Methane and nitrous oxide emissions from rewetted forested peatlands

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One central goal of peatland rewetting is to prevent carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions caused by drainage-induced peat loss. On the other hand, rewetted peatlands emit methane (CH_4), and so far, scientific knowledge on these emissions is scarce and emission estimates variable. Also, while it can be assumed that N_2O emissions are low after rewetting, the exact size of these emissions is largely unknown.

To fill these knowledge gaps, we measured CH_4 and N_2O emissions at 27 rewetted forested peatland sites in Southern and Central Finland. These sites had been rewetted 1–28 years prior to the measurements; and measurement were conducted during 2021–2022 with portable trace gas analyzers and closed chambers. The sites include eutrophic, mesotrophic and oligotrophic boreal mires that were drained for forestry for several decades and then rewetted by blocking the ditches.

In this presentation, we address the following questions: What is the level of CH_4 emissions after rewetting and how much do these emissions vary? Are N_2O emissions always low at rewetted forested peatlands? Do the N_2O and CH_4 emissions change as the time from rewetting increases? Do the emissions differ between strips and blocked ditches? To what extent tree stand, water table depth and trophic level control the emissions?

Greenhouse Gas (CO_2, CH_4, N_2O) Emissions of Undrained and Drained Nutrient-Rich Organic Forest Soil

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The impact of the moisture regime on the greenhouse gas emissions (carbon dioxide, methane, nitrous oxide) of organic soils with different nutrient statuses has not been fully studied in hemiboreal forests thus far. This study evaluated soil methane (CH_4) and nitrous oxide (N_2O) emissions of drained and undrained nutrient-rich organic forest soils as well as soil carbon (C) stock changes by estimating C loss through respiration and C input through the litter. The study sites included forest stands dominated by Norway spruce (*Picea abies*), silver birch (*Betula pendula*), black alder (*Alnus glutinosa*), and clear-cuts. Soil emissions were measured using the chamber method, and to estimate the soil C input by litter—the biomass and the C content of the foliar litter, ground vegetation, and fine-root production were measured. The soil in forest stands acted as a C sink. The carbon dioxide (CO_2) removal rates of 0.4 ± 0.4 t C ha^{-1} year^{-1} and 0.1 ± 0.4 t C ha^{-1} year^{-1} were estimated for undrained and drained soil in forest stands, respectively. The soil in the clearcuts acted as a CO_2 source, and the annual emissions were 0.4 ± 0.4 t C ha^{-1} year^{-1} in undrained and 0.9 ± 0.7 t C ha^{-1} year^{-1} in drained conditions. The reason for the soil in clearcuts being a C source was increased C loss by respiration and reduced soil C input by litter. The mean soil C input by ground vegetation biomass in the clearcuts was considerably higher than in the forest stands, which did not compensate for the increase in soil respiration and the absence of C input by foliar litter and the fine roots of trees. Annual CH_4 emissions from soil in drained sites ranged from −10.9 to 20.4 kg CH_4 ha^{-1} year^{-1} (mean −4.6 ± 1.3 kg CH_4 ha^{-1} year^{-1}) and from –8.7 to 1355 kg CH_4 ha^{-1} year^{-1} (mean 142.1 ± 134.7 kg CH4 ha^{-1} year^{-1}) in undrained sites. Groundwater level depth of 20 cm acted as a threshold to determine if the soil acted as a source or sink of CH_4 emissions. While neither groundwater level depth nor soil temperature had a significant impact on the variation of instantaneous N_2O emissions. However, mean annual soil N_2O emissions in drained sites (1.7 ± 0.6 kg N_2O ha^{-1} yr^{-1}) and undrained sites (4.1 ± 1.4 kg N_2O ha^{-1} yr^{-1}) were significantly different. The results of the can be used as an emission factors in national greenhouse gas inventories of forest land in the hemiboreal zone.

The role of vascular plants and Sphagnum mosses regulating the net CO_2 exchange in a boreal peatland

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The project aims to provide further insights on how the greenhouse gas balance (CO_2 and CH_4) of boreal peatlands is influenced by vegetation, especially by the occurrence of vascular plants and Sphagnum mosses. Gas flux measurements are conducted with an automated chamber system providing high temporal resolution data in Degerö stormyr, an oligotrophic minerogenic mire. Inside some of the chambers, vascular plants or the total vegetation were removed and in combination with transparent and dark chambers, all components of the net ecosystem exchange can be measured or calculated. Differences and similarities in the response on CO_2 exchange of Sphagnum mosses and vascular plants to various environmental factors and plant phenology are investigated in diurnal to seasonal timescales. This will improve understanding of the processes influencing peatland greenhouse gas emissions and uptake, which will in turn improve the modelling of these emissions in a changing climate, and enhance the understanding of potential feedbacks of peatlands on climate change.

Abstract

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Soil respiration in rewetted peatlands – towards natural levels?

Peatland restoration starts with rewetting by blocking ditches. Successfull rewetting is anticipated to start restoration process towards the conditions of natural peatland. One of the major processes, affected by drainage and restoration, is soil respiration (Rsoil), which is a sum of respiration by heterotrophic (Rh) and autotrophic (Ra) organisms. Drainage increases the both components of Rsoil, through the increases in soil organic matter and litter decomposition and through increased tree root respiration. Increased Rhet in drained peatlands typically leads to the loss of soil C to the atmosphere. Successfull rewetting is expected to restore anoxic conditions and thus decrease Rhet and soil C loss. How good the Rsoil restoration success been in boreal drained peatland forests, is still inadequately known.

We measured total Rsoil and Rhet in 27 rewetted and 6 natural, fertile peatland forests in Southern and Middle Finland in 2021-2023. The rewetted sites were 1 to 28 years old. We used the closed chamber method with portable gas analyzers. Rhet was separated from total Rsoil by cutting roots and above ground vegetation from the plot. Fluxes were measured biweekly-monthly 17-18 times during 7/2021 to 3/2023. We will compare Rsoil in natural, drained and rewetted peatlands using this new material and old published data from Finnish peatlands, mainly of our own research group. We hypothesize to see a decrease of Rsoil in time after rewetting from drained towards natural conditions. We expect to see faster decrease in sites where rewetting has been more successfull, i.e. WT has risen faster and higher. We also expect to see higher seasonal Rsoil dynamics in rewetted than in natural peatlands, as WT dynamics appears to be higher in rewetted than in natural mires.

The simultaneous effects of groundwater table dynamics on greenhouse gas emissions and nutrient leaching in drained peatlands

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Peatland drainage causes CO_2 and N_2O emissions, and even though CH_4 emissions are typically lowered down, draining has a net warming impact on climate. In Finland, a major part of original peatland area is drained for forestry (55 %) and agriculture (10 %). Greenhouse gas (GHG) emissions from drained peat areas influence notably the net carbon sink of Finland and their reductions are seen as a potential way to reach national climate goals. Net GHG emissions of drained peatland can be lowered by raising groundwater table level (GWT), which in turn may promote the leaching of nutrients and lead to the eutrophication risk of nearby water courses. Therefore, more knowledge about the simultaneous effects of GWT dynamics on nutrient leaching and GHG emissions in drained peatlands is needed.

We aim to study how GHG emissions and nutrient leaching of different peatland land use types behave simultaneously in different GWT conditions and with different GWT dynamics. This study is done in collaboration with University of Oulu and Natural Resources Institute Finland (Luke).

We collected intact soil cores from five different peatland land use types with similar geological history: an undrained peatland, afforested peatland, abandoned peat field, and two cultivated peatlands with different peat depths. We conducted a column experiment with 60 cm high peat profiles (3/land use) in a laboratory. The experiment included three major phases: constant saturation, the gradual lowering of GWT and cyclical fluctuation of GWT. We measured GHG emissions from the top of the columns, sampled GHG samples and soil pore water samples from three depths, sampled leached water samples from the bottom of the columns, recorded moisture and redox conditions, and took soil samples for microbial analyses from three depths. We analyzed concentrations of nitrite/nitrate, phosphorus, ammonium, iron, and sulfate from soil pore water and leaching samples with colorimetric microplate analyses. After the experiment, we cut the columns into parts and analyzed soil properties of different column sections. The soil property results are compared to similar results from initial conditions.

Our study setup enables us to study the simultaneous effects of GWT dynamics on emissions of major GHGs and the dissolution and leaching of nutrients in various peatland usages. The peat profiles were collected from study sites, where Luke studies intensively GHG emissions and nutrient leaching. Therefore, our results provide valuable information for responsible water management in drained peatlands as part of the broader network of experiments.

UAS-SfM-derived Topography for Monitoring the Changed Flow Paths and Wetness in Minerotrophic Peatland Restoration

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Most northern peatlands are severely degraded by land use and drainage activities. Peatland restoration is an effective way to return the natural functions of peatlands in the catchment hydrology, discontinue the peat degradation and re-establish the long-term carbon sinks. The main aim of the restoration is to direct the water flows back to the pristine routes and to increase the water-table levels.

We introduced a novel approach to evaluate the changed surface flow paths and accumulation of water in peatland restoration by applying a UAS SfM (Unmanned Aerial System Structure-from-Motion) method to produce digital elevation models, flow accumulation maps and SAGA Wetness Index (SWI) models for the restoration sites and their pristine control sites.

According to our results, the hydrological restoration succeeded at the sites showing that the wetness increased by 2.9–6.9% and its deviation decreased by 13–15% 1–10 months after the restoration. Absolute changes derived with data from simultaneous flights at the control sites were 0.4–2.4% for wetness and 3.1–3.6% for the deviation. Also, restoration increased the total length of the main flow routes by 25–37% while the change was 3.1–8.1% for the pristine sites.

The validity of the topography-derived wetness was tested with field samples which showed a statistically significant correlation (R^2 = 0.26–0.42) for the restoration sites but not for the control sites. We conclude the water accumulation modelling based on topographical data potential for assessing the changed surface flows in peatland restoration monitoring. However, the uncertainties related to the heterogenic soil properties and complex groundwater interactions require further method development.

Typha latifolia and *Phalaris arundinacea* as recolonizing species in rewetted peatlands: Implications for soil carbon accumulation

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Tall helophytes such as common cattail (*Typha latifolia*) and reed canary grass (*Phalaris arundinacea*) often dominate after rewetting on peat soil used for agriculture. Though both species are well-adapted to waterlogged and anoxic soils due to their aerenchymous tissue, they still differ in their aeration mechanism, where *P. arundinacea* is dominated by simple diffusion and *T. latifolia* is dominated by pressurized flow. Therefore, recolonization by tall helophytes such as *T. latifolia* and *P. arundinacea* after wetland rewetting is likely to support considerably different carbon sequestration rates and carbon cycling compared with natural wetland sites.

In this study we carried out a mesocosm experiment where the two species grew at three different water levels relative to the soil surface (-15 cm, 0 cm, +15 cm). After eight weeks' growth, measurements of photosynthetic CO_2-response curves and chlorophyll fluorescence of photosystem II were carried out to detect flooding stress. After 10 weeks' growth, the plants were harvested and biomass production and allocation were quantified.

The study showed that *T. latifolia* had a stable photosynthesis for all water level treatments, which resulted in an overall higher aboveground and belowground production than *P. arundinacea*. In contrast, *P. arundinacea* showed a drastic decrease in photosynthesis and signs of damage to the photosynthetic apparatus with increasing water level. Moreover, increasing water level resulted in a higher allocation to the aboveground parts for *P. arundinacea* with a simultaneous decrease in belowground parts. From -15 cm to 0 cm, *P. arundinacea* had a 68% reduction in belowground biomass, which indicates that the direct contribution to the carbon pool can be drastically reduced when the water level increases within this range. High biomass production when the water level is close to the surface is an important aspect of peatland rewetting because this water table regime ensures low soil respiration and appropriate CH_4 emissions. On the other hand, recolonization of *T. latifolia* is likely to be a suitable contributor to the soil carbon pool due to its stable physiology and high biomass production even at different raised water table regimes.

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The effect of afforestation on soil respiration and methane flux at cutaway peatlands

A large amount of cutaway peatlands will become available for after-use in the near future. In Finland afforestation has been the main after-use for cutaway peatlands but only a few studies have been conducted on the climate impacts of afforestation. In the LULUCF sector, the goal is to increase carbon sinks and storages by afforesting waste lands such as cutaway peatlands to decrease greenhouse gas emissions. The main purpose of this research is to study the effect of afforestation on soil respiration and methane flux at cutaway peatlands.

This study was conducted at five cutaway peatlands in Pirkanmaa and South Ostrobothnia areas in 2021-2022. CO_2 and CH_4 fluxes, water table level (WT) and soil temperature at 5 and 30 cm depths were measured from altogether 14 sample plots. Closed chambre method was used to measure the greenhouse gas fluxes from vegetated (Rtot) and unvegetated (Rhet) measuring points. Total soil respiration (Rtot) was measured from the vegetated points and heterotrophic respiration (Rhet) was measured from the unvegetated points where the root connections were cut, and the above parts of ground vegetation was removed. The age of the forest stand and the thickness of the peat layer were recorded from each sample plot. The variation of forest stand age and peat layer thickness were quite well represented in the sample plots (0-57 years and 10-100+ cm).

The instantaneous Rtot fluxes varied between -39 and 1662 mg m^{-2} h^{-1} while the mean fluxes from sample plots were 58-694 mg m^{-2} h^{-1} (2021 data). The instantaneous Rhet fluxes varied between -39 and 836 mg m^{-2} h^{-1} while the mean fluxes from sample plots were 58-366 mg m^{-2} h^{-1}. Soil respiration was on similar level than in previous studies from cutaway peatlands. Compared to forestry-drained peatlands, soil respiration from cutaway peatlands was on slightly lower level. Soil temperature varied between 0 and 25 ℃ during the measuring period (July-November 2021). Both Rtot and Rhet increased with warmer soil temperatures up to a point after which soil respiration started to decrease.

Forest stand age correlated positively with soil respiration, soil respiration being larger when the forest was older. Peat layer thickness on the other hand correlated negatively, i.e. soil respiration was smaller in the sample plots with thick peat layer. Water table depth (WT) didn't influence the soil respiration according to the regression model.

The instantaneous CH_4 fluxes measured from the vegetated points varied between -0,148 and 1,206 mg m^{-2} h^{-1} while the mean fluxes from sample plots were -0,056-0,111 mg m^{-2} h^{-1} (2021 data). Open ditches situated in the non-afforested cutaway peatland site caused methane emissions. Forest stand age and peat layer thickness explained best the methane flux from cutaway peatland with multiple linear regression. WT didn't influence the methane flux. Non-afforested sample plots acted as methane sources and the sample plots with the more mature forest acted as methane sinks.

Based on this study, afforestation increases soil respiration and decreases methane emissions. However, the suitability of afforestation as an after-use method based on greenhouse gas emissions cannot be concluded based only on these results. Ecosystem level results will be reported later to estimate the climate impact of afforestation.

The power of long-term research for increasing our understanding of rewetted peatlands

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Peatlands are important carbon stores. However, the large majority of them, especially in temperate Europe, are now sources of CO_2 because they have been drained for agriculture, forestry or peat extraction. To stop these greenhouse gas emission sources more and more peatlands are rewetted. Yet, rewetted peatlands represent (at least locally) novel ecosystems and their characteristics and ecological functioning cannot be compared to their near-natural counterparts.

Due to the relatively strong influence of climatic variability and other larger scale factors like occasional flooding on the realised GHG exchange, long-term monitoring projects in rewetted peatlands are necessary to foster our understanding of the ecological functioning of these systems. Based on over 10-years of accumulated data from a long-term research site, complemented with further results from different rewetted peatlands, I will show how long-term monitoring can help us to better understand these novel ecosystems.

The effect *Sphagnum* moss harvesting has on GHG emissions on boreal peatlands

Abstract

Sphagnum moss harvesting from Northern peatlands is a relatively new form of land use in Finland. Moss is harvested by commercial operators from bogs to be used as a substrate for plant cultivation, bedding for cattle or as a thermal insulator. The *Sphagnum* moss is considered a viable option for peat that has been traditionally used for these purposes. As the boreal peatlands where moss is harvested form a major soil carbon (C) stock and *Sphagnum* based growing media is proposed as more sustainable than peat, it is necessary to study how *Sphagnum* harvesting affects peatland greenhouse gas exchange (CO_2 and CH_4) right after and during the vegetation recovery following the harvesting. The hypothesis is that right after harvesting the peatland will be a source of CO_2 and CH_4 but gradually when the vegetation starts to renew itself the peatland becomes CO_2 sink again. However, the renewal of the vegetation and the time it takes seems to vary, depending on factors like the harvesting method, water table depth and vegetation composition that needs to be studied further. Especially the development on CH_4 emissions is likely dependent on the direction and speed of vegetation recovery.

The study is done on eight boreal bogs in the Pirkanmaa region, Finland where mosses have been harvested in the years 2015 – 2021. The study sites have a harvested and non-harvested areas, each with five measuring points from where net ecosystem exchange (NEE) and CH_4 flux is measured using closed chamber method over the growing seasons 2022–2023. Measurements made with different levels of light intensity, complemented with temperature and water table depth and the vegetation green chromatic coordinate (GCC) and vegetation coverage are done in 2-3 weeks intervals.

The collected data provides the basis for deeper understanding of the ecosystem level changes in the harvesting sites and sheds light on what are the most impactful abiotic and biotic factors that contribute to the balanced renewal of the vegetation and the carbon storage in these peatlands. Based on these finding a statistical model is build, to describe the relationship between these different factors that contribute to the carbon cycling. These results will be used in the Life Cycle Assessment (LCA) of the moss-based end product and will help to guide the commercial harvest to be done on sites and with methods that support lowest greenhouse gas emissions.

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The perspective from peatland restoration (carbon) projects – a call for cooperation with science

Restoration of mire ecosystems on the drained peatlands is a recognized necessity for both climate mitigation, climate adaptation, restoring natural water flow regimes as well as addressing the biodiversity crisis and ecosystem degradations in Europe. Currently new opportunities for this arise due to carbon financing. This is, however, a minefield and many initiatives may not use the best knowledge and best methods. Wetlands International together with partners, is developing projects in Europe (including Sweden) to improve standards for such projects. For such initiatives there is a need to get input from science regarding tested methodologies for project-level GHG-monitoring and assessments and data, such as emission factors from restored – rewetted peatlands previously used for forestry. WI also participates in Wet Horizon (Horizon 2020) project to stimulate and facilitate collecting and making available such data, on European scale. One of our ambitions is to set up a meta-database of the restored (rewetted) peatlands with GHG measurements and (annual) emission factors. We present a practical insight from the project as well as the results of European survey where the carbon and ghg monitoring issues were explored with the wetland restoration community (WaterLands project, Green Deal Horizon 2020). Additionally, we discuss the land selection process in the North of Sweden where a large-scale peatland restoration initiative, "Rewilding Climate Solutions" has been launched.

Peat respiration in drained peatland forests under varying tree harvest regimes

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Peatland drainage for forestry aims to increase the volume of aerobic peat available for tree roots, but simultaneously makes the previously anoxic peat available for aerobic decomposers, resulting in increased CO_2 emissions through respiration. To mitigate these CO_2 emissions a proposed solution is to switch from clearcuts to continuous cover forestry targeting to regulate water table (WT) with tree stand evapotranspiration and maintain an optimum WT low enough for tree growth and high enough to protect peat from decomposition. However, it is yet unknown how tree stand volume and site properties interact in controlling WT and peat decomposition.

We aimed at quantifying the effect of tree harvest intensity on WT and heterotrophic peat respiration (R_{HP}) at eight drained peatland forests of varying fertility. We conducted chamber measurements of R_{HP} at plots where autotrophic root respiration was excluded by trenching and the respiration of mosses and fresh litter was excluded by temporarily removing the upmost 5 cm soil layer before the measurements. Seasonal R_{HP} measurements were conducted up to nine years after tree harvesting, with intensities varying from clearcut to different selection harvest regimes and unharvested controls.

Unharvested controls had an average WT depth of about 50 cm, which rose after tree harvesting with the largest increase of 22 cm observed in clearcut sites and a smaller effect found in the selection harvest treatments. The highest R_{HP} rates of 307 mg m^2 h^{-1} were measured at the most nutrient rich site types. Deeper WT and higher tree basal area left at site after harvest increased R_{HP}, and these effects differed among the peatland forest site types. However, although the effect of tree harvest intensity was significant, the differences between the harvest treatments were small in magnitude. The largest harvest-induced change was the decrease in R_{HP} after clearcut. This suggests that although WT depth of drained peatland forests can be regulated with the tree stand volume, the resulting shallower WT may still be too deep to markedly reduce R_{HP}.

Greenhouse gas exchange of different fen paludicultures during establishment

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Drainage is necessary for conventional agriculture on peatlands, but this practice causes high emissions of the greenhouse gases (GHG) carbon dioxide (CO_2) and nitrous oxide (N_2O). Paludiculture is an option to mitigate these adverse environmental effects while maintaining productive land use. Whereas the GHG exchange of paludiculture on rewetted bog peat, i.e. *Sphagnum* farming, is relatively well examined, data on GHG emissions from fen paludicultures is still very scarce. As typical fen paludiculture species are aerenchymous plants, the release of methane (CH_4) is of particular interest when optimising the GHG balance of such systems. An option to reduce the methane emissions upon rewetting is the removal of topsoil but retaining a nutrient rich topsoil might foster the biomass growth.

In this project, *Typha angustifolia*, *Typha latifolia*, and *Phragmites australis* are grown at a fen peatland formerly used as grassland. Water levels will be kept at the surface or slightly above it. In parts of the newly created polder surrounded by a peat dam, the topsoil is removed. In order to be able to separate the effects of topsoil removal and water level, four smaller sub-polders are installed. Here, the water levels can be adjusted independently from the main polder. Greenhouse gas exchange is measured for all three species with and without topsoil removal. Additionally, a reference grassland site close by and a site on the dam are included in the measurements. Using manual chambers and a portable analyser for both CH_4 and CO_2, GHG measurements are carried out every two to four weeks on a campaign basis. Here we present GHG balances of the first two years after planting the paludicultures.

Despite of imperfect water management during the first year after planting, all paludiculture species were both a net CO_2 and GHG sink regardless the topsoil treatment. During this period, fluctuating water levels resulted in low CH_4 emissions while N_2O emissions were of greater importance regarding the GHG balance. Due to more stable water levels in the second year, higher methane emissions are expected. Carbon export by the first biomass harvest will also be taken into account.

Peatland methane dynamics in a changing climate: A 13-year time series of a boreal fen in Northern Finland

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Boreal peatlands are a major source of global wetland methane emissions. With ongoing climate change, these emissions could rise sharply in future, further enhancing climate change. Yet, long-term studies evaluating the impact of climate change on boreal peatland ecosystems are scarce. We have monitored methane emissions at a boreal fen in Lompolojänkkä, Northern Finland (ICOS ecosystem class II site) for 13 years (2007-2019) using the eddy covariance technique, accompanied by measurements of abiotic and biotic variables such as peat temperature, water levels, and vegetation parameters. Peat temperatures strongly drove methane emissions, i.e., methane emissions were increasing markedly with peat temperature. Year-to-year variation in CH_4 emissions was correlated to year-to-year variation in peat temperatures. Annual variation in water levels had no significant impact. Our results confirm that peat temperature explains CH_4 variation to a large extent.

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A study concept: The use of horticultural peat in Estonia and its actual carbon dynamics

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The major quantities of extracted peat are used in horticulture as a substrate for plant growth – 7.8 Mt in the EU and 0.09 Mt in Estonia each year – though similarly to energy peat its whole carbon content is considered as an emission. Accordingly, a study to find out the substrate amounts, using practices and resulting actual greenhouse gas emissions from the use of horticultural peat was started from January 2023 in Estonia. The aim of the current study is to find out how large part of the extracted and horticulturally used peat and over how long period of time causes greenhouse gas emissions in Estonia. For that, we have chosen three types of plant cultures that are widely grown on peat substrates: (1) the ones later planted to the soil with the peat substrate (tree seedlings); (2) the long-living plants sold to the customer within the peat substrate (hyacinths and azaleas); and (3) the ones sold to the customer within the peat substrate that after the plant consumption will be disposed (salad). CO_2, CH_4 and N_2O emissions from these species are being measured during their growth cycle with a dynamic chamber. Also, the carbon contents of their above- and belowground parts as well as the peat substrate are analyzed during their growth cycle. The measured emissions will be up-scaled according to the statistics of the used amounts of horticultural peat in Estonia. As due to plant diseases the substrate cannot usually be used multiple times, the after-use alternatives of the already used substrates will be analyzed. The used amounts, grown cultures, substrate additives, using and after-use practices will be found out through a survey among the plant growers. According to the latter information, the possibilities of circular peat use and actual climate effect of horticultural peat use will be assessed.

Peatland microbial photosynthesis controlled by peatland type but not water level drawdown

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Phototrophic microbes fix 6% of all terrestrial carbon globally, and they are highly abundant in peatlands. Not surprisingly, microbes play a role in peatland carbon fixation: on average, 10 % of carbon fixation in the bryosphere (mosses and associated micro-organisms) is conducted by microbes, but it can reach up to 30 %. However, only few studies have been focusing on the phototrophic microbes on peatlands so far.

Peatland drying is an expected response to the ongoing climate change and following increased evaporation. Long-term drying changes habitat conditions for soil microbes by several mechanisms, including decreased moisture availability, changes in vegetation and shading, and increased nutrient availability. We tested the effects of a long-term water level drawdown (WLD) on the photosynthetic capacity of peatland microbes in three peatland types.

The data originates from Lakkasuo WLD experiment, Central Finland. The experiment was begun in 2000-2002, and it simulates climate-induced drying. Microbes were extracted from moss samples and their photosynthetic capacity was measured in a laboratory using PhytoPAM (Phytoplankton Analyzer, Heinz Walz GMBH, Effeltrich, Germany). Our results showed no significant impact by WLD, however, the photosynthetic activity varied significantly between peatland types, being highest on the most nutrient-rich site and lowest in the most nutrient-poor site.

Abstract to poster session:

"Nordic-Baltic Workshop on Greenhouse Gas Exchanges and Carbon Cycling in Managed Peatlands", June 12-15 (Mon-Thu), 2023, in Vindeln, Sweden

How will the preferred after-use alternatives of cutover peatlands affect the national greenhouse gas budget in Finland?

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Abstract
More and more attention has been drawn to the greenhouse gas emissions in the Land use, Land use Change and Forestry sector (LULUCF). In the Finnish LULUCF sector, the soil-originated emissions from the after-use of cutover peatland have become a more relevant question. This is due to the rapid increase in the amount of former peat harvesting sites, caused by the decline in the combustion of energy peat due to its high CO_2 emissions. According to the IPCC peat is fossil due to its slow formation.

We conducted a nationally representative survey to study which after-use options of cutover peatlands landowners prefer, and based on the preferred after-use options, we estimated the impact on national greenhouse gas emissions in the Finnish regions in 2035. We found that the most popular after-use alternatives were afforestation (71%), agriculture (24%) and production of wind and solar power (22%) when the respondent chose three the most attractive alternatives. However, there were clear regional differences in the preferred after-use method which might lead to, if realized, different soil-originated emissions at the regional level in the near future. The preferred after-use choices could produce emissions of 0.35 Mt CO_2 eq y^{-1} by 2035 in Finland. Most of these emissions (30.1%) would come from South Ostrobothnia in western Finland, mainly due to the indicated high interest in the agricultural after-use. We suggest that multiple support mechanisms should be used to encourage landowners prefer climate friendly after-use methods to meet the climate emission reductions of LULUCF sector in Finland.

How much particulate organic matter is lost after ditch cleaning? A Swedish case study

Eliza Maher Hasselquist, Mika Nieminen, Lina Polvi Sjöberg, Hjalmar Laudon, and Hannu Marttila

One million kilometres of ditches have been dug across the Swedish landscape, a majority with the goal to improve forest production. Most were dug in the 1930s and the forests that are associated with these drainage ditches are now ready for harvest, leaving the question of if we should clean them or not after forest harvest. Finland researchers have done extensive research on the effects of ditch cleaning on water quality, but the history and ditch configuration is different from Sweden, and it is unclear to what extent it can apply to Sweden. In a catchment scale study in northern Sweden started in 2018, we measured suspended sediments in three ways 2 years before, during and one year after ditch cleaning. We sampled total suspended solids (TSS) ~35 times per year, monitored turbidity as a proxy for TSS every 15 minutes during the snow-free season, as well as collected suspended sediments using time integrated mass flux samplers (TIMS). We identified the total mass of sediments transported out of the catchments as well as the proportion that is organic, and thus, approximately how much carbon (C) is lost via particles after various ditch cleaning.

Impacts of partial harvest and clearcut on methane and nitrous oxide emissions of forestry-drained boreal peatlands

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Drainage can cause large greenhouse gas emissions from peat soils. While the effect of water table (WT) depth on these emissions at peatlands with developing forests has been extensively studied, the impacts of tree stand cuttings have received little attention so far.

We measured methane and nitrous oxide emissions from soil during several years following various types of cuttings in peatland forests in Finland. The data include two sites with thinning from below, two sites with overstorey harvesting, two sites with selective thinning from above, four sites with small-gap harvesting, and five sites with clearcut. All the sites had uncut plots as control treatment.

Changes in WT depth varied depending on harvesting intensity, and this was an important control of methane emissions. If WT rose high enough, soils turned into methane sources. On the other hand, even a considerable WT rise did not necessarily cause methane emissions if water table stayed well below soil surface.

The effect of cuttings on nitrous oxide emissions was not clearly controlled by the WT depth. Instead, nitrous oxide emissions likely result from the excess nitrogen due to release from logging residues and dying ground vegetation and decreased nitrogen uptake by living vegetation.

In the presentation, we discuss the longevity of the impacts of cuttings and suggest emissions factors for the various cutting methods.

Impact of soil moisture changes on nitrogen cycle microbiome during thawing-freezing experiment in a drained peatland forest

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Freeze-thaw events are well-known as initiating N_2O emission from soil. Although there are several hypotheses explaining the impact of freeze-thaw cycles on soil N_2O emissions (e.g., disruption of soil aggregates exposing physically protected organic matter to rapid mineralization by microorganisms; the death of microorganisms, fine roots, and mycorrhiza during the freeze, providing rapidly decomposable organic matter for the thaw; the death of fine roots decreasing competition between roots and microorganisms for nitrate, the main substrate for N_2O production), a generally accepted theory of the impact of freeze-thaw on N_2O fluxes is still missing. Some previous studies demonstrated that increasing soil water content (SWC) at the end of the freeze-thaw event initiated rapid N_2O emission.

To check this relationship we conducted a 3-week experiment of 5 thaw-freeze events in March 2022 using artificial heating with electrical cables installed in collars of greenhouse gas sampling chambers conducted in a drained Downy birch peatland forest. The main aim was to analyse the impact of short-term thaw-freeze cycles on the diversity and abundance of control genes of soil nitrogen cycle responsible for N_2O fluxes. Soil temperature, SWC, NO_3-N, NH_4-N, abundance of bacterial and archaeal *amoA*, *nirS*, *nirK*, *nosZ*I and *nosZ*II genes in soil, were measured in 9 replicates. N_2O gas samples were taken in 9 replicates with opaque chambers before, during and after the heating event, and analayzed with GC. In morning hours the 0.5-1.5 cm thick top layer of soil was frozen and heating initiated rapid SWC change. Reference N_2O samples were taken from chambers installed above the 0.5 m snow cover.

Preliminary results show increasing abundance of denitrification genes at the end of thawing experiment linked with the increasing SWC and N_2O emissions. We assume that in N-rich drained peat even the short-term heating of snow-free peat surface initiates both microbial activity and consequent N_2O emission.

Greenhouse gas emissions from drained nutrient-rich organic forest soils in Estonia

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In the terrestrial biosphere, peatlands constitute the most important long-term carbon storage, covering only 3% of the land surface yet accounting for approximately one-third of all carbon storage. The degradation of peatlands is a major and growing source of nutrient discharge; any changes in the ecology and hydrology can affect peatland biogeochemistry and, together with the predicted global warming, may result in significant variations of GHG fluxes. Drainage for agriculture, forestry, and other purposes increase the aerobic decomposition of organic matter, turning the wetland from a carbon sink into an emitter of carbon dioxide. Lower water levels and soil water content in drained histosols lead to reduced CH_4 emissions. In contrast, N_2O emissions can increase due to increased mineralization and more favorable conditions for nitrification.

However, GHG fluxes in peatlands have a spatial and temporal (interannual, seasonal, diurnal) variability, and detailed information on drained nutrient-rich organic soils in the hemiboreal zone remains scarce. We conducted a two-year-long study with different tree species (Scots pine, Norway spruce, Downy birch, and Black alder) in a drained peatland and a natural wetland (fen) as a reference site in Estonia. In this presentation, the first-year results will be presented.

The GHG fluxes were measured twice per month using the manual static (CH_4 and N_2O) and dynamic (heterotrophic respiration (CO_2)) closed chamber method from Jan 2021 to Dec 2022. Additionally, groundwater level, soil temperature, and moisture were measured hourly with automatic loggers to determine soil conditions.

Our preliminary results show that all drained forest sites were high emitters of CO_2 (716 ± 47.9 mg m^{-2} h^{-1}; mean ± SE) during the vegetative season. Soil CO_2 fluxes were highest in summer, and the temporal variability was associated with soil water content within the sites. Overall, drained forest soils were annual methane sinks (−58.6 ± 2.5 µg m^{-2} h^{-1}), while the studied reference fen has the lowest uptake potential of –11.9 ± 4.3 µg m^{-2} h^{-1}. The birch forest with poor drainage soil consumed less CH_4 than heavily drained birch. Methane flux had a statistically significant correlation with water level and soil temperature. Most of the sites were annual emitters of N_2O; forest sites were more robust emitters (48.5 ± 7 µg m^{-2} h^{-1}) than fen soils (27.4 ± 8.2 µg m^{-2} h^{-1}). Higher N_2O emissions and temporal variability were associated with sites where the water level had high seasonal fluctuations. N_2O flux was controlled by soil temperature and moisture content, and peaks in emission occurred during the spring (freeze-thaw) period.

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CAN WINTER HARVESTING OF WETLAND PLANTS INCREASE THE CARBON LOSS FROM THE ECOSYSTEM?

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Constructed wetlands are often planted with different emergent macrophytes such as *Phragmites* spp and *Typha* spp. to efficiently reduce pollution caused by nutrient loss from agricultural fields. However, biomass harvesting is needed to maintain the treatment efficiency in the wetland. In addition to constructed wetlands, vegetation harvesting is a common approach to manage the lake and sea shorelines and reduce the spreading of fast-growing macrophytes or invasive species. In boreal countries, harvesting is often carried out on the ice during wintertime. However, little is known about how harvesting could affect ecosystems' annual carbon balance.

The study was carried out to estimate wintertime gaseous carbon fluxes during the harvesting of two wetland plant species, *Typha latifolia* and *Phragmites australis*, from a constructed wetland in Southern Estonia. A trace gas analyzer (LI-7810; LI-COR Biosciences, Lincoln, NE, USA) was used to measure the CO_2 and CH_4 emissions at an in-stream free surface flow constructed wetland during the peak of the winter season. The catchment area of Vända CW is 2.2 km^2, with approximately 62% of it under intensive agricultural management.

Results showed that wintertime fluxes are of importance. Over 70% of the CO_2 wintertime fluxes originated from plots with *Typha latifolia*, while *Phragmites australis* emitted over 80% of CH_4 fluxes. The fluxes from *Typha latifolia* and *Phragmites australis* ranged from 110 to 401 µg CH_4-C m^{-2} h^{-1} and 41 to 96 mg CO_2-C m^{-2} h^{-1}, and from 610 to 3246 µg CH_4-C m^{-2} h^{-1} and 9.4 to 42.1 mg CO_2-C m^{-2} h^{-1}, respectively. In contrast, no emissions were seen from the ice-free/open-water zones.

Previous studies have shown that vegetation harvesting should be carried out at the end of the growing season to maximize nutrient removal and keep CH_4 emissions low. Some studies have suggested that winter harvesting will result in lower nutrient removal but also close to zero gas emissions. Our study, on the other hand, shows that the emission of CO_2 and CH_4 can increase substantially after harvesting and should not be overseen when calculating the annual carbon budgets for managed wetland ecosystems.

Abstract

Long-term changes in the pore and runoff water quality in restored peatlands

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Restoration is seen as an important tool to improve the status of degraded peatlands. In Finland over half of the mire habitat types are endangered mainly due to drainage-induced succession towards more forested type ecosystems. National and European Union (EU) level strategies to improve nature conservation have targets for increasing the allocation of restoration actions to peatlands in Finland, and thus also more understanding of the long-term impacts of peatland restoration is urgently needed.

Drainage lowers the water table and exposes peat to decomposition. Restoration aims to raise the water table level of a peatland but also causes a new disturbance to surface layers often resulting in elevated nutrient and organic carbon concentrations in pore and runoff waters. Typically, the water quality disturbance starts to dampen out in the subsequent years after restoration, but the speed and disturbance level depend on e.g., peatland type and trophic level. Knowledge of the long-term (over 10 years) effects of restoration actions is lacking.

The hydrology of drained, restored, and pristine counterpart peatlands have now been monitored for almost 15 years in the Parks and Wildlife Finland's (Metsähallitus) extensive peatland restoration monitoring network. The data consists of high-frequency water table data and pore water quality measurements (four times per growing season) from the frost-free period from 46 sites all over Finland with varying nutrient levels and openness. Additionally, runoff water quality and quantity have been monitored in three pristine and seven drained and restored sites. In this study, we report the long-term effects of peatland restoration on the water table and water quality in different peatland types. We also focus on understanding the connection of water quality variation in pore and runoff waters, aiming to simplify the practical evaluation of peatland restoration success.

Abstract for Nordic-Baltic Workshop on Greenhouse Gas Exchanges and Carbon Cycling in Managed Peatlands

Quantifying the Mobilization of Dissolved Organic Carbon (DOC) of an Extracted Peatland in Eastern Quebec, Canada

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The objective of this research was to examine how changes in peatland hydrology affect the transformation and transportation of DOC in an actively extracted peatland nested within a larger intact peatland, located in Eastern Quebec. Our research is aimed at exploring the mechanisms that transport DOC out of the peat matrix by drainage and compare DOC flows from natural and extracted peatland sites using a combination of ^{13}C-DOC and ^{2}H-H_2O measurements. Fluxes of CO_2 and CH_4 were measured simultaneously in drainage channels using static chamber measurements and compared to determine the correlation with DOC measurements.

The collected data is currently being analyzed and the results will be presented in the coming meeting. We anticipate that the water and DOC are transported primarily through preferential flow (macropore flow), immediately following a large precipitation event (or "flushing events"). The periods of time between these large flushing events allows DOC to accumulate within the peat matrix near the surface therefore, we also anticipate seeing that larger periods of time between large flushing events will release greater amounts DOC into the drainage channels. We expect to see that only a minimal proportion of DOC within the drainage channels is originating from the natural section while most DOC should be sourced from the extracted section. The ^{13}C-DOC and ^{2}H-H_2O data will be used to identify the origins of the DOC and water entering the drainage channels. This will allow us to use a two-way mixing model and partition the source of DOC into natural and extracted sites. Correlation analysis will be shown for the DOC measured and the CO_2 and CH_4 fluxes, expecting a positive correlation between DOC and the gas fluxes.

This research will improve our understanding of DOC transport via lateral drainage in extracted peatlands, highlighting the differences in transport mechanisms between natural and extracted sites.

Leaching of nutrients and solutes from controlled drainage cultivated peatland in Ruukki, Finland

Authors: Tung Pham, Markku Yli-Halla, Hannu Marttila, Timo Lötjönen, Maarit Liimatainen, Miika Läpikivi, Jarkko Kekkonen, Björn Klöve, Erkki Joki-Tokola

Abstract

Drained peatlands are favorable environments for cereals and grass production, though they can be major sources of increased leaching of nitrogen (N), phosphorus (P) and organic carbon. However, extensive monitoring of leaching from cultivated peatlands is scarce. The Ruukki field, located in Siikajoki, Finland, is an agricultural peat site drained with subsurface pipes, the peat thickness being 20 – 80 cm. This article documents the concentrations and loading of N, P, total organic carbon (TOC) along with other supporting water quality parameters of the field discharge in 2018-2021. Subsurface leaching of N was 25 kg ha^{-1} $year^{-1}$ (11-40 kg ha^{-1} $year^{-1}$, 74% as nitrate NO_3-N). Less N leaching was recorded from plots of thinner peat topsoil and those with grass cover, as the majority of N leaching originated from thicker peat plots (bare/under barley) in spring. Leaching of N strongly decreased during the period of vigorous grass cover. Significant N leaching also occurred during the mild winter of 2019-2020, characterized by alternating freeze and thaw periods. Annual P loading in subsurface drainage was 0.30 kg ha^{-1} (0.20-0.43 kg ha^{-1}), low compared to average cultivated soils. It was estimated that 13% of total N and 50% of total P leaching occurred in surface runoff. Leaching of TOC was significant at 87 kg ha^{-1} $year^{-1}$ (31-137 kg ha^{-1} $year^{-1}$). Abundant loading of sulfate and acidity suggests oxidation of sulfidic materials in the subsoil. Leaching concentrations correlated with the discharge quantity, suggesting that conversion and accumulation processes during the dry periods resulted in leaching during high discharge periods. The results show the importance of avoiding bare peat soil for NO_3-N leaching reduction, even during wintertime.

Impact of rewetting on the carbon balance of a drained nutrient-poor peatland forest in Northern Sweden

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Natural peatlands represent a small but long-term carbon sink. For forest management approximately 1.5 to 2.0 million hectares in Sweden were drained over the past century. The Swedish government has therefore identified peatland restoration as part of its strategy to reduce greenhouse gas (GHG) emissions in the land use sector. However, while peatland restoration may lead to reductions in CO_2 emissions from drained peatlands, rewetted peatlands show initially higher CH_4 emissions. Most empirical evidence in the boreal zone was obtained from sites in Finland, while data is lacking in Sweden. In our study, we investigate the spatial variability of GHG exchange before and after peatland rewetting, determine the biogeochemical factors that govern these variations and examine the overall impact of rewetting on the GHG balance of drained peatland forests in boreal Sweden. We use the manual closed-chamber method to measure the soil-atmosphere fluxes of CO_2 and CH_4 along six transects at the Trollberget rewetted peatland forest near Vindeln, Sweden. The rewetting actions at the site were carried out in November 2020 and the drained conditions have been kept as control at the outlet of the mire. We observe higher CH_4 emissions and lower CO_2 emissions compared to drained conditions, however, no significant change in the soil-atmosphere C exchange within the initial years following rewetting.

Spatial and temporal variability in fluxes across Degerö Stormyr, a 23 year flux record is compared to three new Eddy Covariance sites across a boreal peatland complex

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Northern mires respond to climate drivers in a highly in consistent way, both spatially and over time. But what is more important? Variability in fluxes across years and decades? or spatial variability across mire complexes? Degerö Stormyr is uniquely placed to answer this question. It is one of the oldest running flux sites situated on a mire anywhere in the world. For one location we have 23 years of flux data, which is being re-processed using the most up-to-date techniques. This time series is now complemented by a further 3 years of data from three additional flux sites. In this presentation I will present the most up-to-date reprocessing of the flux data for Degerö Stormyr and compare this to the spatial variability in CO_2 flux across the broader mire complex. From this work we hope to determine how static (or not) the mire is in response to water table drawdown as well to check for trends in fundamental properties such as the photosynthetic capacity of the ecosystem. We will then compare such variation with that recorded spatially across the mire complex.

Helena Rautakoski

Abstract for Nordic-Baltic Workshop on GHG Exchanges and C Cycling in Managed Peatlands in June 2023

CO2 fluxes and their controls in drained nutrient-rich peatland forest: Does selective harvesting help to reduce soil emissions?

Greenhouse gas emissions of drained peatlands have received attention in recent years as countries are aiming to minimize emissions on land-use sector as part of their climate change mitigation actions. In Finland, drained peatland forests are actively used for forestry and there's a pressure to be able to reduce peatland forest soil emissions while still being able to use the wood. Continuous cover forestry has been suggested as one solution, although the wish for climate benefits largely relies on hypothesis.

We tackle this question of the impact of continuous cover forestry on the CO2 emissions of drained peatland forest soils by using recent eddy covariance and automatic chamber data measured in a nutrient-rich peatland forest in Southern Finland. Year-round CO2 flux data before and after selection harvest is examined to see if harvesting has resulted in chances in the net CO2 balance of the forest or affected CO2 exchange at the forest floor. Heterotrophic respiration data is used to find controls of peat decomposition and to evaluate the impact of changing ground water table level on soil CO2 emissions.

The results provide understanding of peatland forest CO2 flux dynamics showing how CO2 fluxes on ecosystem scale, on forest floor and soil alone are controlled by environmental conditions and affected by selective harvesting. Therefore, the results contribute to the understanding needed to reduce emissions originating from drained peatlands.

Surface energy balance on boreal pristine and managed peatlands

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Managed or drained peatlands in the boreal zone (especially in Finland and Sweden) constitute a large portion of the total peatland area. Restoration of peatlands by rewetting might offer considerable climate change mitigation potential as peat decomposition and resulting carbon dioxide emissions are reduced. Rewetting also changes the biophysical surface properties, which leads to changes in local microclimate, e.g. surface temperature. To fully understand the climate change mitigation potential of peatland rewetting, also these local effects need to be estimated properly.

Surface energy balance (SEB) describes the division of incoming radiation energy to the turbulent heat fluxes in the atmosphere and heat conducted into the soil. We first determine the components of SEB and their diel and seasonal variation in boreal pristine and managed peatlands. Furthermore, we assess how boreal peatlands respond to changes in surface parameters and driving meteorological variables, and how different surface characteristics lead to different responses.

We analyse here long-term SEB data from three pristine peatland sites (Halssiaapa, Kaamanen and Lompolojänkkä) located in northern Finland as well as from one or more managed peatland sites in southern Finland. Sensible and latent heat fluxes were measured using the eddy covariance method, and other measurements include radiation components, soil heat flux and meteorological variables. The measurement data are filtered and gap-filled using state-of-the-art methods.

The SEB of the peatland ecosystems is established based on the measured data. The changes in the aerodynamic surface temperatures are attributed to the changes in the most important biophysical properties using the two-resistance mechanism method for parametrizing the latent heat flux. The results establish a better understanding of SEB in boreal peatlands and indicate what kind of changes are expected from changes in their land cover. The sites differ in their trophic status and vegetation, which provides additional information about the connection of environmental and ecological variables to the microclimate response to land cover change.

Peatland restoration leads to global and local impacts, both of which should be taken into account and balanced against each other. Understanding the SEB of pristine peatlands helps to attribute the local climate changes to the changes in surface properties after restoration. Understanding the local effects of peatland restoration helps to better understand its potential for climate change mitigation and thus to prioritize restoration efforts and methods.

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Climate and management effects on peatland carbon dynamics: An experimental mescosms approach

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There is concern that peatlands are degrading in the face of global warming and diminishing their function as climate change mitigation, shifting from carbon sinks to carbon sources. The situation may be more severe in peatlands that have already been drained for forestry or other human utilizations. Peatland restoration is regarded as an important climate change mitigation strategy, protecting peat decomposition and re-establishment of vegetation, which can maintain negative climate feedback (i.e. carbon sequestration in form of biomass). Few studies have examined the initial response of peatlands to various ditch maintenance activities, but the impact of climate change on boreal peatlands under different management strategies has not yet been investigated. Since January 2023, we have been conducting a mesocosm experiment in the climate control rooms to fill in this knowledge gap. This study aims to investigate the impact of both current and a moderate future climate scenario (RCP 4.5) on a) methane and carbon dioxide emissions, b) hydrology and flood control services, c) water quality and, d) decomposition of boreal peatlands under different ditch maintenance treatments: 1) restoration, 2) ditch cleaning, and 3) left alone.

Abstract for oral presentation session:

“Nordic-Baltic Workshop on Greenhouse Gas Exchanges and Carbon Cycling in Managed Peatlands”, June 12-15 (Mon-Thu), 2023, in Vindeln, Sweden

Implementation and evaluation of Landscape-DNDC model for forestry management scenarios at Lettosuo peatland site in southern Finland.

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Abstract

Nutrient rich peatlands are drained for forestry purposes. Trees grown in the peat soil are taking up carbon, however a well aerated peat soil is a source of carbon. When forest is harvested, the wood products can be considered as a carbon source e.g. when wood products are used as timber or in paper industry, while harvest residues are adding carbon to the soil carbon pool. Process based model Landscape De-Nitrification De-Composition (LDNDC) has been used to simulate a drained peatland forest ecosystem for Lettosuo in southern Finland. To our knowledge LDNDC model has not been used to simulate peatland forest yet. LDNDC utilizes several sub models for physiology, biogeochemistry, hydrology and microclimate. Multiple species can be simulated simultaneously as a mixed forest cohort, and contributions of the ground vegetation can be included. Different management procedures of the forestry industry, e.g clear cutting or selection cutting have been simulated successfully.

Here, a 47 year old forest, which had pine as a dominant tree species along with spruce and birch as a secondary canopy and ground vegetation was simulated from seedlings for both management scenarios and for a patch of untouched reference forest. Local meterological data was used to drive the model and the amount of carbon storage in the soil was originally set at 186 kgm^{-2}. Eddy covariance and chamber measurements from both management sites and reference site were used to evaluate model performance. Model captured the net ecosystem exchange (NEE), gross primary production (GPP), terrestrial ecosystem respiration (TER) nicely. Model also captured the changes in soil moisture and water-table due to the applied forest management processes. Correlation coefficient, root-mean-square deviation and Nash-Sutcliff efficiency for reference forest were for NEE (0.86, 11.52, 0.66), GPP (0.97, 10.24, 0.93), TER (0.95, 11.51, 0.79) and methane (0.64, 0.002, 0.39, respectively). Leaf area index (LAI) of the combined vegetation cohort represented the measured LAI quite well along with the growth of the individual vegetation cohorts. Successful implementation of the model resulted in application of the model to simulate future forestry scenarios, which can be utilized to provide recommendations for forest management that will ensure reduction in forestry related emissions and improve the possibilities for the peatland forest to act as a sink of carbon.

Forget about methane: Planting *Typha* minimizes methane emissions from rewetted peat soil

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Peatlands that have been drained for agriculture are one of the worst anthropogenic contributors to global carbon emissions; globally, drained peat soils emit >2 gigatonnes of CO_2-equivalents per year, some 30% of all agricultural emissions. The solution to this problem is retiring farmland and restoring wetland hydrology by rewetting. Raising the water table slows peat oxidation and allows re-colonizing wetland plants to add carbon to the soil. However, reflooding raises the spectre of enhanced methane (CH_4) emissions, an oft-cited bugbear for wetland restoration. In this experiment, CH_4 fluxes were measured over an entire growth season from peat cores with or without *Typha,* subjected to four different hydrologies. In cores without plants, CH_4 fluxes remained low in partially drained treatments, but were particularly notable in cores flooded with 10 cm standing water. This is consistent with enhanced methanogenesis in anaerobic soils isolated from the atmosphere by a standing water layer. In contrast, CH_4 emissions in cores planted with *Typha* were negligible. The most likely explanation is effective soil oxidation by roots of *Typha*, a species with extensive aerenchyma and efficient internal oxygen transport, inhibiting methanogenesis and enhancing CH_4 oxidation. Our study suggests that CH_4 emissions are not a significant problem when rewetting and restoring peat wetlands. They can be effectively neutered by appropriate water level and vegetation management.

Evaluating the GHG balances of drained and restored peatland forests in boreal Sweden

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Abstract

Rewetting of drained peatland forests potentially reduces carbon dioxide (CO_2) emissions but also re-establishes the emission of methane (CH_4), thus the impact of rewetting on the net greenhouse gas and carbon balance remains uncertain. In this study, we compared fluxes of CO_2 and CH_4 based on eddy covariance measurements for a drained peatland forest and a rewetted peatland in boreal Sweden for two years after rewetting. The rewetted site was a net carbon source to the atmosphere (75 ± 4 g m^{-2} yr^{-1}) for both years, relative to the drained forest which was a net carbon sink (−167 ± 30 g m^{-2} yr^{-1}). The carbon budget was dominated by CO_2 flux in both rewetted (NEE = 71 ± 4 g m^{-2} yr^{-1}) and drained forest (NEE = −167 ± 30 g m^{-2} yr^{-1}) areas. The CO_2 component fluxes of ecosystem respiration and vegetation uptake (GPP) was 65% and 79% lower at the rewetted site than in the drained forest. In the second year after rewetting, the GPP increases by 26% in response to vegetation recovery, resulting in a 47% smaller net source of CO_2 from the site. While CH_4 emission remained small (< 0.62 g m^{-2} yr^{-1}) at the drained forest for both years, it increased substantially in the rewetted site from the first (2.8 ± 0.1 g m^{-2} yr^{-1}) to the second year (4.8 ± 0.3 g m^{-2} yr^{-1}) after rewetting, likely in response to the rise in water table by 3.0 cm in the second growing season. Overall, our study highlights that rewetting of drained peatland forests may considerably increase GHG and C emissions during the initial years. However, long-term observations under various site conditions are warranted to better understand such effects on the GHG balance.

Abstract: Long-term effects of ash fertilization on the greenhouse gas exchange of peatland forests (SuoHiTu-project)

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Ash fertilization has a profound and durable effect on forest growth on drained peatlands through improved soil and tree nutrient status. Currently ash fertilization is considered as a tool to combat climate change via increasing tree growth, and therefore carbon sink, in peatland forests. However, projections of the climate effect of ash fertilization are based solely on the increased stand growth. One critical question is whether ash fertilization enhances soil processes in a way that results in increased soil greenhouse gas (GHG) emissions, which could undermine the positive climate impact of tree stand C sink. Previous studies imply that ash fertilization has long term effects on soil properties, microbial community, and biological activity in peat. In soil, ash fertilization increases heterotrophic respiration, which in long term may lead to net loss of carbon unless respiration is counterbalanced through increased litter input. Increased peat decomposition rate in turn may elevate stand N_2O-emissions, while deeper water table level induced by higher foliage biomass generally prevent CH_4 emissions but increase decomposition. Hence, to estimate the net effect of ash fertilization on the ecosystem GHG exchange, changes in all these components need to be accounted for. Additionally, as the effects of ash fertilization in the ecosystem are long termed due to the induced pH increase, it is crucial to understand responses of the microbial communities.

The goals of SuoHiTu-project are to determine the long-term effects of ash fertilization on peat decomposition, GHG-exchange, and water quality through extensive field measurements and modelling. Further, we will investigate the long-term effects of ash fertilization on soil microbial communities by using the eDNA based metagenomic approach, which allows the identification of all microbial genes and taxa adapted to ash fertilization. New information is brought to practice by developing tools to model the function of peatland forests (SUSI-model), and by refining the national GHG-inventory. This scientific information will also have high societal relevance as it has the potential to shape fertilization programs and subsidies as well as the utilization of the waste ash, when the whole climate impact of ash fertilization will be evaluated in long-term.

SuoHiTu-project was launched on April 2022 as a part of the “Catch the Carbon”-research and innovation program funded by the Ministry of Agriculture and Forestry of Finland, which aims to increase climate-sustainability of the LULUCF-sector. The preliminary results of the effects of ash fertilization on soil properties and GHG-exchange will be presented.

HOW DOES DRAINAGE IMPACT GREENHOUSE GAS FLUX EMISSIONS FROM GRASSLANDS AND CROPLANDS ON DRAINED NUTRIENT-RICH ORGANIC SOILS IN BALTIC COUNTRIES?

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Organic soils are one of the largest natural terrestrial carbon stores, mainly in boreal, temperate, and tropical wet climate zones. These environments are deficient in oxygen; therefore, organic matter decomposes slowly and accumulates. In Europe, organic soils account only for 3% (4.4 Mha) of the total utilized agricultural area, but they clearly play a role in meeting Europe's 2030 and 2050 climate change mitigation targets to reduce GHG by 55% compared to 1990. That is because, as a common management practice, drainage turns those carbon-rich soils into a significant GHG source. Drainage and water level management are crucial processes in agriculture to minimize soil degradation and nutrient leaching. The fluctuations in water level can damage the soil and can potentially cause emissions of GHG. Drainage causes increased carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions due to increased soil mineralization. On the other hand, methane (CH_4) emissions are reduced compared to natural wetlands where no soil drainage and tillage are done. Land use, climate zone, soil nutrient status, and drainage status are closely linked to estimating GHG budgets from managed sites on organic soils.

Our study's main objective is to calculate a carbon and nitrogen budget and correct GHG emission factors for GHG fluxes from organic soils in drained croplands and grasslands in the Baltic Countries. A two-full-year study was conducted to assess the impact of drainage and land use on greenhouse gas fluxes in the Baltic countries. The study was carried out from January 2021 to December 2022.

Fluxes in nutrient-rich croplands and perennial grassland with different drainage statuses were determined on different groups: (I) excessively drained croplands, (II) excessively drained grasslands, (III) moderately drained grasslands, (IV) rewetted grasslands and for comparison, (V) non-managed fens as reference sites. Measurements were made monthly (Latvia and Lithuania) or biweekly (Estonia) using the manual dark static chamber method (N_2O, CH_4), the transparent chamber method for net ecosystem exchange, and the analyzer with a dynamic dark chamber for heterotrophic respiration (CO_2). In addition, we measured different environmental parameters.

Our preliminary results show that all grasslands were annual CH_4 sinks, while fens soils were a source of CH_4. All studied sites were annual emitters of N_2O; as expected, croplands were the highest emitter. Higher N_2O emissions and temporal variability were associated with sites where the water level had high seasonal fluctuations. Soil CO_2 fluxes peaked over all the study sites during the summer.

A two-full-year study was conducted to assess the impact of drainage and land use on greenhouse gas fluxes in the Baltic countries. The study was carried out from January 2021 to December 2022

Improving land use greenhouse-gas accounting in Canada: How management practices affect emissions in actively extracted peatlands

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Natural peatlands can undergo land-use change to actively harvest peat for anthropogenic uses (i.e., horticulture, fuel), shifting the biogeochemistry and carbon function of the ecosystem from a net carbon sink to a carbon source. Our work aims to evaluate the effect of peat extraction management practices on greenhouse gas (GHG) emissions. Fieldwork was conducted at two actively extracted field sites implementing different management techniques in Riviere-du-Loup Quebec, from May to November 2022. Using a closed chamber and portable infra-red gas analyzer (LI-COR), we collected data on CO_2 and CH_4 fluxes on uncovered peat stockpiles, and on actively extracted peat fields in 4 phases: recently harrowed, drying, conditioned, and vacuum harvested. For stockpiles, we aim to quantify GHG emission rates, capturing seasonal variability and evaluating the effect of changes in temperature and moisture. Preliminary results suggest that stockpiles emit little CH_4, and four times more CO_2 than the fields, with greater fluxes occurring at the top of the piles. For peat fields, we aim to identify differences in field emissions between the four extraction phases due to changes resulting from machine manipulation of the uppermost layer of the field. We also collected gas samples using sippers at different depths of stockpiles covered with a gas/water impermeable reflective tarp. We aim to quantify the concentration of GHGs stored in these piles and determine the rate of concentration increase from the time the pile was tarped. We also consider the effect of temperature, moisture, time, grade, and position on these concentrations. Samples preliminarily analyzed through Gas Chromatography read high concentrations of CH_4 (>1,000 ppm) and CO_2 (>100,000 ppm). Finally, to determine the effect of using an impermeable reflective tarp on the biogeochemistry of the stockpiles, we instrumented 2 stockpiles (one covered and one uncovered) with continuous temperature and moisture probes, sampling periodically for gas concentrations, fluxes, and microbial biomass. Our results will help better account for land-use GHG emissions and guide the industry towards more sustainable practices.

Changes in aquatic carbon following wetland rewetting – findings from a boreal wetland in northern Sweden

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To restore drained wetlands (WR) by raising the groundwater table has been suggested as an efficient measure to reduce degradation of peat soils and in turn decrease atmospheric CO_2 emissions. Such restoration efforts are already being widely conducted across Sweden and the plan is to continue at large scales. However, limited information exists regarding the effects of WR on lateral export of carbon (C) via the aquatic pathway. Any changes in the lateral C flux are critical to consider as it affects the overall wetland carbon balance and may offset any climatic benefits from the restoration. In addition to the carbon balance perspective, changes in the aquatic C export could affect downstream surface water quality. In this study, we monitored aquatic C (DOC, DIC and CH_4) in streams draining a boreal wetland that was rewetted during autumn 2020. By comparing pre- (2018-2020) and post- (2020-2022) restoration periods we were able to detect any changes in the aquatic C pool. The results will be fundamental when evaluating the environmental benefits of rewetting formerly drained wetlands.

Unlocked organic matter in rewetted peatlands: a comprehensive overview on concentrations, composition, and discharge patterns

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During the last three decades, concentrations of dissolved organic carbon (DOC) have nearly doubled in many inland waters of Central Europe and Northern America. This phenomenon has been proposed to be caused by a decrease in atmospheric sulfate depositions and the large-scale drainage and agricultural use of riparian peatlands. An analysis of field investigations over the last 20 years suggests that also the rewetting of degraded peatlands, an established restoration measure, might contribute to the higher DOC export into downstream systems.

We performed field and lab investigations in numerous degraded peatlands (bogs and fens) to assess their potential role as DOC sources. In detail, we assessed the temporal and spatial heterogeneity of DOC concentrations in peatland pore waters including the factors controlling the mobilization and retention of dissolved organic matter. DOC concentrations of pore waters close to the soil surface were up to 10-fold higher in rewetted peatlands (> 200 mg/L) compared to natural peatlands (< 50 mg/L). These high DOC concentrations in pore waters of rewetted peatlands corresponded with an increased DOC mobilization potential in the upper degraded peat layer. The comparison of experimental net release rates of DOC with atmospheric fluxes of carbon dioxide and methane suggest that DOC export may be an important pathway of carbon loss after rewetting degraded organic soils. Further investigations implied that a major proportion of DOC is constituted by less-reactive humic substances and that DOC is retained at the redox-barrier, which was corroborated by low in-situ DOC surface water concentrations of inundated peatlands. Moreover, higher nitrate concentrations in rewetting waters lowered the level of DOC mobilization. Therefore, only a minor part of DOC released from the peat will be exported to adjacent water courses, which, however, is still resulting in very high DOC concentrations within rewetted peatlands in comparison to natural wetlands.

Minimising the loss of DOC to downstream ecosystems can be achieved by either removing the degraded peat before rewetting or by increasing the water tables step wise over a couple of years, in contrast to abrupt rewetting. Both restoration measures are more costly than common rewetting strategies. Therefore, we should also consider the possible economic and ecologic consequences of increased carbon loss on biogeochemical cycles in affected ecosystems.

Regional scale effects of wetland restoration on aquatic carbon

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Large-scale efforts to restore previously drained wetlands (wetland restoration, WR) are currently made in Sweden with the aim to reduce carbon dioxide emissions, improve biodiversity and to mitigate both hydrological floods and droughts. However, limited information exists regarding the effects of WR on other types of ecosystem services such as aquatic carbon export. One of the most emerging issues from a water quality perspective is the brownification of many surface waters caused by increasing dissolved organic carbon (DOC) concentrations. Stream networks are also substantial emitters of greenhouse gases (GHG) to the atmosphere, and where wetlands are a main source for downstream emissions. The literature on WR effects on surface water DOC and GHG is scarce and with divergent results, both positive, negative as well as non-existing effects. In the worst case, large-scale restoration of wetlands could result in an acceleration of the brownification and increase surface water emissions of GHG´s. Hence, science-based knowledge is urgently needed to make well-founded decisions about WR efforts, including an aquatic C perspective. In this study, large-scale effects of WR on aquatic carbon have been explored based on a regional spatial sampling across Sweden covering 33 restored and 33 non-restored wetlands that have historically been drained. The wetlands were selected to cover a large latitudinal gradient as well as differences in nutrient status. Wetland outlets were sampled on two occasions (spring and autumn) during 2022 for a full set of water chemistry variables, and with particular focus on DOC and GHG contents. The results from this unique dataset will contribute to improve our understanding on how WR will affect the quality of water resources.

The mitigation of greenhouse gas emissions by manipulating water table level on peat soil growing grass in eastern Finland – presentation of ongoing mesocosm and field experiments

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Keywords: greenhouse gas, grassland, peatland, water table, HONO.

Peat soils drained for agriculture are significant sources of greenhouse gases, especially carbon dioxide (CO2) and nitrous oxide (N2O). Evidently, the most effective way to reduce N_2O and CO_2 emissions from cultivated peat soils would be raising water table close to soil surface, which is not feasible for crop production and leading to CH_4 emissions (Regina et al. 2019). It is not clear how the annual GHG balance and grassland crop yield will be affected by changing water table levels in boreal conditions. In addition, the impact of water table on the peat soil emissions of gaseous nitrous acid (HONO) and nitric oxide (NO), which are reactive gases in the atmospheric chemistry, are not understood so far (Bhattarai et al. 2018). This study consists of field and mesocosm experiments where annual greenhouse gas exchange is measured by chamber techniques in snow free season and with snow gradient method in winter. In the field experiment, background measurements were accomplished from June 2021 to May 2022. Treatment (higher water table vs. lower water table) measurements are proceeding until September 2023. In the mesocosm experiment, 20 soil monoliths from the field site were randomized into four water table depth: -70, -50, -30, -20 cm. The flux measurements will last from June 2022 to September 2023. Also HONO and NO emissions will be measured in 2023 in campaigns. The results of both experiments will be ready by the end of 2023 and published during 2024,

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Modelling water table level effect on greenhouse gas emissions and biomass

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Wetland ecosystems, including wetland forests, are important natural sources of methane (CH4) emissions, while drainage often results in increased carbon emissions. Soil physical properties, as well as local climate factors, influence plant growth and the activity of micro-organisms, therefore, also GHG fluxes. The study aimed to develop a model system under semi-controlled conditions to assess the impact on the GHG emission at the height of the water table and accumulated biomass using the mid-infrared light spectrometer. The study was set up in five boxes with different water levels relative to soil (Fig. 1). In each box, two separate soil boxes with forest soil as substrate were installed. One perennial grass species was grown, and one was left without vegetation cover. The continuous measurements were carried out by an automated developed program, which uses a spectrometer to analyse gas samples. Measurements were made during the growth period from July to September, with several 7-day-long cycles. With this method, it is possible to obtain periodic and continuous measurements. This results in a much denser dataset compared to traditional gas measurement methods (mobile gas chambers) and provides a better insight into the role of photosynthesis in GHG emissions.

The results showed that total underground and aboveground biomass correlated with each other and increased with the increased water level, except for groups where water levels were above soil level in which a decrease in total biomass was observed. CH^4 and CO^2 emissions were lower in groups with vegetation than without, except in the group with the lowest water level (-35cm). CH^4 emissions were low in the first two groups with lower water levels (-35cm and -25cm) but increased rapidly in groups with higher water levels. Reduced CO^2 emissions were also observed as the water level rises, and these changes were more rapid in the groups with vegetation. It was concluded that this methodology may be applied for modelling one or more factor effects on GHG emissions.

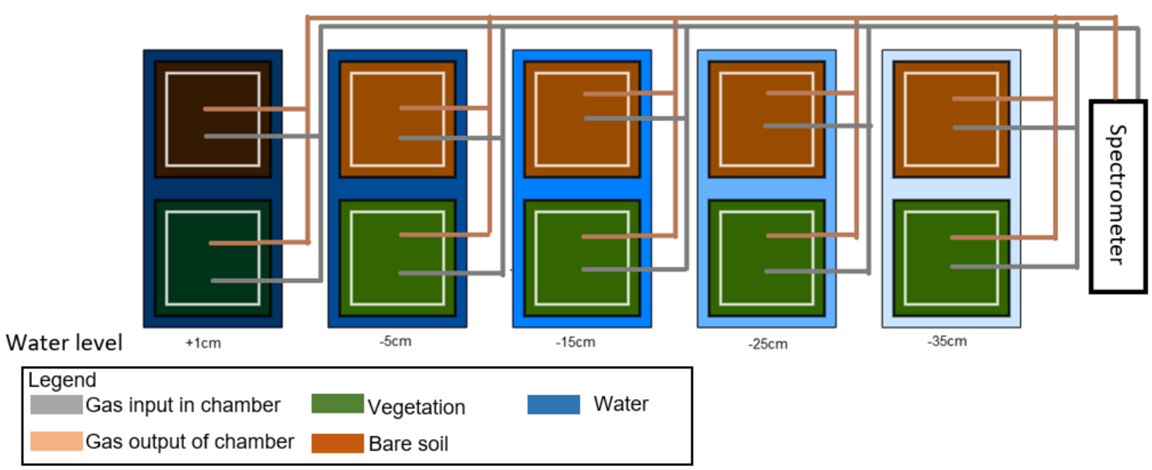

Figure 1. *Scheme of study design.*

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