Greenhouse Gas Emissions from Cultivated Peat Soils in Sweden

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Cover: Cultivated peat soil at Örke
(photo: Ö. Berglund)

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Abstract

Greenhouse gas emissions and peat subsidence are major concerns both from an environmental perspective and for farmers with declining soil production capacity. Agricultural databases, digitised maps of quaternary deposits and ^{40}K radiation have been used in a GIS analysis to estimate the distribution and land use of agricultural organic soils in Sweden. The total area of agricultural land in Sweden is estimated to be 3,525,259 ha and 7.6% (267,990 ha) of this area is classified as agricultural organic soil. One-quarter of the agricultural area of peat soils is intensively cultivated with annual crops and the remainder is sparsely used, predominantly for managed grasslands and pastures. These data on the acreage and cultivation intensity of agricultural peat soils were used to calculate annual greenhouse gas emissions, which were estimated to be between 3.1 and 4.6 M ton CO_2 eq. (6-8% of total national emissions).

Lysimeters with undisturbed soil columns (50 cm high, ⌀29.5 cm) from two sites sown with ryegrass (*Lolium perenne*) were used to investigate the effects of water table depth and soil properties on soil organic matter decomposition and greenhouse gas emissions. The water table depth was set to either 40 cm or 80 cm. Dark static chambers were used to measure gas emissions from the soil surface. CO_2 emissions were greater with the water table at 40 cm than at 80 cm, and the plant contribution to CO_2 flux was 47-57%. N_2O emissions peaked in springtime and CH_4 emissions were very low or negative. The differences observed in GHG emissions between the soils were attributed to differences in organic matter resilience and soil physical properties.

Keywords: Peat soil, organic soil, greenhouse gas emission, GIS, water table, lysimeter, root respiration, priming effect

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Dedication

To my grandfather Gösta Berglund

Det var dans bort i vägen på lördagsnatten
över nejden gick låten av spelet och skratten,
det var tjoh! det var hopp! det var hej!
Nils Utterman, token och spelmansfanten,
han satt med sitt bälgspel vid landsvägskanten,
för dudeli! dudeli! dej!
Gustaf Fröding

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Berglund, Ö. and Berglund K. (2010). Distribution and cultivation intensity of agricultural peat and gyttja soils in Sweden and estimation of greenhouse gas emissions from cultivated peat soils. *Geoderma* 154(3-4), 173-180.

II Berglund, Ö., Berglund, K. and Klemedtsson, L. (2010). A lysimeter study on the effect of temperature on CO_2 emission from cultivated peat soils. *Geoderma* 154(3-4), 211-218.

III Berglund, Ö., Berglund, K. and Klemedtsson, L. Plant-derived CO_2 flux from cultivated peat soils. *Acta Agriculturae Scandinavica Section B – Soil and Plant Science* (Accepted).

IV Berglund, Ö. and Berglund, K. (2011). Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil. *Soil Biology & Biochemistry*, doi:10.1016/j.soilbio.2011.01.00.

Papers I-IV are reproduced with the permission of the publishers.

The contribution of Örjan Berglund to the papers included in this thesis was as follows:

Paper I. Collected the data required, developed the GIS method and performed all GIS analyses. Wrote the manuscript assisted by the co-author.

Papers II-IV (which are based on data collected from the same lysimeter study). Planned the study together with Associate Professor K. Berglund and Professor Klemedtsson, was responsible for the lysimeter experiment and carried out most of the measurements. Performed the data analyses. Wrote the manuscript assisted by the co-authors.

Abbreviations

CEC	Cation Exchange Capacity
DM	Dry Matter
GHG	Greenhouse Gas
GIS	Geographic Information System
IACS	Integrated Administrative Control System
IPCC	Intergovernmental Panel on Climate Change
LSD	Least Significant Difference
PAR	Photosynthetically Active Radiation
SGU	Geological Survey of Sweden
SOM	Soil Organic Matter
UNFCCC	United Nations Framework Convention on Climate Change
WT@40 cm	Water table at 40 cm depth
WT@80 cm	Water table at 80 cm depth

Introduction

For a long time Swedish peatlands were considered to be of little or no value to agriculture. Farmers used some of the areas in times of crisis, but not much was done to improve their use. It was not until the 18th century that interest in the use of peatlands increased. The underlying reasons were the need to improve the Swedish economy and the rapid increase in population, which demanded more land for food production (Runefelt, 2008). In 1840 the Swedish economy was improving and the government started to subsidise drainage of lakes and peatlands. In 1886 the Swedish Peat Society (Svenska Mosskulturföreningen) was founded, with the main aim of promoting the cultivation of peat, based on scientific methods. Owing to improved methods and to the recently introduced mineral fertilisers, yields and acreage increased and the latter peaked at about 700,000 ha in the mid-1940s (Hjertstedt, 1946). The mechanisation of agriculture, an increasing focus on improving productivity on existing mineral soils and problems with drainage of peat soils eventually led to the abandonment of peat soils.

Under natural conditions most peatlands act as accumulators of plant residues and, at least in their early life, carbon sinks. Peat represents approximately one-third of the total global soil carbon pool (Joosten & Clarke, 2002). Drainage and cultivation of peat soils increase soil aeration and reverse the carbon flux, resulting in net carbon dioxide (CO_2) emissions and soil subsidence (Hallakorpi, 1936; Osvald, 1937; Neller, 1944; Armstrong & Watson, 1974; van der Molen, 1975; Eggelsmann, 1976; Stephens & Stewart, 1977; Sorteberg, 1978; Schothorst, 1980). Peatlands dominate the emissions of CO_2 from agricultural land in Sweden and are also major contributors of nitrous oxide (N_2O) (EEA, 2004; SNIR, 2010).

Greenhouse gas (GHG) emissions from agricultural organic soils are included in the National Inventory Report under the United Nations Framework Convention on Climate Change (UNFCCC). However, to date national estimates of emissions have generally been based on uncertain assumptions about the oxidation rate of the organic material, land use and the extent of the peatland area used for agriculture (Eriksson, 1991; Kasimir-Klemedtsson *et al.*, 1997). Thus the former problem of food security has changed to being a problem of greenhouse gas emissions and climate change (Benton, 1970).

Peatlands are extremely vulnerable to changes in water management, land use and climate. Subsidence and greenhouse gas emissions from cultivated peat soils need to be investigated scientifically, to help farmers preserve their land and reduce GHG emissions. However, before future GHG can be calculated and measures to mitigate them formulated, more insights are needed into how drainage affects these emissions.

Objectives

The overall aims of this thesis were to increase our knowledge of the distribution and cultivation intensity of organic soils in Sweden and to compare the effects of different agricultural management options on the breakdown of peat. Specific objectives were to:

- Develop a GIS method for investigating the distribution and cultivation intensity of farmed Swedish organic soils (Paper I).
- Develop a lysimeter procedure for organic soils in order to study the effect of water management on GHG emissions under well-defined conditions (Paper II).
- Quantify the contribution by roots to total soil respiration (Paper III).
- Investigate the effect of water table depth on emissions of GHG from two types of peat soil (Paper IV).

Background

Organic material produced by plants and secondary producers ultimately dies, falls to the ground and forms litter. A similar process in lakes creates mud. When the production of litter or mud is greater than decomposition, litter forms peat and mud forms gyttja (Osvald, 1937). Lack of oxygen (water-logging) and a cold climate reduce decomposition rates and can lead to formation of organic soils. In Sweden this process started after the last ice age and the deepest peat soils are several metres deep. There are many types of peat-forming ecosystems, making these soils very heterogeneous. Peat soils developed in a fen area that receives nutrient-rich water from the surroundings are more suitable for agriculture than acidic sphagnum peat that only obtains water from precipitation (ombrotrophic peat). Today, almost all previously cultivated ombrotrophic peat in Sweden has been abandoned (Paper I).

In order to be classified as an organic soil in the Swedish soil classification system, the organic matter concentration must be at least 30% (Jordartsnomenklatur, 1953) except for gyttja soils, where the limit is 6% organic matter. Internationally, soils with 20-30% organic matter that also satisfy a certain depth criterion are classified as organic soils (Soil Survey Staff, 2003).

When peatlands are drained, the peat loses the mechanical support of the water (flotation) and the initial subsidence is rapid, augmented by the pressure from the drained but still water-holding top layer of the peat (consolidation). The dry peat is decomposed by microbes and assumes a tighter packing, increased bulk density and subsidence (shrinkage). Peat soils also subside at a rate of 2-20 mm yr^{-1} due to oxidation, *i.e.* microbial respiration emitting CO_2 (Schothorst, 1977; McAfee, 1985; Berglund, 1996; Wösten *et al.*, 1997; Schipper & McLeod, 2002) and continue to subside until the water table reaches the soil surface (McAfee, 1985; Reddy *et al.*,

2006) or until all the peat is oxidised. This means that a 2-m deep peat profile could be completely gone 100 years after drainage, despite carbon inputs from crop production as illustrated in *Figure 1* by the Holme fen post (Hutchinson, 1980) and the Bälinge mosse subsidence rod (Berglund, 2008). Restoring these soils as carbon sinks while keeping them in production is an unlikely option (Stephens, 1956; Paustian *et al.*, 1998), as we can only slow down or speed up the decomposition process. In contrast to natural peatlands where plant debris is accumulated, the crops produced on cultivated peatlands are removed at harvest 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 emissions perspective, not the carbon input or output originating from the plant.

Figure 1. There has been almost 2 m subsidence since 1908 on Bälinge mosse (Berglund, 2008) (left, photo by Kerstin Berglund), and about 4 m since 1848 at the Holme fen post (Hutchinson, 1980) (right, original photo by Rodney Burton, height visualisation by Örjan Berglund).

Materials and methods

Digital soil survey

Greenhouse gas emissions from agricultural organic soils must be included in the National Inventory Report under the UNFCCC. In order to produce better estimates of the release of greenhouse gases from peat soils for the Swedish inventory, a soil survey was needed to determine the area of peat and gyttja soils under agriculture. A conventional soil survey of agricultural land in Sweden was considered too expensive, so an alternative method was developed based on digitised maps of quaternary deposits, maps of potassium content produced from ^{40}K radiation data and information on cultivation intensity and acreage taken from existing agricultural databases.

Soil data

The Geological Survey of Sweden (SGU) has map data on quaternary deposits at local, regional and national level (1:50,000-1:1,000,000) covering the majority of Sweden. The level of accuracy varies, since the databases are based on maps that vary in scale, quality and age. Since the year 2000 38% of the area has been updated, while 29%, 24%, 7% and 2% were updated during the 1990s, 1980s, 1970s and 1960s, respectively. Most maps are based on aerial photo interpretation combined with extensive fieldwork. The maps generally show the type of deposit at a depth of 0.5 m below the surface, with the exception of shallow peat, which is defined as less than 0.5 m deep. If peat is found at a depth of 0.5 m, this means in most cases that the overlying soil is a peat soil and this information can therefore be used as a proxy for the type of topsoil.

Radiation data

As a complement to the digitised soil data, SGU has produced a digitised map of potassium (K) content (%) in the upper soil/bedrock layers based on aerial γ-radiation measurements of ^{40}K. Aerial measurements of natural terrestrial gamma radiation have also been used in soil moisture assessments (Carroll, 1981), uranium prospecting and bedrock surveys (Ek *et al.*, 1992). Airborne measurements of gamma radiation started in 1968 in Sweden and currently have more coverage than the geological database. Measurements are made every 20 m at 60 m height and with 200 m between the flight lines. The height and coordinates of every measured point are recorded, together with the radiation of ^{238}U, ^{232}Th and ^{40}K. ^{40}K radiation is blocked by water and since peat soils usually hold a very large proportion of water, the radiation data can be used to detect these soils (Ek, 1987). A wet peat layer exceeding 0.5 m depth screens off all radiation. Peat soils are thus identifiable as land areas with low ^{40}K radiation and a 'peat map' can be created from those areas.

IACS agricultural database

IACS (Integrated Administrative Control System) is the administration system for EU subsidies used by the Swedish Board of Agriculture. It contains information about crops grown (database) on each block of farm land (digital maps) each year.

GIS method

Geographical Information System (GIS) technology was used in the present study to analyse the digitised maps of quaternary deposits and agricultural databases.

The GIS operation *intersect* (ArcGIS 9.2, ESRI, Redlands, California, USA) was used to estimate the area of cultivated organic soils using the digitised maps of quaternary deposits and ^{40}K radiation maps. The intersect shows the area that is common to the peat and field layer (*Figure 2*). These data were combined with information on crops and acreage in existing IACS databases. The method is described in detail in Paper I.

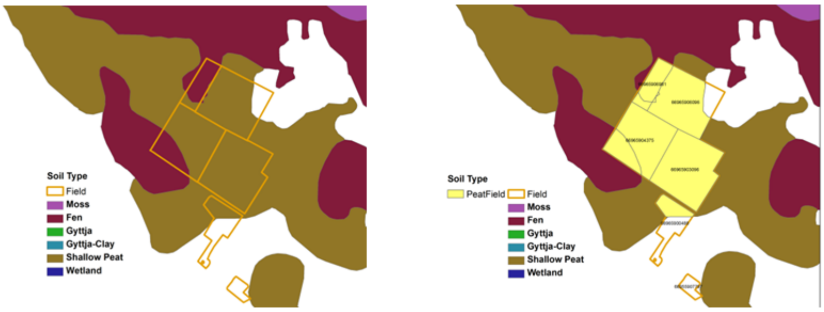


Figure 2. Intersect between peat and field layer (IACS block), identifying peat fields.

Lysimeter and incubation study

The aim of the lysimeter experiment was to study the effects of water management on GHG emissions.

Site location and description

Subsidence was measured in an ongoing series of long-term field experiments on seven sites with organic soil in Sweden (*Figure 3*). In order to study the effect of drainage on GHG emissions, we used soil lysimeters from two of these long-term sites, Majnegården and Örke (*Figure 4*, *Figure 5*), which have different soil properties. Both sites are dominated by pasture and hay production, but the Majnegården site, described by Klemedtsson *et al.* (2009) has higher mean annual precipitation and is more intensively cultivated, whereas Örke, described as site B in McAfee (1985), is sparsely managed.

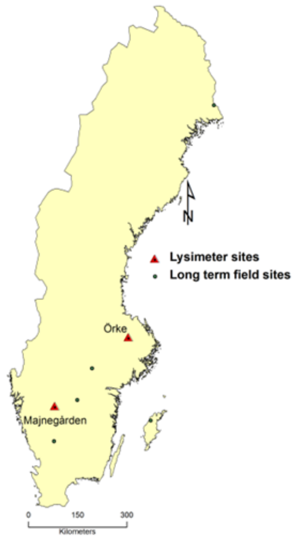


Figure 3. Location of long-term field experiment sites on peat soils in Sweden. Sites marked with a triangle were used for lysimeter collection.

Majnegården Örke

Figure 4. Field sites at Majnegården and Örke.

Mean annual air temperature 5.5 °C
Estimated mean annual soil temp at 50 cm depth 7 °C
Mean annual precipitation 640 mm
Land use: arable land with cereals, ley and pasture. Artificially drained, pipe drains at 26 m spacing

Mean annual air temperature 5.3 °C
Estimated mean annual soil temp at 50 cm depth 6.8 °C
Mean annual precipitation 563 mm
Land use: arable land. Last 10 years ley. Artificially drained, open ditches at 75 m spacing

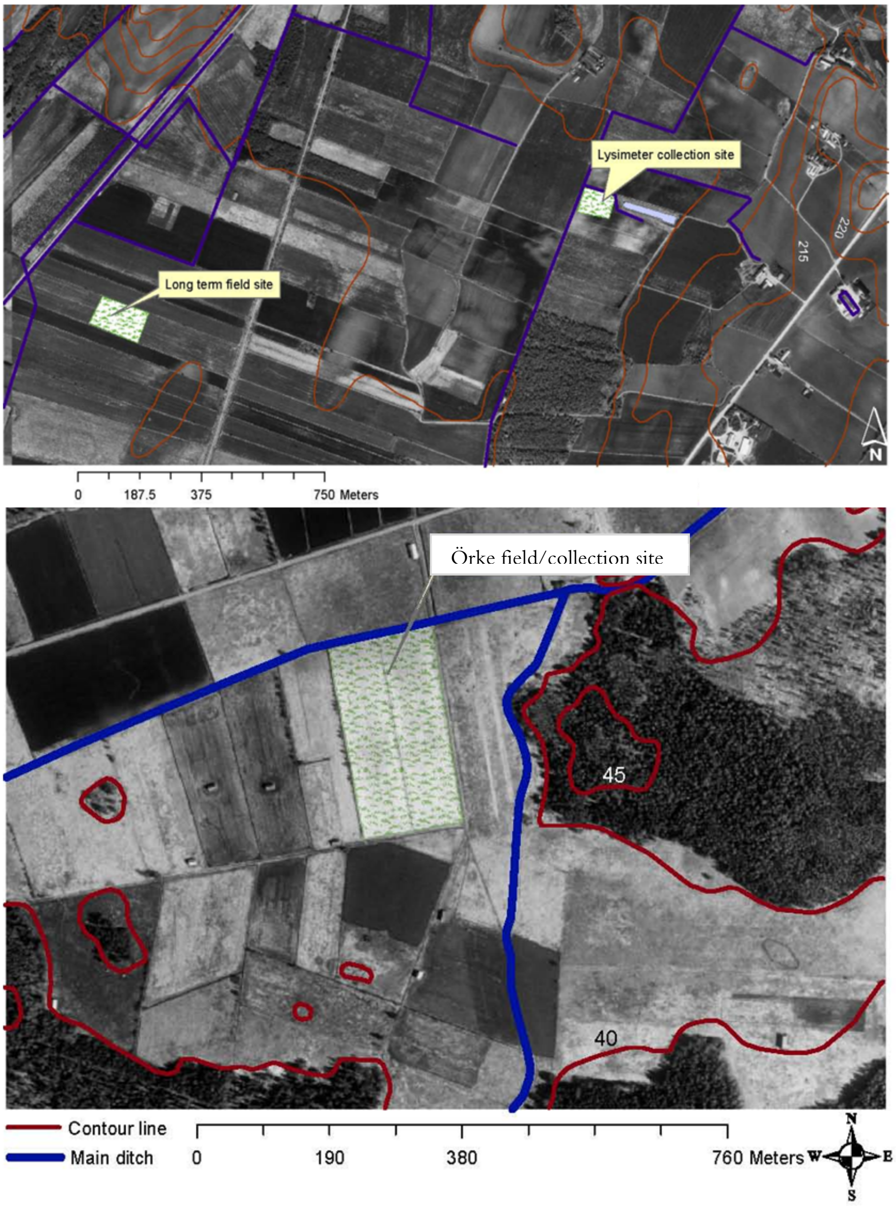


Figure 5. Location of the lysimeter collection site at Majnegården (top map, 58°7'49"N, 13°32'38"E) and Örke (lower map, 60°1'39"N, 17°26'39"E).

Soil physical and chemical analysis

Soil core samples (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 the Örke and Majnegården sites. These soil cores were used for determination of dry bulk density, water content at sampling and water content (4 replicates) at a matric tension of 5, 30, 50, 70, 100 and 600 cm water column (Andersson, 1955). The data obtained were then used to construct a soil water retention curve using the van Genuchten equation (Eq. 1):

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^n]^{1-1/n}} \qquad \text{Eq. 1}$$

where $\theta(\psi)$ is the water retention curve $[L^3L^{-3}]$;$|\psi|$ is tension ($[L^{-1}]$ or cm of water); θ_s is saturated water content $[L^3L^{-3}]$; θ_r is residual water content $[L^3L^{-3}]$; α is related to the inverse of the air entry suction, $\alpha > 0$ ($[L^{-1}]$, or cm^{-1}); and n is a measure of the pore size distribution, $n > 1$ (dimensionless).

All soil cores were vacuum-dried at 50-60 °C before dry bulk density measurements were made. This was done instead of drying the samples at 105 °C until no further weight loss occurs, as is usually done for mineral soils, because this can create charring problems where the sample never reaches a stable weight (Landva *et al.*, 1983), as illustrated in *Figure 6*. The physical wilting point (water content at a matric tension of 150 m water column) and particle density were determined on disturbed soil samples (Andersson, 1955). Porosity (ϕ) was calculated from particle density (ρparticle) and dry bulk (ρbulk) density (Eq. 2):

$$\phi = 1 - \frac{\rho bulk}{\rho particle} \qquad \text{Eq. 2}$$

Shrinkage was not considered when calculating water content at different tensions, which might have led to underestimation of the water content at high water tensions (Schwärzel *et al.*, 2002). Saturated hydraulic conductivity was determined using a constant head method (unit hydraulic gradient) on another set of undisturbed soil cores (4 replicates).

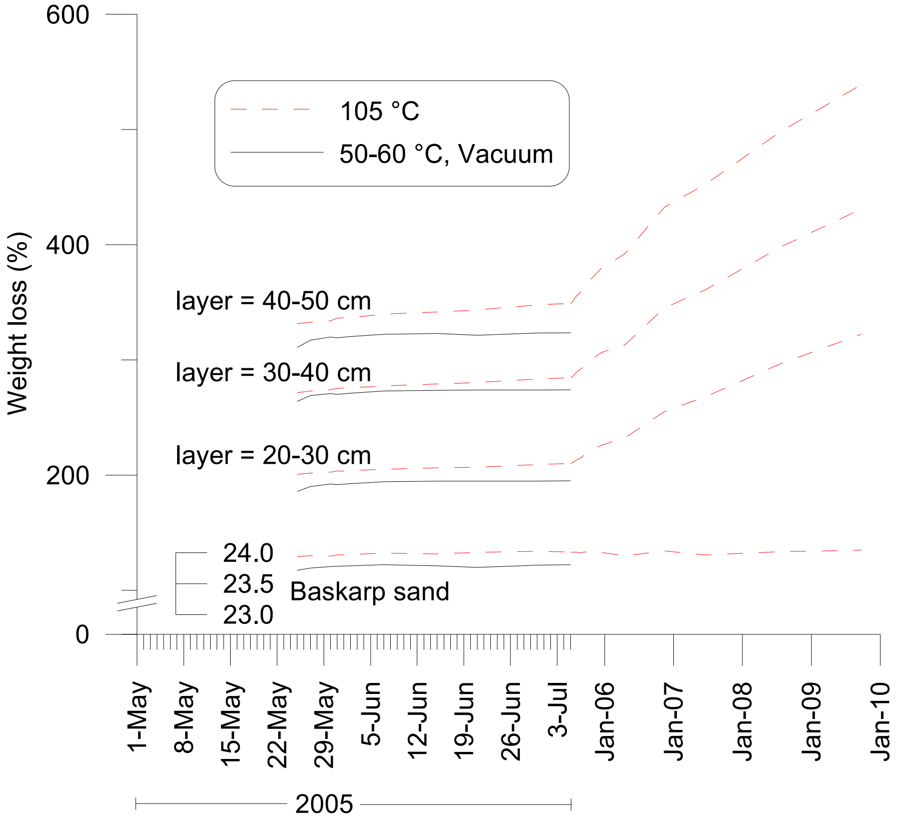


Figure 6. Weight loss from Örke peat and Baskarp sand, dried at 105 °C or at 50-60 °C under vacuum. When Örke soil samples were dried at 50-60 °C under vacuum a point was reached where there was no more weight loss, but with drying at 105 °C the soil kept losing weight for more than 4 years.

Soil pH was measured in deionised water extracts at a soil-solution ratio of 1:2.5 using a pH electrode. Organic matter content (loss on ignition) was determined by dry combustion at 550 °C for 8 h. Total carbon and nitrogen in soil were analysed by dry combustion on a LECO CHN-932 analyser (St. Joseph, MI, USA). $CaCO_3$ was analysed using a Passon apparatus (Talme & Almén, 1975). Ammonium oxalate-extractable iron, aluminium and phosphorus were determined according to Schwertmann (1964). Base cations were analysed on a Perkin Elmer Analyst 300 spectrometer after shaking 2.5 g soil with 90 mL 0.1 M $BaCl_2$ according to SS-ISO 11260. Acidity was measured by 0.1 M NaOH titration to pH 7 of $BaCl_2$ extracts. Copper and phosphorus were analysed using an inductively coupled plasma spectrometer (Perkin Elmer Optima 3000 DV). Water-soluble nitrate and phosphate were determined by anion chromatography.

Soil profile description, classification and properties

Profile description

Descriptions of the soil profiles are given in *Figure* 7.

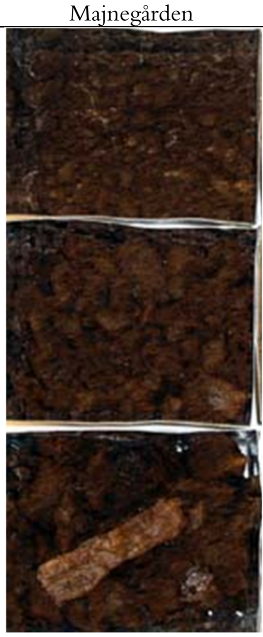
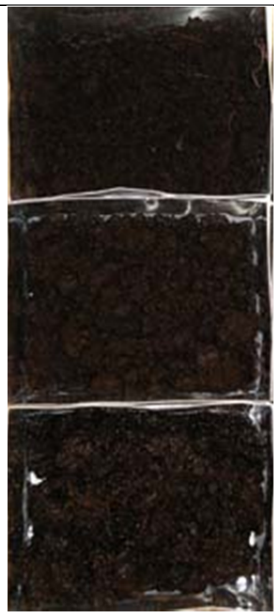
Depth (cm)	Majnegården	Örke
0-20		
20-30		
30-40		
0-20	Fen peat, decomposition degree (dd) H7-8, plough layer, mixed with inorganic sediments (clay and shells), dark brown 10YR 2/3	Fen peat, dd H9-10, plough layer, black 5YR 1.7/1
20-30	*Phragmites* peat (reed peat, fen peat), dd H3-4, plant remains in a layered structure, dark brown 10YR 2/3	Fen peat, dd H9-10, plough layer, black 5YR 1.7/1
30-50	*Phragmites-Carex* peat (reed/sedge peat, fen peat), dd H1-2, plant remains in a layered structure, dark brown 10YR 2/3 with yellowish spots 10YR 4/6	*Carex-Amblystegium* (sedge/brown moss peat, fen peat), dd H8-9, black 5YR 1.7/1
50-100	*Phragmites-Carex* peat, dd H1-2, plant remains include *Carex* roots, *Phragmites* and wood (*Alnus*)	*Carex-Amblystegium* with tree remains (*Alnus* and *Betula*), dd H8-9
100-150	*Phragmites-Carex* peat mixed with gyttja. Increasing clay content with depth	*Carex-Amblystegium* with a few tree remains (*Alnus* and *Betula*), dd H7-8
150-170	Clay	*Carex-Amblystegium*, dd H8, increasing gyttja content with depth
170-	Clay	Clay gyttja gradually changing to clay

Figure 7. Some characteristics of the soil profiles at the lysimeter collection sites. Decomposition degree according to the von Post scale. Soil colour according to the Munsell colour chart.

Even though the soil at both Majnegården and Örke is a fen peat, there is a great difference in soil properties between the sites. The Örke site has a very well decomposed peat dominated by *Carex-Amblystegium*, while the soil at Majnegården is dominated by *Phragmites-Carex* peat, is less decomposed, especially in the subsoil, and has quite a lot of mineral material and shells mixed into the upper layers (Table *1*). Majnegården has a high pH (7.4-7.7) and a low organic matter content (30%) in the topsoil, with 50% organic matter in the subsoil. Örke is a very well decomposed fen peat (von Post H9-10) with a pH of around 5.7 and an organic matter content of 85%. The peat types indicate that the peat at Majnegården was deposited in wetter conditions than the peat at Örke.

Physical properties

Soil physical properties differ between the sites and also between the Majnegården topsoil and subsoil. The Majnegården topsoil has a much higher degree of decomposition, higher bulk density and lower organic matter content than the subsoil, whereas the Örke soil is more homogeneous throughout the profile (Table *1*).

Soil water retention characteristics are of great importance both for crop growth and for greenhouse gas emissions. The critical air content for crop production on peat soils has been suggested to be between 8-15% by volume (McAfee Graham, 1989). As shown by the pF curves (*Figure 8*) and drainage curves (*Figure 9*), sufficient air enters the Örke profile even at a water table depth of 40 cm, whereas the Majnegården profile has a low air-filled porosity even at a water table depth of 80 cm. The van Genuchten parameters are shown in the inset table in *Figure 8*. 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 (Table *1*).

Table 1. *Physical properties of the Majnegården and Örke soils. Standard deviation in brackets*

Site and depth	Decomp.	Loss on ignition	Dry bulk density	Density of solids	Porosity	Sat. hydr. cond.
(cm)	(H1-10)	(%)	(g cm^{-3})	(g cm^{-3})	% (v/v)	cm h^{-1}
Majneg.						
0-10	7-8	32	0.64 (0.03)	2.07	69	12
10-20	7-8	29	0.62 (0.01)	2.12	71	25
20-30	3-4	30	0.53 (0.03)	2.16	76	31
30-40	1-2	53	0.21 (0.01)	1.80	88	4
40-50	1-2	48	0.21 (0.02)	1.87	89	71
Örke						
0-10	9-10	86	0.31 (0.02)	1.62	81	9
10-20	9-10	86	0.28 (0.02)	1.57	82	13
20-30	9-10	86	0.22 (0.01)	1.59	86	12
30-40	8-9	83	0.22 (0.02)	1.60	86	12
40-50	8-9	87	0.18 (0.00)	1.59	88	1

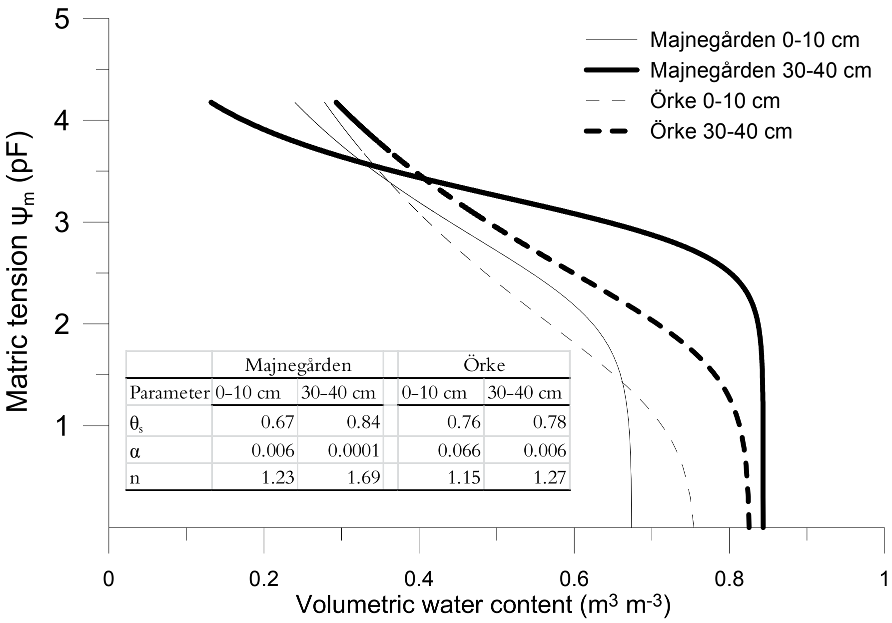


Figure 8. Soil water retention curves for Örke and Majnegården at 0-10 cm depth and 30-40 cm depth (pF=-log$_{10}$ (tension in cm water column)).

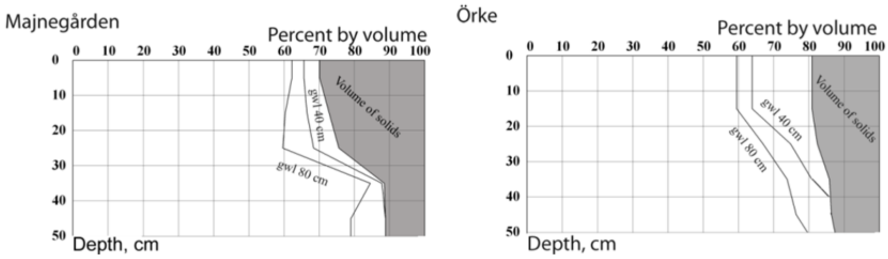


Figure 9. Volume relationships with a groundwater level (gwl) of 40 cm and 80 cm at Majnegården and Örke.

Chemical properties

The chemical properties differ greatly between the soils, mainly due to the lime and mineral-rich material (shells) originating from ancient molluscs (*Ancylus fluviatilis*) mixed into the upper layers at Majnegården. It is important to bear in mind the great difference in bulk density between the sites when evaluating soil nutrient status, as the bulk density in the topsoil at Majnegården is twice that at Örke. The nitrogen (N) concentrations at Majnegården and Örke (Table *2*) are normal for cultivated peat soils (Brady, 1974; Berglund, 1996). As humification progresses, the C/N ratio decreases. The C/N ratio is around 14 in the topsoil at both sites, which is within the normal range for a well decomposed peat soil (Naucke *et al.*, 1993; Berglund, 1996). The C/N ratio increases with depth in the less humified subsoil layers. The nutrient storage capacity of organic soils can be very high (Puustjärvi & Robertson, 1975) and this is reflected in a high cation exchange capacity (CEC). CEC is high for both soils but is extremely high at Örke, with Ca^{2+} as the dominant cation.

Table 2. *Chemical properties of Majnegården and Örke soil*

		Majnegården		Örke	
	Depth (cm)	0-20	30-50	0-20	30-50
Tot-C	%	21.4	27.5	37.7	38
Tot-N	%	1.5	1.3	2.6	2.3
Tot-P	%	10.4	3.6	10.1	2.8
$CaCO_3$	%	32	0.1		
pH		7.5	7.7	5.8	5.3
Ox-Al	$mg\ 100g^{-1}$	18.3	6	170	55.3
Ox-Fe	$mg\ 100g^{-1}$	283.3	320.8	1014	613.5
Ox-P	$mg\ 100g^{-1}$	19.4	1.3	31.2	1.5
Na	$mg\ 100g^{-1}$	1	1.6	0.7	0.9
K	$mg\ 100g^{-1}$	5.5	2.9	1.6	0.6
Mg	$mg\ 100g^{-1}$	2.4	1.7	11.1	23.9
Ca	$mg\ 100g^{-1}$	631	616.8	980.3	1074.5

Soil classification

Örke is a typical Swedish cultivated fen peat but Majnegården, with its high pH, low organic matter content and high bulk density in the topsoil, is a more uncommon type. The classification of the soils according to the national classification system of Sweden (Osvald, 1937), the American Soil Taxonomy (NRCS, 2005) and the WRB system (The World Reference Base for Soil Resources) is shown in Table *3*.

Table 3. *Soil classification of the Majnegården and Örke soils*

Classification system	Majnegården	Örke
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

The Swedish system is simplified for agricultural purposes and the organic soils are divided into three main groups; moss peat, fen peat and gyttja soils. The decomposition degree is very often indicated, sometimes together with pH. The American Soil Taxonomy or the WRB classification system is very often used for mineral soils. However, when it comes to organic soils a number of national classification systems are used rather than an international standard.

When choosing classification system, different criteria can be used, such as the amount of knowledge required to use the system, the amount of information that can be obtained from the soil name or whether laboratory measurements are needed to perform the classification. For peat soils information about the decomposition degree of both topsoil and subsoil is very important, since this has a great influence on the physical and chemical properties of the soil. Some indication of the nutritional status of the soil is also valuable.

All systems give information about the decomposition degree of the topsoil (fibrist/saprist, fibric/sapric, H1-10) but the international systems ignore this for the subsoil (Table *3*). However, such information is crucial, especially at the Majnegården site, since there is a much lower decomposition degree in the subsoil at that site. Some information about the nutritional status is given in all systems (euic, eutric, fen). The international systems require laboratory measurements. The Soil Taxonomy system requires pH determination, which is an easy and cheap measurement, but the WRB system requires determination of the base saturation, which is rather costly.

In the simple Swedish system, no laboratory measurements are required unless pH is used. The only knowledge required with the system is how to determine decomposition degree according to the von Post method, which is quite easy to learn (a soil sample is squeezed in the hand and the outcome compared against a table of options) and how to distinguish between fen peat, moss peat and gyttja soil. This requires some experience, but they are well known peat types internationally. In conclusion, the simple Swedish system is easy to use, provides important basic information about the soil and requires no laboratory measurements. The major advantage of the Soil Taxonomy and WRB classification systems is that they are international and well documented.

Spatial variation

The variation in soil properties within and between organic soils is huge. Depending on how the soil was formed, the plant species that created the organic matter and the hydrology, the chemical, physical and biological properties of the peat vary widely. For agricultural applications, measurements of soil conductivity can be used for mapping variation in soil properties such as concentration of salts and soil moisture content. To investigate the spatial variation in peat soils, a pilot study was carried out at the Örke site (Berglund & Berglund, 2010). The electromagnetic induction meter used in this study was the Geonics EM38, which has a transmitter and receiver coil 1 m apart. The instrument, which measures apparent soil electrical conductivity, was drawn over the field at 5-m intervals by a small four-wheeler and CO_2 emissions were measured simultaneously at 40 points. The data obtained revealed that electrical conductivity (EM38 values) and CO_2 emissions both varied rather widely (*Figure 10*), even though the area appeared to be very homogeneous on the surface (Berglund & Berglund, 2010). Since these soils show such large variation in properties, it is very important to always include soil properties together with *e.g.* GHG measurements in order to allow the results to be compared with those of other investigations.

Lysimeter collection

Soil sampling at Majnegården was carried out in autumn 2002 and at Örke in late spring 2003. A drilling method with minimal soil disturbance (Persson & Bergström, 1991) was used at each site to collect undisturbed soil monoliths in PVC lysimeter casings (*Figure 11*).

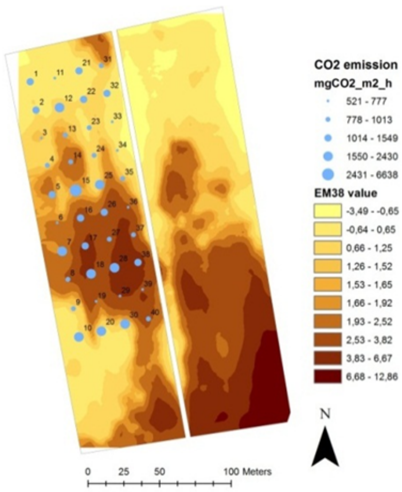


Figure 10. Spatial variation in EM38 values and CO_2 emissions at the Örke field site.

Figure 11. Soil monoliths collected with minimal disturbance in PVC casings.

The casings consisted of PVC pipes (29.7 cm inner diameter and 59.8 cm in length), which were lidded above and below and transported to the Swedish University of Agricultural Sciences (SLU), Uppsala. In lysimeter studies of peat soils, shrinkage on drying can create problems such as gas and water flux from the sides of the soil column (Cameron *et al.*, 1990; Cameron *et al.*, 1992; Schwärzel *et al.*, 2002; Schwärzel & Bohl, 2003). This was the case in a small pilot study where methane (CH_4) was observed to escape from the sides of the soil column instead of through the soil, where it would be oxidised (*Figure 12*). When the gap was blocked, CH_4 emissions stopped and did not reappear even when the water table was raised (*Figure 13*). To avoid these problems, a system was devised (Paper II) that included a flexible 0.5 mm neoprene rubber sheet as an inner wall, giving the peat core the opportunity to shrink or swell (*Figure 14*).

Figure 12. Gap between lysimeter wall and soil monolith after drying.

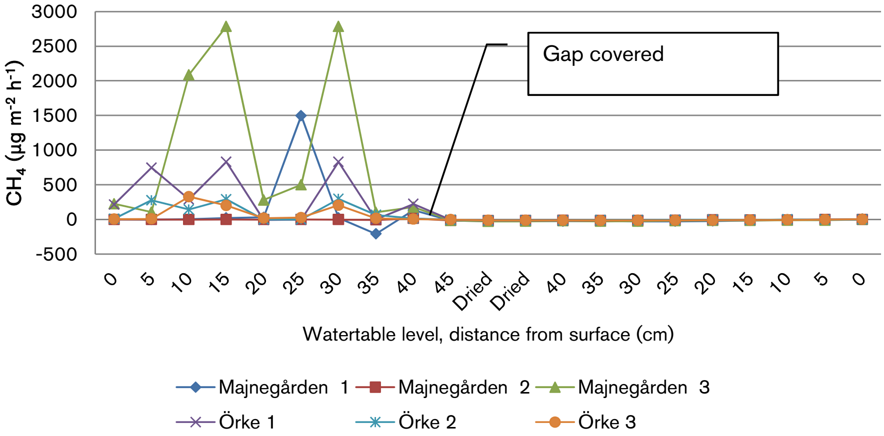


Figure 13. CH_4 emissions from lysimeters during drainage experiments. CH_4 emissions ceased after closure of the gap between soil and lysimeter wall.

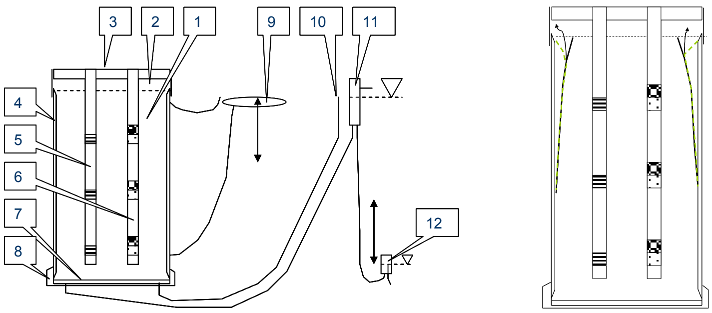


Figure 14. Construction of lysimeter used in peat soil studies. The picture on the right shows how the flexible rubber membrane filled out the gap between lysimeter wall and soil monolith when the peat had shrunk.

1. Undisturbed soil sample
2. Vegetation (cut grass)
3. Bridge to hold probes
4. Double wall (external layer made of hard plastic, internal layer made of flexible rubber sheet)
5. Probe for measurement of soil moisture at three levels
6. Probe for measurement of temperature and sampling soil water
7. Tension filter
8. Frame for the tension filter sheet
9. Flexible plastic bag filled with water. Elevation is adjustable to control water pressure at the double wall (4)
10. Hose with stopcock for drainage water sampling
11. Air trap with frost protection to maintain hanging water column
12. Overflow device to control the water table (elevation is adjustable)

To allow the water table beneath the base of the lysimeter to be regulated, a tension sheet was created. It consisted of (from top to bottom): polyester cloth, 3 layers of fibreglass filter (Munktell MG 160), polyester cloth and 2 layers of plastic netting. The air bubbling pressure of the tension filter was 2 m water column. A more detailed description of the set-up is given in Paper II. The soil cores collected were transferred to the new improved lysimeters and placed in the lysimeter station at Ultuna (59°49'2"N, 17°39'41"E) (*Figure 15*).

Figure 15. Lysimeter station used in the experiment. Service pits in the middle. The overflow device to control the water table is in a temporary elevated position in the second row. The dark chamber and the pumping device for gas sampling can be seen to the right.

Treatments

Lysimeter studies

The effect of water management on GHG emissions was studied using a factorial experimental design with twelve lysimeters of each peat type. The following treatments were used:

A. Static water table at 40 cm depth (WT@40 cm)
B. Static water table at 80 cm depth (WT@80 cm)

The lysimeters were saturated from below with water and sown with ryegrass (*Lolium perenne*). The ryegrass was cut before every gas measurement and dried at 105 °C. Air temperature and precipitation were monitored throughout the season. During the growing season, water was supplied from below with a 1-L flask connected to the air trap (no. 11 in *Figure 14*). This flask was continuously filled so the water table could be kept constant. Water content was measured each sampling day with a Profile Probe (Delta-T devices, 128 Low Road, Burwell, Cambridge, CB5 0EJ, UK). The whole system set-up is illustrated in *Figure 16*.

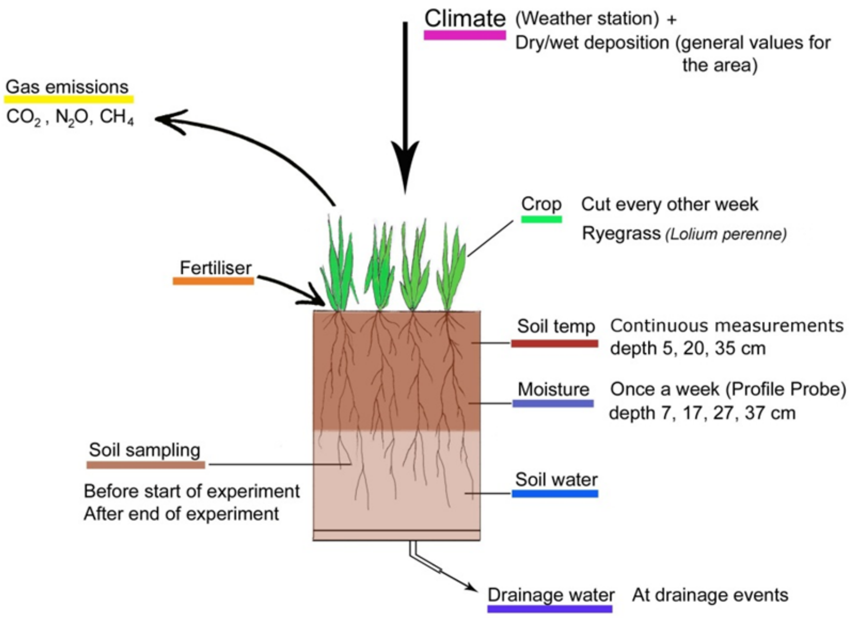


Figure 16. Lysimeter set-up and measurement schedule.

Root respiration experiment

To study the effect of crop and root respiration, CO_2 emissions from vegetated and bare soil lysimeters were measured in the same way as described above, with three replicates of each treatment and with the water table at 40 cm depth (Paper III).

Incubation study

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 (Robertson *et al.*, 1993). All soil cores were saturated with water for five days. Tension 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. Four to six replicates were used. Soil cores were kept at 20 °C throughout the incubation experiment (Paper IV). The effect of temperature on CO_2 emissions was modelled from lysimeter measurements and studied on another set of steel cylinders incubated at 2, 13 and 25 °C (Paper II).

Weather conditions at the lysimeter site

The summer of 2004 was wetter than normal except for August, when precipitation was lower than the 30-year average. The temperature was near normal except for August, which was warmer *Figure 17*.

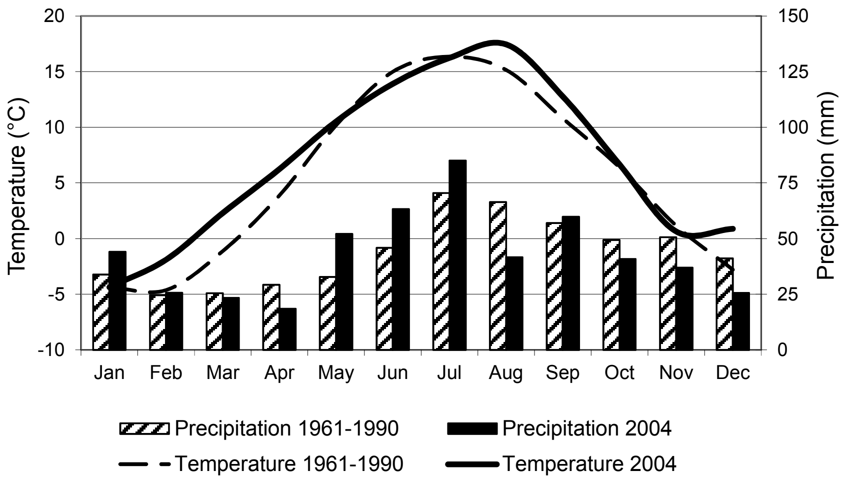


Figure 17. Air temperature (°C) and precipitation (mm) in 2004 compared with average values for the period 1961-1990.

Gas measurements

Gas flux measurements were made using the closed dark chamber method (Mosier, 1990), which measures the combined effect of soil respiration and plant respiration (*Figure 18*). When used on bare soil, only soil respiration is measured. Advantages of closed chambers include:

- Very small fluxes can be measured.
- No electrical supply is needed.
- The chambers are simple to construct.

Disadvantages include:

- The design of the chamber can influence the absolute value of the measured gas flux (Norman *et al.*, 1997).
- A concentration of gas can build up inside the chambers to levels where they inhibit the normal gas diffusion.
- The closed cover eliminates the turbulence normally affecting the soil surface.
- The chamber disturbs the soil air boundary layer.
- Positioning the chamber can cause pressure changes in the soil.
- The chamber can cause temperature changes in the soil and atmosphere under the chamber.

The chamber was 20 cm high, insulated and covered with a reflecting layer. It was placed in a collar above 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. In the experiment with the bare soil treatment, the same chambers were used, but instead of collecting gas in headspace flasks, the atmosphere in the chamber was circulated through a Vaisala Carbocap probe (GMP 343, Vaisala, Helsinki, Finland) for 3-5 minutes depending on emission rates. In the field we used collars with the same diameter as the lysimeters, pushed down 3-5 cm into the

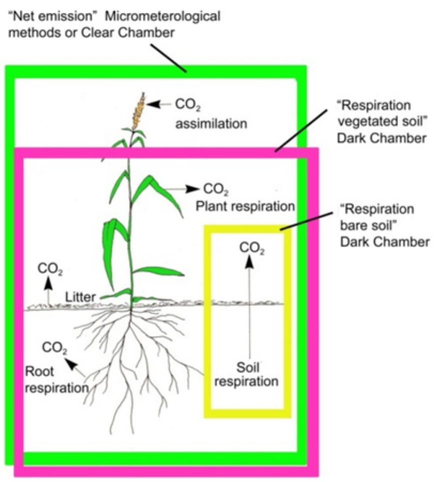


Figure 18. Origins of CO_2 measured with different types of chambers or micrometeoro-logical methods.

soil, and the atmosphere within the chamber was circulated through the Vaisala Carbocap (*Figure 19* A).

A B

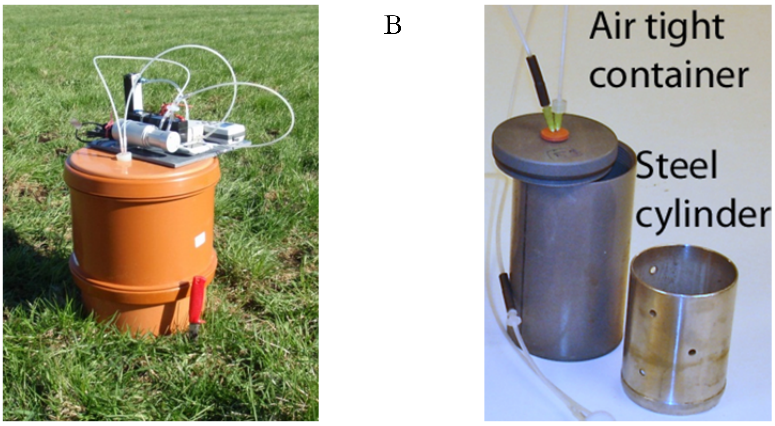


Figure 19. A) Field equipment for GHG measurements with a Vaisala GMP 323 connected to the chamber for CO_2 measurements. B) Incubation equipment for GHG measurements from soil in perforated steel cylinders.

The soil cores in the incubation experiment (in the small perforated steel cylinders) were placed in air-tight PVC jars (*Figure 19* B) before gas emission measurements (Robertson *et al.*, 1993). Ten-mL samples of the atmosphere were extracted 1, 2 and 3 h after closure of the jars and transferred to 22-mL headspace flasks sealed with butyl rubber septa.

All gas samples captured in the headspace flasks (CO_2, N_2O and CH_4) were analysed by gas chromatography (Klemedtsson *et al.*, 1997). The emission rate in all studies was calculated using linear regression and the ideal gas law from Eq. 3, using measurements with $R^2 \geq 0.85$ (94% of all CO_2 measurements) for CO_2:

$$F=\rho \times V/A \times \Delta c/\Delta t \times 273/(T+273) \qquad \text{Eq. 3}$$

where F is the flux (mg m^{-2} h^{-1}), ρ is the density of gas (mg m^{-3}), V is the volume of the chamber (m^3), A is the base area of the 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).

In the lysimeter experiment all measurements of 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 Grapher 6.3.28 software (Golden Software, Golden, Colorado, USA).

The sampling interval can affect the result quite strongly even if the regression has a good linear fit. One problem with too long a sampling interval is the build-up of CO_2 inside the chamber, decreasing the gradient between the soil and the chamber (Nay *et al.*, 1994). Using the first 3 minutes (B in *Figure 20*) instead of the first 40 minutes (A in *Figure 20*) resulted in an estimated emission rate that was twice as high.

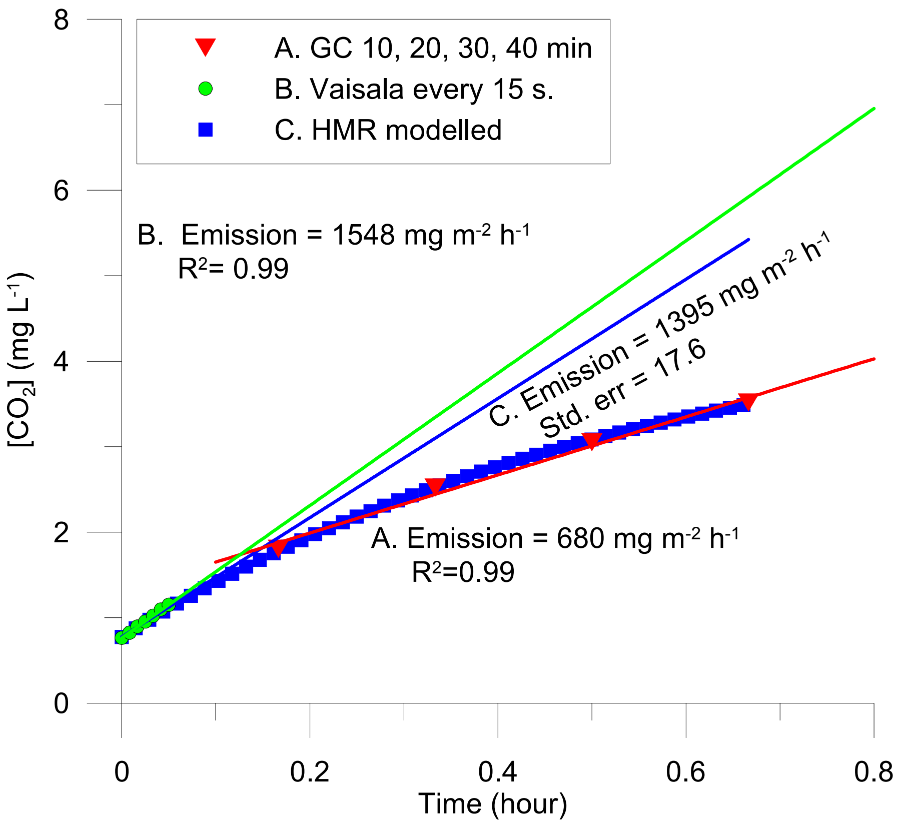


Figure 20. CO_2 emission rates calculated from the same data but with different sampling time using a linear or non-linear regression. Triangles (A) represent measurements every 10 minutes up to 40 minutes. Circles (B) are measurements every 15 seconds for 3 minutes and the squares (C) are HMR-modelled concentrations using the same data as the triangles. The regression lines represent the emission rates for the different methods.

This problem can to some extent be handled by using a non-linear model (Pedersen, 2000; Pedersen *et al.*, 2001), for example the HMR package for the software R, and calculating the emission rate at time=0 (C in *Figure 20*). The short sampling time with the Vaisala probe and linear regression gave almost the same emission rate as using the non-linear model. As long as the same method is used when comparing treatments, the choice of sampling interval is of less importance, but trying to upscale the emission rates to field or regional scale could result in large uncertainties.

Crop analysis

The cuttings taken during spring, summer and autumn were mixed in bulk samples for each lysimeter and season. The N content was measured with a LECO 2000 CNS analyser (Leco Corp, St. Joseph, Mich.), while for P analysis the soil samples were treated with HNO_3 (7 M) and analysed using inductively coupled plasma-optical emission spectroscopy (ICP, Optima 3000 DV, Perkin Elmer, Waltham, Mass.).

Statistics

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 in mean yield between sites and treatments were tested both within the same soil and between the soils with one-way ANOVA with blocks and multiway ANOVA using SAS. PROC NLIN was used for estimating the fitting parameters θs, α and n for the water retention curve constructed using the van Genuchten equation.

Modelling

Soil temperature, water content and snow depth were modelled with the Soil, Water, Atmosphere and Plant (SWAP) model, which was adapted to Nordic conditions (SWAP, 2005) and validated against measured data. SWAP simulates transport of water, solutes and heat in unsaturated/saturated soils. Long-term changes in ecosystem functions at the Örke site were modelled using the PMDSS and PMDSS redrainage models developed by Knieß (2007). The objective of the model runs was to determine the effect of future land management scenarios in combination with two different climate change scenarios.

Results and discussion

Digital soil survey

Map data quality

Digital soil data were not available for 9% of the total agricultural area (including mineral soils) and the ^{40}K radiation method was used instead. Comparisons of the accuracy of the ^{40}K method in identifying peat soil areas compared with the country-scale map (1:1,000,000) were made using Kappa analysis (Monserud & Leemans, 1992). The ^{40}K method had similar or better accuracy (overall accuracy = 81%, KHAT= 0.45) than the country-scale map (overall accuracy = 82%, KHAT=0.28) (Paper I). More accurate assessment of the spatial distribution of agricultural peat and gyttja soils will be possible when maps of the whole country have been digitised by the SGU, but the accuracy in the present study is still a major improvement compared with earlier estimates.

Area of agricultural peat and gyttja soils

According to the block database (IACS block), the total area of agricultural soils (arable and grazing land) in Sweden in 2008 was 3,525,259 ha. Of this total area, 7.6% or 267,990 ha were classified as peat and gyttja soils (Berglund *et al.*, 2009). This is less than half the corresponding percentage and acreage estimated in 1946 (20% or 705,000 ha cultivated peat soils; Hjertstedt, 1946). The assessment in 1946 was made by the engineers of the Swedish Peat Society and can be considered quite accurate, as half the area was inspected and more than 10,000 soil samples were analysed with respect to soil type and cultivation value. Large areas of cultivated organic soils have been abandoned since then, mainly due to insufficient drainage, and might constitute 35-45% of what is now classified as drained organic forestland (Von Arnold *et al.*, 2005). The percentage of peat and gyttja soils varies greatly between Swedish counties ( ), from 1.3% in Västernorrland to 12.8% in Örebro. Peat soils dominate, comprising 5.6% (198,264 ha) of the total area, while gyttja soils comprise 2.0% (69,726 ha). The proportion of gyttja soils in 2008 (26% of the total area of peat + gyttja soils) was greater than earlier estimates of 11% (Hjertstedt, 1946). This is due to gyttja soils with organic matter content lower than 20% (clay gyttja / gyttja clay) being included in our analysis, but also to subsidence uncovering the gyttja underlying the peat soil in many places. These values are now used by the Swedish Environmental Protection Agency to estimate GHG emissions from cultivated organic soils for the National Inventory Report, submitted under the UNFCCC and the Kyoto Protocol.

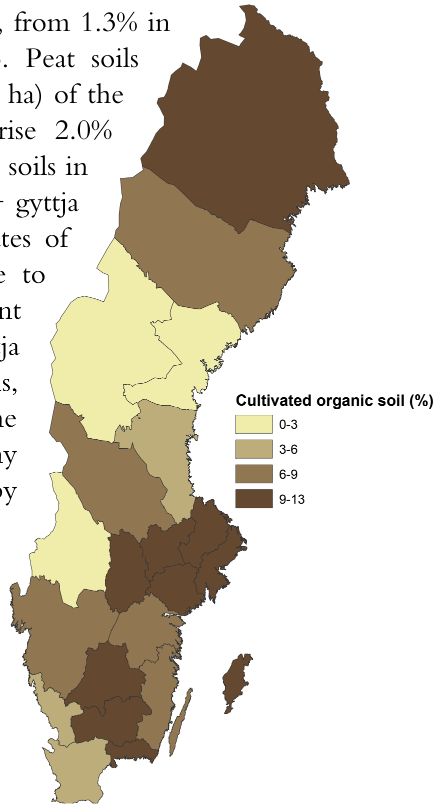


Figure 21. Distribution of cultivated organic soils (% of total agricultural area) per county in Sweden.

Cultivation intensity

The cultivation intensity is generally lower on peat soils than on mineral soils. Managed grassland and low intensity land use (such as permanent pasture and set-aside) dominate and only 23.3% of the area in 2008 was intensively cultivated with annual crops including row crops, compared with 37% of the total agricultural area (both mineral and organic soils) (SCB, 2009). The areas most intensively cultivated are in general polder areas with very fertile organic soils with the potential to regulate the water table by pumping.

Continuity analysis

To examine how the cultivation intensity and crop acreage on organic soils have changed over the past 10 years, an analysis was made of the distribution of crops grown on organic soils for the years 1999, 2005, 2006, 2007 and 2008 (Berglund *et al.*, 2009) (*Figure 22*). Much of the variation in crop area over the period 1999-2008 can be explained by the EU payment reform implemented in 2005.

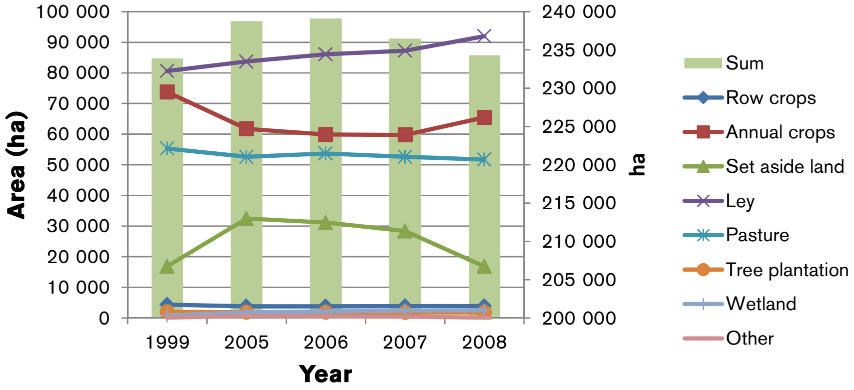


Figure 22. Area of cultivated organic soils in different crop categories and total area of cultivated organic soil, 1999-2008.

Total acreage increased until 2005 because the reported area in that year formed the basis of support rights in the new system. The total cereal area in the country, regardless of soil type, decreased sharply in the first years after introduction of the single farm payment because of low grain prices, while there was a slight increase in the area of oilseeds due to better profitability (Jordbruksverket, 2007). With rising grain prices in 2007/2008 the area of cereals increased again, as can be seen in *Figure 22*. With the payment reform grassland became more profitable, with increasing area as a result (SCB, 2009). The requirement for set-aside land (mandatory 5 or 10% of area) disappeared in 2008, after which reported fallow acreage practically halved (SCB, 2009). Our continuity analysis (Berglund & Berglund, 2008) verified that the cultivation intensity on organic soils is relatively low, with permanent grassland (ley in 10 out of 10 years) on about 16% of the area. Intensive cultivation (row crop cultivation in at least five out of 10 years) is practised on a small area, primarily in Skåne and to some extent in Blekinge.

Crop yield and nutrient content

Yields were significantly greater with the water table at 40 cm (WT@40 cm) compared with 80 cm (WT@80 cm) on both soils. For WT@40 cm the ryegrass dry matter (DM) yield in Majnegården lysimeters was signifycantly higher ($p<0.05$) than the yield in Örke lysimeters (+2232 kg ha^{-1}, LSD=2144 kg ha^{-1}). The tendency was the same for WT@80 cm, but the difference was not significant ($p=0.08$) (*Figure 23*). The N and P content were somewhat higher in the Majnegården crop than in the Örke crop, indicating that Majnegården soil was more fertile (Table *4*).

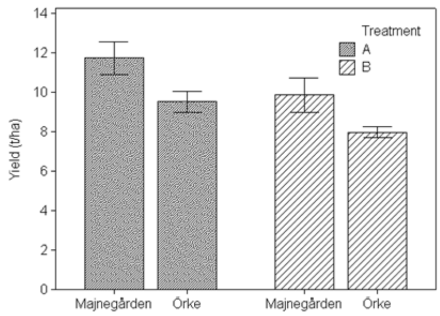


Figure 23. Ryegrass yield (ton DM ha^{-1}) at Majnegården and Örke with the water table at 40 cm (left) and 80 cm (right).

Table 4. *N and P content in ryegrass in spring, summer and autumn*

	Majnegården		Örke	
	N	P	N	P
		(%)		
Spring	4.23	0.28	3.32	0.23
Summer	3.15	0.40	2.95	0.26
Fall	3.45	0.43	3.30	0.23

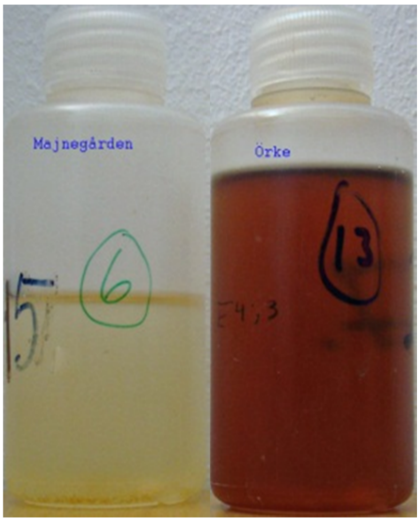


Figure 24. Soil water from the Majnegården lysimeter (left) and the Örke lysimeter (right) with the water table at 40 cm depth.

Soil water properties

Besides being lost through the GHG emissions, carbon and nitrogen are lost in drainage water, so therefore we studied the nutrient content in the soil water. Water samples were taken from 40 cm depth using a probe with a water-permeable filter (no. 6 in *Figure 14*) after the growing season in November 2004 and analysed with respect to dissolved organic carbon (DOC), dissolved organic nitrogen (DON), total phosphorus (tot-P), ammonium-N (NH_4-N), nitrate-N (NO_3-N) and phosphate-P (PO_4-P). The soil water at Örke had a much darker colour than the water from Majnegården soil (*Figure 24*) and the DOC and DON values were higher than at Majnegården (Table *5*). However, the DOC and DON values in both soils were in the range reported in other studies (Chow *et al.*, 2006).

Table 5. *Chemical properties of soil water from the Majnegården and Örke lysimeters*

	DOC	DON	NH_4-N	NO_3-N	Tot-P	PO_4-P
Site/treatment	mg L^{-1}					
Majnegården WT@40 cm	36.4	3.0	0.3	0.5	0.1	0.0
Majnegården WT@80 cm	25.7	2.2	0.4	0.3	0.1	0.0
Örke WT@40 cm	240.3	8.0	0.5	0.2	0.1	0.0
Örke WT@80 cm	163.1	6.2	0.5	0.4	0.1	0.0

CO_2 emissions

Effect of temperature

Temperature is often used to model the rate of CO_2 emission from peat soils (Moore & Dalva, 1993; Lloyd & Taylor, 1994; Fang & Moncrieff, 2001; Lafleur *et al.*, 2005; Rutledge *et al.*, 2008; Tuomi *et al.*, 2008), but its use has recently been questioned by Kuzyakov & Gavrichkova (2010), who argue that soil temperature is an indirect factor driven by solar radiation. In Paper II, to allow the results to be compared with those from other studies, data on the lysimeter soils were fitted to a semi-empirical model describing CO_2 emissions as a function of temperature (Eq. 4.) (Lloyd & Taylor, 1994):

$$R_e = R_{10}\, e^{308.56\left(\frac{1}{56.02} - \frac{1}{T_S - 227.13}\right)} \qquad \text{Eq. 4}$$

where R_e is total respiration of CO_2 (μmol m^{-2} s^{-1}), R_{10} is the sum of plant and soil respiration at 10 °C and T_s is temperature (°K). R_e and T_s are measured data and R_{10} is the result of the fitting procedure. There was a considerable amount of scatter in the emissions data. To overcome this, the CO_2 emissions data were averaged in 1 °C bins and plotted against temperature (*Figure 25*). This gave a better correlation (R^2=0.92, n=19) between air temperature and CO_2 emissions from the lysimeters, with a R_{10} value of 2.42 μmol m^{-2} s^{-1}. The equation had a better fit at high temperatures than at low temperatures. The R_{10} value is in agreement with results reported by Nieveen *et al.* (2005) for a drained rush and sedge peat in New Zealand (R_{10} = 2.44 μmol m^{-2} s^{-1}) and in the same range as reported by

Lohila *et al.* (2003) for a peat soil under pasture (R_{10} = 3.1 μmol m^{-2} s^{-1}). Conditions in the New Zealand experiments were very similar to those in the present experiment in that groundwater depth ranged between 0.2 and 0.8 m (in our experiment between 0.4 and 0.8 m) and the vegetation at their site was a mixture of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). Other studies with water-logged conditions (Nieveen *et al.*, 1998) report a lower R_{10} of 1.3 μmol m^{-2} s^{-1}, indicating anaerobic conditions.

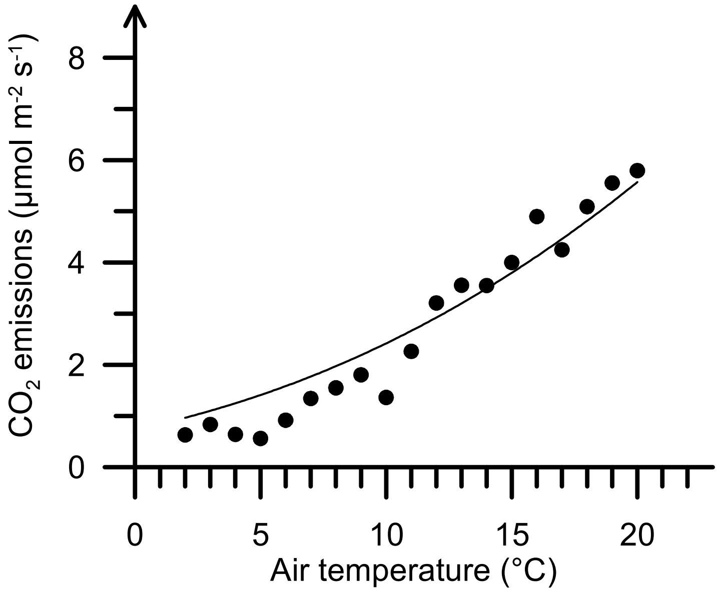


Figure 25. Results of CO_2 emissions. Pooled averaged transformed data from all lysimeters 1 April – 8 Dec 2004 and modelled effect of air temperature on emissions using an equation from Lloyd & Taylor (1994).

Effect of water table depth

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 °C, the emission rates were higher from WT@40 cm than from WT@80 cm (Table *6*). Contrary to our results, many investigations have reported increasing CO_2 emissions following lowering of the water table (Eggelsmann, 1976; Renger *et al.*, 2002; Wessolek *et al.*, 2002). Findings supporting our results, with a higher emission rate at intermediate water table depths compared with low depths (dry soil), have been reported by Davidson *et al.* (1998), Chimner & Cooper (2003), Kechavarzi *et al.* (2007) and Mäkiranta *et al.* (2009).

Table 6. *Mean daytime emissions of CO_2, N_2O and CH_4 from lysimeters with soil from Majnegården and Örke. Standard errors in brackets. Means within columns with different superscripts are significantly different ($p<0.05$)*

Site	Depth to water table (cm)	CO_2 ($mg\ m^{-2}\ h^{-1}$) Apr-Nov	CO_2 ($mg\ m^{-2}\ h^{-1}$) Dec-Apr	N_2O ($\mu g\ m^{-2}\ h^{-1}$) Apr-Apr	CH_4 ($\mu g\ m^{-2}\ h^{-1}$) Apr-Apr
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]

Nieveen *et al.* (2005) found that the distance to the water table did not influence emissions of CO_2, while Aerts & Ludwig (1997) and Maljanen *et al.* (2001) reported similar results. Laiho (2006) described the complexity of peatland behaviour following persistent lowering of the water table, with multiple interactions between many factors such as time scale and soil type. The results from the incubation experiment (*Figure 26*) were in agreement with emissions results from the lysimeter experiments.

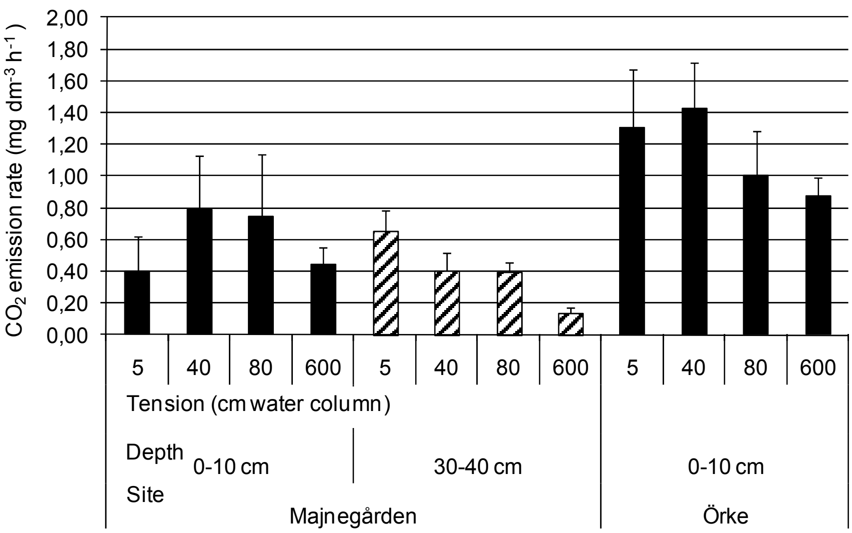


Figure 26. Incubation experiment with undisturbed soil samples from two different depths at Majnegården (0-10 cm and 30-40 cm; left) and from the topsoil at Örke (0-10 cm; right). CO_2 emission rate with increasing tension (from 5 to 600 cm water column) applied to soil cores. Error bars show standard deviation.

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

The topsoil from Majnegården is very compact and only a limited amount of air can enter the soil matrix at low tensions (*Figure 8*). The Örke profile allows air to enter the upper layers at normal drainage (*Figure 9*) (McAfee, 1989). The incubation results indicate that in these soils a very small proportion of air-filled pores is sufficient to stimulate soil respiration at a high rate and that drier conditions (lower water table) hamper soil respiration even at shallow drainage depths.

The findings in this investigation are similar to those reported by Lafleur *et al.* (2005), and the explanation can be that the air-filled porosity in the upper part of the soil profile, where most CO_2 is produced by respiration, was sufficient for oxygen diffusion and that water was not rate-limiting at 40 cm drainage depth. At 80 cm drainage depth the topsoil was too dry and the CO_2 production from the lower parts of the peat profile was low due to low substrate quality, and did not contribute to the emissions, despite an adequate oxygen supply.

The decreased plant growth in the lysimeter experiment when the water table was lowered from 40 cm to 80 cm (*Figure 23*) (Berglund, 1996) could also have affected the CO_2 emission rate. Even though the grass was cut prior to gas measurements, plant respiration contributed to some extent to the measured gas flux, producing a higher flux than soil respiration alone. Root respiration has been reported to contribute 27-63% of the emissions produced (Laiho, 2006; Paper III), which might explain some of the differences in emission rates observed between the two water table depths investigated.

When climate conditions were the same, differences in emission rates between the sites were related to soil type and C availability to microorganisms, since CO_2 emissions mainly reflect the abundance of easily available carbon. Emission rates were approximately eight times higher during the growing season compared with the winter period (*Figure 27*), due to the low temperature and the absence of plants in winter. CO_2 emission rates were significantly greater for WT@40 cm than for 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 for WT@80 cm (754 mg CO_2 m^{-2} h^{-1}). Outside the growing season, there was no difference between the treatments. 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). Outside the growing season, there was no difference between the treatments but the average CO_2 emission rate during winter was significantly higher from the Örke soil than from the Majnegården soil.

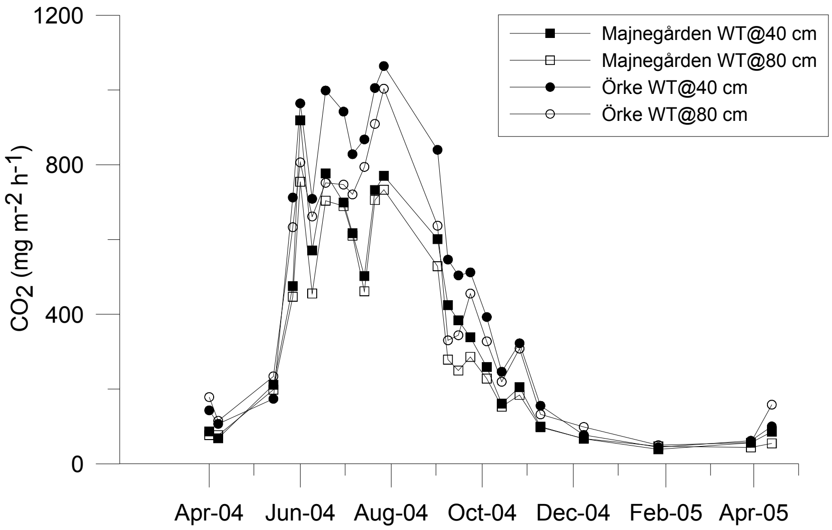


Figure 27. Carbon dioxide emissions from lysimeters with Majnegården and Örke soil with the water table at 40 cm depth (WT@40 cm) or 80 cm depth (WT@80 cm) during the period April 2004 - April 2005.

These findings were expected, but are often overlooked by policymakers, who in attempting to reduce GHG emissions tend to promote abandonment of cultivated organic soils or their conversion into bird habitats with a fluctuating water table. However, these measures might create even greater problems, namely equal or higher GHG emissions but diminished photosynthesis and mitigation of CO_2 and lower or no economic return from the areas, reducing the incentive to deal with the continuing emissions.

Origin of soil respiration

The CO_2 flux from cultivated soils is commonly measured as total flux including both soil organic matter (SOM)-derived CO_2 and plant-derived CO_2. With regard to the CO_2-driven greenhouse effect, there is a need to distinguish between heterotrophic soil respiration and autotrophic, plant-derived respiration (net CO_2 emissions). The plant input of atmospheric C to the soil is of minor or no importance regarding the greenhouse effect, since this carbon just circulates between the systems and the residence time in the soil is very short compared with the age of the peat. This is very well illustrated by Kuzyakov (2006), who divided the total CO_2 efflux from the soil into five sources (marked 1-5 in *Figure 28*) and also indicated the residence time of carbon in the soil for the different sources.

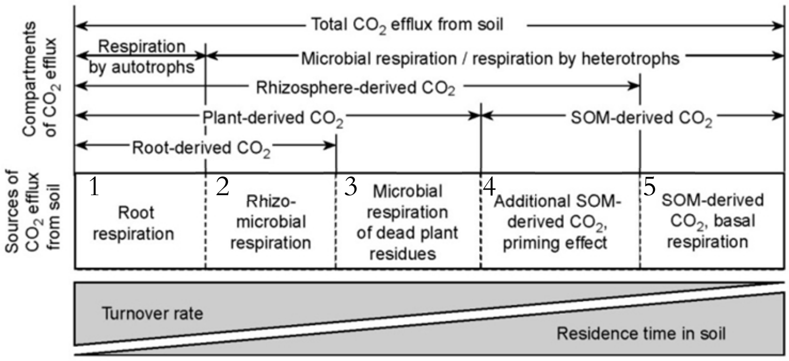


Figure 28. Five main sources of biogenic CO_2 efflux from soil, arranged according to turnover rate and mean residence time of C in soil. Figure 1 in Kuzyakov (2006).

Sources 1-3 in *Figure 28* are plant-derived and sources 4 and 5 contribute to the greenhouse effect. With the root exclusion method (comparing gas emissions from vegetated soil and bare soil), it is possible to distinguish between source 5 (basal respiration) and sources 1-3 (plant-derived) (Kuzyakov, 2006). This rough method can be used to estimate the net CO_2 emissions if the priming effect (4) is small. In Paper III, CO_2 emissions from vegetated and bare soil lysimeters were compared to estimate plant-derived CO_2 emissions as a fraction of total CO_2 emissions. The results showed that great variations in plant contribution occurred during the growing season, with plant-derived emissions being low in the beginning of the growing season and high at the end (*Table 7*). The contribution also differed between soil types. When estimating net emissions to the atmosphere it is

Table 7. Plant contribution to total soil CO_2 efflux estimated from measured data during the whole season (5 May – 11 Nov) and also divided into seasonal emissions

	Plant contribution (% of total emission)	
	Majnegården	Örke
Whole season	47	57
Spring (18/5 - 22/6)	27	49
Summer (5/7 - 2/8)	42	54
Autumn (15/8 - 1/11)	57	63

important to know the plant-derived CO_2 flux, otherwise soil CO_2 emissions can be considerably overestimated.

The uptake of substrate (low molecular weight carbon) by soil microorganisms occurs primarily through the soluble phase (Marschner & Kalbitz, 2003) and the degradation of the more resistant fractions, the peat itself, is dependent upon the action of extracellular enzymes. There are several ways to inhibit these enzymes and thus minimise the subsidence, and hence the net contribution of GHG. A high water table and anoxic conditions have been shown to inhibit phenol oxidase from eliminating phenolic compounds that inhibit the degradation of organic material (Freeman *et al.*, 2001). The treatment with WT@40 cm did not create sufficiently severe anoxia to limit peat degradation, but the dry conditions with WT@80 cm might have decreased the diffusive transport of substrate towards the remaining moist sites of activity (Marschner & Kalbitz, 2003). Another way to inhibit enzyme activity is to treat the soil with high levels of copper sulphate (Mathur & Sanderson, 1978; Mathur *et al.*, 1979; Mathur & Sanderson, 1980; Mathur, 1981; Levesque & Mathur, 1983). When this was tested in the lysimeter experiment, CO_2 emissions were found to decrease at a copper fertilisation level of 170 kg ha^{-1} (Berglund *et al.*, unpublished data).

N_2O and CH_4 emissions

N_2O is produced in soil by nitrification or denitrification depending on the aeration status and the availability of ammonium and nitrate, as often illustrated by the hole-in-the-pipe model (Davidson *et al.*, 2000) (*Figure 29*). This links NO and N_2O production and takes into account the total nitrogen in the system (the amount flowing through the pipes) and the ratio between NO and N_2O (symbolised by the size of the holes in the pipes).

Nitrification is an aerobic microbial process performed by *Nitrosomonas*, *Nitrobacter* and sometimes *Nitrosospira* when there is ammonium present, and is favoured by intermediate moisture content. Denitrification is an anaerobic process occurring when nitrate is available (Focht & Verstraete, 1977) and the soil air contains less than 10% oxygen (Hochstein *et al.*, 1984; Wrage *et al.*, 2001). Depending on soil water content, N_2O and NO will 'leak out' during both nitrification and denitrification.

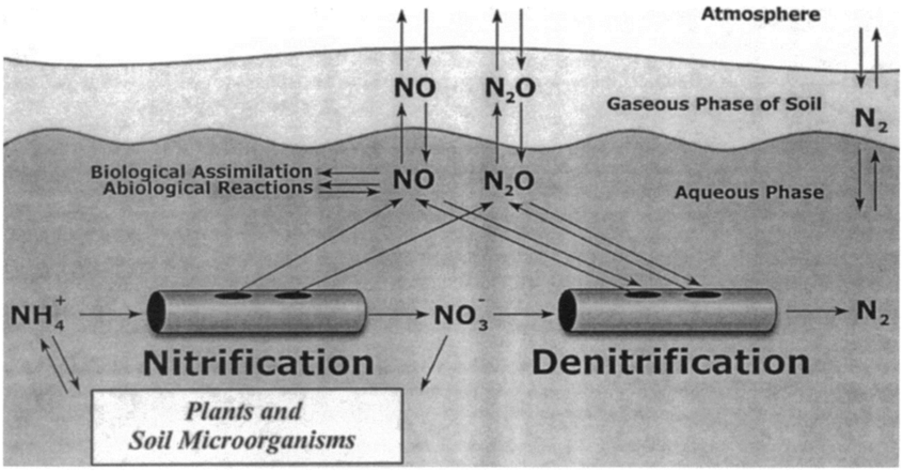


Figure 29. Hole-in-the-pipe model often used to explain the factors determining the regulation of N_2O and NO flux. From: Eric A. Davidson, Michael Keller, Heather E. Erickson, Louis V. Verchot, and Edzo Veldkamp, "Testing a Conceptual Model of Soil Emissions of Nitrous and Nitric Oxides," in BioScience vol. 50, no. 8 (August 2000), pp. 667-680. (c) 2000 by the American Institute of Biological Sciences. Published by the University of California Press.

N_2O emissions were greater ($p=0.01$) from WT@40 cm (177.7 µg N_2O m^{-2} h^{-1}, s.d. 26.2) than from WT@80 cm (77.1 µg N_2O m^{-2} h^{-1}; s.d. 34.6) and peaked during spring (*Figure 30*). This could be due to the production of readily available nitrogen for microorganisms by freeze-thaw cycles in winter (Regina *et al.*, 2004), combined with the absence of plants competing for nitrogen (Paper IV). This is shown in *Figure 31* in terms of N_2O emissions from vegetated and bare soil lysimeters.

N_2O emissions were higher from the bare soil lysimeters during summer and especially during thawing in springtime. It is often reported that N_2O emissions can be very erratic, characterised 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).

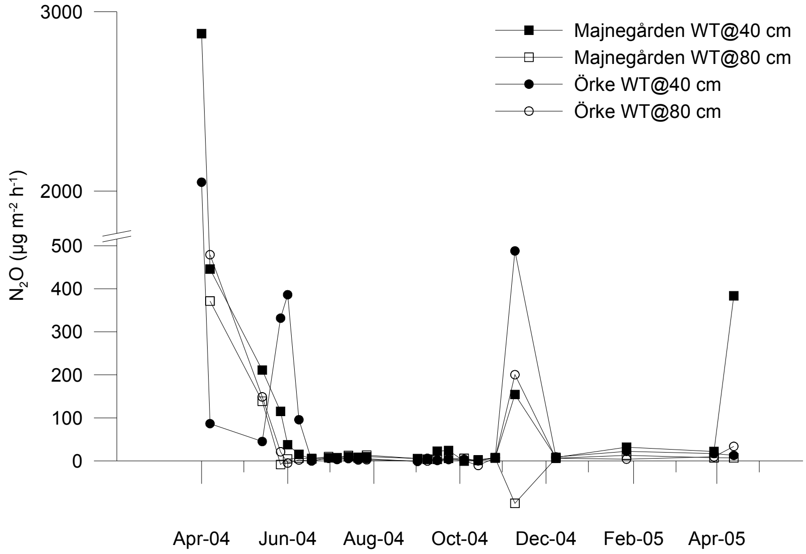


Figure 30. Nitrous oxide emissions from lysimeters with Majnegården and Örke soil with the water table at 40 cm (WT@40) or at 80 cm (WT@80) during the period April 2004 - April 2005.

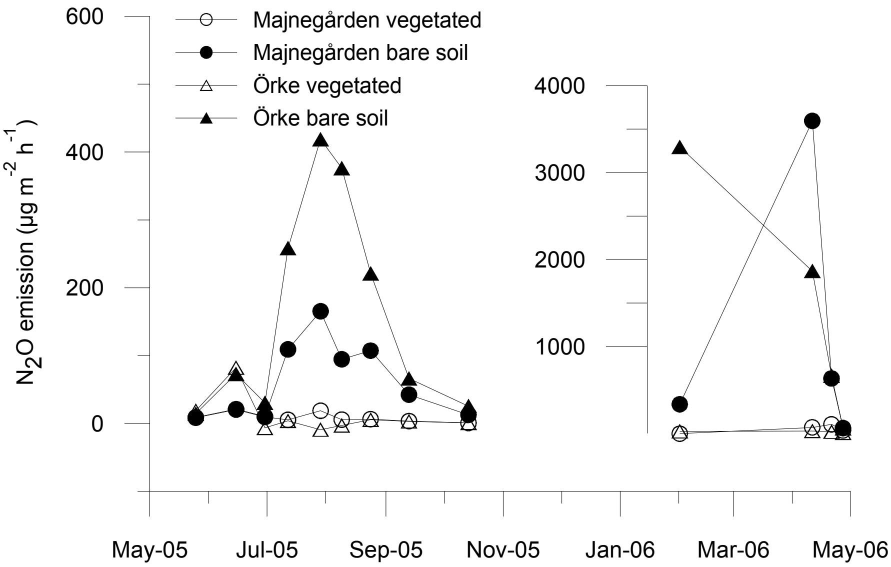


Figure 31. N_2O emissions from Majnegården and Örke soil, vegetated and with bare soil, during the period May 2005 - May 2006. N_2O emissions were higher from the lysimeters without a crop competing for nitrogen during summer and during spring thaw.

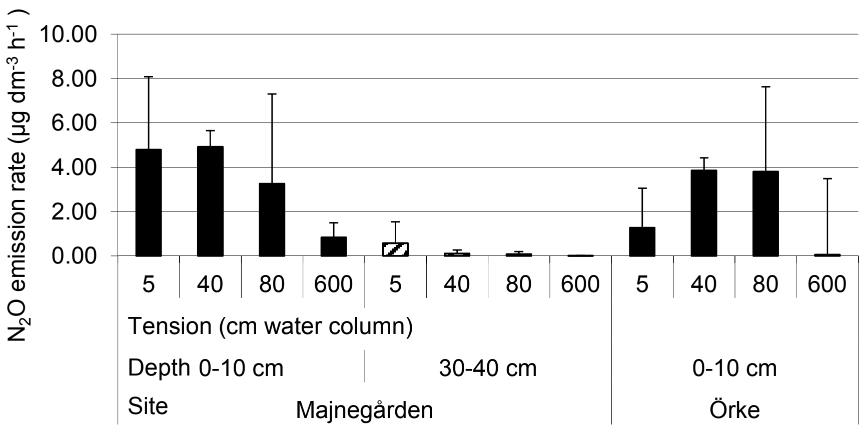


Figure 32. Incubation experiment with undisturbed soil samples from two different depths at Majnegården (0-10 cm and 30-40 cm; left) and from the topsoil at Örke (0-10 cm; right). N_2O emission rate with increasing tension (from 5 to 600 cm water column) applied to soil cores.

According to Klemedtsson *et al.* (2005), soil C/N ratio is a good predictor of annual N_2O emissions. The results from our incubation experiment (*Figure 32*) support 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 at Majnegården and Örke was 12 and 14, respectively, while it was 21 in the subsoil (30-40 cm) at Majnegården. Accordingly, N_2O emissions were 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 higher pH, lower air-filled porosity and better nutritional status (Yamulki *et al.*, 1997).

Methane (CH_4) is produced in anaerobic conditions by methanogenic bacteria and oxidised to CO_2 in the aerobic zone by methanotrophs (Le Mer & Roger, 2001). In this investigation CH_4 fluxes were very small or negative (consumption), which is often the case with drained peat soils (Glenn *et al.*, 1993; Nykänen *et al.*, 1995; van den Pol-van Dasselaar *et al.*, 1998; Blodau & Moore, 2003; Maljanen *et al.*, 2003b; Kasimir-Klemedtsson *et al.*, 2009). The average consumption of CH_4 was higher ($p<0.001$) for all Majnegården soil samples (20.08 µg CH_4 m^{-2} h^{-1}, s.d. 1.17) than for all Örke soil samples (9.7 µg CH_4 m^{-2} h^{-1}, s.d. 1.17) and higher ($p<0.05$) with WT@80 cm (16.4 µg CH_4 m^{-2} h^{-1} , s.d. 1.29) than with WT@40 cm (13.4 µg CH_4 m^{-2} h^{-1} , s.d. 1.29), irrespective of soil.

Cumulative GHG emissions

The GHG emissions from cultivated organic soils can be very high and in Sweden are reported to contribute about 6-8% of total national emissions (SNIR, 2010; Paper I). The cumulative gas emissions from the peat soil in the lysimeter experiment were converted into CO_2 equivalents for comparison (Paper IV). The average cumulative CO_2 emissions originating from the organic matter were 1.315 kg CO_2 eq. m^{-2}. The corresponding values for N_2O and CH_4 were 0.195 kg CO_2 eq. m^{-2} and -0.002 kg CO_2 eq. m^{-2}, respectively, amounting to a total of 1.5 kg CO_2 eq. m^{-2}. That would give a GHG contribution of 4 M ton CO_2 eq. from the whole area of cultivated organic soils in Sweden. This value lies between the two values of 3.1 and 4.6 M ton CO_2 eq. estimated in Paper I using an indirect method to calculate GHG emissions (different subsidence rates depending on cultivation intensity and two bulk densities, 0.2 and 0.3 g cm^{-3}). However, it must be borne in mind that it is very difficult to scale GHG emissions up from lysimeter studies to national estimates and also to handle the uncertainties regarding how to distinguish between plant respiration and soil respiration.

When plant respiration from the lysimeters, 47% and 57% for Majnegården and Örke, respectively (Paper III), was subtracted from the total CO_2 emissions, the CO_2 emissions still dominated and CH_4 emissions were negligible. 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 emissions 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. The effects of crop type and cultivation intensity on GHG emissions are under debate both in the scientific community and within the Swedish Board of Agriculture. Preliminary results from ongoing field experiments where GHG emissions are being measured from the same soil, but with different crops, have revealed no statistical differences between crops so far (Berglund *et al.*, unpublished data). Comparisons of lysimeter CO_2 emission rates with field measurements at long-term field experiment sites (Kerstin Berglund, unpublished data) showed that the emissions were within the same range (*Figure 33*).

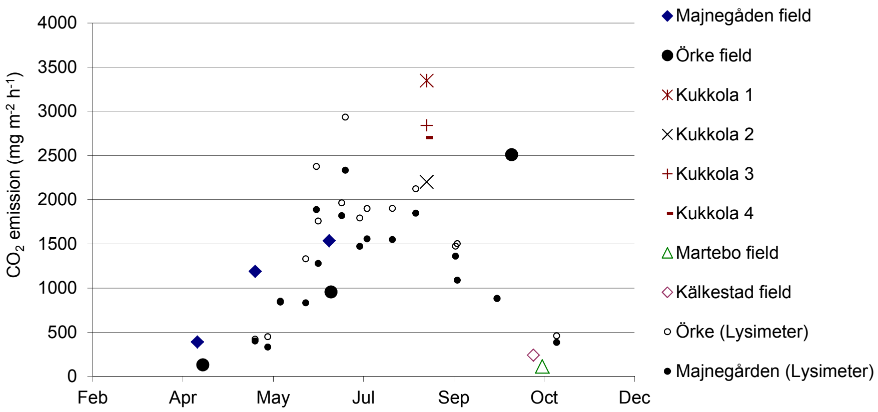


Figure 33. Lysimeter CO_2 emissions and field CO_2 emissions. The lysimeter emissions (small circles) are in the same range as CO_2 emissions measured in the field during 2005.

Modelling

The Nordic SWAP model was developed in the EU project EUROPEAT (van den Akker, 2010) to obtain a better fit to the Nordic conditions of snow and soil freezing. The original model had problems with simulating winter conditions, *i.e.* the effect of snow on reduced heat transport, water-holding capacity of the snow, hydraulic conductivity, heat transport below 0 °C and snow melt. The result of a simulation of soil temperature and snow depth at Majnegården is shown in *Figure 34*. The original SWAP model could not handle soil temperatures once snowing had started (unbroken lines), as the insulating effect of snow was not included in the model. The simulation of soil temperature in the improved Nordic SWAP (dotted line) is much better and the simulated snow depth is also in reasonable agreement with measured data. The soil hydrology output from the SWAP model was used in the present study as input to the ANIMO model (Renaud *et al.*, 2005) in order to model GHG emissions from cultivated peat sites. Even though the Nordic SWAP was an improvement, water balance and water content simulations were not sufficiently accurate for GHG emissions simulations with the ANIMO model. Much less complex models such as the ICBM (Andrén & Kätterer, 1997) might be sufficient for estimating the carbon emissions from cultivated soils over larger areas, as done by Andrén *et al.* (2008). Furthermore, the ICBM model is probably much easier to calibrate for different types of organic soils than process-orientated models such as ANIMO and COUP, with their almost infinite numbers of parameters (Jansson & Moon, 2001).

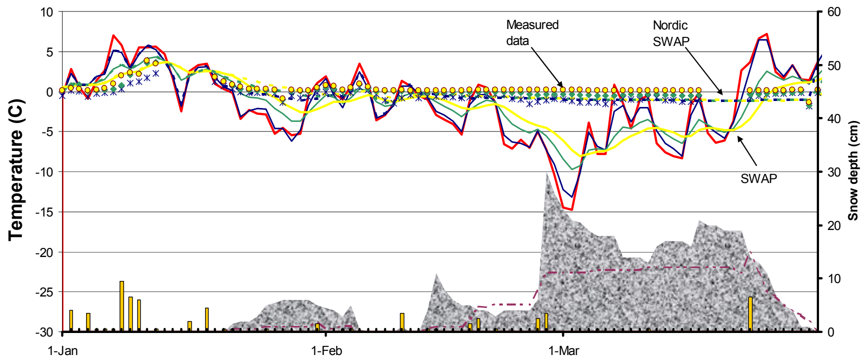


Figure 34. Measured and modelled soil temperature and snow depth in the Majnegården lysimeter with WT@40 cm.

When the PMDSS and PMDSS redrainage model was used on Örke, the model predicted that the subsidence would be more than twice as great if the area were to be re-drained compared with the status quo (Knieß, 2007).

Conclusions and recommendations

Area of cultivated organic soils

The current area of agricultural peat and gyttja soils in Sweden is estimated to be 267,990 ha, which is 7.6% of the total area (3,525,259 ha) of agricultural soils. Peat soils dominate, with 5.6% of the total area, while gyttja soils occupy 2.0%. The GIS analysis of cultivation intensity revealed that gyttja soils are often more intensively cultivated than mineral soils, while peat soils are less intensively cultivated.

Future improvements: When a larger area of Sweden is digitised with regard to soil type, more accurate estimates can be made. With the use of satellite imagery and old maps, it might be possible to identify abandoned, formerly drained peat soils.

Methods

The lysimeter method worked very well for the emission studies. CO_2 emissions measured in the lysimeter experiment were similar to those measured in field trials and were within the range reported in the literature. The lysimeter method accurately mimics natural conditions and makes it possible to work with different soil types and treatments in undisturbed soil cores but under the same climate conditions. Climate conditions are easy to monitor and the experimental set-up is flexible.

Future improvements: In this study there were very few drainage events, but the ability to measure carbon and nutrient losses through drainage water would be very useful. In order to use a non-linear approach for N_2O and CH_4 studies, samples must also be taken immediately after chamber closure. Since a large proportion of N_2O emissions may arise during winter, methods for wintertime measurements should be developed. It is important to choose the right quality of rubber for the inner sheet in the lysimeters in order to prolong the lifespan of the lysimeter. To improve our understanding of the fate of carbon, the measurements should be complemented with photosynthetically active radiation (PAR) readings and CO_2 measurements with clear chambers.

Plant-induced CO_2 emissions

The contribution of plant-induced CO_2 emissions to total soil CO_2 emissions showed great variation during the growing season, being low in the beginning of the growing season and high at the end. The contribution also differed between soil types. When estimating net emissions to the atmosphere, it is important to know the plant-derived CO_2 flux, since otherwise soil CO_2 emissions can be considerably overestimated. In the present study the plant contribution to CO_2 emissions was on average 47% for Majnegården and 57% for Örke.

Future improvements: To improve the estimation of plant contribution to total CO_2 emissions, high-resolution measurements of CO_2 efflux and PAR combined with pulse labelling of plants with *e.g.* $^{14}CO_2$ could be used (Kuzyakov & Gavrichkova, 2010).

Effect of water table depth on GHG emissions

Soil organic matter quality, temperature and water retention properties are very important factors determining the emission rate of GHG from cultivated peat soils. Plant growth and root respiration accentuate the effects of soil aeration status. In extreme moisture conditions (desiccation or waterlogging), soil moisture is rate-limiting. The layer sequence and the soil properties of the different layers determine the effect of water table regulation. In this study, lowering the water table from 40 cm to 80 cm depth decreased GHG emissions from two peat soils with contrasting soil properties.

Future improvements: Detailed studies of water table regulation using a wider range of drainage levels, together with determination of enzyme activity and identification and quantification of microorganisms, could enhance our understanding of peat decomposition and provide an insight into the drainage intensity farmers should use to decrease subsidence and GHG emissions. Future research should also look into the effect of different crops, peatland abandonment and cultivation intensity on GHG emissions.

Modelling

The SWAP model was difficult to calibrate, but it should be possible to use the Nordic version of the SWAP model in future research on peat soils in areas with winter conditions. However, peat soils are difficult to model since the peat material changes over time and the massive amount of input data required to describe the soil makes the process expensive. It would be interesting to simulate subsidence and GHG emissions when SWAP output is sufficiently accurate to be used together with the ANIMO model.

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