dark chamber method.

2.6 Incubation experiment

The incubation experiment was carried out with a separate set of undisturbed soil cores from Majnegården and Örke. The soil cores were collected in steel cylinders (10 cm high, ⌀7.2 cm) with holes in the cylinder wall to increase aeration (Robertsson et al., 1993). All soil cores were saturated with water for five days. Suction was applied to the soil cores until equilibrium was reached. The tension steps applied were -5, -40, -80 and -600 cm water column. The soil cores were collected from two different depths at Majnegården (0-10 cm and 30-40 cm) and from the topsoil (0-10 cm) at Örke (Table 2). Four to six replicates were used. Soil cores were kept at 20 ^{o}C throughout the incubation experiment.

Table 2. Physical properties of the soils from Majnegården and Örke

Site and depth	Degree of decomp.	Loss on ignition	Dry bulk density	Porosity	Sat. hydr. cond.
cm	von Post	% (w/w)	g cm^{-3}	% (v/v)	cm h^{-1}
Majnegården					
0-10	H7-8	32	0.64	69	12
10-20	H7-8	29	0.62	71	25
20-30	H3-4	30	0.53	76	31
30-40	H1-2	53	0.21	88	4
40-50	H1-2	48	0.21	89	71
Örke					
0-10	H9-10	86	0.31	81	9
10-20	H9-10	86	0.28	82	13
20-30	H9-10	86	0.22	86	12
30-40	H8-9	81	0.22	86	12
40-50	H8-9	87	0.18	88	1

2.7 Gas sampling and measurements

During the growing season, weekly gas flux measurements were made in the lysimeter experiment using the closed dark chamber method (Mosier, 1990). The chamber was 20 cm high, insulated and covered with a reflecting layer. It was placed in a collar over the lysimeter, and sealed with an impermeable plastic material. The chambers were sampled at 10, 20, 30 and 40 minutes after closure by circulating air (300-500 mL min^{-1}) from the chambers through 22 mL headspace flasks (sealed with butyl rubber septa) for 30 seconds. A shorter sampling interval can be used when only CO_2 emissions are determined but the very low emission rates of CH_4 and N_2O require longer collection periods. This method estimates the total respiration, this includes that from plants, newly formed (i.e. grass derived) OM and oxidation of the peat. As the chamber prevents light from reaching the plants, the uptake of CO_2 by photosynthesis is excluded from the flux (Kasimir-Klemedtsson et al., 1997) and CO_2 emission is used as a proxy for OM decomposition.

The soil cores in the incubation experiment (in the steel cylinders) were placed in air-tight PVC jars before gas emission measurements (Robertson et al., 1993). Ten mL of the atmosphere was sampled 1, 2 and 3 h after closure of the jars and collected in 22 mL headspace flasks sealed with butyl rubber septa.

All gas samples (CO_2, N_2O and CH_4) were analysed by gas chromatography (Klemedtsson et al., 1997). A preliminary study indicated that the increases in gas concentrations within the chamber headspace were generally linear over a sampling period of up to 4 hours. Therefore, the fluxes were calculated (Mosier & Mack, 1980) using linear regression and the ideal gas law from equation (1):

$$F = \rho \times V/A \times \Delta c/\Delta t \times 273/(T + 273) \quad (1)$$

where F is the flux (mg m^{-2} h^{-1}), ρ is the density of gas (mg m^{-3}), V is the volume of chamber (m^3), A is the base area of chamber (m^2), $\Delta c/\Delta t$ is the average rate of change of concentration with time (ppmv h^{-1}) and T is the temperature in the chamber (°C). We used measurements with a R^2 of 0.85 or greater (94% of all CO_2 measurements) for CO_2. In the lysimeter experiment all measurements for N_2O and CH_4 were used regardless of R^2. Cumulative fluxes were calculated by plotting daily mean fluxes against time, interpolating linearly between them, and integrating the area under the curve using the software Grapher 6.3.28 (Golden software, Golden, Colorado, USA).

2.8 Statistics

Diagnostic plots indicate that the normality assumption is reasonable. Differences in mean water content and mean GHG emissions between treatments and soils were tested with a mixed model for repeated measurements (special ANOVA routine) using SAS 8.2 software (Littel, 1996; SAS, 2006). No significant interaction between treatment and site was found. Differences of mean yield between sites and between treatments were tested both within the same soils and between the soils with one-way ANOVA with blocks and multiway ANOVA using SAS.

3 Results

3.1 Soil physical and chemical properties

Majnegården is a carbonate-rich fen peat with well-decomposed topsoil and a very low degree of decomposition in the subsoil (Table 2).
The upper layers at Majnegården have some mineral soil mixed in with the peat, which is reflected in a low loss on ignition and a very high dry bulk density. Only a limited amount of air can enter the compacted topsoil at small tensions (Figure 1).
Figure 1.
The soil in the 30-40 cm layer, with its very compacted and layered structure, has very few macropores that can be drained at normal drainage depths (Figures 1 and 2).
Figure 2
Örke is a very well-decomposed fen peat with dry bulk density and porosity values more representative of a cultivated peat soil (Table 2). The Örke profile has a great amount of air entering the upper layers at normal drainage (Figure 1 and 2). The saturated hydraulic conductivity at both sites is generally high, especially for peat soils with such a high degree of decomposition (Päivänen, 1973). The layered structure at 30-40 cm depth in the subsoil at Majnegården is probably the reason for the lower vertical hydraulic conductivity of this layer. The lime- and mineral-rich material mixed into the upper layers at Majnegården also has an effect on chemical properties such as pH (Table 3). Carbon and nitrogen contents differ greatly between the soils but the amount of carbon or nitrogen per volume (density), is quite similar. The carbon content is generally much higher in peat soils than

Table 3. Chemical properties of the soils from Majnegården and Örke

Site and depth cm	pH (H_2O)	Tot-C % (w/w)	Org-C % (w/w)	Carbon density g dm^{-3}	Tot-N % (w/w)	Nitrogen density g dm^{-3}	C/N ratio
Majnegården							
0-10	7.4	21.4	17.6	113	1.48	9.32	11.9
10-20	7.5	21.4	17.6	109	1.48	9.32	11.9
20-30	7.6	25.3	23.9	127	1.45	7.68	16.4
30-40	7.7	27.5	27.5	58	1.34	2.80	20.6
40-50	7.7	-	-	-	-	-	-
Örke							
0-10	5.9	37.7		117	2.60	7.80	14.5
10-20	5.7	37.7		106	2.60	7.80	14.5
20-30	5.6	39.3		86	2.56	5.63	15.4
30-40	5.6	38.0		84	2.29	5.04	16.6
40-50	5.1	-		-	-	-	-

in mineral soils, but the carbon density of the deepest layer at Majnegården is similar to that of clay topsoil. The C/N ratio is low in the topsoil and increases with depth and decreases with degree of decomposition at both sites. The Örke soil is a typical cultivated Swedish fen peat but the Majnegården soil, with its high pH, low organic matter content and high bulk density in the topsoil, is a very rare type. This type of soil is very fertile, and even though the area is small it plays an essential role in the production of high value crops such as carrots and potatoes (Berglund & Berglund, 2010).

3.2 Weather conditions

The mean annual precipitation (1971-2000) at the lysimeter site is 535 mm and the mean temperature 5.9 ^{o}C. Daily precipitation during the experiment period is shown in Figure 3 and air temperature at gas sampling in Figure 4. The summer of 2004 was 30% wetter than normal (May 52 mm, June 63 mm and July 85 mm) except for August (42 mm), when precipitation was 35% lower than the 30-year average. Air temperature (average May 10.5 ^{o}C, June 13.9 and July 16.2) was near normal except for August (17.4 ^{o}C), which was two degrees warmer than the 30-year average.

FIGURE 3

3.3 Soil moisture in the lysimeter experiment

At the start of the experiment, the water content between treatments was similar in Majnegården lysimeters, and it took almost 3 months before the different treatments showed significantly different water contents at 20 cm depth (Figure 3). The average difference in water content at 20 cm depth between the treatments in Örke lysimeters during the growing season (1 Apr - 9 Nov), when most of the gas sampling was carried out, was 9.5% ± 2.1%. In Majnegården lysimeters the difference was 8.2 % ± 3.1 %. Measured water contents in the lysimeter experiment correspond quite well with drainage curves constructed from water retention data (Figure 2). The aeration status is much better in Örke soil than in Majnegården soil at the same drainage intensity.

3.4 Crop yields in the lysimeter experiment

Yields were significantly greater with WT@40 cm compared with WT@80 cm on both soils and the yields of Majnegården lysimeters were higher than from Örke lysimeters. With the WT@40 cm the ryegrass yield in Majnegården lysimeters was significantly higher ($p<0.05$) than the yield in Örke lysimeters (+2232 kg ha^{-1}, LSD=2144 kg ha^{-1}). The tendency was the same with WT@80 cm but the difference was not significant ($p=0.08$) (Table 4).

Table 4. Yield (dry weight) of ryegrass (Mg ha^{-1}) in soil monoliths with soil from Örke and Majnegården with a watertable depth of 40 cm (WT@40cm) or 80 cm (WT@80 cm)*

Site	WT@40 cm	WT@80 cm
Majnegården	11.73^{a}	9.85^{abc}
Örke	9.50^{c}	7.96^{b}

3.5 Gas emissions in the lysimeter experiment

CO_2 emissions were low in spring and increased with temperature during the vegetation period, with a peak in late July (Figure 4). Outside the growing season, there was no difference between the treatments in either soil but the average CO_2 emission rate during the winter was significantly higher from the Örke soil than from the Majnegården soil (Table 5).

Table 5. Mean daytime emission of CO_2, N_2O and CH_4 from soil monoliths with soil from Majnegården and Örke. Standard errors within parentheses. Means within columns with different superscripts are significantly different ($p<0.05$)

Site	Depth to water table (cm)	CO_2 Apr-Nov (mg m^{-2} h^{-1})	CO_2 Dec-Apr (mg m^{-2} h^{-1})	N_2O Apr-Apr (µg m^{-2} h^{-1})	CH_4 Apr-Apr (µg m^{-2} h^{-1})
Majnegården	40	465 (18.7)^{a}	66.1 (4.22)^{a}	205 (41.0)^{a}	-18.9 (1.32)^{a}
	80	417 (20.7)^{b}		45 (51.9)^{b}	-21.3 (1.83)^{a}
Örke	40	619 (18.7)^{c}	93.4 (4.22)^{b}	150 (41.0)^{ab}	-7.81 (1.32)^{b}
	80	534 (20.7)^{a}		108 (51.9)^{ab}	-11.5 (1.83)^{b}

With climatic conditions being the same, differences in emission rates between the two soil types should be related to their intrinsic soil properties. CO_2 emissions from Örke lysimeters were higher than from Majnegården lysimeters throughout the year, with an average daytime emission rate of 508 mg CO_2 m^{-2} h^{-1} for WT@40 cm and 442 mg CO_2 m^{-2} h^{-1} for WT@80 cm. Corresponding values for Majnegården lysimeters were 384 and 343 mg CO_2 m^{-2} h^{-1}. Emission rates were approximately eight times higher during the growing season compared with the winter period (Table 5), which emphasises the importance of temperature and the influence of plants. CO_2 emission rates were significantly greater with WT@40 cm compared to WT@80 cm in both soils. Maximum emission rate in Majnegården lysimeters was recorded on 1 June and was higher for WT@40 cm (919 mg CO_2 m^{-2} h^{-1}) than WT@80 cm (754 mg CO_2 m^{-2} h^{-1}). Similar results were found in Örke lysimeters, with maximum CO_2 emissions recorded on 27 July, 1064 mg CO_2 m^{-2} h^{-1} for WT@40 cm and 1003 mg CO_2 m^{-2} h^{-1} for WT@80 cm.

FIGURE 4

N_2O emissions from the lysimeters (Figure 5) were very low during the whole period except for a flush in early spring before the grass started to grow (first cut 4 May). N_2O emissions were greater from WT@40 cm compared to WT@80 cm ($p=0.01$) comparing all lysimeters and also within the Majnegården soil ($p=0.02$).

FIGURE 5

CH_4 fluxes were very small or negative (consumption) (Figure 5, Table 5). The consumption of CH_4 was higher for all Majnegården soil ($p<0.001$) compared to all Örke soil and higher with WT@80 cm ($p<0.05$) compared to WT@40 cm independent of soil.

3.6 Gas emissions in the incubation experiment

The results from the incubation experiment (Figures 6 and 7) were in agreement with emissions results from the lysimeter experiments. CO_2 emissions were significantly higher ($p<0.05$) from the Örke topsoil compared with the Majnegården topsoil. Increasing matric suction from 40 cm to 80 cm water column decreased the CO_2 emissions from both soils. The highest emission rate occurred with a matric suction of 40 cm water column, with lower emission rates at both lower and higher suctions. The less decomposed soil samples from the deeper layer (30-40 cm) in Majnegården soil had significantly lower emission rates than the well-decomposed topsoil.

FIGURE 6

N_2O emission rates were higher form Majnegården soil than in Örke soil (Figure 7), which was in agreement with the lysimeter experiment, but the differences were significant only for emission rates with a matric suction of 600 cm water column. The great difference in physical and chemical properties between the topsoil and the subsoil in Majnegården soil (Tables 1 and 3) was reflected in a considerable difference in N_2O emission rates, with significantly higher emission rates in the topsoil than in the subsoil at matric suctions of 40 and 600 cm water column. Differences in emission rates at different tensions within the same site and soil depth were not significant but showed the same tendency as in the lysimeter experiment, with higher emission rates with a matric suction of 40 cm water column compared with matric suction of 80 cm.

CH_4 emission rates were very low and only a few measurements were sufficiently accurate (R^2>0.85) to be used for CH_4 emission estimations. No far-reaching conclusions can be drawn from the results, other than that CH_4 fluxes in drained and cultivated peat soils are very small and can be positive or negative. This is also shown to be the case for mineral soils (Johnson et al., 2010).

FIGURE 7

4 Discussion

Decomposition of the organic matter in peat soils depends mainly on peat type, environmental conditions, the decomposers present and nutrient availability (Laiho, 2006). All these factors interact, making it complicated to predict the decomposition rate. The emission of greenhouse gases is strongly related to the decomposition rate. To be able to quantify the CO_2 emission from the breakdown of the peat there is a need to distinguish between soil organic matter-derived CO_2 respiration and plant-derived respiration (Kuzyakov, 2006). Berglund et al. (2010b) showed by comparing the CO_2 emissions from uncropped lysimeters with those growing ryegrass that the part of the total emission originating from the peat organic matter, changed during the vegetation season from 73% in the beginning of the season to 43% at the end (average 53%) for the Majnegården soil and 51% to 37% (average 43%) for the Örke soil. The lysimeter set-up made it possible to control some of the factors in the present study. Climatic conditions were the same for all lysimeters (both soil types), the water table level was regulated and two different peat types were used. In the incubation experiment on small undisturbed soil cores the influence of actively growing plants on emissions were eliminated so their data relate to intrinsic soil properties. Overall this study gave GHG emission data from soil whose environment was well controlled and measured.

4.1 Effect of water table regulation on emission rates

The CO_2 emission rate was low at both sites in the beginning of the growing season when temperatures were low and rate-limiting. In the middle of the summer, with temperatures between 15-20 ^oC, the emission rates were higher from WT@40 cm compared to WT@80 cm. Contrary to our results, many investigations have reported increasing CO_2 emissions following lowering of the groundwater level (Eggelsman, 1976; Renger et al., 2002; Wessolek et al., 2002). Findings supporting our results, with a higher emission rate at intermediate groundwater levels compared with low (dry soil), have been reported by Davidson et al. (1998), Chimner and Cooper (2003) and Kechavarzi, C. et al. (2007). Nieveen et al. (2005) found that the distance to the groundwater did not influence the emission of CO_2 and Aerts and Ludwig (1997) and Maljanen et al. (2001) reported similar results. Laiho (2006) emphasises the complexity of peatland behaviour following persistent lowering of the groundwater level, with multiple interactions between many factors such as time scale and soil type.

The topsoil from Majnegården is very compact and only a limited amount of air can enter the soil matrix at low tensions. As shown by the water retention curve (Figure 1) and the drainage curve (Figure 2), the Majnegården soil has less air-filled pore space at a drainage depth of 40 cm than the critical, aerobic maintaining, air content of 8-15 % suggested by McAfee Graham (1989) for peat soils. With a drainage depth of 80 cm there was enough air in the soil, but with the plants competing for water, moisture is the limiting factor for optimal microbial activity (respiration). The incubation results indicated that a very small amount of air-filled pore space (approx. 1-8 %, Figure 6) was sufficient to stimulate soil respiration at a high rate, but as seen in Figure 6 the Majnegården soil suffered from hypoxia at 5 cm tension and the soil respiration was hampered. There was no significant difference in CO_2 emission between the 40 and 80 cm tension in the Majnegården soil in the incubation experiment and optimum conditions for soil respiration could maybe be achieved with a tension between 40 and 80 cm as in the studies of Mäkiranta et al. (2009). Moisture was probably a limiting factor with tensions below 80 cm. At normal drainage the upper layers of the Örke profile were well aerated (Figures 1 and 2) (McAfee, 1989). In the Örke soil 5 cm tension allowed enough air into the profile (8 % air-filled pore space, Figure 6) and 40 cm tension results in the highest respiration level (Figure 6). Optimal conditions for soil respiration could probably be achieved with tensions lower than 40 cm water column since the soil was quite dry with higher tensions (air-filled pore space ≥23 %, Figure 6). The findings in the lysimeter study, with highest CO_2 emissions at the intermediate water table level (40 cm) are similar to results reported by Lafleur et al. (2005) and Mäkiranta (2009).

Berglund (1996) showed that plant growth was better at high water tables (40 cm compared to 60 and 70 cm) on peat soils with similar pore size distribution as Örke, but compacted peat soil types required deeper drainage in order to avoid aeration problems. This is in agreement with the yield results in this study (Table 4). It is very likely that optimal conditions for plant growth coincide with optimal conditions for soil respiration. Even though the grass was cut prior to gas measurements in the lysimeter experiment, plant root respiration will to some extent contribute to the measured gas flux producing a higher flux then just the contribution from soil respiration. Root respiration has been estimated to contribute with 27-63% of the emissions (Berglund et al., 2010b; Laiho, 2006), which might explain some of the differences in emission rates observed between the two water table levels investigated. Contrary to the yield results (Table 4), CO_2 emissions were higher from the Örke soil than the Majnegården soil (Table 5).
Substrate quality often varies with depth (Waddington et al., 2001) and Van den Bos (2003) argues that it is just the upper 30 cm of the peat profile that contributes to emissions, so even if the deeper soil layers are exposed to oxygen when lowering the water table, decomposition rate in these layers might be very low due to substrate quality as in the Majnegården profile. Cultivated peat soils have in general been exposed to aerobic conditions during a long period and the organic matter remaining might be recalcitrant to further breakdown.

Klemedtsson et al. (2005) were unable to find a relationship between mean annual groundwater level at peat field sites and N_2O emissions, but with a controlled water regime in our lysimeter experiment N_2O emissions were greater at high water table levels (40 cm) compared with low (80 cm). The incubation experiment showed no significant differences in N_2O emissions between 40 and 80 cm tensions in topsoil from either site even if the tendencies were the same as in the lysimeter experiment. A tension of 600 cm water column dried the soil too much and hampered N_2O emissions in both soils. In soil from the deeper layer (30-40 cm) at Majnegården N_2O emissions were closed to zero (Figure 7), and nitrogen was rate-limiting (C/N ratios above 20) which is in accordance with results by Klemedtsson et al. (2005).

4.2 Effect of soil type on emission rates

Under similar environmental conditions, differences in GHG emissions between soils should be due to intrinsic differences in soil properties and largely an indicator of carbon availability to micro-organisms (Figure 6). Even though carbon and nitrogen contents differ greatly between the two soils (Table 3), the amount of carbon or nitrogen per volume (density), which is important in studies involving microbial activity (Gosselink et al., 1984), was quite similar and is within the range reported by Minkkinen and Laine (1998) for drained peats. Carbon availability measured as carbon density was similar in both soils in the top layer and could not explain differences in CO_2 emission rates between the soils. The lower carbon density of the 30-40 cm layer in Majnegården soil compared with the topsoil resulted in lower emission rates in the incubation study. The higher degree of decomposition in the topsoil from Örke than in the Majnegården topsoil indicates a more disintegrated organic material that might decompose more easily (Regina et al., 2004). The Örke soil was better aerated at low tensions, which also could explain the higher CO_2 emission rates from this soil (Figure 6).

CH_4 fluxes were very small or negative (consumption) (Figure 5, Table 5), which often is the case with drained peat soils (Glenn et al., 1993; Nykänen et al., 1995; van den Pol-van Dasselaar et al., 1998; Kasimir-Klemedtsson et al., 2009; Maljanen et al., 2003b; Blodau and Moore, 2003).

N_2O emissions peaked during spring (Figure 5), maybe due to the production of easily available nitrogen for micro-organisms by freeze-thaw cycles in winter (Regina et al., 2004), combined with the absence of plants competing for nitrogen. It is often reported that N_2O emissions can be very erratic, characterized by high emissions during short time periods (Flessa et al., 1998) and with peaks during spring after thawing or during winter (Maljanen et al., 2003a; Regina et al., 2004). According to Klemedtsson et al. (2005), soil C/N ratio can be used as a good predictor of annual N_2O emissions. No N_2O emissions occurred at C/N ratios above 25 in their studies. The results from our incubation experiment (Figure 7) support the results of Aasen (1986) and Klemedtsson et al. (2005), who reported that nitrogen is released from peat soils with a C/N ratio below 20. The C/N ratio in the topsoil from Majnegården and Örke was 12 and 14 respectively, while it was 21 for the subsoil (30-40 cm) in

Majnegården soil. Accordingly, N_2O emissions are negligible from the Majnegården subsoil and significantly higher from both topsoils. The higher N_2O emission rate from the Majnegården topsoil compared with the Örke soil could also be explained by a higher pH, a lower air-filled porosity and a better nutritional status (Yamulki et al., 1997).

4.3 Accumulated GHG emissions

The GHG emissions from cultivated organic soils can be very high, in Sweden reported to be about 6-8% of the total national emissions (SNIR, 2006; Berglund and Berglund, 2010). In Table 6, cumulative gas emissions are converted into CO_2 equivalents for comparison. It is very difficult to upscale GHG emissions from lysimeter experiments to field scale and, when considering the critical question "- at what rate is the peat organic matter being oxidized?", there is also a need to distinguish between plant respiration and soil respiration. Even when plant respiration from these soils were subtracted from the total CO_2 emissions (47% and 57% for Majnegården and Örke soil respectively (Berglund et al., 2010b)), the CO_2 emissions still dominated and CH_4 emissions were negligible (Table 6).

Table 6. Estimated accumulated GHG emissions in the lysimeter experiments during one year (April -04 to April -05). The global warming potential varies for the different gases. Conversion factors of 310 for N_2O and 21 for CH_4 were used in the conversion of CH_4 and N_2O fluxes into CO_2 equivalents (Houghton et al., 1995). Data given as means with standard errors in parentheses

Site	Depth to water table (cm)	kg CO_2 eq. m^{-2}					
		$CO_{2(tot)}$	$CO_{2(soil)}$	N_2O	CH_4	Sum	$Sum_{(Soil)}$
Majnegården	40	2.44 (0.17)	1.29	0.26 (0.07)	-0.003	2.70	1.56
	80	2.37 (0.20)	1.25	0.12 (0.09)	-0.003	2.49	1.37
Örke	40	3.33 (0.17)	1.43	0.22 (0.07)	-0.001	3.55	1.65
	80	3.00 (0.20)	1.29	0.18 (0.09)	-0.002	3.18	1.47

The annual flux of N_2O varied from 2.6 to 5.4 kg N_2O-N ha^{-1}, which is lower than the IPCC emission factor (8 kg N_2O-N ha^{-1}) but in agreement with values reported by Regina et al. (2004) for grassed plots in northern Finland. Measurements were too infrequent during the winter to allow a very good estimate for the whole period. If N_2O emissions were measured more intensively during winter, in order to capture fluxes of short duration, N_2O emissions could have a greater impact on total GHG emissions.

5 Conclusions

Optimal conditions for plant growth and soil respiration on cultivated peat soils are achieved with an intermediate water table level and CO_2 and N_2O emissions do not necessarily increase with deeper drainage. The peat profile layer sequence and the soil physical properties of the different layers define the water retention curve and the effect of water table regulation on aeration status. In this study, lowering the water table from 40 cm depth to 80 cm depth decreased the greenhouse gas emissions on two soils with contrasting soil properties. Plant growth and root respiration accentuated the effects of soil aeration status. Soil moisture and air-filled porosity were rate-limiting in extreme moisture conditions such as desiccation and water logging.
It is sometimes suggested that abandonment of insufficiently drained cultivated organic soils or creation of bird habitats with a fluctuating water table could be used as mitigation measures. But these measures might, according to our results, create even bigger problems with equal or higher GHG emissions compared with a well-drained cultivated field. With no economic return from these areas there is no incentive to deal with the still existing emissions.

Future research should further investigate and develop management strategies for cultivated peat soils to reduce subsidence and emission rates. Studies have to be conducted under controlled conditions and in undisturbed soils. The effects of groundwater fluctuations in the range from saturated down to normal drainage depths are of special interest, due both to management aspects and to possible contribution of GHG emissions from peat soils to future climate change.

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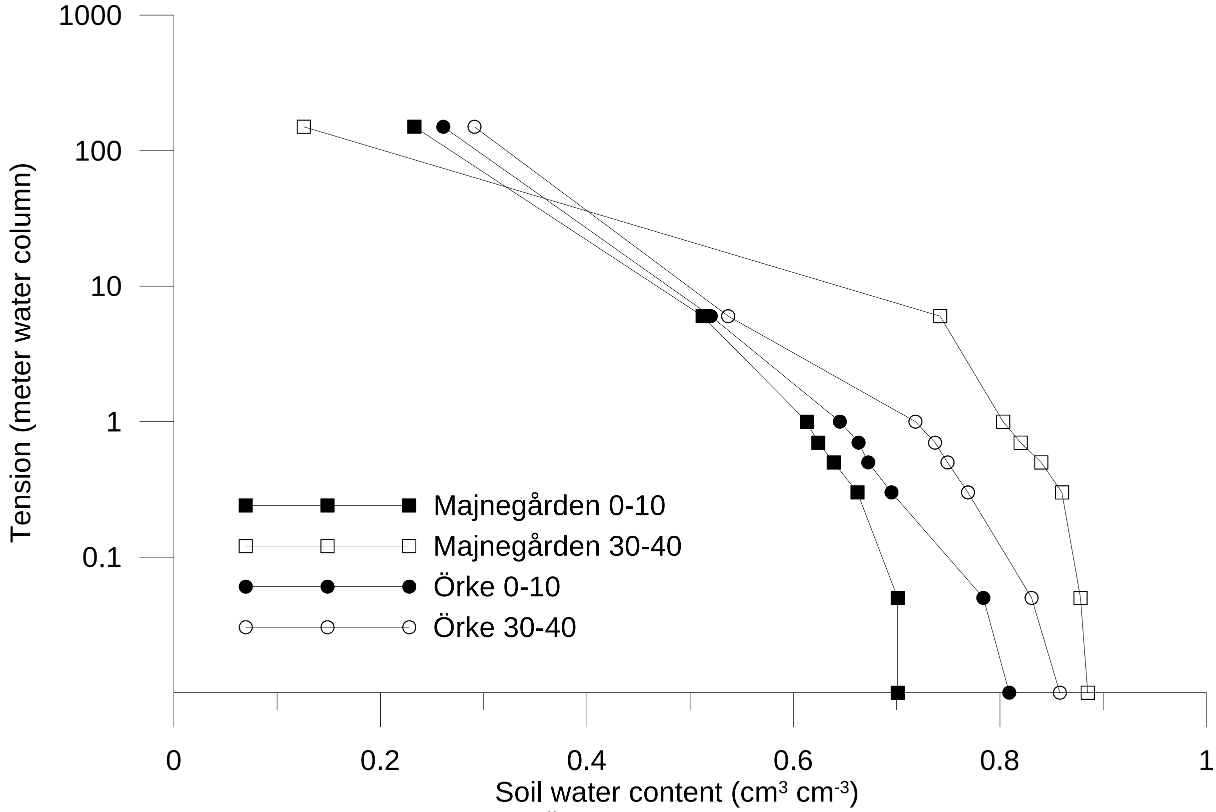

Figure 1. Soil water retention curves for Örke and Majnegården at 0-10 cm depth and 30-40 cm depth.

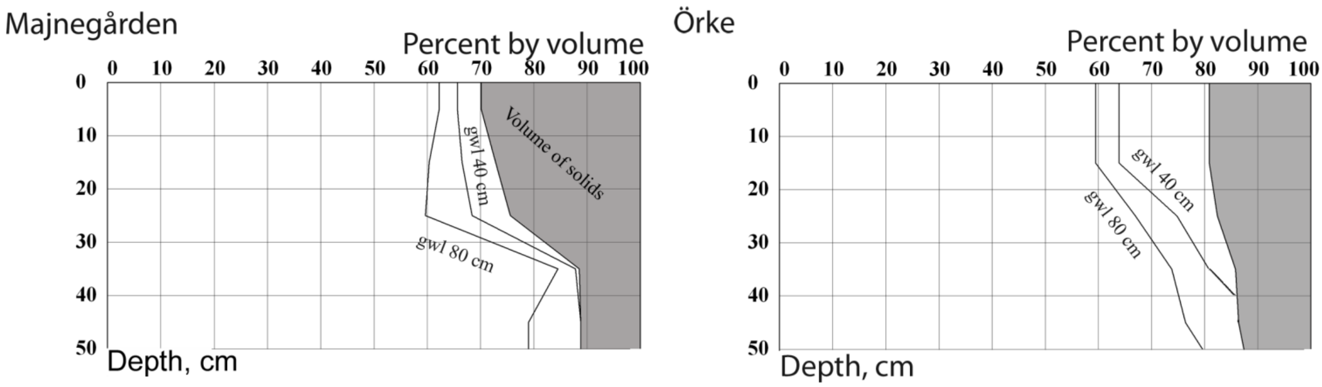

Figure 2. Drainage curves constructed from water retention data, showing volume relationships with depth in the profiles from Majnegården and Örke. Water content with drainage depth of 40 cm (gwl 40 cm) and 80 cm (gwl 80 cm) corresponding to the water table levels in the lysimeter experiment.

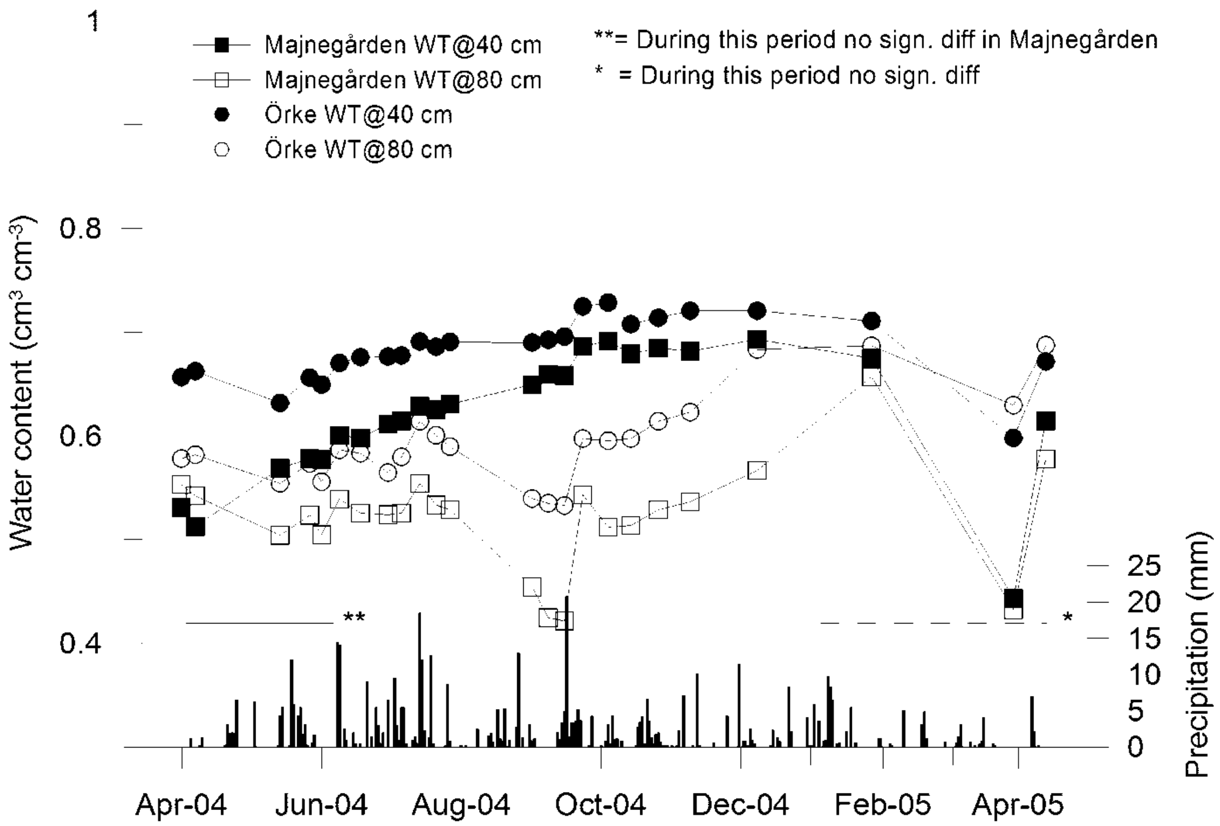

Figure 3. Precipitation and water content at 20 cm depth in the lysimeters from April 2004 to April 2005. Averages of 8 (WT@40 cm) or 4 lysimeters (WT@80 cm). During the winter (Dec-Feb), the drainage system froze and the water content in lysimeters with WT@80 cm rose. Time periods with non-significant water content differences between treatments are shown by horizontal lines.

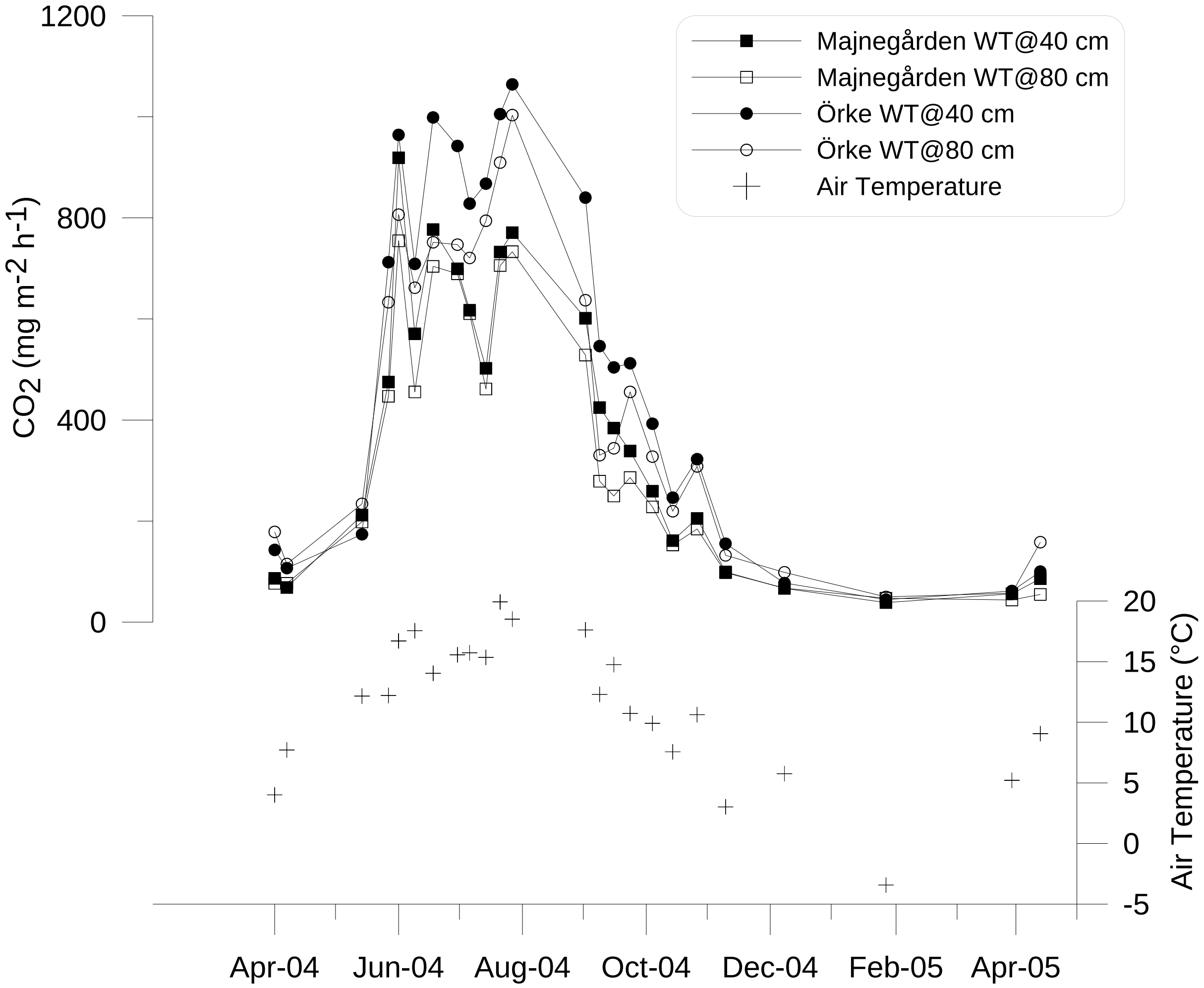

Figure 4. Carbon dioxide emissions from lysimeters with Majnegården and Örke soil with watertable at 40 cm (WT@40 cm) or watertable at 80 cm (WT@80) complemented with air temperature at gas sampling events during the experiment period April 2004 to April 2005.

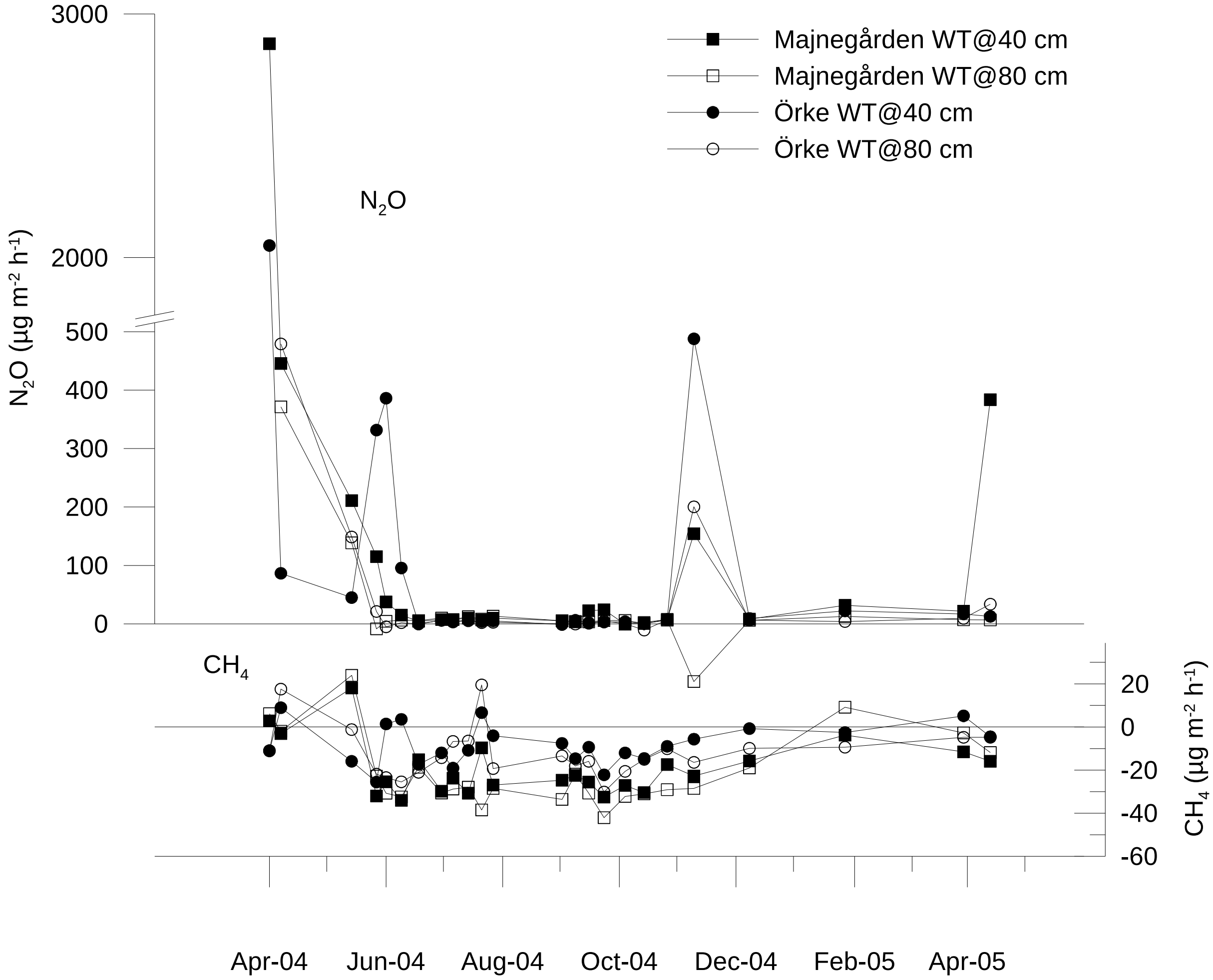

Figure 5. Methane and nitrous oxide emissions from lysimeters with Majnegården and Örke soil with watertable at 40 cm (WT@40) cm or watertable at 80 cm (WT@80) during the experiment period April 2004 to April 2005.

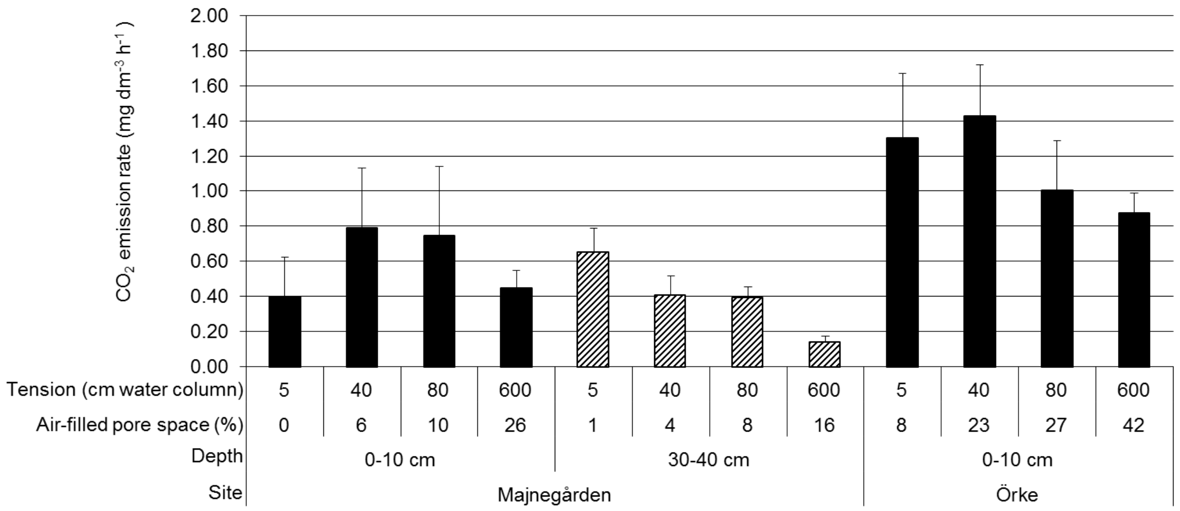

Figure 6. Incubation experiment with undisturbed soil samples from two different depths at Majnegården (0-10 cm and 30-40 cm) and from the topsoil at Örke (0-10 cm). CO_2 emission rate with increasing suction (from 5 to 600 cm water column) applied to soil cores. Error bars show standard deviation.

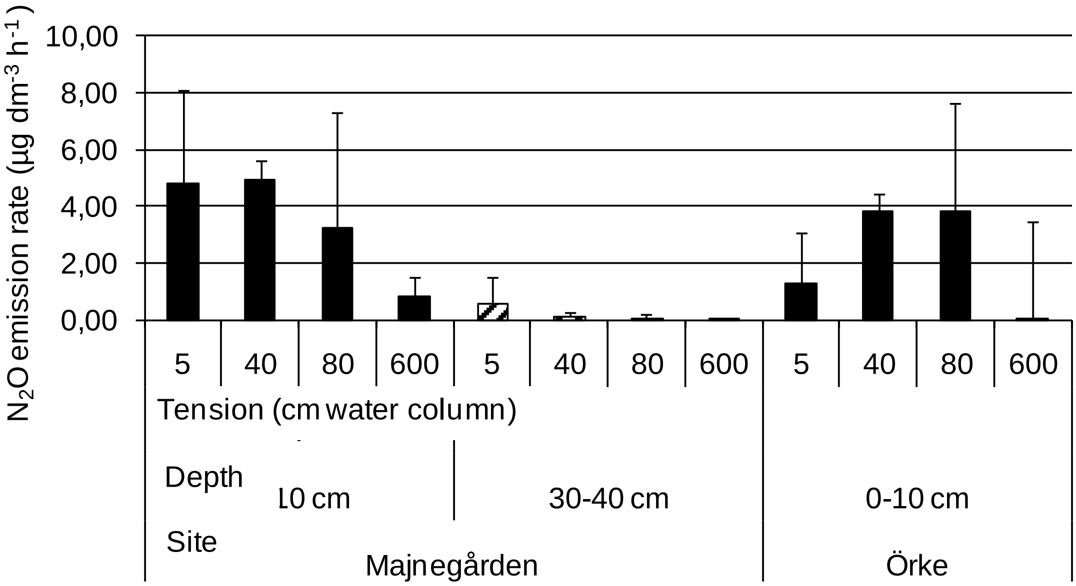

Figure7 . Incubation experiment with undisturbed soil samples from two different depths at Majnegården (0-10 cm and 30-40 cm) and from the topsoil at Örke (0-10 cm). N_2O emission rate with increasing suction (from 5 to 600 cm water column) applied to soil cores. Error bars show standard deviation.