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ORIGINAL RESEARCH ARTICLE

Mitigation of Greenhouse Gas Emissions by Optimizing Groundwater Level in Boreal Cultivated Peatland

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Abstract

Optimizing the level of groundwater presents a viable strategy for mitigating the greenhouse gas (GHG) emissions associated with the cultivation of peatlands. This study investigated the impact of soil hydrological conditions on carbon dioxide (CO_2) and methane (CH_4) emissions. The CO_2 and CH_4 emissions from bare soil were continuously measured using an automated chamber system throughout the growing seasons from 2021 to 2023 at a boreal cultivated peat soil site. Annual CO_2 emissions from soil respiration averaged to 21,600 kg ha^{-1} (April-November) corresponding to carbon (C) loss of 5890 kg ha^{-1}. The CO_2 emissions were highly temperature dependent. Lowering the groundwater level (GWL) was found to increase the CO_2 emissions nearly linearly. The soil functioned as a CH_4 sink for the majority of the growing season, and the total sink corresponded to 27 and 20 kg ha^{-1} yr^{-1} CO_2 equivalent in 2022 and 2023, respectively. The CH_4 emissions occurred generally when soil water content (SWC) exceeded 0.6 m^3 m^{-3} and when GWL was at the depth of less than 30 cm from soil surface. For optimal climate efficiency the mitigation measures must be implemented during the mid-growing season, and the water table should be brought close to the soil surface. Potentially, this can hamper the operation of machinery on the field and reduce the harvested yield. Thus, comprehensive cost-benefit analysis is necessary before adopting a raised water table level in large-scale crop production.

Keywords Peatland Cultivation · Soil Hydrological Conditions · GHG Fluxes · Climate Impact · Controlled Drainage

Introduction

Although agricultural peatlands cover globally a relatively small area, they are a major source of global greenhouse gas (GHG) emissions (UNEP 2022) and can account for up to one fourth of the carbon footprint of food products in countries with a high density of peatlands (Heusala et al. 2020). In cultivated peatlands, the groundwater level (GWL) is lowered either by surface- or subsurface drainage system, and consequently the accumulated peat is exposed to aerobic decomposition causing CO_2 emissions which are further enhanced by agricultural practices such as tillage, fertilizing and liming (Säurich et al. 2019). Cultivated peat soils are usually a small sink of CH_4, and CH_4 emissions occur only occasionally (Maljanen et al. 2010). The flux of CH_4 is mainly the net result of methanogenesis in the anaerobic zone and aerobic methane consumption around and above the water table (Sundh et al. 1994). Although CH_4 fluxes are small as element flows, the global warming potential of CH_4 is 27 times higher in comparison to CO_2 (IPCC 2021) and thus it is crucial to understand the factors affecting the balance of both gases to optimise land management.

GWL is the major controller of GHG fluxes from peat soils (Wilson et al. 2016; Evans et al. 2021). A global meta-analysis on water table manipulations studies found that GWL explained most of the variation in GHG emissions but e.g. climate zone affected the result as well (Huang et al. 2021). Another extensive dataset from field measurements of GHGs from various land use types in the temperate regions showed that there is a strong linear relationship between the annual mean GWL and CO_2 emissions and an exponential relationship between the GWL and CH_4 emissions (Evans et al. 2021). At annual level, other climatic,

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hydrological or soil parameters did not improve the estimates. The within-year variation in CO_2 emissions is, however, strongly driven by temperature and often exhibits an exponential relationship (Kätterer et al. 1998; Hendriks et al. 2007; Renou-Wilson et al. 2016). Temperature can also play a minor role in regulating CH_4 emissions from cultivated peatlands (Hendriks et al. 2007; Mustamo et al. 2016).

Climate change mitigation requires prompt actions for restoring the ecological functions of peatlands (Tanneberger et al. 2021). Climate change mitigation strategies differ with respect to the scale of management change, and even modest raise in GWL is beneficial as it is well known that the higher the GWL is, the lower are the CO_2 emissions. A 10 cm raise in the mean annual GWL was found to decrease CO_2 emissions by 3 t ha^{-1} yr^{-1} in the review by Evans et al. (2021), and the result agreed well with the study by Huang et al. (2021). Emissions of CH_4 usually occur only when the GWL is closer the soil surface than 30 cm, and with total rewetting the annual emissions may equal to 7 t CO_2 eq. per hectare (Evans et al. 2021).

GHG fluxes from soils exhibit a great deal of temporal and spatial variability, and detection of statistically significant relationships requires high number of observations. We measured fluxes of CO_2 and CH_4 from unvegetated plots on a drained grassland with manipulated GWL using an automated closed chamber system which enables continuous data collection with a short interval in comparison to manually operated chamber systems. Objective of this study was to understand the relationship between the gaseous carbon emissions and GWL taking into account the seasonality caused by soil temperature variation.

Materials and Methods

Study Site

The study was carried out on a cultivated peat soil in south-western Finland (WGS84: 60°47’19”, 23°32’41”) where the mean annual temperature is approximately 5.5 °C and precipitation 620 mm. On average, the growing season lasts for 175 days, and the snow cover period for 130 days (1991–2020). The thickness of the peat layer varied between 120 and 150 cm. The soil was moderately humified fen peat. According to the classification of von Post the degree of humification varied between 4 and 7 from the soil surface down to the drainage depth. Organic carbon (OC) content was 39.5%, carbon-to-nitrogen ratio (C/N) 21.1, total porosity 80%, and pH 5.3 in the 10–15 cm soil layer. In the deeper soils layer 25–65 cm OC, C/N, total porosity and pH were on average 50.4%, 22.3, 85% and 4.8, respectively. The underlying soil was heavy clay. Based on the historical maps (vanhatkartat.fi) the site was converted to agricultural use sometime after 1886 but before 1960. It was drained with subsurface pipes in the 1960s. The present subsurface drainage pipes were installed in 2020 with the drain spacing of 8 m and drain depth of 1.1–1.2 m. The soil has not been ploughed for years. Instead, it has been prepared by harrowing with an S-tine cultivator. The last harrowing was done in June 2021, before the establishment of the perennial grass. Two or three silage yields are harvested every year, and each harvest is fertilized with N 50 kg/ha, P 5 kg/ha and K 30 kg/ha.

The study site consisted of four 0.5 ha plots in the middle of a larger experimental field (of altogether 12 plots). Two of the plots featured regular subsurface drainage, while the other two were equipped with control wells. In these wells, the groundwater level (GWL) could be adjusted by opening and closing the locks. For most of the time the locks were kept closed, meaning water outflow was prevented. The locks were only opened for short periods before farm operations to ensure the sufficient bearing capacity. The target level of GWL was 30 cm below the soil surface on the plots with controlled drainage.

Experimental Set-Up

The study field was equipped with a Licor long-term soil gas flux system (Fig. 1). The system includes LI-7810 trace gas analyser, LI-8250 multiplexer, and eight opaque chambers (Licor 8200 – 104) connected to the multiplexer with 15-meter-long tubing. The gas analyser and multiplexer were placed at the intersection of four experimental blocks—two with conventional subsurface drainage (SD) and two with controlled drainage (CD). Furthermore, to maximize variability in GWL each block was equipped with two chambers, with one chamber positioned right next to the drainage line and the other situated in the middle of the drainage lines. Measurements were conducted from bare soil (i.e., heterotrophic respiration) as decomposition of the large reservoir of peat deposits is the major contributor to carbon balance in organic soils and the effect of GWL on carbon decomposition was the main interest in this study. The measurement area was kept free of vegetation by hand weeding at about half a meter around the collar of the chamber. GWL was measured in the vicinity of each chamber from perforated observations tubes with pressure sensors. Soil temperature and moisture content were assessed at the depth of 15 cm using Stevens HydraProbe sensors.

The chamber system was programmed to continuously measure CH_4 and CO_2 fluxes at one-hour interval. During the two-minute closure of the chambers, the gas concentrations were recorded every second. Subsequently, the gas flux rates were calculated by analysing the increase in

Fig. 1 Image of the experimental setup (left panel) and the schematic illustration of the setup (right panel) displaying eight opaque chambers (numbered 1–8) and a shelter positioned at the experiment's centre, housing the trace gas analyser (GA) and multiplexer (MP). The experiment comprised two plots with conventional subsurface drainage (SD) and two blocks with controlled drainage (CD). Four chambers (2,3,6,7) were situated right beside the drainage pipeline, and another four chambers (1,4,5,8) were positioned between the subsurface drainage lines

gas content over time. Non-linear regression, as outlined in the operating instructions of the LI-8250 multiplexer, was employed for this calculation. The system was set up and gas fluxes were calculated using the recommended default settings of the chamber system.

In the beginning of the experiment, the cables of Stevens HydraProbe sensors were occasionally damaged by animals, leading to gaps in the soil temperature and moisture data. In the summer of 2022, the experimental field was enclosed with a fence, resulting in fewer gaps in the data. The measured soil temperatures were consistent across chambers, and the missing data gaps in temperature were estimated based on data collected by other sensors. In contrast, there was a noticeable disparity in soil moisture measurements between the chambers, and therefore data with missing soil moisture was omitted from the analysis.

Statistical Analysis

The data for CO_2 fluxes were analysed using linear mixed-effect models. Fixed effects included soil temperature, GWL, and their interaction, while chamber and observation year served as random effects. Soil water content (SWC) was omitted from the analysis due to its correlation with GWL. Prior to analysis, both measured CO_2 flux (the response variable) and GWL were log-transformed, with the latter transformation aimed at linearizing its relationship with the response variable. The model was fitted using the restricted maximum likelihood estimation method. Dataset had altogether 79,798 observations, of which 227 observations (0.3% of the total) were excluded as outliers based on the residual plot. Residuals were assessed for normality through histograms and plots against the fitted values. A significance level of $\alpha = 0.05$ was applied.

Dependency of CO_2 emissions on soil temperature and hydrological conditions, including SWC and GWL, was also explored using regression trees. Regression tree was created for each chamber-year combination ($n = 21$). Mean squared error was used as split criterion and the minimum leaf size was set to ten to control the complexity of the tree. Performance of the regression trees was evaluated by computing the mean absolute percentage error (MAPE) and visually inspecting plots comparing observed and predicted values. Each regression tree was employed to predict the CO_2 flux for a predefined set of GWL and SWC at soil temperature of 5 °C and 15 °C degrees. Finally, the mean CO_2 flux was calculated based on the 21 regression trees created.

Cumulative CO_2 emissions between measurement period from April to November were calculated by summing up the estimated mean monthly CO_2 emissions. Mean monthly emission were estimated using linear mixed-effect model with month as fixed effect and chamber and observation year as random effects. The CO_2 flux was log-transformed prior analysis.

Preliminary data analysis indicated generally modest CH_4 fluxes, with predominantly net CH_4 uptake and occasional net emission periods. The data exhibited substantial tailing, preventing the construction of a linear model between CH_4

fluxes and predictor variables without violating the assumption of normality. Consequently, instead of developing a quantitative model, a classification trees (CT) (Breiman et al. 1984) was employed to investigate the hydrological conditions (GWL and SWC) under which the soil acted as a sink or source for CH_4. Classification tree was created for the measurements of each chamber-year combination ($n=21$). Gini's diversity index was used as a split criterion. The complexity of the classification tree was controlled by setting the maximum number of splits to three. The performance of the decision trees was evaluated by calculating the metrics for accuracy and precision. Finally, each decision tree was employed to predict the direction of CH_4 flux for a predefined set of GWL and SWC combinations at equal intervals. Results were summarized by calculating the share of CTs predicting CH_4 emissions (i.e. the risk for CH_4 emissions) under specific hydrological conditions.

Global warming potential of 27 was used to convert CH_4 fluxes to CO_2 equivalent (IPCC 2021). All statistical analyses were conducted using Matlab with the Statistics Toolbox (The MathWorks, Natick, MA).

Results

Descriptive Monthly Statistics

The average monthly air temperatures during the experiment ranged from − 1.3 to 20.0 °C, with the highest temperatures recorded in the summer months from June to August. Monthly rainfall varied between 19 and 165 mm. There was no clear seasonal pattern in rainfall throughout the experimental period (Fig. 2). Topsoil temperature in the 15 cm depth followed closely the air temperature although there was time lag between the observed soil and air temperatures. Due to heat capacity of the soil, the soil temperatures in the early spring tended to be lower than air temperature, while in the autumn the situation was the opposite. SWC in the topsoil (15 cm) was relatively high during autumn 2021, coinciding with months of high rainfall. In the growing season 2022 when monthly rainfall rates were lower also the SWC was generally lower than in 2021 and 2023. Otherwise, SWC did not show clear dependence on the monthly rainfall pattern, which is understandable as SWC is affected also by runoff and evapotranspiration, the latter being a highly temperature dependent process. The average monthly SWC ranged between 0.11 and 0.69 $m^3\ m^{-3}$ depending on the year and the month. SWC was negatively associated with GWL (r_s=-0.68); the deeper the GWL was, the lower the SWC tended to be.

Average monthly soil CO_2 flux ranged from 0.1 to 1.2 g $m^{-2}\ h^{-1}$ (Fig. 2). The decomposition of organic matter is a highly temperature driven process and thus the highest soil CO_2 fluxes were observed in the mid-summer coinciding with months with highest soil temperatures. Daily maximum occurred between 2 and 4 PM and were on average 10.4% higher than the lowest daily CO_2 emissions observed between 8 and 10 AM. Diurnal variation tended to increase with higher CO_2 emission (Fig. 2).

Apart from April 2022, the soil acted generally as a small sink for CH_4 throughout the measurement period (Fig. 2). Observed average monthly fluxes ranged between − 30 and 7 µg $m^{-2}\ h^{-1}$ and the occasions of CH_4 emissions occurred especially in early spring and late autumn. However, it should be noted that there was large variation between the replicate measurements like in CO_2 measurements. Monthly average CH_4 fluxes followed the topsoil SWC (but also GWL), the sink being greatest in the months when SWC was low. The CH_4 sink tended to be weaker in the afternoon between noon and 2 PM, when the daily maximum occurred, than during the daily minimum between 4 and 6 AM (Fig. 2). As with CO_2 the diurnal variation tended to increase with the absolute level of CH_4 flux.

Effect of Soil Temperature and GWL on Soil Respiration

Both topsoil temperature ($p<0.001$) and GWL ($p=0.002$) showed statistically significant effects on soil CO_2 emissions. On the log-transformed scale, CO_2 emissions exhibited a linear increase of 0.072 units for every one-degree rise in topsoil temperature. On the original scale (g $m^{-2}\ h^{-1}$), there was an exponential pattern between temperature and CO_2 emissions (Fig. 3, left panel). For instance, at GWL of 80 cm, the estimated CO_2 emissions were 0.27, 0.40, 0.58 and 0.83 g $m^{-2}\ h^{-1}$ at the temperature of 5 °C, 10 °C, 15 °C and 20 °C, respectively. The Q_{10} coefficient was 2.1, indicating a 2.1-fold increase in CO_2 emissions with a 10 °C increase in temperature (5 °C→15 °C and 10 °C→20 °C).

The soil CO_2 production demonstrated an increase with lowering GWL (Fig. 3, left panel). The increase was nearly linear, although there was indication that CO_2 emissions plateaued as GWL got deeper. At a topsoil temperature of 15 °C (typical for summer months), reducing GWL from 30 cm to 80 cm led to a 1.7-fold increase in CO_2 emissions. The modelled cumulative monthly CO_2 emissions between April and November (2021–2023) averaged 21,600 kg $ha^{-1}\ yr^{-1}$ corresponding to a soil carbon loss of 5890 kg C $ha^{-1}\ yr^{-1}$.

Results of the regression tree analysis (Fig. 3, right panel) showed that soil temperature, GWL and SWC all contribute to the rate of CO_2 flux. The CO_2 flux was higher in 15 °C than in 5°Ctemperature. Likewise, there was continuous increase in CO_2 emission with lowering the GWL in

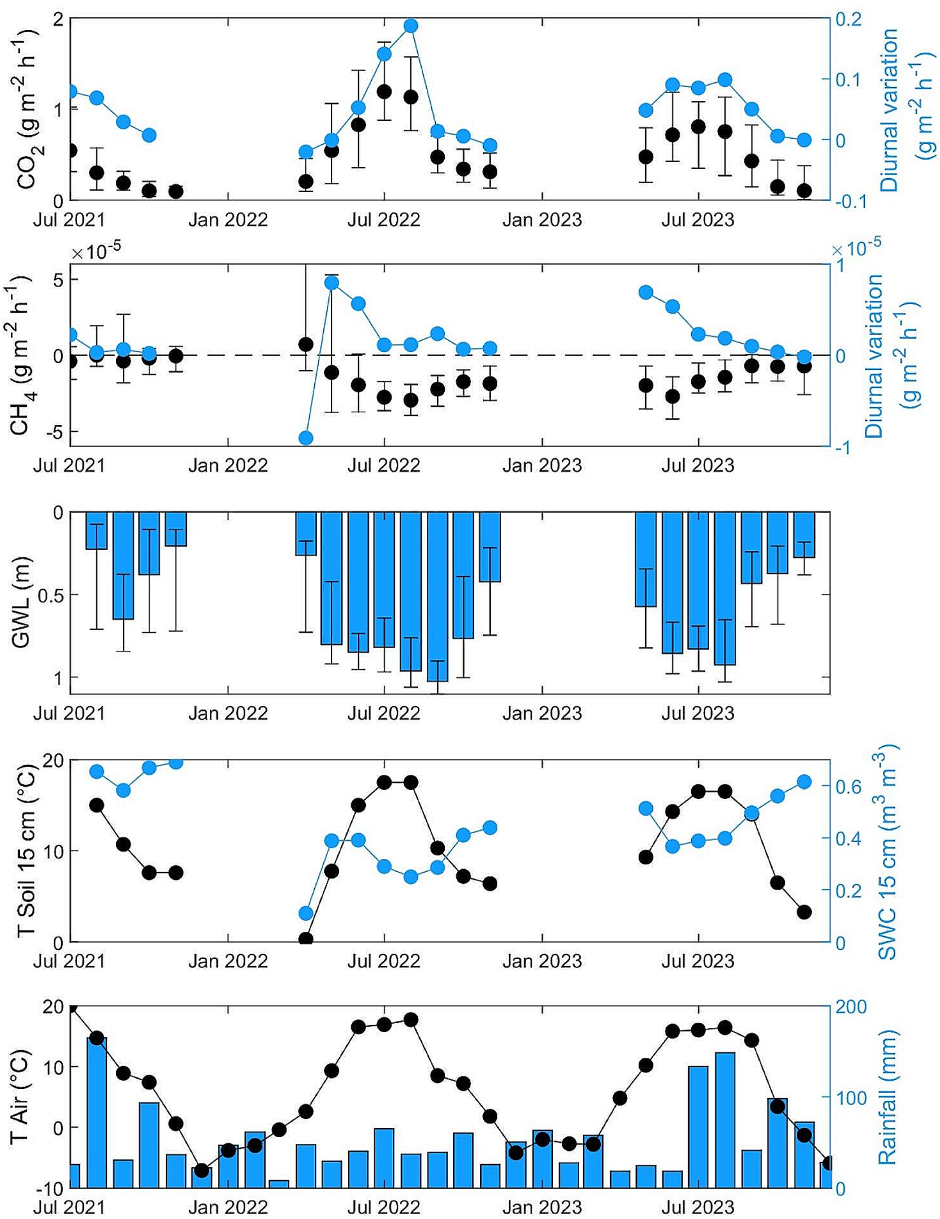


Fig. 2 Monthly CO_2 and CH_4 fluxes measured from bare soil, groundwater level (GWL), soil water content (SWC, blue line) and soil temperature (black line). Median values across measurements of eight chambers with 80% quantiles are shown. Diurnal variation of CO_2 and CH_4 fluxes has been calculated as a difference between daily maximum and minimum. The lowest panel displays monthly rainfall sum and air temperature taken from the 1 km×1 km gridded weather data provided by the Finnish Meteorological Institute

all other SWC levels except SWC of 0.4 $m^3\ m^{-3}$. The CO_2 emission tended to increase as SWC decreased. Mean absolute percentage error of the regression trees ranged from 9 to 55% and was on average 18%.

Dependency of CH_4 Flux on Soil Hydrological Conditions

The results of the classification trees (CTs) presented in Fig. 4 reveal that both GWL and SWC have a role in determining whether the soil functions as a sink or source for CH_4. The risk of CH_4 emissions increases with higher SWC and when the GWL is close to the soil surface. The soil tended to act as a source for CH_4 when GWL was shallower than 30 cm and SWC exceeded 0.6 $m^3\ m^{-3}$. Conversely, the CH_4 emissions practically did not occur when the GWL was deeper than 50 cm and when SWC was lower than 0.5 $m^3\ m^{-3}$. Based on the predictor importance calculated for each CT, GWL had impact on CH_4 fluxes in 17 cases and SWC in 14 cases out of 21 CTs. The GWL turned out to be more important driver for CH_4 fluxes than SWC in 12 out of 21 CTs.

The accuracy of the CTs for each chamber and year combination ($n = 21$) ranged between 0.64 and 0.99. However,

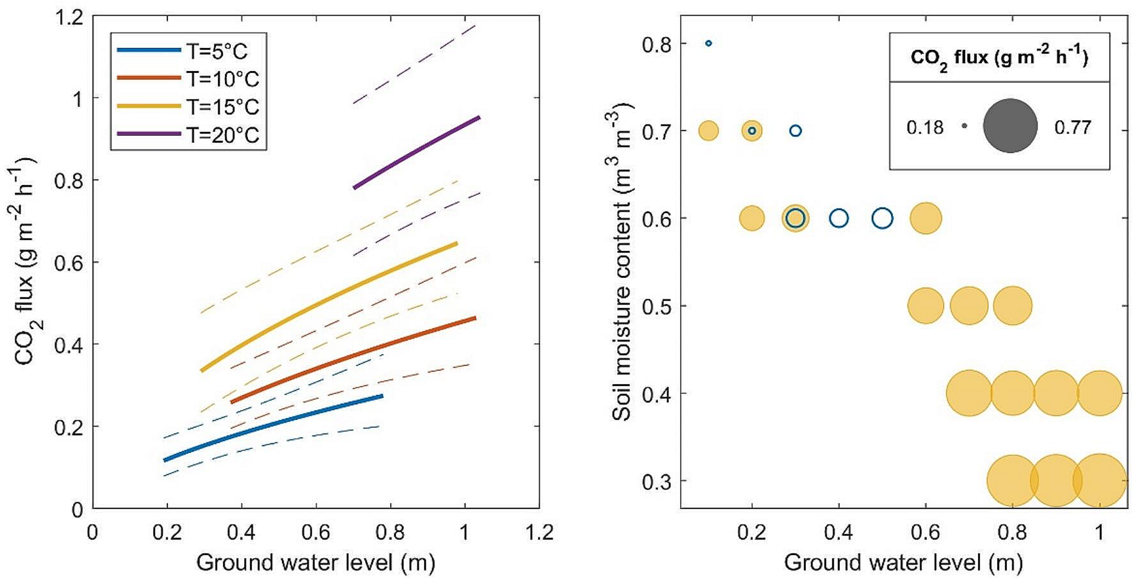
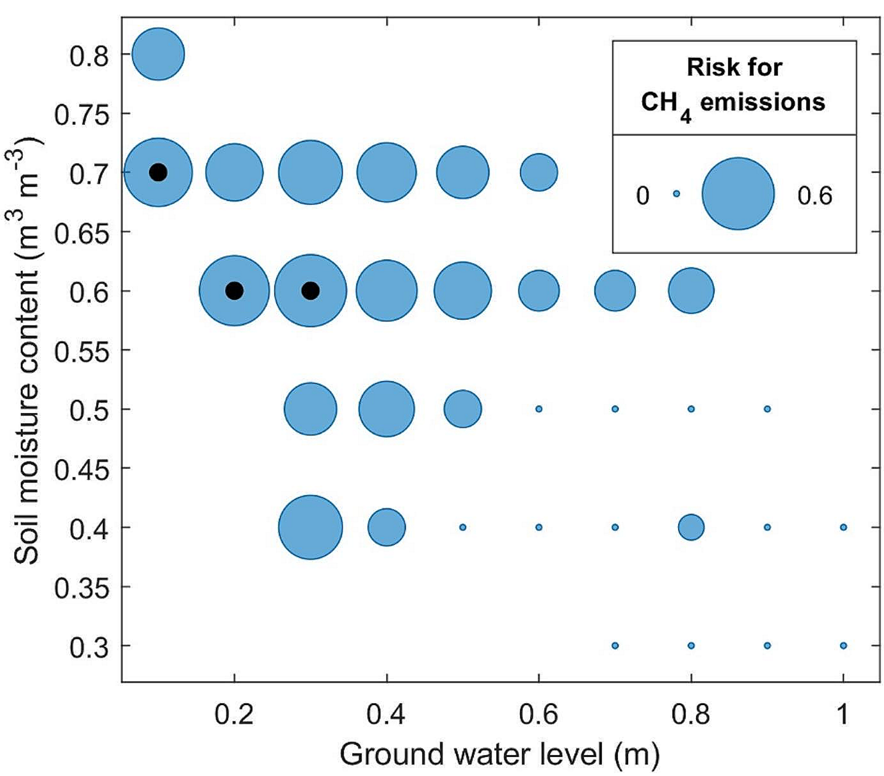


Fig. 3 Modelled dependence of soil CO_2 flux on topsoil temperature and ground water level (GWL) with 95% confidence intervals after adjusting the soil temperature to 5, 10, 15 and 20 °C degrees (left panel). The estimated CO_2 fluxes are shown for the range of GWL to which 80% of the observations fit. The right panel shows the dependency of soil CO_2 flux on soil temperature at 5 °C (blue circles) and at 15 °C (filled yellow circles)), GWL, and soil moisture content (SWC). Size of the bubble indicates the rate of CO_2 flux. Only those soil temperature, GWL and SWC combinations are shown which have data from more than five chambers

Fig. 4 Effect of ground water level (GWL) and soil moisture content (SWC) on the risk of soil CH_4 emissions. Size of the bubble indicates the share of the classification tree (CT) predicting the CH_4 emissions. Black circles within the bubbles indicate the hydrological conditions (GWL and SWC class combinations) which likely result to CH_4 emissions (i.e. the share of the CT predicting the CH_4 emissions is more than 0.5)



the classes were rather imbalanced, with the number of emissions measurements in most cases comprising less than 13% of the total number of measurements. Precision of the CTs in correctly predicting the occurrence of CH_4 emissions varied from 0.05 to 0.98, with an average of 0.48 (excluding one chamber and year combination with no occurrence of CH_4 emissions at all).

Cumulative CH_4 fluxes between April and November (calculated based on the monthly medians presented in Fig. 2) summed up to -1.0 in 2022 and to -0.7 kg ha^{-1} yr^{-1} in 2023 corresponding to sink of 27 and 20 kg ha^{-1} yr^{-1} CO_2 equivalent, respectively.

Discussion

High CO_2 emissions related to the cultivation of peat soils are well established (Kasimir-Klemedtsson et al. 1997; Qiu et al. 2021). According to a summary of 11 studies by the IPCC (IPCC 2014), the emissions from peat decomposition in drained boreal cropland are on average 7900 kg C ha^{-1} yr^{-1}, with 95% confidence intervals ranging from 6500 to 9400 kg C ha^{-1} yr^{-1}. The corresponding emission factor for drained grassland soil is 5700 kg C ha^{-1} yr^{-1} (2900–8600 kg C ha^{-1} yr^{-1}, 7 studies). The cumulative CO_2 emissions of 5890 kg C ha^{-1} yr^{-1} (April-November) found in the present study are well in line with those estimates. The peat depth of 1.2–1.5 m found in the experimental site also corresponds to the average peat depth in Finnish cultivated organic soils, which was estimated to be approximately 1.2 m (Räsänen et al. 2023). Average diurnal variation of CO_2 emission of 10.4% observed in this study was more modest than that observed by Maljanen et al. (2002). However, in their study, measurements were conducted only in midsummer when diurnal variation tends to be higher. In this study, the measurement period covered the growing season, but as shown by Honkanen et al. (2023) the wintertime emission represents only a minor fraction of the annual cumulative CO_2 emissions in boreal cultivated peatlands.

In this study, flux measurements were conducted on bare soil, representing soil respiration only. Regarding the long-term soil carbon balance, the results thus do not account for the influence of the stable fraction of crop residues and potential manure application. Based on the study by Palosuo et al. (2015) carbon input to soil in Finnish agricultural land is on average between 1600 and 2900 kg C ha^{-1} yr^{-1} depending on the crop plant. A litter bag study by Kriaučiūnienė et al. (2012) showed that after two years only about 8% of red clover and 15% of wheat stubble are remaining in the soil, whereas the remaining fraction for roots are higher being 16% and 21%, respectively. In agreement with this Heikkinen et al. (2021) showed that the resistant fraction of red clover shoots and roots are 10% and 32%, respectively. It can thus be roughly estimated that the contribution of plant residue to the long-term carbon balance is at most a few hundred kilograms which is an order of magnitude smaller than the decomposition of peat deposits.

In agreement with the review study by Kätterer et al. (1998), the results of the present study show that the decomposition of organic matter is a highly temperature-dependent process. Decomposition exhibited an exponential increase with temperature. The high temperature dependency suggests that climate mitigation measures based on raising the water table level, must be implemented during the mid-growing season to be effective. Since the majority of CO_2 emissions occur during a few months, raising the water table level outside the growing season has little effect on total annual CO_2 emissions.

The CO_2 emissions increased as the depth of the groundwater level (GWL) lowered. The association between CO_2 emissions and GWL was nearly linear as suggested by e.g. Evans et al. (2021). However, there was indication that the increase in CO_2 emissions tended to level off with an increased depth of GWL as was also found by Leiber-Sauheitl et al. (2014). This levelling off can be attributed to the soil temperature gradient, as well as hydrological and gaseous conditions in the vertical soil profile. Soil temperature is usually highest in the topmost layer of the soil controlling the overall soil heterotrophic respiration. In instances of low GWL, a greater amount of organic matter is exposed to aerobic decomposition, but at the same time the decomposition rate of topsoil decreases due to limited moisture availability. In turn, the decomposition of deeper soil layers is constrained by lower temperatures and the limited availability of oxygen. Study by Norberg et al. (2018) showed that at soil water suction corresponding to water table level of only from 0.5 m to 0.75 m, the average soil CO_2 emissions reaches a maximum in most peat soil types. The curved relationship between CO_2 emissions and GWL is crucial with respect of emission reduction efforts. Consequently, for climate mitigation effectiveness, GWL needs to be raised close to soil surface, which may have negative effects on soil bearing capacity and crop yields. The finding that decreasing SWC results in higher CO_2 emissions is consistent with the earlier study by Hadden and Grelle (2017). However, this finding is only applicable within an SWC range of 0.3 to 0.8 m^3 m^{-3} observed in this study, as dry conditions can inhibit the decomposition of soil organic matter as well.

Observed average monthly CH_4 fluxes ranging from − 30 to 7 µg m^{-2} h^{-1} correspond closely to those reported in Swedish cultivated peatlands by Norberg et al. (2016) (seasonal CH_4 fluxes ranged from uptake of 36 µg m^{-2} h^{-1} to release of 4.5 µg m^{-2} h^{-1}) and in Danish soils (Petersen et al. 2012). Results of the present study thus confirm the current understanding that peatlands under active cultivation are rather sinks than sources for CH_4. The climatic impact of CH_4 was approximately two orders of magnitude smaller than that of CO_2 and therefore can be considered insignificant for the GHG balance. Aligned with many previous studies (e.g. Bianchi et al. 2021; Hemes et al. 2018; Regina et al. 2015) the present study emphasizes the importance of soil hydrological conditions as a critical factor in determining whether the soil acts as a sink or source for CH_4. CH_4 continually forms in the anaerobic zone of the soil-water table interface, and topsoil moisture content together with thickness of aerobic layer determine whether CH_4 can pass through the soil profile to the atmosphere without undergoing oxidation to CO_2 (Le Mer and Roger 2001). Based on the results of the present study, it appears that the risk for CH_4 emissions increases when water level is less than 30 cm from the soil surface and SWC exceeds the threshold value of 0.6 m^3 m^{-3}. It is, however, very likely that these estimates are very site-specific and depend on the peat type, degree of peat decomposition, and soil compaction. Regina et al. (2007) found that CH_4 oxidation depends on drainage status of the peat soil and the CH_4 oxidation tended to be higher in well-drained soils. In this study, gas fluxes were measured from bare soil without plant cover. However, since plants influence soil microbial processes and the transport of gases, they can exert both enhancing and diminishing effects on CH_4 emissions (Koelbener et al. 2010; Ström et al. 2005). In contrast to the study by Maljanen et al. (2002) showing no clear diurnal fluctuation in CH_4, this study suggests that the CH_4 sink is smaller in the daytime than in the early morning.

We focused on the carbon emissions only as the gas analyser used in the study was not capable of measuring N_2O fluxes. N_2O is a strong greenhouse gas with the 100-year time horizon global warming potential (GWP) being 273 times as high as for CO_2 (IPCC, 2021). Previous studies have shown that regarding cumulative annual emissions in boreal cultivated peat soils, N_2O is the second most important greenhouse gas after CO_2 (Honkanen et al. 2023; Gerin et al. 2023). N_2O emissions are characterized by high temporal variability and emissions are driven by nutrient availability (Rees et al. 2013), land management (Anthony and Silver 2021) and meteorological conditions such as rainfall, drought and soil freezing and thawing events (Gerin et al. 2023; Wagner-Riddle et al. 2017). N_2O emissions in early spring and in winter can constitute a substantial share of the total annual budget (Gerin et al. 2023; Maljanen et al. 2003; Regina et al. 2004). Since N_2O emissions occur in short-lived pulses and the emissions have not been strongly associated directly with the water table level in previous studies, it is unclear whether including N_2O in this study would have changed the outcome of the study and, if so, in which direction.

Conclusions

In alignment with previous studies, the findings of this study suggest that carbon emissions to the atmosphere from cultivated peat soils can be reduced by raising the water table level. However, the study also indicates that such mitigation measures must be implemented during the mid-growing season, and the water table should be raised close enough to soil surface for optimal climate efficiency. Both requirements are challenging. Maintaining high water table in mid-growing season under conditions of high temperature and evapotranspiration may be difficult. If succeeded, high water table may cause insufficient bearing capacity of the soil for farm operations. High water table level may also reduce crop yields during wet seasons but potentially increase them in dry seasons. Therefore, there is a need for further research on practical obstacles, and a comprehensive cost-benefit analysis before raised water table can be recommended in a large scale. Furthermore, restoration of cultivated peat soils to natural wetlands, should be considered, as it might be more efficient in terms of climate change mitigation.

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Author Contributions JH conceptualized the study and performed the data analysis. JH, HH and MM performed the data collection. JH, HH, KL and MM contributed to interpretation of the results and writing the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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