Effect of soil properties on soil respiration in cultivated soils with varying organic matter content

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SUMMARY

The relationship between carbon dioxide (CO_2) production in soil respiration and soil carbon (C) content was studied using soil samples from agricultural field parcels where the C content changed along a transect within the field. Incubation of soil samples from 30 sampling points within five fields showed increasing CO_2 production with rising soil C content within the range 3–49 %. The amount of CO_2 formed in relation to the C content (specific respiration) decreased as the soil C content increased. Thus, diminishing C content of the peat as time passes after drainage does not necessarily lead to proportionally lower emissions and, indeed, our results suggest that the vulnerability of the organic matter to decomposition increases with time since drainage. When divided into classes of mineral soils (0–12 % C), mull soils (12–23 % C) and peat soils (> 23 % C) according to the Finnish national classification, only the mineral and peat soils differed from each other with respect to respiration rate. These results support including mull soils with peat soils when estimating the emissions from organic soils for greenhouse gas inventories. It is also evident that CO_2 emissions from some soils classified as mineral soils can be comparable to emissions from organic soils.

KEY WORDS: GHG inventories, greenhouse gases, mineralisation, organic soil, soil carbon

INTRODUCTION

Peatlands are important carbon (C) reservoirs and play a critical role in the global C cycle. The latest estimate of the total northern peatland C stocks is 1,055 Gt of C (Nichols & Peteet 2019). Land use is a strong driver of soil organic matter loss (Leifeld *et al.* 2020), and drainage to enable agricultural use enhances aerobic decomposition of the peat and emissions of carbon dioxide (CO_2). The originally high C content of the peat diminishes gradually due to both enhanced decomposition after drainage and progressive mixing of the topsoil with the underlying mineral soil. The peat soil is transformed into different types of organic soils and may eventually need to be reclassified as mineral soil. CO_2 emissions from organic soils are controlled by various drivers including soil temperature, water table depth (Evans *et al.* 2021), the pedo-climatic context (Napora *et al.* 2021), the quantity and nature of biomass inputs (Normand *et al.* 2021), soil organic matter quality (Bader *et al.* 2018, Säurich *et al.* 2021) and agricultural practice (Säurich *et al.* 2019a). This results in high variability of greenhouse gas (GHG) measurement results, and the complexity of interactions between the potential drivers makes it challenging to establish quantitative relationships between the controlling factors and CO_2 emissions (Blodau 2002).

In many countries with high coverage of peat soils, GHG emissions from cultivated organic soils contribute a significant fraction of the total emissions (EEA 2022). Emissions of CO_2 from the decomposition of soil organic matter in all drained organic soils are reported in national GHG inventories as part of the Land use, land-use change and forestry (LULUCF) sector. According to guidance provided by the Intergovernmental Panel on Climate Change (IPCC), the land area of organic soils for reporting should be defined on the basis of two of the criteria (1 and 2 or 1 and 3) listed below (IPCC 2014):

1. Thickness of organic horizon greater than or equal to 10 cm. A horizon of less than 20 cm must have 12 % or more organic carbon when mixed to a depth of 20 cm.

2. Soils that are never saturated with water for more than a few days must contain more than 20 % organic C by weight (i.e., about 35 % organic matter).

3. Soils are subject to water saturation episodes and have:
   a) at least 12 % organic C by weight (i.e., about 20 % organic matter) if the soil has no clay content; or

b) at least 18 % organic C by weight (i.e., about 30 % organic matter) if the soil has 60 % or more clay; or

c) an intermediate proportional amount of organic C for intermediate amounts of clay.

For reporting purposes, emission factors (EF) are used to estimate the GHG emissions from the defined area of organic soils (IPCC 2014). All soils that do not fit the definition of organic soils can be reported as mineral soils. However, the range within these categories is large. For example, Finland applies a national division within organic soils: mull soils have a C content of 12–23 % and the rest are classified as peat soils. Currently, there are insufficient data to support distinct EFs for these two categories.

To better understand the need for greater disaggregation of the area of organic soils and development of a set of EFs for different organic soils, we used data from a laboratory incubation to assess whether CO_2 production differed between the various groups of organic soils. Soil samples were collected from five field transects with a gradient in soil C content. We hypothesised that CO_2 emissions from cultivated soils are related to soil C content and that a laboratory experiment would help to increase our understanding of the existing, highly variable, field results.

METHODS

In autumn 2002, soil samples were collected from the 0–20 cm layers of the soil profiles of five agricultural soils (Table 1). Two of the sites were located in southern Finland (A and B), one in western Finland (C), one in northern Finland (D) and one in eastern Finland (E) (Figure 1). The sites were mainly in varying crop rotations involving cereal and forage production. A transect with six sampling points was established within each field, and an auger (diameter 5 cm) was used to take ten subsamples that were pooled as one sample representing each sampling point. Most of the samples were classified as peat but if the soil changed to a mineral type within the same field parcel, a sample from that area was also included because a large variation in C content within each field was preferred in the sampling scheme. The samples were stored in a freezer until spring 2003. Total nitrogen (N) and C were analysed from air-dried samples with a CN analyser (Leco CN2000, Leco Corp, MI, USA). The pH was measured in a 1:2.5 water solution. Dissolved organic C (DOC) was extracted from 30 g soil samples with 60 ml of deionised water. The soil-water slurry was centrifuged for 30 min (6000 rpm), filtered (0.45 µm) and analysed using a Shimadzu TOC analyser. Mineral N was extracted with 2 M KCl and analysed

Table 1. Site coordinates and soil properties in the 0–20 cm layer (mean with minimum and maximum values along the transect from low to high soil organic carbon content; n = 6). C % = carbon content as mass-%, N % = nitrogen content as mass-%, C/N = quotient of carbon and nitrogen, pH = soil pH measured in water suspension, Ca/K/Mg mg L^{-1} = content of calcium, potassium or magnesium as milligrams per litre of dry soil.

	Site A	Site B	Site C	Site D	Site E
Coordinates (WGS84)	60° 54' 00" N 23° 30' 36" E	60° 59' 24" N 23° 12' 00" E	64° 40' 48" N 25° 05' 24" E	66° 35' 24" N 26° 00' 36" E	61° 38' 24" N 28° 36' 00" E
C %	21.5 (7.40; 34.7)	17.7 (3.13; 32.7)	12.3 (3.96; 20.5)	42.8 (33.3; 49.4)	34.1 (24.0; 41.6)
N %	1.2 (0.44; 1.95)	0.7 (0.16; 1.20)	0.5 (0.19; 0.76)	2.5 (1.91; 2.73)	1.7 (1.35; 1.88)
C/N	18 (16; 20)	24 (20; 29)	17 (16; 19)	25 (21; 27)	20 (18; 22)
pH	5.4 (5.16; 6.02)	5.7 (4.85; 6.36)	5.6 (5.34; 5.87)	5.4 (4.60; 5.58)	5.1 (4.91; 5.37)
Ca mg L^{-1}	3200 (2780; 3690)	2792 (1550; 4090)	1890 (1050; 2590)	1440 (377; 1720)	3180 (2700; 4610)
K mg L^{-1}	190 (92; 318)	115 (62; 178)	51 (30; 86)	41 (30; 52)	74 (57; 100)
Mg mg L^{-1}	359 (276; 470)	392 (168; 728)	174 (72; 296)	464 (109; 628)	193 (160; 242)

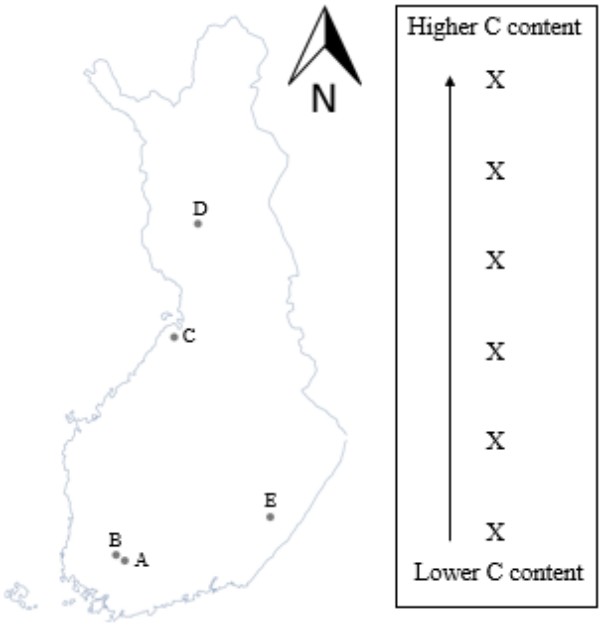

Figure 1. Locations of the fields A–E within Finland and the sampling scheme within a field. The rectangle denotes a field parcel and 'X' denotes a sampling point.

using a Lachat QuikChem AE autoanalyser. Total N and C were analysed from air-dried samples with a Leco-CN2000 analyser and Ca, K and Mg were analysed with an ICP-OES analyser (Thermo Jarrel Ash Iris Advantage ICP Spectrometer). The pH was measured in 1:2.5 water solution.

Six replicate soil samples (5 g dry weight) were incubated in 120 ml serum flasks in an incubation room at 22 °C to achieve constant environmental conditions. As our original intention was to study denitrification potential, the design included an addition of 0.5 mg nitrate and 12 % acetylene, and the headspace was filled with pure nitrogen. Soil moisture was adjusted so that the soil to water ratio was 1:1 by weight. Gas samples were taken from the flasks 0.5, 1, 1.5, 2 and 4 h after beginning the incubation.

All gas samples were taken with polypropylene syringes (BD Plastipak) and stored in 12 ml Exetainer glass vials (Labco, UK). The samples were analysed using a gas chromatograph (HP 6890 Series, GC System, Hewlett Packard, USA) equipped with flame ionisation and electron capture detectors and a nickel catalyst for converting CO_2 to methane (CH_4) (Regina *et al.* 2004). A standard gas (AGA AB, Sweden) with a known concentration of CO_2 was diluted with nitrogen (N_2) to give seven different concentrations for a calibration curve. An autosampler (222 XL Liquid handler, Gilson Medical Electronics, France) fed the samples into the loop of the gas chromatograph. Respiration rates during the four-hour flask enclosure were calculated based on linear regression of the gas concentration versus time, applying the ideal gas equation. The value of a flux estimate was accepted if the coefficient of determination was > 0.8, and in total 29 out of 180 values were discarded.

SAS EG software was used for the statistical analyses. The data were log-transformed before the analyses to meet the requirement of normal distribution. The correlation analysis was performed using the Pearson correlation procedure. Linear and non-linear models were fitted to the data on respiration versus soil C content, and the non-linear models were selected for Figures 2–3. One-way analysis of variance was used to test the differences in CO_2 production between the three soil classes, and the pairwise comparisons were made using Tukey's Studentised Range test.

RESULTS

For most site variables, the range of measured values was high, as might be expected given that the sampling scheme was planned to cover a gradient in soil properties (Figure 1, Table 1). In the laboratory incubation, CO_2 production rate correlated positively with soil C content, C/N quotient and Mg content, and negatively with K content of the peat (Table 2).

Table 2. Correlation of CO_2 flux in soil respiration with properties of the 0–20 cm soil layer. C = carbon content, N = nitrogen content, C/N = quotient of carbon and nitrogen content, DOC = dissolved organic carbon, pH = soil pH measured in water suspension, Ca/K/Mg = content of calcium, potassium or magnesium. The p values for significant correlations are presented in **bold** type.

	N	C	C/N	DOC	pH	Ca	K	Mg
Pearson correlation coefficient	0.350	0.496	0.357	0.428	-0.327	0.069	-0.535	0.373
p value	0.058	**0.005**	**0.053**	**0.018**	0.078	0.719	**0.002**	**0.042**

The trend of CO_2 production increasing with C content of the peat was clear, although it levelled off slightly towards the upper end of the C content range and the explanation rate of the logarithmic model was poor (Figure 2). On the other hand, the specific respiration rate expressed as CO_2 production in relation to the C content of the soil, showed a decreasing trend with the soil C content (Figure 3).

The samples were divided into mineral soil, mull and peat soil classes based on the C content, according to the Finnish national classification (Table 3). The large variation in C content allowed us to come up with six, eight and 16 samples representing mineral soils, mull soils and peat soils, respectively. The highest CO_2 production rates were found in samples that were classified as peat (> 23 % C) and the lowest rates in samples with C content < 12 % (mineral soils). There was a statistically significant difference in CO_2 production rate between mineral and peat soils.

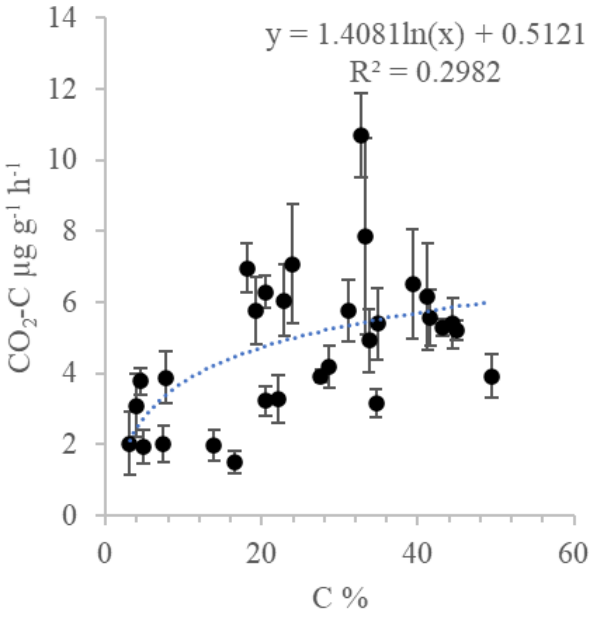

Figure 2. Production of CO_2 in soil respiration in relation to the C content of the soil samples.

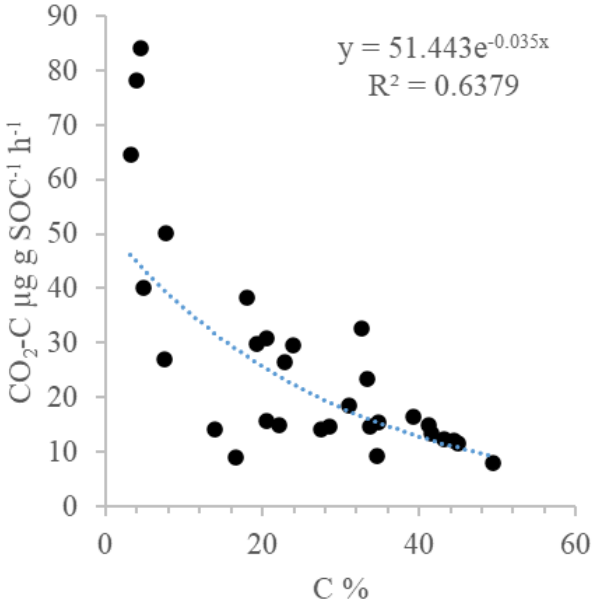

Figure 3. The specific respiration rate in relation to the C content of the soil samples.

Table 3 Mean of CO_2 production rates in classes of mineral soils, mull soils and peat soils. Different letters indicate statistical differences ($p > 0.05$) between soil type classes.

	C %	CO_2-C (µg g^{-1} h^{-1})	n
Mineral	0–12	2.79 ± 0.91a	6
Mull	12–23	4.38 ± 2.13ab	8
Peat	> 23	5.69 ± 1.80b	16

DISCUSSION

As hypothesised, CO_2 production rate increased with increasing C content in the topsoil at these agricultural sites. This is in line with the observations of Bader *et al.* (2018) on a large set of organic soils and of Harrison-Kirk *et al.* (2013), which showed a very clear increase in the rate of C mineralisation with an increase in soil C content in mineral soils. However, there have also been studies on cultivated organic soils in which CO_2 production was not closely associated with C content. In the study by Norberg *et al.* (2018), organic C content in the range 26–44 % was not correlated with CO_2 emissions in peat soils. Similarly, Säurich *et al.* (2019b) did not find significant correlation between basal respiration and C content in drained peat soils across a C content range of 8–50 %. It is likely that the conflicting results are due to unaccounted factors, such as differences in site management, masking the effects of peat properties. Such effects may also underlie our correlation analysis results for the effect of peat nutrient status on respiration (Table 2) that did not clearly support the general view that higher nutrient status promotes respiration, as found in many studies (Brake *et al.* 1999, Larmola *et al.* 2013).

We measured respiration rates in relatively wet and anaerobic conditions and used them to compare the decomposition potential of the tested soils, even

though such wet conditions occur only occasionally in reality. This approach is supported by the fact that our results are similar to aerobic respiration rates measured in peat soils by Säurich *et al.* (2019b) and Glatzel *et al.* (2004) that showed a linear relationship between aerobic and anaerobic CO_2 production.

The amount of DOC released from the soil in water extraction was positively correlated with respiration rate. DOC has been found to be an indicator of available C to soil microorganisms in some studies (Smolander & Kitunen 2002, Fang & Moncrieff 2005) but not in all (Lundquist *et al.* 1999). As DOC was measured only once, the results do not elucidate DOC dynamics or the potential DOC loading of watercourses. However, DOC is an additional potential source of CO_2 emissions as DOC decomposition off-site may add a significant portion to the total CO_2 emissions arising from a peat soil site (Frank *et al.* 2017).

Although the number of samples with high C content was limited, there was some indication that the CO_2 production rate might level out in the C content range above 40 % (Figure 2). The analysis involving specific respiration rate might partly explain this finding. The samples with C content above 40 % were taken from sites that had been cultivated for only a few years and the peat was not highly decomposed. Based on the specific respiration rates, organic matter in the samples with low C content was more vulnerable and easily decomposed compared to that in the least degraded peat samples. Similar observations have been made, for example, by Säurich *et al.* (2019b) who found a decreasing trend of specific basal respiration with increasing C content of peat soil samples. This suggests that the emission potential of drained peat soils does not necessarily decrease as the degradation process proceeds after drainage. High C loss rate was also found in soils that had changed from organic to mineral soils due to a thinning peat layer in a large dataset from Finnish soil monitoring (Heikkinen *et al.* 2022).

When comparing soil types grouped according to the Finnish national classification, peat soils had the greatest respiration rates and the mean respiration rate from mineral soils was about half of those values (Table 3). However, the mull and peat soils did not differ significantly with respect to their CO_2 production. For GHG inventory purposes, these results support the adoption of a clear distinction between mineral and organic soils and the assignment of mull soils to the class of organic, rather than mineral, soils. This finding also reduces the need for GHG inventory compilers to worry about the infrequent updating of soil maps to reflect the transition of land areas from the *Histosol* class to mull soils (*Gleysols*).

Owing to the small number of samples, our data did not allow a division between average mineral soils (~ 3 % C) and organic-rich mineral soils (> 6 % C). Most research on soil CO_2 emissions concentrates on typical mineral soils or typical peat soils and there are few data on soils with C content in the range 6–12 %. Previous research suggests that CO_2 emissions from such soils can be just as high as those from soils classified as organic soils (Leiber-Sauheitl *et al.* 2014, Tiemeyer *et al.* 2016). Also, the findings of Heikkinen *et al.* (2022) showed that soils which had changed from organic to mineral lost C at a higher rate than average mineral soils. This suggests that there can be soils with relatively high CO_2 emissions in the category of mineral soils and that their emissions may be generally under-estimated, at least if simple estimation methods are used. However, if the reporting of C stock changes in mineral soils is based on a process model, the model results for C losses usually reflect the actual C content of the soils, so the risk of under-estimation at national scale is reduced even if a portion of the organic-rich soils are reported within the category of mineral soils.

This was a small laboratory-scale study performed at unrealistically high temperature that does not allow the estimation of CO_2 emissions from these organic soils per any area unit. However, the results corroborate the reporting of mull soils as organic soils in national GHG inventories, as long as their C content is above 12 %, using e.g. the IPCC emission factors for organic soils (IPCC 2014). Attention must be paid to the relatively high potential emissions from organic-rich mineral soils.

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AUTHOR CONTRIBUTIONS

The study design and data analysis were conducted by KL. VH conducted a literature review. Both authors contributed to the interpretation of results and writing of the manuscript.

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