

Impact of drainage and soil properties on carbon dioxide emissions from intact cores of cultivated peat soils

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SUMMARY

Drained peatlands contribute to anthropic emissions of carbon dioxide (CO₂), so a better understanding of the underlying processes and identification of mitigation options for agricultural peatlands are urgently required. Peatland soil properties vary greatly and, in combination with drainage, can affect emissions of CO₂ both directly and indirectly. Drainage reduces soil water content but increases CO₂ production, so it is important to find the optimum drainage level that minimises CO₂ emissions without affecting agricultural use. Intact soil cores from nine different sites (topsoil, plus subsoil at four sites) were collected and brought into a controlled laboratory environment. Repeated measurements of CO₂ fluxes were performed at increasing soil water suctions corresponding to different drainage levels. Physical and chemical properties of the soils were determined and compared with the CO₂ emissions. The soil cores displayed different CO₂ emission patterns with increasing soil water suction head. In some cores, emissions increased rapidly to a high level, while in others they remained at lower levels. At a soil water suction head of only 0.5 m of water, the average soil CO₂ emissions had already reached a maximum. The soil cores represented peat soils with a wide range of soil properties, e.g. bulk density from 0.17 to 0.47 g cm⁻³ and total carbon from 26.3 to 43.5 %, but none of the properties measured was clearly correlated with CO₂ emissions.

KEY WORDS: CO₂, laboratory suction apparatus, peaty marl, subsoil, suction head, topsoil

INTRODUCTION

Global carbon dioxide (CO₂) emissions from drained peatlands increased by about 20 % between 1990 and 2008. After Indonesia, the European Union (EU) is the world's second largest emitter of CO₂ from drained peatlands (Joosten 2009). In Sweden, drained peatlands used for agriculture represent 7 % of all agricultural land and contribute 6–8 % of the country's total anthropic emissions of CO₂ and nitrous oxide (N₂O) (Berglund & Berglund 2010, Pahkakangas *et al.* 2016). Drained agricultural peatlands can subside at rates of 0.5–2.5 cm *per year*, depending on soil type, reflecting a loss of agricultural soil (Berglund 1989). Thus, there is a need to reduce both CO₂ emissions and peat subsidence rates, for climate and farm economic reasons, respectively (Kløve *et al.* 2017). Knowledge of the processes that lead to CO₂ production in peat and how they differ between peat soil types is essential to the search for options to reduce CO₂ emissions.

Temperature and water content (air-filled pore space) are the most important factors controlling CO₂ production in agricultural soil (Mäkiranta *et al.* 2009, Berglund & Berglund 2011, Renou-Wilson *et al.* 2014). Factors such as substrate availability (Carrera

et al. 2015), amendments (e.g. lime) (Susilawati *et al.* 2016) and land management (Haddaway *et al.* 2014) can also influence CO₂ emissions from drained agricultural peat soils, with drainage intensity reported to be the most important factor connected to management (Beyer *et al.* 2015). However, the question of an optimal drainage depth to reduce greenhouse gas emissions without affecting agricultural production is now being intensively discussed and it has been suggested that a drainage depth of 30 cm is optimal in this regard (Renger *et al.* 2002, Regina *et al.* 2015). It has also been reported that CO₂ emissions are doubled by lowering the groundwater level from 30 to 80 cm below the ground surface (Renger *et al.* 2002). However, in a study by Berglund & Berglund (2011) comparing water table depths of 40 and 80 cm, the opposite effect was found. Rewetting of agricultural peatlands is being discussed as a means of reducing emissions (e.g. Hjerpe *et al.* 2014, Schrier-Uijl *et al.* 2014, Knox *et al.* 2015) but this can lead to other problems such as nutrient leaching (Harpenslager *et al.* 2015) and may not be a viable option in all cases.

Studies by Norberg *et al.* (2016a, 2016b) found that greenhouse gas emissions varied between sites (*i.e.* soils), which indicates that soil properties are a regulating factor. Histosols (peat soils) have at least

12–18 % organic carbon by weight, but usually much more (Soil Survey Staff 2014). This means that peat soils can be very diverse in their organic matter content, and contradictory responses of CO₂ emissions to drainage of different peat types have been reported in the literature (Renger *et al.* 2002, Regina *et al.* 2015). Dissolved organic carbon (DOC) is closely linked to microbial activity and C mineralisation in soil (Chow *et al.* 2006, Bowen *et al.* 2009) and could, therefore, be a good indicator of CO₂ emissions. In addition, pH, nitrate (NO₃) content and peat decomposition have been shown to affect soil respiration (Scanlon & Moore 2000, Szafranek-Nakonieczna & Stepniewska 2014). However, in a study of arctic tundra peat soils of varying quality and carbon content, Biasi *et al.* (2014) found soil respiration to be similar at all sites and none of the soil factors tested was correlated with CO₂ production. Eickenscheidt *et al.* (2015) found that the type of agricultural land use was more important than soil organic carbon content for CO₂ emissions from peat soils. On the other hand, Danevčič *et al.* (2010) identified groundwater level as more important than soil organic carbon content and surface cover in controlling CO₂ emissions from a drained fen.

The aim of the present study was to determine whether any particular soil property influences the CO₂ emissions in agricultural peat soils and how drainage (aeration) influences CO₂ emissions from different peat soils. This was done by measuring, in a controlled laboratory environment, the rate of CO₂ emissions from intact soil cores (13 different soils) subjected to different soil water suction heads from 0.05 m (near water-saturated) to 1.0 m water column. Increased suction head leads to decreased soil water content and increased air-filled pore space (Berglund & Berglund 2011). The different soil water suction heads correspond to groundwater depths in field conditions down to 1 m below the soil surface. Soil physical and chemical analyses were carried out on the same soil cores. Since the work was performed in controlled conditions on intact soil cores, it was possible to evaluate the impact of increasing suction head and of soil properties without the disturbing factors, such as weather and vegetation, that complicate field studies. The drainage equilibrium established in the laboratory is seldom found in the field, where topsoil water content normally varies despite a stable groundwater level. The hypotheses tested were that: i) peat soils respond differently in terms of CO₂ emissions to increasing soil water suction, due to differences in soil properties; and ii) one or several soil properties can explain the CO₂ emissions in peat soils.

METHODS

Topsoil samples were collected in autumn 2011 at nine different agricultural sites located in southern Sweden (Table 1). At four of the sites (Sites 6–9), subsoil samples were also collected from the same locations, giving a total of 13 different soils. All the sites had peat soils with the exception of Site 4, where the soil type was peaty marl. All were active farms with the exception of Site 9, which was once a dairy farm but had been abandoned for several years. Site and soil descriptions are provided in Table 1 and some soil properties are presented in Table 2.

Soil sampling

Prior to soil sampling, the surface vegetation was removed. Intact soil cores were sampled in steel cylinders (7.2 cm diameter, 10 cm high) at approximately 5–15 cm depth for topsoil samples and 20–50 cm depth for subsoil samples. Ten replicates, plus a few extra for precaution, were taken within a small area (< 1 m²) from each soil. Upon extraction, the cylinders were sealed at both ends with plastic lids and stored in wooden boxes. The boxes were transported directly from the field to a cold store (5 °C) where they were kept until the experiment started.

Drainage and CO₂ emissions experiment

At the start of the experiment, the soil samples were distributed into seven separate boxes. Each box contained one sample of each of the 13 soils; with a total of 91 samples distributed between the seven boxes. All boxes were treated similarly and were assumed to be independent in the statistical analysis. The boxes were brought from the cold store into the experiment one at a time. Before the start of measurements, the relevant box was kept at laboratory temperature (maintained at 20 °C) for two days and then the 13 soil cylinders were soaked in tap water for three days until saturated. During these initial days, the samples were carefully observed and replaced if necessary, *e.g.* if they were disturbed by any earthworms in the soil. The 13 samples were then placed on a suction sand bed (Romano *et al.* 2002) for successive adjustment to soil water suction heads of 0.5 m and 1.0 m water column (approximately 5 and 10 kPa) (Figure 1). In addition, three of the soil sample boxes were adjusted to a suction head of 0.75 m water column, and one of these boxes was subjected to an additional suction step of 0.25 m water column (Table 3). At each suction step, it took about seven days to reach equilibrium (when drainage of water was observed to have ceased).

Table 1. Descriptions of the soils and farm types at the sampling sites in Sweden. Topsoil samples only were taken at five sites (Soils 1–5), and topsoil plus subsoil samples were taken at four sites (Soils 6–9). Subsoil samples are marked “sub”.

Soil no.	Sample depth	Soil description	Type of farm	Coordinates
1	5–15 cm	Fen peat	Dairy farm growing grass and cereals for feed	59° 18' N 16° 32' E
2	5–15 cm	Fen peat	Farm growing cereals and vegetables (carrot, potato)	59° 11' N 15° 35' E
3	5–15 cm	Fen peat with lime	Dairy farm growing grass and cereals for feed, plus vegetables	57° 34' N 18° 38' E
4	5–15 cm	Peaty marl	Farm growing cereals and vegetables (carrot, potato)	57° 44' N 18° 27' E
5	5–15 cm	Fen peat with lime gyttja subsoil	Farm growing cereals and vegetables (carrot, potato)	57° 42' N 18° 29' E
6 6 _{sub}	5–15 cm 40–50 cm	Fen peat with stones Fen peat (<i>Phragmites</i>) with gyttja intrusion	Dairy farm growing grass and cereals for feed	58° 07' N 13° 32' E
7 7 _{sub}	5–15 cm 20–30 cm	Fen peat with clay intrusion Fen peat (<i>Phragmites</i>)	Dairy farm growing grass and cereals for feed	58° 07' N 13° 32' E
8 8 _{sub}	5–15 cm 20–30 cm	Fen peat Fen peat (<i>Phragmites</i>)	Dairy farm growing grass and cereals for feed	58° 07' N 13° 32' E
9 9 _{sub}	5–15 cm 30–40 cm	Fen peat Fen peat	Old dairy farm, now an abandoned field	60° 01' N 17° 26' E

Table 2. Humification degree, pH, total carbon content (Tot-C) and carbon/nitrogen quotient (C/N) of the 13 topsoil and subsoil samples taken at nine sampling sites in Sweden.

Soil no.	Humification degree (von Post)	pH (H ₂ O)	Tot-C (%)	C/N
1	H9–10	5.2	26.7	16
2	H9–10	5.2	42.7	21
3	H9–10	7.6	31.6	14
4	(peaty marl)	8.0	9.7	11
5	H10	7.5	35.8	14
6	H10	6.1	37.1	11
6 _{sub}	H5–6	6.1	43.5	15
7	H9–10	7.5	26.3	11
7 _{sub}	H3–4	7.6	27.4	16
8	H9–10	5.0	37.3	12
8 _{sub}	H3–4	5.2	42.2	16
9	H9–10	5.4	39.0	14
9 _{sub}	H8–9	5.4	39.2	16

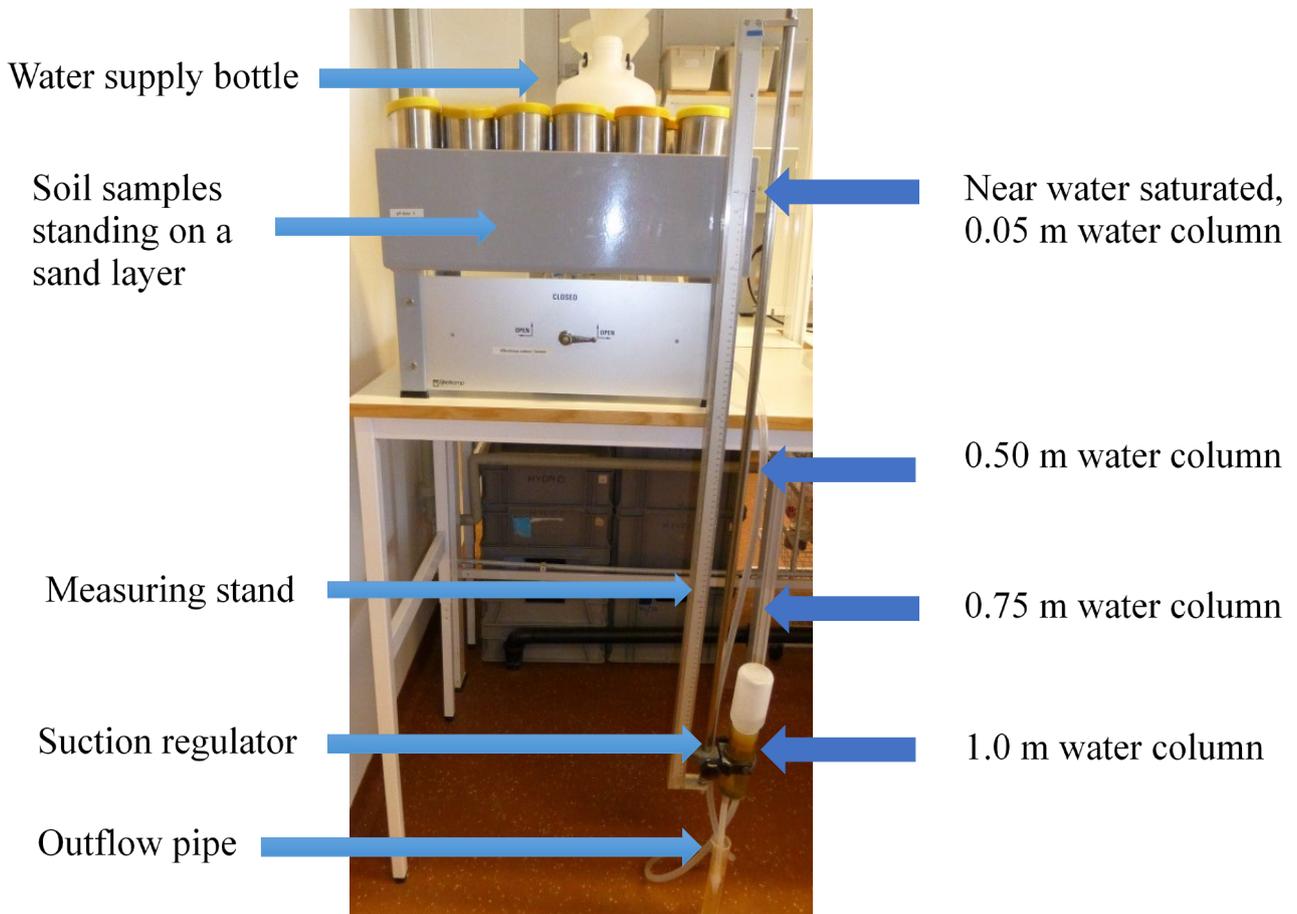


Figure 1. The sand bed that was used to apply suction to the soil samples. The difference in height between the suction regulator and mid-depth in the soil samples determines the amount of suction. Suction heads between 0 m and 1.0 m can be applied. Examples of suction heads used in this study are shown on the right-hand side of the picture.

Table 3. Schematic description of the experimental design with six different soil water suction heads, seven boxes and two after-uses of the samples. The boxes that were subjected to CO₂ measurements at each soil water suction head are marked 'x'. Each box contained one sample from each of the 13 soils. The after-use of the samples in each box was for either soil analyses (sa) or dry weight (dw) calculations.

	soil water suction head (m water column)					after-use
	0.05	0.25	0.5	0.75	1.0	
Box 1	x		x		x	sa
Box 2	x		x		x	sa
Box 3	x		x		x	sa
Box 4	x		x		x	dw
Box 5	x		x	x	x	dw
Box 6	x		x	x	x	dw
Box 7	x	x	x	x	x	dw

Prior to CO₂ emission measurements, the soil samples were weighed for water content. When all of the CO₂ emission measurements were complete, each of the soil cores in three of the boxes was divided into two sub-samples; one for the freezer (-18 °C) and one for the refrigerator (5 °C). These samples were then used for different soil analyses. The soil cores from the four remaining boxes were dried for 72 h at 105 °C and weighed for dry-weight-based emissions calculations. The mean dry weight of the four replicate soil samples in the second set of boxes was taken as the dry weight of each of the three corresponding soil samples in the first set of boxes.

CO₂ emission measurements

For the CO₂ emissions measurements, we used polypropylene jars of suitable size for a soil sample cylinder to fit inside (11 cm diameter, 12 cm high, volume 1140 cm³). Each jar had an airtight screw lid equipped with two injection needles (0.8 mm diameter, 40 mm long). The needles were inserted through the lid and glue was applied around the insertion points to ensure that the modified jar was airtight. The jars had thick walls (approximately 1.5 mm) and potential leakage of gas was considered to be negligible. The CO₂ emissions from the different soils were determined by placing a soil sample cylinder in a jar, immediately closing the lid, and then connecting the injection needles *via* plastic tubing to a portable infrared CO₂ analyser (Carbocap CO₂ Probe GMP343, Vaisala Ltd, Vantaa, Finland). Measurements were made every 30 s for 5–10 minutes. Within this range, longer jar closure times were used at lower emission rates. The CO₂ analyser was calibrated before the experiment started, according to the manufacturer's standard procedures (Vaisala Instruments Service, Vantaa, Finland).

Gas measurements were performed on one sample at a time until all of the samples (1–13) in the tray had been measured. The measuring procedure was performed twice on all samples at each measuring occasion (suction step). The jar and the gas analyser were allowed to ventilate between samples. The rate of CO₂ emission from the soil was calculated from the linear increase in CO₂ concentration in the jar headspace during the closure time. In general, emission fluxes with linearity higher than $r^2=0.85$ were used, but measurements with lower r^2 were included if they did not exhibit any obvious errors on visual inspection. Negative values were omitted. Most of the omitted values (35 out of 51) were obtained near water-saturation. Mean values of the two measurements *per* occasion were used in the statistical analysis except in cases where values were missing, when only one value was used.

The CO₂ emission flux was calculated using Equation 1 (described in Kainiemi *et al.* 2015):

$$F = \Delta\text{CO}_2 \times \frac{PVM}{RT} \quad [1]$$

where F is the CO₂ flux (ng min⁻¹), ΔCO_2 is the increase in CO₂ concentration in the jar during closure (ppm mol CO₂ min⁻¹), P is atmospheric pressure (101,325 Pa), V is the volume of air in the jar (m³), M is the molecular mass of CO₂ (44 g mol⁻¹), R is the gas constant (8.3145 J mol⁻¹ K⁻¹) and T is the ambient temperature (293 K). Air volume (V) was calculated by subtracting the volume of the cylinder from the internal volume of the jar. The CO₂ flux values were then divided by the dry mass of the soil sample to express *per* unit mass of dry soil (ng g⁻¹ min⁻¹).

Soil analysis

Three soil cylinders (not used for CO₂ measurements) from each soil were used for analysis of soil physical properties. Dry bulk density and volumetric water content at suction heads of 0.05, 0.25, 0.5, 0.75 and 1.0 m water column (approximately 0.5, 2.5, 5.0, 7.5, and 10.0 kPa) were determined. Air-filled pore space at different suction heads was calculated from water retention data. Humification degree (H1–H10) of the peat soils was determined according to von Post (1922).

The frozen soil samples from the drainage experiment were used for analysis of mineral N (nitrate (NO₃) and ammonium (NH₄)) on a TRAACS 800 AutoAnalyzer (Bran&Luebbe, Germany). The soil stored in the refrigerator was used for different analyses soon after completion of the gas measurements. Total nitrogen (tot-N), total carbon (tot-C) and carbonate carbon (carb-C) content were determined by dry combustion on a LECO CN-2000 analyser (St. Joseph, MI, USA). Soil pH was measured at a soil:solution ratio of 1:5 with deionised water. Organic matter content (loss on ignition) was measured by dry combustion at 550 °C for 24 h after pre-drying at 105 °C for 24 h.

Water-extractable organic carbon (WEOC), presented here as total and filtered WEOC (WEOC_{tot} and WEOC_{fil}, respectively) was determined by a modified version of the method of Ghani *et al.* (2003). Approximately 3.5 g of soil was placed in a 50 mL polypropylene centrifuge tube, made up to a 1:5 soil:water suspension with deionised water, and placed on an end-over-end shaker for 1 h. The tube was then centrifuged at 3500 rpm for 20 minutes. The supernatant was decanted into a new tube and analysed for WEOC_{tot} on a Shimadzu TOC-5000A. The supernatant was then filtered through a 0.45 µm

membrane filter and analysed again for $WEOC_{fil}$. In parallel, a similar quantity of soil was dried at 105 °C for 24 h (for dry weight determination). The analytical data were then recalculated using the dry weight data and the results were presented as mg $WEOC_{tot}$ or $WEOC_{fil}$ *per g* total C in the soil.

Statistical analysis

One-way ANOVA was used to test for differences in CO_2 emissions caused by suction head increments, soils and boxes. For the ANOVA, the data were square root-transformed to meet the requirements of normality and equal variances. Relationships between CO_2 emissions and soil properties were tested with linear and non-linear regression. Pair-wise comparisons of soils, soil properties and CO_2 emissions at different suction heads and between topsoils and subsoils were performed with T-test and Tukey's adjustment. All statistical analyses were carried out in Minitab 17 (Minitab, Inc. USA). Mean values \pm standard deviation (SD) are presented.

RESULTS

CO_2 emissions and drainage

The mean CO_2 emission rates (\pm SD) for all 13 soils (dry mass basis) were 36 ± 40 , 142 ± 84 , 166 ± 70 and

167 ± 77 $ng\ g^{-1}\ min^{-1}$ at suction heads near saturation (0.05), 0.5, 0.75 and 1.0 m water column, respectively. There were no significant differences in CO_2 emission rates between suction heads of 0.5, 0.75 and 1.0 m water column, but the emission rate near saturation deviated significantly from the others ($p < 0.05$).

The response of CO_2 emission rate to increased suction (decreased soil water content), expressed *per* unit mass of dry soil, varied between the soils. For some soils it increased slowly with increasing suction head, while for others it stayed at the same level when the suction head increased from 0.5 to 1.0 m water column (Figure 2). Mean CO_2 emission rates from topsoil and subsoil at the same site were higher for the topsoil at three out of four sites for which this comparison could be made (Sites 6–9) (Figure 2). The peaty marl soil (Soil 4) had the lowest CO_2 emission rate at all suction steps. At a suction head of 1.0 m water column, CO_2 emission rates for the peat soils (excluding Soil 4) ranged from approximately 100 to 250 $ng\ g^{-1}\ min^{-1}$ (Figure 2). At this suction head, none of the eight peat topsoils deviated significantly from all the other soils (Figure 3), although Soils 1 and 7 (low emission rates) deviated from Soils 3, 5, 6 and 8 (high emissions) ($p < 0.05$).

The air-filled pore space (AFPS) increased with increasing suction head (Figure 4). The highest AFPS

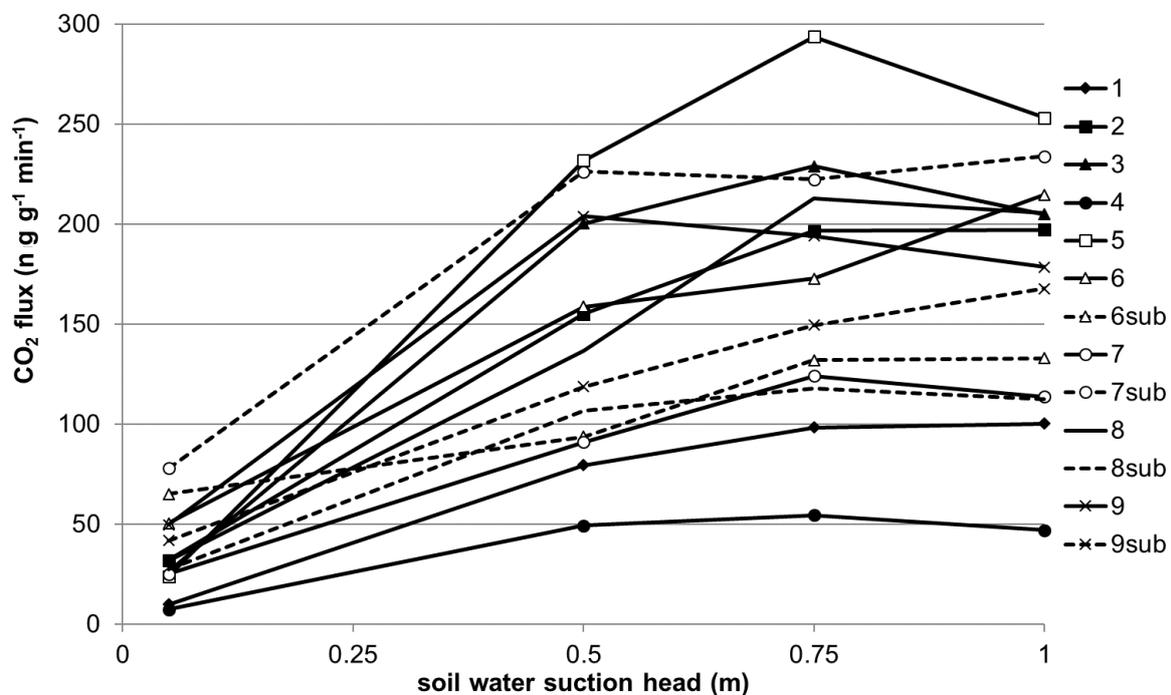


Figure 2. Carbon dioxide emission rates ($ng\ g^{-1}\ min^{-1}$; dry mass basis) from the 13 soils at suction heads of 0.05 (near water-saturated), 0.5, 0.75 and 1.0 m water column. Data for topsoils are indicated by solid lines and those for subsoils (Sites 6–9 only) by dashed lines. For 0.75 m suction head, $n = 3$; for all other suction heads, $n = 7$.

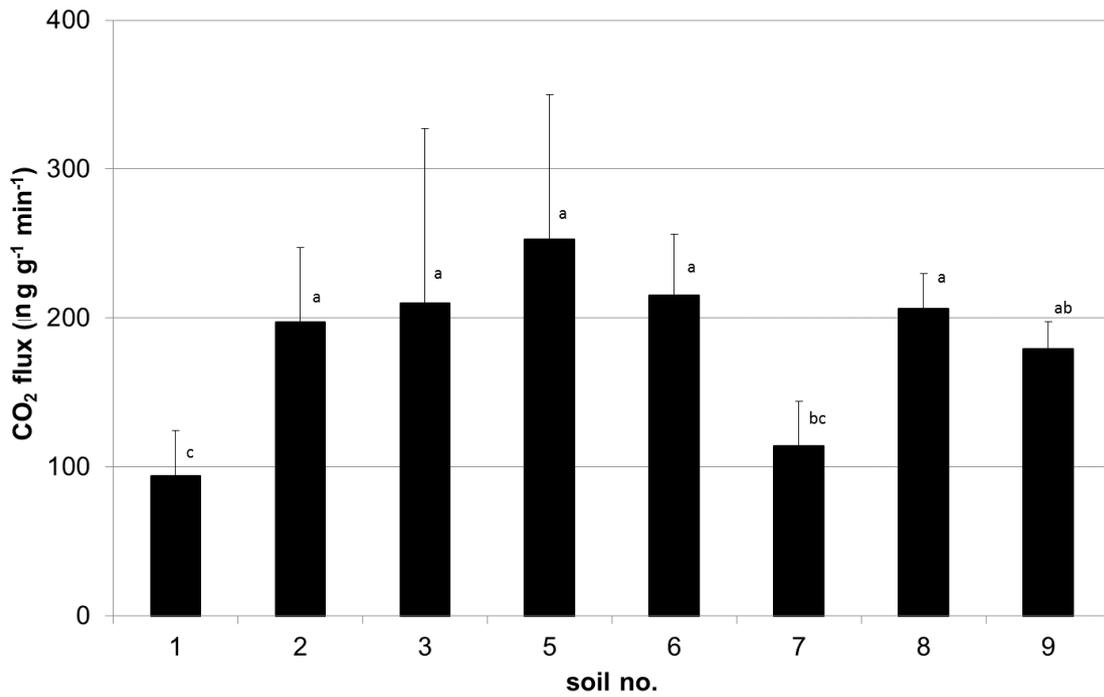


Figure 3. Carbon dioxide emission rates ($\text{ng g}^{-1} \text{min}^{-1}$, dry mass basis) from the eight peat topsoils (Sites 1–3 and 5–9) at a suction head of 1.0 m water column ($n = 7$). Different letters in the labels denote significantly different values ($p < 0.05$).

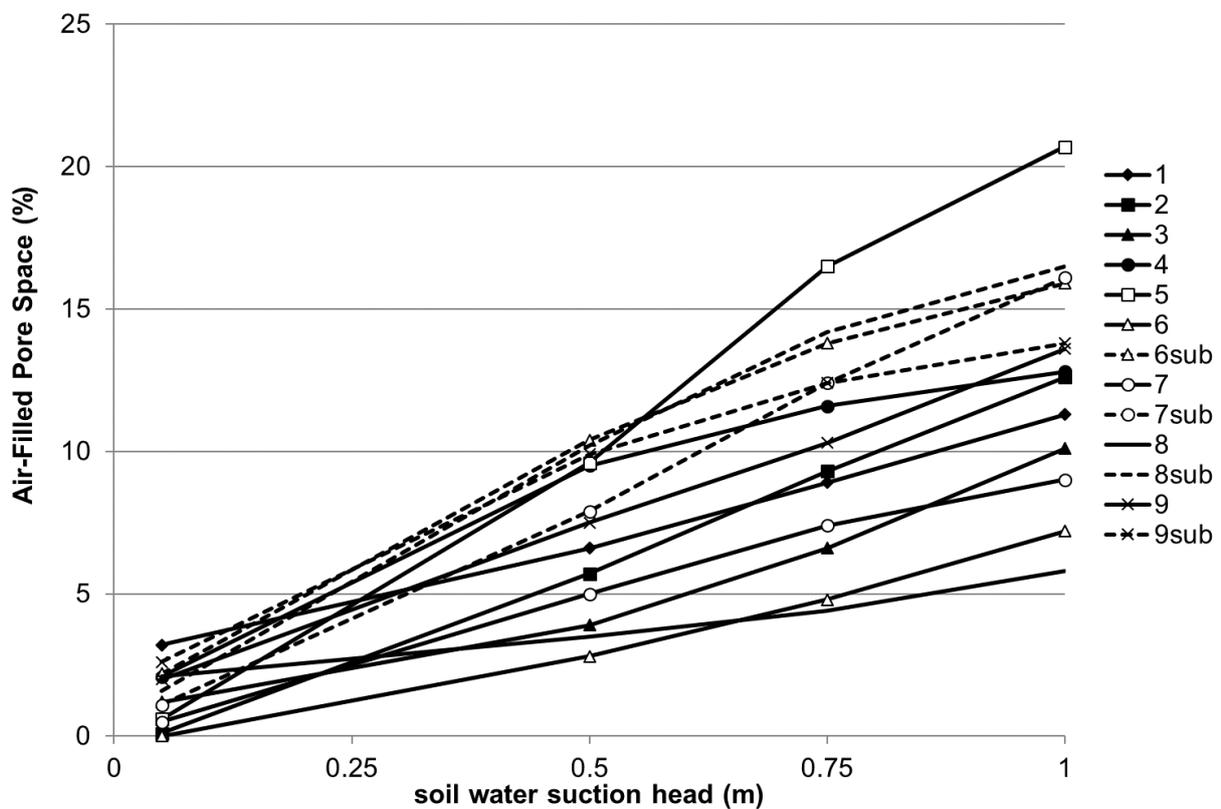


Figure 4. Air-filled pore space (%) for the 13 soils at suction heads of 0.05 (near water-saturated), 0.5, 0.75 and 1.0 m water column ($n = 3$). Data for topsoils are indicated by solid lines and those for subsoils (Sites 6–9 only) by dashed lines.

value recorded at a suction head of 1.0 m water column was 21 % (Soil 5), while the lowest was 6 % (Soil 8). At suction heads of 0.5, 0.75 and 1.0 m water column, AFPS was generally higher in subsoils than in topsoils, which indicates a difference in soil structure (pore size distribution) between topsoil and subsoil. There was no relationship between AFPS and CO₂ emission rate.

For the 13 soil samples in Box 7, whose CO₂ emission rates were measured at five different suction head steps (see Table 1), CO₂ emissions increased rapidly from near water-saturated conditions to their maximum levels at 0.5 m water column, and stayed at these maximum levels at subsequent suction steps (data not shown).

CO₂ emissions and soil properties

The relationship between CO₂ emission rates and soil properties was examined for a suction head of 1.0 m only (because the soil analyses were mainly carried out at the end of the experiment) and without the peaty marl soil (Soil 4, tot-C content 10 %) which deviated strongly from the peat soils (tot-C 26–44 %). The soils exhibited a wide range of organic carbon content, but a statistical relationship with CO₂ emissions was not observed (Figure 5a). Four soils (3, 5, 7 and 7_{sub}) had high carbonate-C content (Figure 5b) due to the presence of calcareous minerals. One of the subsoil samples (Soil 9_{sub}) deviated strongly from the other soils in WEOC_{fil} content, but no general relationship with CO₂ emissions could be found (Figure 5c). Loss on ignition showed no statistical relationship with CO₂ emissions (Figure 5d) and there was no difference between topsoils and subsoils. Soils 9 and 9_{sub} had much higher NO₃ content than the other soils (Figure 5e). Soil 7 had a very high NH₄ content and when that value was omitted there was a linear relationship ($p < 0.05$) between CO₂ emissions and NH₄ content (Figure 5f). Topsoil generally had higher bulk density than subsoil, reflecting the higher humification degree in the topsoil (Figure 5g and Table 2). Two of the soils (1 and 7) deviated from a possible linear relationship between CO₂ emission rate and bulk density (Figure 5g) and had significantly lower CO₂ emission rates than several of the other topsoils (Figure 3). They deviated from the other topsoils by having lower tot-C content, lower organic carbon content and lower WEOC_{fil} while for NH₄ they were at opposite ends of the scale (Table 2, Figure 5). However, they showed no differences from the other soils in terms of pH and NO₃.

DISCUSSION

CO₂ emissions and drainage

In this laboratory experiment, performed under controlled conditions using intact soil cores, the CO₂ emission patterns of peat soils exhibited a wide range of responses to increasing drainage (suction head) (Figure 2). The different suction steps applied to the topsoil samples (0.5, 0.75 and 1.0 m water column) corresponded to water table depths in field conditions of 50, 75 and 100 cm below the soil surface. However, drainage equilibrium occurs in the field only during short periods, *e.g.* early in spring after a wet winter, when the soil frost has gone and evapotranspiration is negligible. Water content in the topsoil is often much lower than the groundwater level indicates, due to evapotranspiration and slow capillary transport from below. The CO₂ emission curves in Figure 2 show a wide range of responses to increasing suction head for the 13 different soils tested. Some soils responded with an instantaneous large increase in CO₂ emission rate, while in other soils the CO₂ emission rate increased only moderately or remained low. This confirms the hypothesis that different peat soils respond to drainage in different ways. This was also seen in a study by Tiemeyer *et al.* (2016), where the response of CO₂ emissions to groundwater level was highly site-specific. Mäkiranta *et al.* (2009) reported that the relationship between groundwater level in the field and peat decomposition rate followed a bell-shaped curve, with an optimum groundwater level approximately 60 cm below the surface. In the present study, some of the CO₂ emission curves showed tendencies towards a bell shape but, on average for all soils, there was no difference between suction heads of 0.5, 0.75 and 1.0 m water column.

For the box subjected to an additional suction step of 0.25 m water column, a linear increase was seen in CO₂ emissions from near water-saturated conditions to a suction head of 0.5 m water column, as reported previously by Moore & Dalva (1993) and Susilawati *et al.* (2016). Moore & Dalva (1993) observed a 4.3-fold increase in CO₂ emissions between water-saturated conditions and drainage to 40 cm depth, compared with the 3.9-fold increase between near water-saturated and a suction head of 0.5 m water column observed in the present study. In our study, the CO₂ emission rate from Soil 9 peaked at a suction head of 0.5 m water column and that from Soil 7 at a suction head of 0.75 m water column, then slowed down. In an earlier incubation experiment (Berglund & Berglund 2011) these same two soil types showed

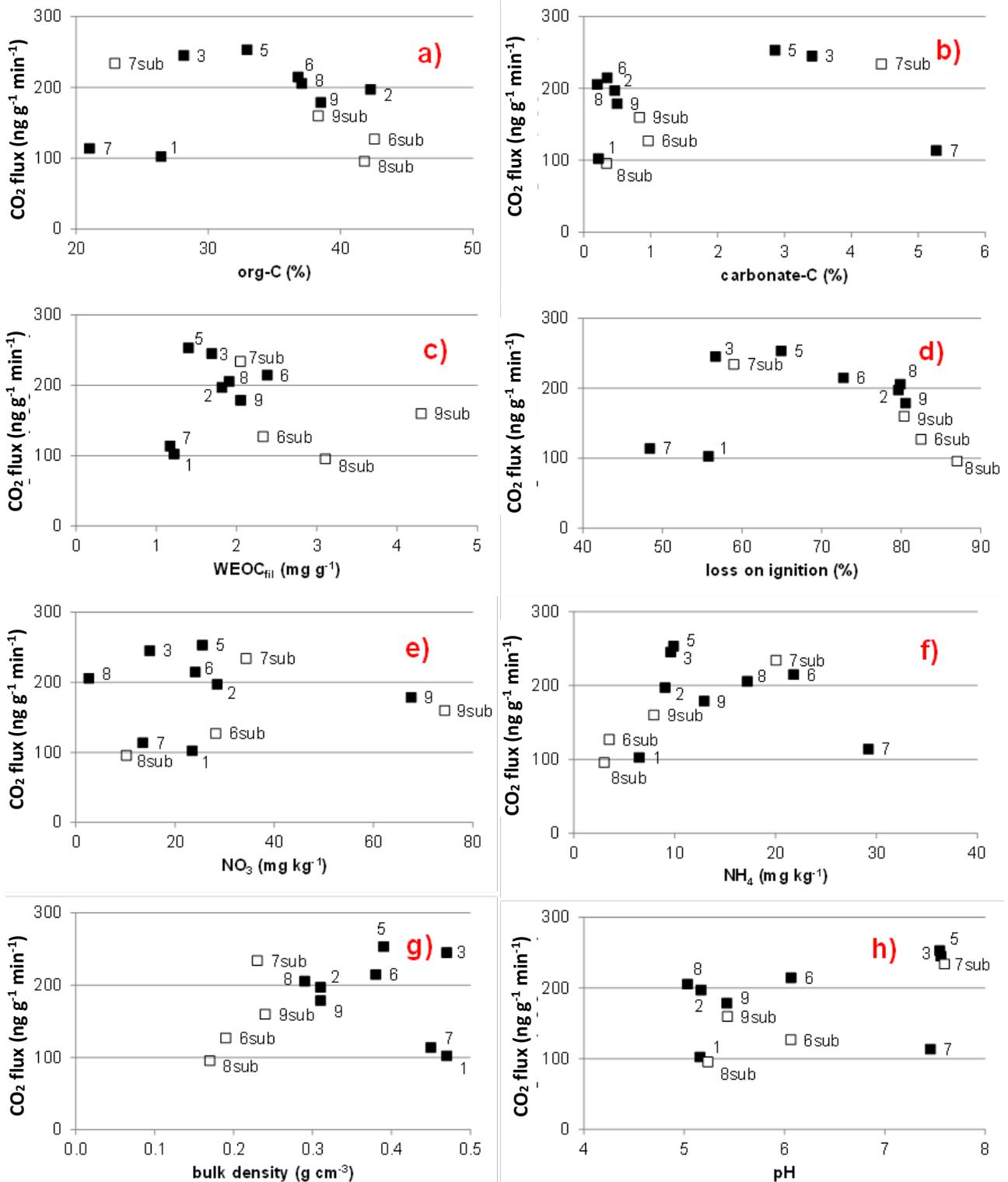


Figure 5. Relationships between carbon dioxide emissions ($\text{ng g}^{-1} \text{min}^{-1}$, dry mass basis) at a suction head of 1.0 m water column and selected soil factors: a) organic carbon (org-C); b) carbonate carbon (carbonate-C); c) water-extractable organic carbon (WEOC_{fil}); d) loss on ignition; e) nitrate (NO_3); f) ammonium (NH_4); g) bulk density; and h) pH. Soil 4 (peaty marl) is not included. Data for topsoils are indicated by filled squares and data for subsoils by open squares.

similar bell-shaped behaviour and CO₂ emissions slowed down considerably at a suction head of 6 m water column.

In this study, mean CO₂ emission rates (dry mass basis) at near water-saturated conditions ranged from 7 to 78 ng g⁻¹ min⁻¹ (Figure 2). This wide range of relatively high emissions could be due to the presence of oxygen in the water used for saturation, the presence of trapped air (and CO₂) in micropores, and some drainage of water that occurred when the soil samples were moved and placed in the measuring jars. The CO₂ emissions under near water-saturated conditions might have been lower if the water had been boiled before use (to remove air bubbles) and with a slower and more prolonged saturation time. Another reason for this wide range in CO₂ emissions could be that several measurements that were omitted should perhaps have been treated as zero emissions, thus giving lower mean values.

According to Renger *et al.* (2002) the lifespan of a drained fen peat can be extended from 130 years to more than 500 years by raising the groundwater level from 70 cm to 30 cm below the ground surface and thus preventing subsidence. This would be of great economic importance for farmers. However, yield and trafficability also need to be considered when managing groundwater levels in agricultural systems. Poyda *et al.* (2016) demonstrated the potential for reducing greenhouse gas emissions from agricultural areas in northern Germany without giving up traditional forage production, by changing land use intensity and groundwater level. Moreover, Renou-Wilson *et al.* (2016) reported lower CO₂ emissions from extensively grazed unfertilised fields than from other agricultural areas on peat because of higher annual mean groundwater levels (above -25 cm). Also, different plant species can respond in different ways to higher groundwater levels. For example, field and mesocosm experiments have demonstrated that pasture plants (used for grazing) and reed canary grass (used for energy biomass) are suitable for production on organic soils with shallow groundwater levels (Karki *et al.* 2014, Campbell *et al.* 2015).

In practice, it is difficult to keep the water table at a specific level. Furthermore, both groundwater levels and CO₂ emissions vary greatly between years in the field (Danevčič *et al.* 2010, Poyda *et al.* 2016), and Regina *et al.* (2015) found that CO₂ flux rates also vary when the groundwater level is stable. Very low hydraulic conductivity and slow capillary rise are common in many peat soils (*e.g.* Mustamo *et al.* 2016), which means that water content in the topsoil during the growing season is determined more by weather and uptake of water by plants than by

groundwater level. The outcome is variable CO₂ emissions and a weak relationship between groundwater level and CO₂ emissions in the field (Tiemeyer *et al.* 2016). Soil moisture or aeration could be a better predictor for CO₂ emissions than groundwater level under field conditions, since water table depth does not determine the soil moisture content in the upper layers of soil (Price 1997). It is worth noting that, in this laboratory study, the topsoil moisture content never reached such low levels as are commonly found in the field (Norberg *et al.* 2016a).

Temperature is important for CO₂ production. In this laboratory study, the temperature was kept constant at 20 °C, which is much warmer than the average field temperature during the growing season in Sweden. Soils 7 and 9 were used in a previous study, where a rise in temperature from 13 °C to 25 °C in an incubation experiment increased CO₂ emissions 4.2-fold and 2.6-fold, respectively (Berglund *et al.* 2010). In a related lysimeter experiment, the average Q₁₀ value for both soils was 2.1 for temperatures between 13 °C and 25 °C. In a study by Moore & Dalva (1993), a rise in temperature from 10 °C to 23 °C increased CO₂ emissions 2.4-fold. The constant temperature in the laboratory could also be a reason for the shape of the average CO₂ emissions curve. The high temperature may permit soil microbes to operate at constantly high levels of activity, especially as the soil water content in the samples was relatively high even at a suction head of 1.0 m water column. Another reason for the shape of the average CO₂ emissions curve observed here could be changes in microbial populations, whose composition might have altered during the experiment due to the long period of warm temperature and possibly a change in substrate availability (Moore & Dalva 1993). Since the samples were intact, they still contained roots and other easily degradable carbohydrates and the availability of this substrate may have changed over the experimental period of several weeks. This could be a reason why CO₂ emissions did not increase at suction heads higher than 0.5 m water column. If the substrate availability had been constant, a greater suction head (more aeration/deeper drainage) would perhaps have led to higher emissions.

CO₂ emissions: subsoil versus topsoil

With all soils included, there was no apparent difference between subsoil and topsoil samples in the magnitude of CO₂ emissions and the shapes of CO₂ emission curves, except that the subsoils appeared to have higher CO₂ emissions under near water-saturated conditions (Figure 2). This may be related to the fact that the microbes in the subsoil were better

adapted to anoxic conditions than those in the topsoil, which is more aerated. It is important to remember that under field conditions a groundwater level of 1.0 m below the soil surface, for example, results in a different soil water suction head for every sublayer depth in the soil profile, so subsoil and topsoil do not experience the same soil water suction head at the same time. Thus, the laboratory study is not totally realistic.

A similar trend to our observation of higher CO₂ emissions from topsoil than from subsoil was reported by Glatzel *et al.* (2004), while Harpenslager *et al.* (2015) did not find any difference. Newly deposited fresh organic matter (roots and plant litter) from agricultural crops generates the potential for higher CO₂ production in topsoils. Furthermore, the humification degree decreased with depth in the soil profile at all of our study sites (Table 2).

For the four sites with subsoil and topsoil samples available (Sites 6–9), bulk density was lower in the subsoil (mean 0.21 g cm⁻³) than in the topsoil (mean 0.36 g cm⁻³) (Figure 5g). This difference is greater than reported by Harpenslager *et al.* (2015). There was no difference in organic matter content (loss on ignition) between topsoil and subsoil at Sites 6–9 (Figure 5d), while the opposite was found by Harpenslager *et al.* (2015).

CO₂ emissions and soil properties

Even though 12 of the 13 soils analysed were classified as Histosols, they exhibited a wide range in measured soil properties and CO₂ emissions. Soil 5 had the highest CO₂ emissions and the peaty marl (Soil 4) had the lowest. These two soils were collected a few kilometres apart in the same peatland belt. Site 5 is highly influenced by its CaCO₃ rich marl subsoil. However, abiotic production of CO₂ from CaCO₃ is considered negligible compared with biotic CO₂ emissions (Kuzyakov 2006). Moreover, Soils 6–8, all taken from the same farm, illustrate how peat soil properties and CO₂ emissions can differ within a relatively small area (< 1 km apart).

The linear relationship found between CO₂ emissions and NH₄ concentrations when Soil 7 was omitted (Figure 5f) suggests that the nutrient status of the soils influenced CO₂ emissions. This was also seen by Renou-Wilson *et al.* (2014), where a nutrient-rich drained peatland emitted more CO₂ than a parallel nutrient-poor drained peatland. Pohl *et al.* (2015) reported a strong relationship between nitrogen content and CO₂ flux from organic soils, although with wide variation in CO₂ emissions between different soils, as was also found in the present study. The subsoil at Site 9 had high WEOC_{tot} and WEOC_{fil} values, which could be the reason for

the dark colour of drainage water from Soil 9 observed by Berglund & Berglund (2011). There was no clear relationship between WEOC_{tot}/WEOC_{fil} and CO₂ emissions although the high WEOC_{tot}/WEOC_{fil} values could potentially lead to high leaching losses to surrounding waters, with subsequent CO₂ emissions (Evans *et al.* 2016).

In this study the cultivated peat soils were of similar fen peat origin, probably because of the suitability of fen peat for agriculture. In a study by Moore & Dalva (1997), the botanical origin of the peat was the most important factor regulating CO₂ production, with herbaceous peat giving higher CO₂ production than peat originating from mosses or ligneous vegetation. The nutrient status of the original peat can also influence CO₂ production, with a eutrophic soil producing higher CO₂ emissions than a mesotrophic soil in a study by Aerts & Ludwig (1997).

The great variation in soil properties and CO₂ emissions between soils, and the great spatial variation within short distances, must be taken into account when deciding how to manage these soils in the future.

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