Greenhouse gas emissions from incubated peat cores under dynamic groundwater conditions

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Introduction

In 2021, 19% of grasslands in the Netherlands were situated on drained peat soils, a large part of which is in use for grazing and grass production in dairy farming (Arets et al., 2022). To accommodate for this use of peat soils, groundwater levels (GWL) are maintained relatively deep (-40 to -90 cm below soil surface). Prolonged drainage of peat soils ultimately leads to subsidence as it stimulates both compaction and oxidation of the soil material (Erkens et al., 2016). Additionally, aerobic oxidation under drained conditions releases the greenhouse gases CO_2 and N_2O to the atmosphere, while, to a lesser extent, CH_4 is produced from anaerobic oxidation under very wet conditions (Tiemeyer et al., 2016). Recently, national and international agreements on mitigating climate change require a substantial decrease in the emission of these greenhouse gases from peat soils (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2019). It is, therefore, essential to understand the mechanisms leading to GHG emissions from peat soils and the concurrent subsidence and how these are affected by management practices.

CO_2 emissions from several incubation experiments on peat soils show that a limited amount of air infiltration can be sufficient to stimulate microbial respiration, while extreme drying actually starts to constrain microbial activity (Berglund & Berglund, 2011; Norberg et al., 2018). Like CO_2, N_2O emissions are limited by both aeration and water content as they affect nitrification (and thus NO_3^- availability) and denitrification (Van Beek et al., 2010). Particularly dynamic groundwater conditions are favorable to N_2O production (Tiemeyer et al., 2016). High CH_4 emissions are generally not observed in drained peat soils (Van den Pol-Van Dasselaar et al., 1997). Rewetting a previously drained peat soil, however, can turn it back into a net CH_4 source (e.g. Karki et al., 2016; Van de Riet et al., 2013). Incubation or mesocosm studies on intact soil cores provide an opportunity to study peat mineralization in a controlled environment, while approaching the water retention and gas diffusion processes of the field situation as much as possible (Askaer et al., 2010; Berglund & Berglund, 2011; Karki et al., 2016; Regina et al., 2015; van de Riet et al., 2013). However, to our knowledge, there have been no peat column experiments, where replicated objects were subjected to a wide range of water table fluctuations.

Aims and hypotheses of this study

In this project, which is part of the Dutch research program Living On Soft Soils (LOSS), we aim to get a better understanding of the effects of GWL strategies on GHG emissions from Dutch peat soils. We included three Dutch pastures on peat soils with different compositions in our experiment to obtain a range of representative emission values, since we hypothesize that CO_2 and N_2O emissions are positively affected by type and contents of organic matter and N-contents of the soil and negatively by a clay cover on top of the soil. Secondly, we hypothesize that peat oxidation is higher under a low GWL and the strength of CO_2, N_2O and CH_4 emissions will result from a balance between oxygen limitation and water limitation. Therefore, intact peat cores from the upper 5 - 110 cm of the soil are treated with GWL treatments, ranging from 0 to -100 cm below the sample surface. Finally, since we hypothesize that CO_2 and N_2O production depend on abundance and composition of organic matter, smaller cores derived from the different soil horizons were incubated and emissions were measured at varying moisture conditions.

Methods

Field sampling

We measured greenhouse gas emissions from large and small soil cores in a laboratory environment. Large soil columns were sampled in transparent plexiglass tubes (120 cm long, 24 cm inner diameter) from three peat meadows used for dairy farming in The Netherlands of varying soil composition. The first soil profile near the municipality of Zegveld consists of a clayey anthropogenic layer on top of forest and sedge peat. The second sampling took place near Vlist, in an area of forest peat with a peaty clay top layer. The soil from the third field near Aldeboarn contains a thick clay layer on top and sphagnum peat beneath. These three locations are all part of the Dutch national research program on greenhouse gas emissions from peat pastures (NOBV). Three replicates were sampled by cutting off the top grass layer (5 cm) in the field and carefully pushing the tubes vertically down into the soil. Additionally, we sampled one column per location with vegetation, to check for the effect of the living grass on N_2O and CO_2 emissions. In addition to the large columns, small intact cores (5 cm length, 5.1 cm diameter) were sampled in metal rings, out of each soil horizon down to 120 cm below the soil surface.

Laboratory setup peat columns

After sampling, the large columns were brought to a climate-controlled room (16°C, 70% relative humidity), where they stayed until the start of and during the experiment. The bottom 10 cm of the soil was replaced with a layer of fine sand after which the bottom of the tube was closed air tight with a PVC cap and the column was placed on a 50 cm high platform. Two drainage pipes were installed in each column, through which a groundwater level could be imposed by applying a pressure head at a specific place below in the soil. The first drain in the bottom of the peat soil was used for positive pressure heads (at the drain location) and the second in the sand layer was used to apply a suction to the entire peat core. The distance of the applied pressure head to the soil surface was then used as a proxy for the achieved GWL.

Groundwater level fluctuation and GHG flux measurements

Biological and physical soil processes are studied in two drying-wetting cycles taking place between January 2022 and January 2023. During the first drying-wetting cycle, the pressure head of the drain in the peat layer was changed weekly for eleven weeks to fluctuate the GWL between 0 cm and -100 cm below soil surface. Fluxes of CO_2, N_2O and CH_4 were measured twice a week (on the first and the last day of a GWL step) using dark closed chambers connected to a Gasera One photo acoustic gas monitor (Gasera Ltd, Finland). Three measurements over a closure time of 24 minutes were used to calculate flux values, assuming a linear concentration change between the measurement points.

Setup and measurements small soil cores

Four replicates per soil horizon and location of the field moist intact core samples were taken and placed on a sandbox located in the same climate room (16°C, 70% relative humidity) to saturate over two weeks. After reaching saturation, the samples were taken from the sand box and placed in open polyethylene jars, to dry to the air over a period of 3.5 weeks. Fluxes of CO_2, N_2O and CH_4 were measured 2-3 times a week, by closing the jars and measuring their headspace concentration at 27 minutes using the Gasera One photo acoustic gas monitor. A linear concentration increase between the first (background concentration) and second measurement point was assumed and checked occasionally. The mass of these ring samples was recorded before each flux measurement and after drying at 105°C, at the end of the experiment, from which volumetric water contents and water holding capacity were calculated at each measurement time.

Statistical analyses

The statistical software R was used for all data analyses (v4.1.2; R core Team 2021). Cumulative CO_2-C and N_2O-N fluxes from the large columns were calculated assuming linear changes between two measurement instances and log transformed in the case of N_2O-N. An analysis of variance was used to test for the effect of soil type on cumulative emissions from the bare columns.

Results and discussions

Moisture effect

CO_2 fluxes in the large columns showed an increase within the first groundwater step (Figure 1a). Further GWL changes during the drying and wetting of the columns did not result in clear effects on CO_2 emissions, until the columns were rewetted close to the surface again. From -40 cm below soil surface onwards, CO_2 emissions decreased slightly. As expected, CO_2 fluxes were higher in the grass columns than the bare columns from the corresponding locations. The difference can be attributed to grass and roots respiration (photosynthesis is assumed to be absent in the dark flux chambers). The CO_2 flux values from our grass columns were comparable in size to those from the grass-vegetated peat columns of Van de Riet et al. (2013). In contrast to the observations in the columns, CO_2 emission peaks were measured in the small cores near saturation (100% of WHC), which quickly dropped during the first days of evaporation (Figure 2).

N_2O emissions in the large columns peaked during near-saturation (GWL at 0 cm) both at the start of the drying track and at the end of the rewetting track (Figure 1b). The latter followed our expectations that N_2O emissions will be strongest during consecutive aerobic and anaerobic conditions. Similarly, the peaks during the initial saturation condition may be caused by denitrification during anaerobicity after an extra application of water to the columns, which was applied to fully saturate them. N_2O emissions from the small cores were very high from all layers and locations during saturation at the first measurement event (83- 2117 mg N_2O-N m^{-2} day^{-1}), but had decreased to 0-22 mg m^{-2} day^{-1} by the second measurement day. Saturation may have caused high denitrification rates, while the small core size may have prevented full reduction to N_2. CH_4 emissions in the large columns were generally low or slightly negative (Figure 1c), even during near-saturated conditions. During low GWL steps, any produced CH_4 is likely to have been oxidized before reaching the surface. Under high GWL, methanogenesis was potentially limited by labile carbon sources. High CH_4 emissions were only found in one of the bare Aldeboarn columns, during the GWL of -40 to -60 in the drying track. Possibly, the high clay content of the top layer caused a delay in aeration of this column, making it possible for produced CH_4 to diffuse upwards without oxidizing.

Soil type effect

Mean cumulative CO_2-C emissions over 75 days were higher from the Zegveld and Aldeboarn soils than from Vlist (respectively 0.2 and 0.3 ton ha^{-1}), but the soil type effect was not significant ($p = 0.09$). A soil type effect was not clearly seen in the small cores either, though the CO_2 peak was lower in the Zegveld samples than those from Vlist or Aldeboarn.

The mean cumulative N_2O flux from the Aldeboarn columns was over two or three times as high as the mean from the Vlist and Zegveld soils. However, the variation in N2O emission between replicates was large and there were no significant differences in N2O emissions between the three soils ($p = 0.06$).

Continuation of the experiment

A second, longer drying-wetting cycle in the large soil columns is taking place at present (October 2022). Herein, the time steps for the different water levels are extended to two weeks and the columns are drained down to a water level of -160 cm below surface. The outcomes of this cycle will help us to understand the potential effect of incubation time on the measured GHG fluxes, as well as respiration during very dry conditions. Additionally, biochemical as well as soil physical variables, which remained undiscussed in this abstract, are recorded in drying-wetting cycles 1 and 2. By analyzing these together, we aim to improve our understanding of the coupled processes of groundwater dynamics, water retention, peat mineralization and shrinkage.

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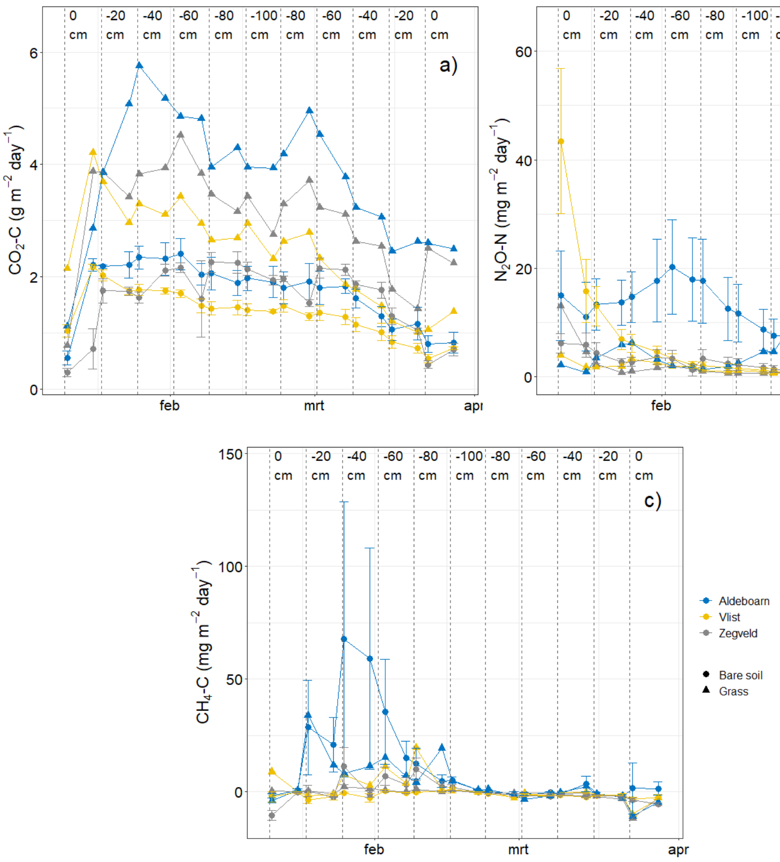

Figure 1 Fluxes of CO_2-C (a), N_2O-N (b) and CH_4-C (c) from the peat columns (with, n=1, and without, n = 3, grass sod) during the drying-rewetting cycle from January 12 – March 27 2022, with a GWL ranging between 0 and -100 cm below soil surface.

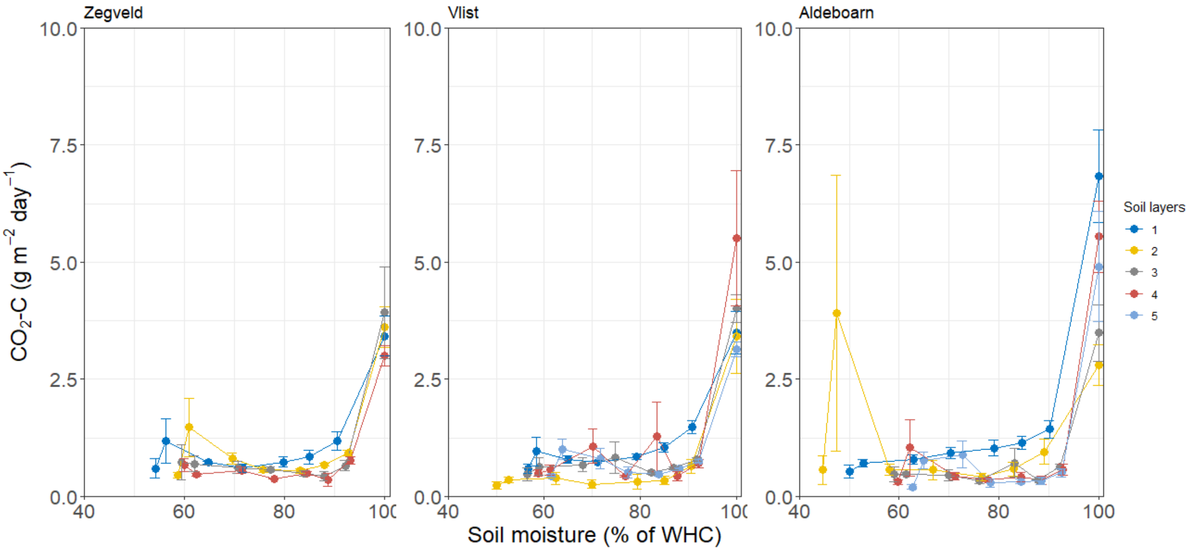

Figure 2 Fluxes of CO_2-C in the small soil cores against the moisture content of the samples. Samples originate from one of the four (Zegveld) or five (Vlist, Aldeboarn) soil horizons of which the upper 120 cm in the sampling location was composed, where 1 is the shallowest and 5 the deepest layer. Moisture content is represented by the percentage of the samples' initial water holding capacities.

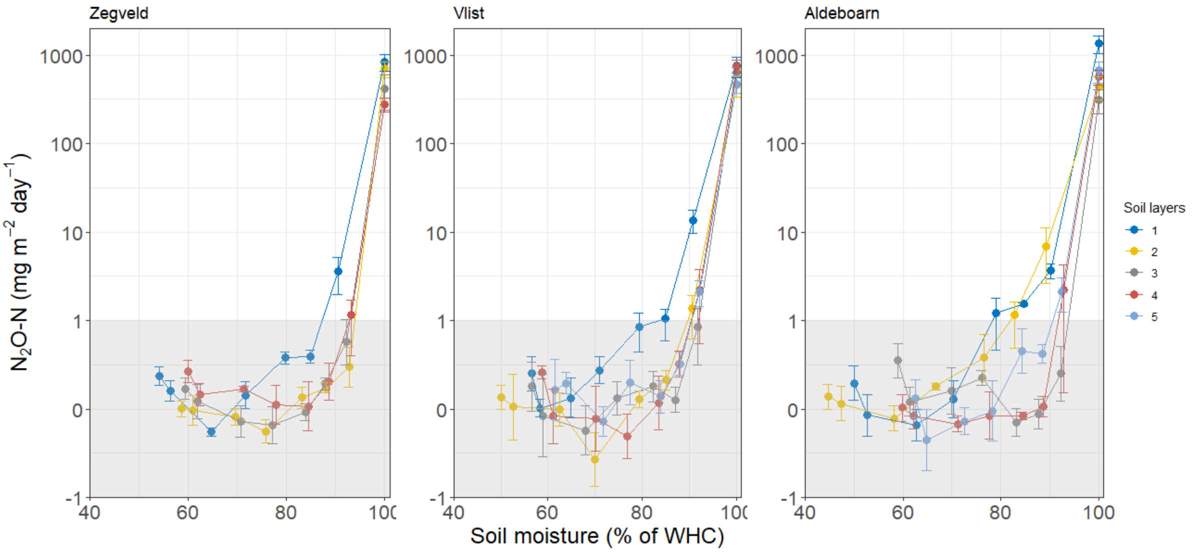

Figure 3 Fluxes of N$_2$O-N in the small soil cores against the moisture content of the samples. Samples originate from one of the four (Zegveld) or five (Vlist, Aldeboarn) soil horizons of which the upper 120 cm in the sampling location was composed, where 1 is the shallowest and 5 the deepest layer. Moisture content is represented by the percentage of the samples' initial water holding capacities. The y-axis values are log(10) transformed, except for the grey area, where the y-axis is scaled linearly.

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