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Raisa Mäkipää, ORCID ID, https://orcid.org/0000–0003–3146–4425

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Abstract

Tuomas Laurila[2], Mika Aurela[2], Juha Hatakka[2], Juha-Pekka Hotanen[1], Jyrki Jauhiainen[1], Mika Korkiakoski[2], Leila Korpela[1], Markku Koskinen[2], Timo Mäkelä[2], Raija Laiho[1], Aleksi Lehtonen[1], Kersti Leppä[1], Maiju Linkosalmi[2], Annalea Lohila[2, 3], Kari Minkkinen[3], Päivi Mäkiranta[1], Mika Nieminen[1], Paavo Ojanen[1,3], Mikko Peltoniemi[1], Timo Penttilä[1], Juuso Rainne[2], Helena Rautakoski[2], Markku Saarinen[1], Petri Salovaara[1], Sakari Sarkkola[1] and Raisa Mäkipää[1]

[1]Natural Resources Institute Finland (Luke), [2]Finnish Meteorological Institute (FMI), [3]University of Helsinki (UH)

A set of experimental study sites was established to monitor greenhouse gas (GHG) emissions from drained peatland forests under different harvesting regimes in Finland. The purpose of these experimental sites is to study the effects of continuous cover forestry (CCF) and clear-cutting (CC) on ecosystem processes including GHG emissions and stand development on drained peatland forests. The sites represent fertile Norway spruce dominated peatland forests, where soil GHG emissions are high due to drainage that has exposed peat to decomposition in aerobic conditions. Two "flagship" sites for greenhouse gas (GHG) monitoring have been established and instrumented by the Natural Resources Institute Finland (Luke), University of Helsinki (UH) and the Finnish Meteorological Institute (FMI). The sites host continuous GHG monitoring with Eddy Covariance (EC) towers and with automatic chambers. In addition, greenhouse gas (CO2, CH4, and N2O) emissions are monitored with manually operated chambers at four sites, where effects of selection (CCF) harvests are studied with replicated treatments. These data will be used to calculate the ecosystem and soil GHG balances of the sites by using methodologies standardized earlier and compatible with the IPCC guidelines.

On all experimental sites, ground water table (WT), tree growth and regeneration are monitored in different management trials. These data will form the basic data needed for designing and demonstrating optimal harvesting cycles and evaluating and generalizing the climate impacts. The results including the biological drainage capacity (evapotranspiration) of different-sized tree stands as well as the soil GHG balance of different tree stand – WT combinations will be incorporated into existing models that can be used to estimate the mitigation obtained with different management options and in different site and climatic conditions.

The study sites are actively used for training and demonstration of alternative peatland management practices by host projects and by multiple stakeholders. The host projects and organizations also promote further extensions for the measurements and all complementary research activities are welcome to these study sites.

Keywords: climate change, continuous cover forestry (CCF), drained peatland forest, ecosystem study, eddy covariance, greenhouse gas (GHG), managed peatland, water quality and water table.

Contents

1. Introduction

A set of experimental study sites was established to monitor GHG emissions from drained peatland forests under different harvesting regimes in Finland. The purpose of these sites is to study the effects of forest management options alternative to current drainage and clear-cut practice, such as continuous cover forestry (CCF), on GHG emissions from drained peatland forests. The basic idea of CCF on peatland is to regulate the ground water table (WT) through evapotranspiration of a tree stand on site by retaining a significant proportion of the tree stand after each harvesting (see, Nieminen et al. 2018, Leppä et al. 2020a, 2020b).

Two “flagship” sites for greenhouse gas (GHG) monitoring have been established and instrumented by the Natural Resources Institute Finland (Luke), University of Helsinki (UH) and the Finnish Meteorological Institute (FMI). The sites host continuous GHG monitoring with Eddy Covariance (EC) towers and the data will be made available on-line (open access). In addition, greenhouse gas (CO_2, CH_4, and N_2O) emissions are monitored with manually operated chambers at four sites, where effects of selection (CCF) harvests are studied with replicated treatments. These data will be used to calculate the soil GHG balance of the sites by using methodologies standardized earlier and compatible with the IPCC guidelines.

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The study sites are actively used for training and demonstration of alternative peatland management practices by host projects and by multiple stakeholders. The host projects and organizations also promote further extensions for the measurements and all complementary research activities are welcome to these study sites.

2. Ränskälänkorpi flagship demonstration and experimental site

2.1. Location, characteristics and stand measurements

Ränskälänkorpi experimental peatland area (ca 25 ha) is located in Asikkala municipality in Southern Finland (N61°10.966' E25°15.985') (Figure 1). The long-term (1981–2010) annual precipitation in the region averages 600 mm, the long-term mean annual temperature is +3.8 °C and the temperature sum 1.220 dd (+5˚C daily temperature as the threshold value). The mean temperatures for July and February are +16.6 and –7.6 °C, respectively.

The area has been drained for forestry before 1960's (exact year of drainage not known). At present the area is well-drained and represents mainly nutrient-rich Herb-rich (Rhtkg II) and *Vaccinium myrtillus* (Mtkg II) site types drained peatland forest. About 5% of the area is poorer *Vaccinium vitis-idaea* (Ptkg II) type site located in the northernmost part of the area. The tree stand consists of a dominant tree layer of mature Norway spruce (*Picea abies*) mixed with Scots pine (*Pinus sylvestris*) and pubescent birch (*Betula pubescens*), and a patchy understorey of Norway spruce trees of varying age and height. Ground vegetation is sparse and consists of forest mosses (*Hylocomium splendens, Pleurozium schreberi, Dicranum polysetum* etc.), dwarf shrubs (mainly *Vaccinium myrtillus* and *Vaccinium vitis-idaea*), as well as forbs such as *Dryopteris carthusiana, Gymnocarpium dryopteris, Trientalis europaea*, and *Oxalis acetosella*.

The thickness of the peat layer consisting of sedge (*Carex*) and wood dominated peat, is mainly >1 m.

The site is divided into three blocks (Figure 2) for demonstrating the impacts of different forest management treatments on tree stand development, hydrology, and GHG fluxes between the soil and atmosphere. Each block is divided into two sub-blocks according to site trophic status. Except for sub-block 6, each sub-block forms an artificial small catchment isolated by ditches. The study site consists three different stand treatments: selection cutting (CCF, ca 10.0 ha), clear-cutting (ca 6.1 ha), and non-harvested control area (ca 7.3 ha). The harvesting treatments have been placed on the blocks in accordance with the ecosystem level GHG-exchange measurements (Eddy covariance-method, see chapter 2.3). The monitoring of the site was initiated in 2019 and the harvesting, according to treatments, was carried out in March 2021.

Figure 1. Location of the Lettosuo and Ränskälänkorpi study sites in Southern Finland.

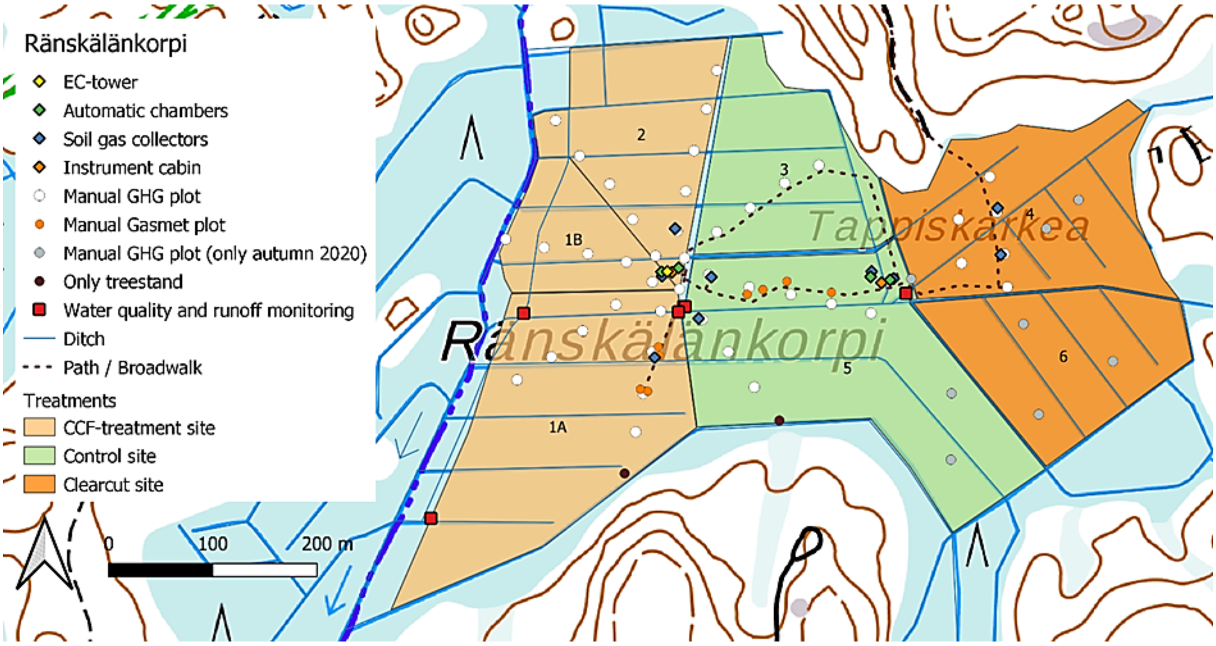

Figure 2. Experimental setup of the Ränskälänkorpi site. Permanent sample plots for tree stand measurements and coverage of understorey vegetation (n=45) and for GHG measurements (n=43, white circles) were established in 2019.

The tree stands were measured on 45 systematically arranged permanent circular sample plots. A total of 39 plots were located on eight radial transects extending 160–200 m from the eddy-covariance mast and 6 plots were placed on the planned clear-cut sub-block 4. All circular sample plots had an area of 200 m^2. In August 2019 to May 2020, trees on the sample plots were measured for their locations relative to plot center, and tree species, stem diameter at the height of 1.3 m (DBH), tree height, and crown length was recorded for all tallied trees.

2.2. Instrumentation

The preparatory measures and instrumentations at Ränskälänkorpi site during the establishment in 2019–2020 (chronological order):

Year 2019

1.–31.3.: Openings for new ditches and maintenance tracks were cut in March 2019

29.4.–3.5.: Digging of new ditches for monitoring runoff from the designated management blocks, installation of pipe weirs for water quality sampling, and installation of electricity transformer and underground electric cables for powering the GHG measurement instrumentation. The biweekly manual water sample collections and runoff measurements were started.

4.7.–15.7.: Setting up the grid of permanent sample plots (PSP's; Fig. 2) for tree stand measurements and ground vegetation monitoring (HAMK-students). Tree stand measurements (tree species, tree diameter, tree height and crown length, various classifications of tree status and vitality) done on PSP's of north, northeast, east, southeast, south, and southwest survey lines. The rest of PSP's for characteristics will be measured in May 2020.

30.7.–30.8.: Setting up soil respiration and CH_4 manual chamber measurements on the permanent sample plots: measurement points, ground water pipes, photos for vegetation analysis and temperature loggers at 5 cm depth on even-numbered plots (2 temperature profiles, 5 cm 15 cm on non-harvested control and selection harvest (CCF) blocks). Building of boardwalks over the ditches where necessary. Setting up soil respiration measurements plots (n=43). Setting up Eddy covariance for GHG measurements (see Chapter 2.3.1).

4.9.: Setting up automatic GHG chamber system on control and clearcut plots.

13.9.: Setting up a GHG measurement grid on clear-cut treatment; 6 measurement points.

13.9.: Setting up traps for collecting above ground litter from trees and ground vegetation: grid points 11, 52, 61, 31, 42, 3, 2, and points close to automatic chambers on control and clearcut sites, 5 traps/point.

13.–17.9.: First soil respiration and CH_4 measurement round completed. All plots measured.

21.11.: Installation of soil temperature loggers (-5 and -30cm) to all treatment blocks.

21.11.: Installation of root ingrowth cores to selection harvest block close to grid points 52 and 11, and clearcut treatment block points 1, 2 and 3 (20 cores per block). Selection harvest and clearcut blocks: Litter collected from the traps.

Year 2020

13.1.2020.: Setup of trenching (Figure 3).

Figure 3. The measurement site of heterotrophic soil respiration (CO_2) in Ränskälänkorpi close to the Eddy Covariance tower. The root layer of the site was isolated from the surroundings by inserting a root exclusion fabric vertically into the soil. The trunk inside the measurement site is a dead tree.

19.3.2020: Soil temperature and humidity profile measurements started near automated chambers.

May 2020: Tree stand measurements (on the grid of the permanent circular sample plots) were completed (4.–8.5.).

May 2020: Set up of measurements of moss growth on grid points 11, 52, 61, 31, 42, 3, 2, and points close to automatic chambers on control and clearcut sites, 5 nets/point/dominate moss types.

May 2020: Continuous water table monitoring was complemented by installing altogether 7 automatic data loggers (Odyssey® Capacitance Water Level Logger).

May–June 2020: set up of sapflow measurements to 8 spruce trees in control and 8 spruce trees and 4 pines and spruces in harvesting experiment). Set up of point dendrometers to all these spruce trees and a subset of pines and birches.

July 2020: Set up soil gas concentration tubing on grid points 11, 52, 61, 31, 42, 3, 2, and points close to automatic chambers on control and clearcut sites, tubes in depths 10 cm, 30 cm and 40–60 cm /point.

July 2020: Set up of heterotrophic soil respiration plots on grid points: 11, 52, 31, 42, 3, 2. Three measurement plots/point.

August 2020: Vegetation analyses on 43 permanent sample plots (GHG measurement points) and on additional 60 vegetation quadrats (20 per treatment).

September 2020: Setup of six automatic chambers on CCF harvesting treatment. Permanent circular seedling plots were established within the stand plots (three 4 m^2 seedling plots within each stand plot) in the CCF- and control areas, and the seedlings in the sample plots were inventoried.

September 2020: Supplements to litter traps and dendrometers on grid points: 22, 23, 31–33, 52–54, 63 and 64. 5 traps/point and 3 dendrometers/point.

September 2020: Set up of soil moisture probes on grid points: 2–6, 22, 23, 31–33, 52–54, 63 and 64.

23.9.2020: Automated chamber GHG measurements system started near the EC tower.

3.–26.11.2020: Peat sampling was done in every manual GHG plot (n=43) and EC tower -site. Peat cores (one per plot, extending to the depth of 50 cm) were taken approx. 3 meters to the north, east or south from the center of the plots, depending on the presence of other measurement devices and ditches. Cores were cut to 10 cm-pieces and bagged individually.

Year 2021

March 2021: Stand treatments (Selection harvesting with a target post-harvest basal area of 12 $m^2\ ha^{-1}$ (CCF), and clear-cutting) implemented on western and eastern bock. The model of the harvesting machine was Ponsse Ergo -harvester with C44+ crane (total typical weight 21,500 kg and radius of operation 10m). The harvesting area completed in 18.3.–1.4. shown in Figure 4.

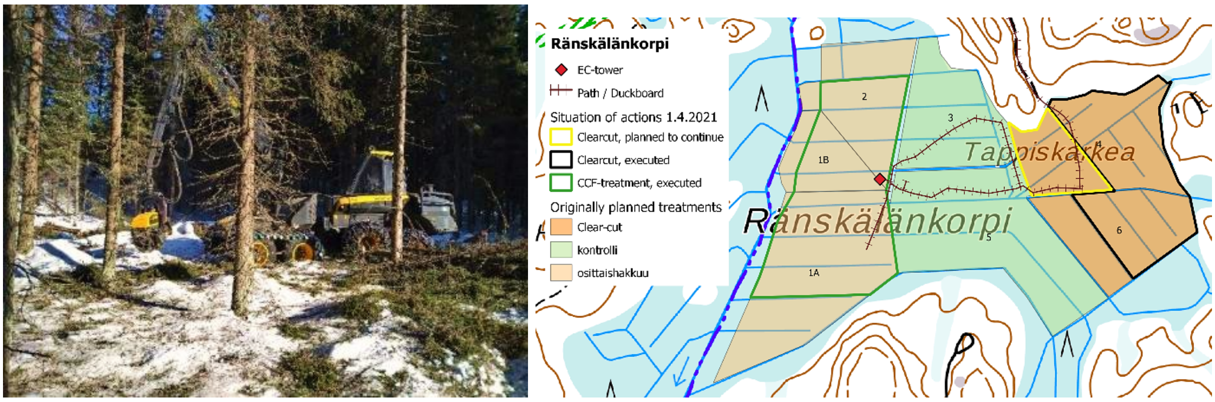

Figure 4. Selection harvesting and clear-cutting started in March 18, 2021. Green and black lines show, which part was harvested in winter conditions by April 1. Yellow line indicates an area, where harvesting is planned to continue in 2021. Photo: Sakari Sarkkola.

2.3. Greenhouse gas (GHG) measurements

2.3.1. Ecosystem level GHG exchange measurements above canopy

In August 2019, we started micrometeorological flux measurements of carbon dioxide and evaporation in the eastern border of the planned selection harvest (CCF) N61°10.973' E25°15.761' area. Main electricity, a small cabin for instrumentation, scaffolds for the mast and a telescopic carbon fiber mast, which may be elevated up to 32 m, were constructed (Figure 5). We measure eddy-covariance fluxes above the canopy at height of 29 m. Instrumentation (Figure 5) include 3-D sonic anemometer Metek uSonic-3 Sci sn 0112027572 and a fast response CO_2-H_2O gas concentration analyzer LI-COR LI-7200RS. Electronics is LI7550 sn AIU-1909 and the sensor head is 72H-0861.

Figure 5. Micrometeorological flux measurement site. The instrumentations on top of the telescopic mast are as shown in Figure 6. Photo: Tuomas Laurila.

Air is sucked to the analyzer via 52 cm SS (stainless steel) tubing from a point 20 cm from the center of the anemometer. The SS tube is heated and there is a 2mikron sinter filter between the tube and the LI-COR sensor head to protect NDIR optics become dirty. Flow rate is 12 liter per minute, which is monitored by a digital flowmeter down in the cabin, in which also a vacuum pump is located. In the mast top there are temperature and relative humidity sensor (Vaisala HMP155, sn N4810854) and radiation sensor Kipp&Zonen CNR4 (sn 192090) which houses upward and downward looking solar radiation pyranometers and infrared pyrgeometers. Two Kipp&Zonen PQS radiometers (upward looking sn 191682, downward 191683) are used for photosynthetically active radiation (PAR). Data are collected by Moxa serieportserver/switch and transmitted by ethernet to a Linux PC in the cabin. Atmospheric concentrations of CO_2 and CH_4 were measured by Picarro G2401 (CFKADS-2068) for the estimation of so-called storage term. Inlet sonde was at 6 m height.

Figure 6. On the right sonic anemometer. Air is sucked via heated and insulated tube to the sensor head of the CO2-H2O analyzer. The LI-COR electronic box and radiation shield in the middle and radiation sensors on the left. Photo: Tuomas Laurila.

At a distance from 4 meters to the cabin we measure soil parameters using a Vaisala QML data logger. Soil temperature by individually calibrated Nokevak IKES Pt100 sensors (-50, -20, -10, -5, 0 cm) (Figure 7). The sensor 0 cm is laying on the surface and there is also one sensor measuring air temperature at 2 m. Soil moisture is measured by DeltaT ML3 sensors -20 (sn M008849), -5 cm (sn M008850). Soil heat flux is measured by Hukseflux HFP01 (-7.5 cm) heat flux plate (sn 5226). For the below canopy photosynthetically active solar radiation there is Kipp & Zonen PQS sensor (sn 191685) at height of 30 cm.

Figure 7. Assembly of the soil sensors close to the micrometeorological cabin. Photo: Tuomas Laurila.

First measured winter season (2019–2020) was mild and that continued over February 2020 as well. Our data shows a period when air temperature is close to or above zero and forest act as net sink of CO_2 during daytime (Figure 8). Freezing air temperatures usually prohibit photosynthesis. Negative value indicates net flux downwards (CO_2 uptake by the forest).

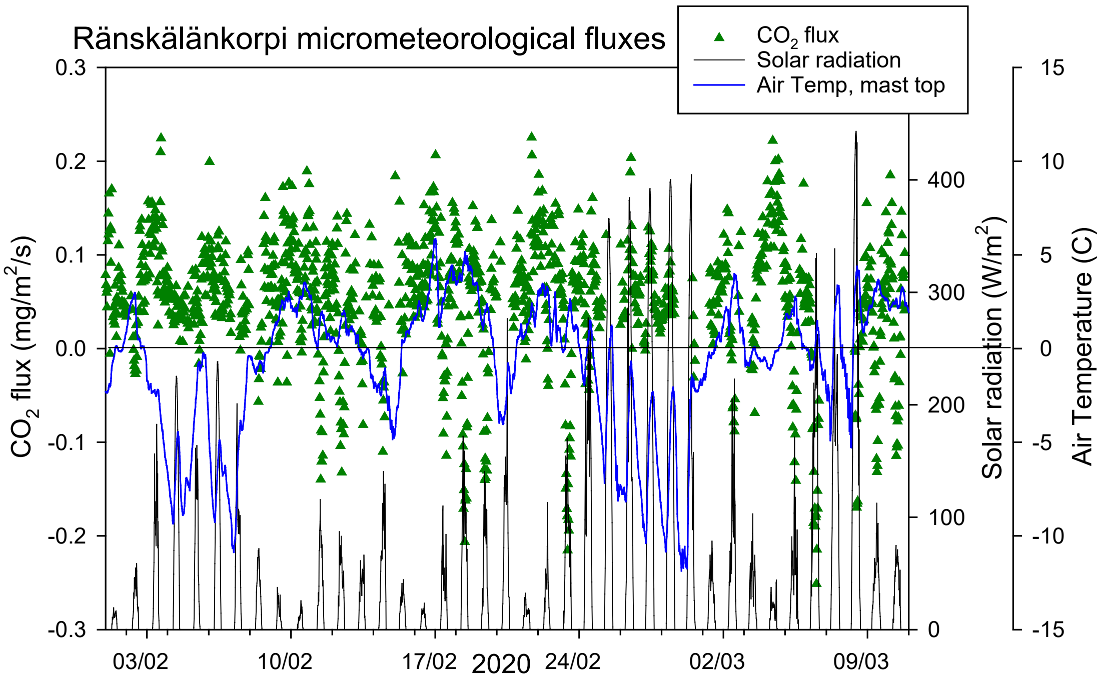

Figure 8. Half-hourly averages of CO_2 fluxes (EC tower) in winter 2020. Negative values indicate net uptake by the forest. Time series of air temperature at top level of the canopy and solar radiation are shown, too.

In September 2019, air temperature and solar radiation decreased very much from summer levels to values in autumn (Figure 9). After late October air temperatures varied around zero typically to this very mild winter. Levels of solar radiation were very low in December and the period of daylight was short. Beginning in February, levels of solar radiation increased again.

We calculated average net CO_2 fluxes at noon, during dark hours and daily 24h averages for 15-day periods (Figure 10). Measurements began in the latter half of August when total respiration values were high. Average nighttime flux was 2.7 g CO_2 m^{-2} $hour^{-1}$. At noon on the average we observed uptake -0.9 g CO_2 m^{-2} $hour^{-1}$. On the average (24 hour), the site was a net source of CO_2 to the atmosphere, about 1 g CO_2 m^{-2} $hour^{-1}$. September was a month of change. Starting in October, average fluxes at noon were close to zero and nighttime total respiration 0.3 g CO_2 m^{-2} $hour^{-1}$, resulting in daily average net efflux of little bit less than 0.3 g CO_2 m^{-2} $hour^{-1}$. In April, the site turned into a net sink of CO_2.

The western part of the forest was continuous cover harvested in March 2021. During the harvest, EC measurement mast was not operational. EC flux measurements restarted 25.3.2021. Since that dated flux measurements from the western sector represent continuous cover harvested forest.

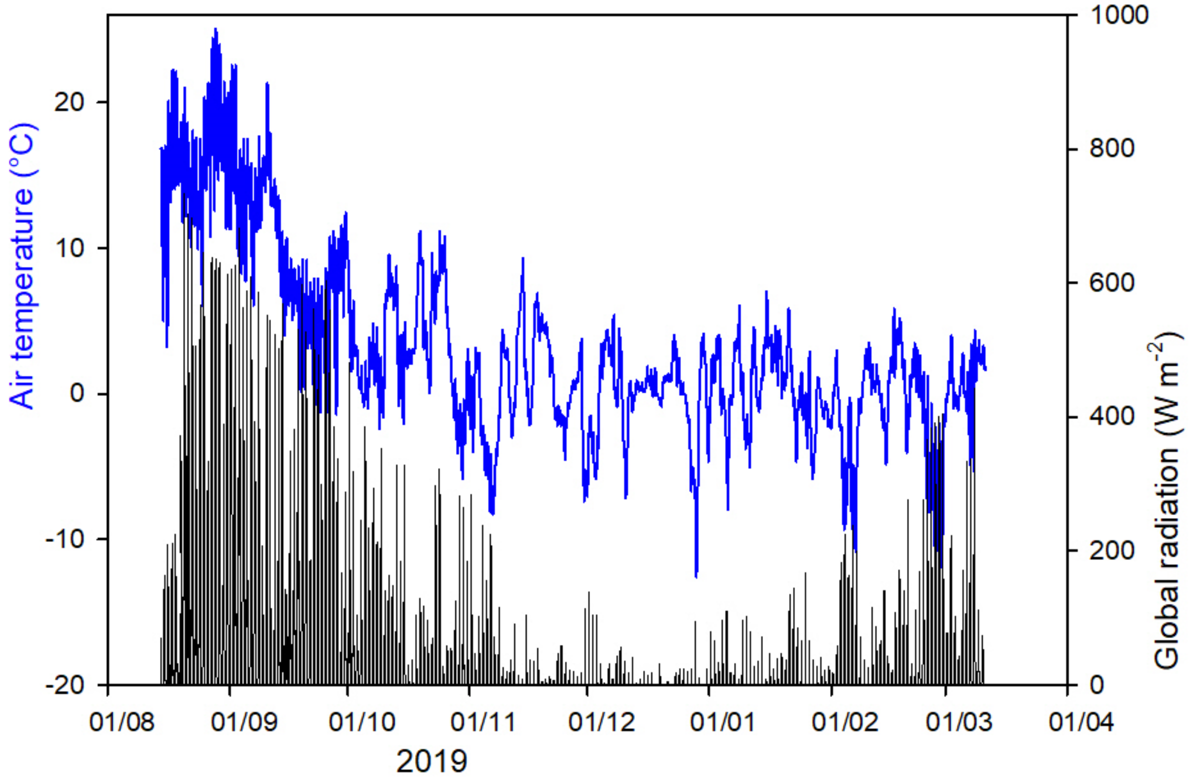

Figure 9. Air temperature and global radiation.

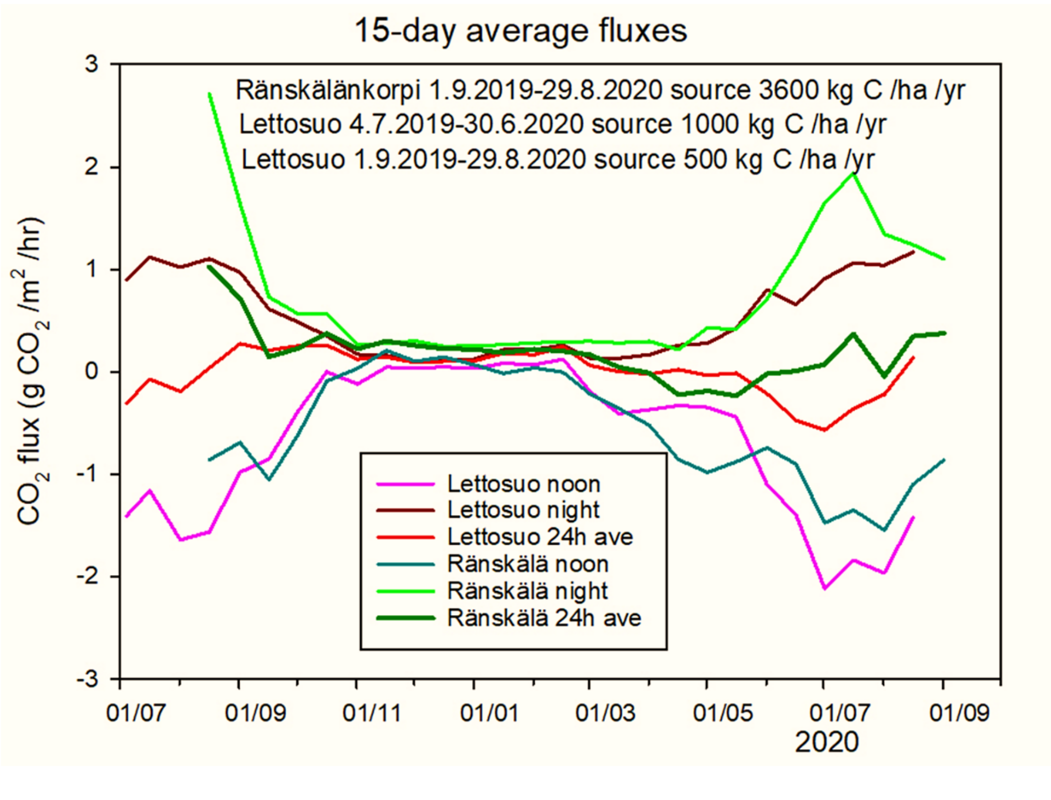

Figure 10. Fifteen-day averages of CO_2 fluxes at noon, during dark night hours, and daily averages at Ränskälänkorpi and Lettosuo and together with annual balances.

2.3.2. Chamber measurements of soil GHG fluxes

Automated chambers for CO_2, CH_4 and N_2O flux measurements

An automatic chamber measurement system was constructed for use at the Ränskälänkorpi site. Cabin and a first set of automated chambers were installed in summer 2019 (Figures 11 and 12) and additional six chambers were installed on CCF block (near EC) in September 2020.

The system has been originally constructed by Koskinen et al. (2014) and further used by Korkiakoski et al. (2017). The present system is similar with some developments. The CO_2 flux measurements by automated chambers at Ränskälänkorpi started in September 2019 and since October 2019 also methane (CH_4) and nitrous oxide (N_2O) fluxes are measured.

Figure 11. Cabin for the instrumentation. Installation was ongoing in April 2019. Photo: Tuomas Laurila.

Figure 12. In 2019, six automated chambers for forest floor greenhouse gas flux measurements were made operational at Ränskälänkorpi site. Photo: Tuomas Laurila.

Forest floor gas exchange, including vegetation, soil, and tree roots, are monitored using six transparent polycarbonate soil chambers connected to an instrument cabin (Figure 11 and 12). The cabin was located close to the border of the non-harvested control area (CA) and the future clear-cut area (CC). Coordinates of the site are N61°10.966' E25°15.985'. Initially, all six chambers measure in the mature forest, but after harvesting, three of the chambers will measure the CC- area.

The locations of the chambers were selected to represent the dominating ground vegetation compositions within a circle of ca. 15m radius around the instrument cabin. Three ground vegetation types were selected from the mature forest and the future clear-cut area so that at both sides, all three vegetation types were represented.

The detailed description of the chamber system can be found in Koskinen et al. (2014), and thus here we follow text by Koskinen et al. who summarizes the system. The size of the transparent polycarbonate chamber boxes was 57 cm * 57 cm * 30 cm (length_width_height). We used a permanently installed steel collar height 20 cm of which 5-10 cm was inserted into the moss. There was a U profile at the bottom of the chamber edges, insulated with a foam tape, to improve the sealing. In winter, the whole chamber frame will be raised above the snow level by placing one or two extension collars (height 16 cm) between the frame and soil. A 24V fan (Maglev KDE2408PTV1, Sunon Ltd, Kaohsiung, Taiwan) (size 8 cm_8 cm) is used to mix the air inside the chamber headspace. The voltage of the fan is regulated to 4V (15mA) to keep the mixing steady, but as low as possible (Koskinen et al., 2014). Sample gas is drawn from the chamber typically once an hour at a flow rate of about 1 L/min and returned back to the chamber from the gas analyzers. The inlet tubes are made of fluoropolymer (i.d.4mm, o.d.6mm, Fluorplast Oy, Petolahti, Finland) and return outlet tubes of polyamide (PAN, i.d. 4mm, o.d. 6mm, Festo Oy, Vantaa, Finland). Length of the tubes are 15 m. The tubes are flushed with ambient air just before the chamber is closed. When all the chambers are open, ambient air is sampled.

CO2, and water vapor concentrations are measured every 1 s by Li-840A (Li-Cor, Inc., U.S.A.) CO2/H20 analyser. For N2O, CH4, CO2 we used Gasmet DX4015 (Gasmet Technologies Oy, Helsinki, Finland), which produced concentrations every 5 s (Figure 13). Gasmet was replaced on 4.6.2020 by LGR analyzer. Picarro G2308 (JFAADS2137) N2O, CH4, and H2O analyzer was installed at the first chamber system (CA/CC) 16.1.2020 and moved to the other system (CCF) 23.9.2020. A more sensitive N_2O, CO analyzer by Los Gatos Res., Inc was added to the chamber measurements system on 4.6.2020.

Figure 13. Data collection and chamber control board together with the green Li-Cor CO_2 analyzer on the right and on the left the yellow Gasmet analyzer for CO_2, CH_4, and N_2O concentrations. Photo: Tuomas Laurila.

Another set of six automated chambers were installed at the Ränskälänkorpi micrometeorological flux site using the same kind of technology as used in the first set. There are three opaque chambers for soil emissions at the trenching plot (Figure 14) and three transparent chambers for forest understory vegetation fluxes. Chamber flux measurements started 23.9.2020. Fluxes of CO_2 are measured by LI-COR LI-850 CO_2/H_2O analyzer and for N_2O and CH_4 fluxes we moved G2308 to this site 23.9.2020. A set of soil temperature and moisture sensors and air temperature and radiation sensors were installed to support chamber flux measurements. In each chamber, air and topsoil (-5cm below green moss) temperature are measured by IKES Pt100 sensors (Nokeval), and in transparent chambers photosynthetically active solar radiation is measured by PQS sensors (Kipp&Zonen). One DeltaT ML3 soil moisture sensor was installed at -10 cm close to the opaque and one close to the transparent chambers. These sensors are logged by Vaisala QML data collection boards. Lumberjack cut some nearby trees on 18.3.2021, which date can be considered as the date from CA to CCF. Forest around the flux tower was machine harvested a few days later.

Figure 14. Three opaque chambers at the trenching experiment close to the micromet flux tower. Photo: Tuomas Laurila.

Manual chamber measurements

Measurements of soil respiration (CO_2) and methane (CH_4) fluxes between the soil and atmosphere are carried out weekly to biweekly during the snowless period with a portable measurement system on part of the permanent measurement plots on the selection harvest (CCF) and non-harvested (control) blocks (Figure 15). In 2019, the number of measured plots was 43 of which 6 were located on planned clear-cut area (Figure 15). This is necessary to explore the spatial variability of these GHG fluxes in all parts of the site as the automatic chambers only cover a very limited part of the site. Thereby the representativeness of the continuous data obtained from the automatic chambers can be analyzed and evaluated. During autumn 2020, two campaigns of measurements were also executed on temporary GHG measurements plots (Figure 15).

The fluxes were measured using a closed-chamber system with an opaque cylindrical chamber (height 30.5 cm, diameter 32 cm) including a mixing fan. The measurements of CO_2 and CH_4 concentrations were made every 5 s using LI-7810 (LI-COR Inc., Lincoln, NE, USA) and N_2O concentrations were recorded with separate measurements using Gasmet DX4015 (Gasmet Technologies Oy, Helsinki, Finland). The air was circulated in a loop between the gas analyser and the chamber with a closure time of 5 min. In summer 2020, the number of measured plots was 17 (Figure 15).

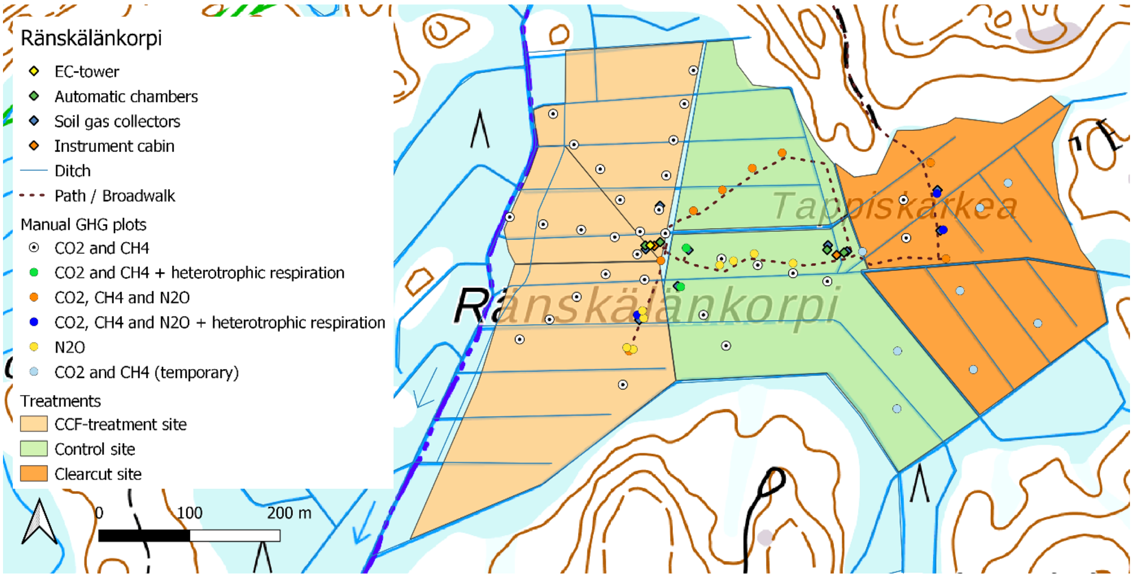

Figure 15. Grid of permanent GHG measurement points in Ränskälänkorpi.

2.3.3. Ancillary measurements

At the automated system at CA site, air and soil temperature data for automated chambers are collected every 10 s using Pt100 probes (PT4T, Nokeval Oy, Nokia, Finland) and Nokeval 680 loggers (Nokeval Oy, Nokia, Finland). One probe is located inside each chamber at a height of 30 cm to measure the air temperature in the chamber and is positioned next to the fan under a metal heat shield to prevent direct solar radiation from affecting the measurements. In the center of each chamber there is PQS1 sensor for photosynthetically active solar radiation (Kipp & Zonen B.V., Netherlands). Furthermore, soil surface temperature is monitored inside each chamber just below the surface of the moss or litter layer (5 cm depth).

Figure 16. Soil temperature and humidity sensors. Photo: Tuomas Laurila.

Near the chambers one **soil temperature** profile is measured using PT100 sensors placed at depths of 5, 10, 20, and 50 cm and one on the moss surface (Figure 16). **Soil moisture** is measured at 5 and 20 cm depths by DeltaT ML3 probes (Delta-T Devices, UK) (Figure 17).

Peat Eh was recorded at three points per treatment, using probes with four Pt electrodes placed at 5, 15, 25 and 40 cm depth and Ag-AgCl reference electrodes in KCl solution (PaleoTerra, Oijen, Netherlands). The probes were installed close to the soil gas exchange measurement chambers.

Air temperature and humidity are measured by PT100 and Humicap (Vaisala HMP155, digital version, Vaisala Oyj, Finland) in a radiation shield at 2 m height. **Precipitation** is monitored by a weighing pluviometer Pluvio2 (OTT Messtechnik GMBH & Co. KG, digital output) with wind shield.

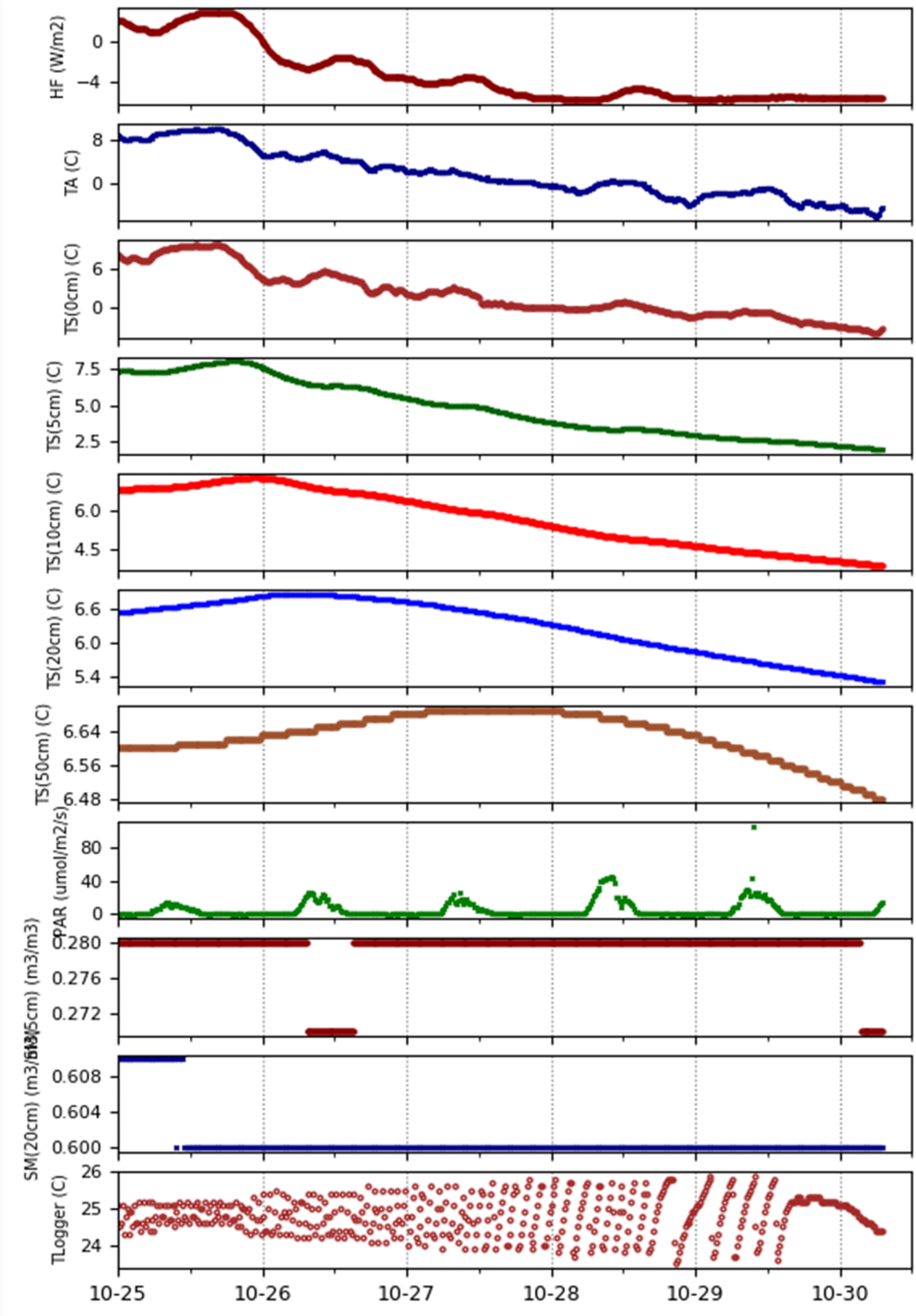

Figure 17. Soil measurements at Ränskälänkorpi 25.–30.10.2019. From top: Soil heat flux, air temperature, temperatures at surface, and depths of 5, 10, 20, 50 cm, photosynthetically active radiation (PAR) below tree canopy, soil moistures at depths 5 and 20 cm, and measurement cabin temperature.

2.4. Water table (WT) measurements

Water table level was monitored both manually and continuously by automatic data loggers. The manual measurements are done from the plastic tubes on each permanent point of manual GHG measurements (n=43) during the gas measurement campaigns. The manual measurements will be utilised both in the GHG modeling and in the calibration of the logger measurements.

The automatic monitoring is carried out by water pressure sensors. Water table level is monitored continuously by Trafag 8438.66.2646 submersible pressure sensor, which is in a 2.1m steel tube hammered to the peat. The sensors are measuring the difference between the water hydrostatic pressure and air pressure as well as the temperature. The information measured by sensors are stored in the loggerbox and the data will be delivered further wirelessly as mobile data. Together five different units of sensors were installed on the CCF-, non-harvested and clear-cut areas. Furthermore, the water table level will be monitored with automatic Odyssey Capacitance Water loggers (Dataflow Systems Limited, Christchurch, New Zealand), which are installed on each block (together 7 loggers) (Figure 18). Both logger types provide continuous water table data for modelling purposes.

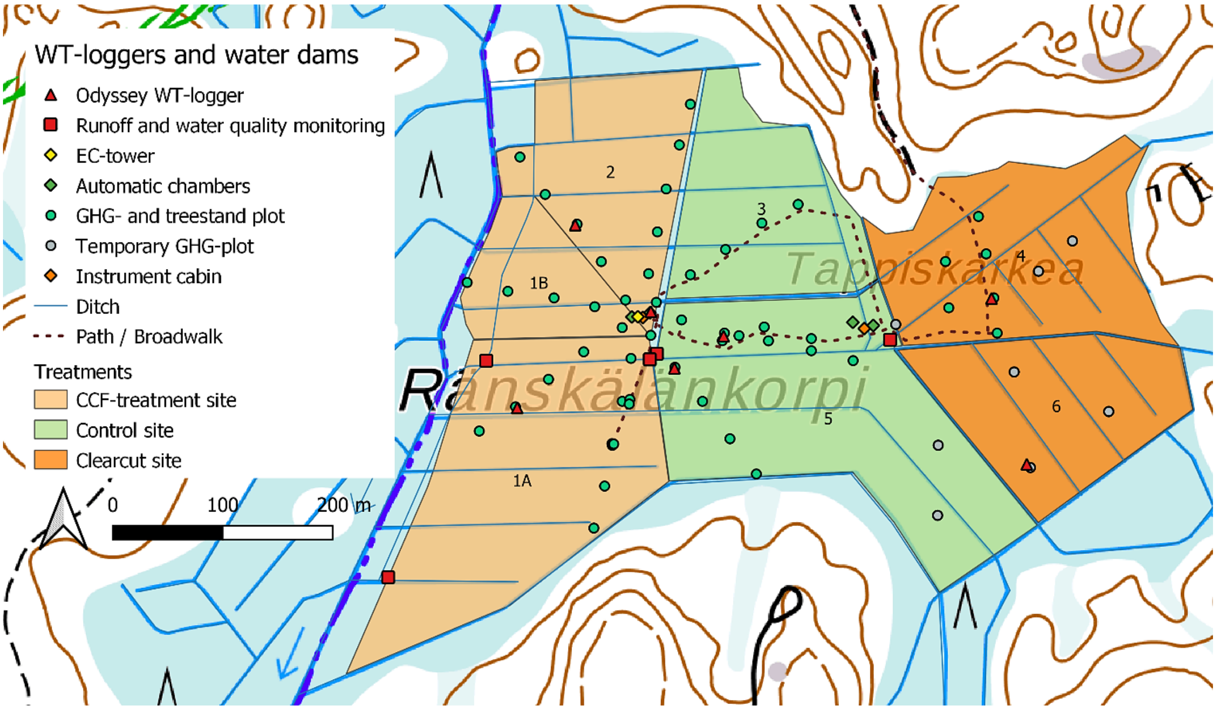

Figure 18. Water table (WT) loggers and water quality / runoff dams.

2.5. Sapflow and dendrometer measurements

Sapflow and dendrometer measurement devices were installed at the harvest and non-harvested block to monitor the transpiration and diameter variation of trees. Altogether, 24 trees are monitored, of which 16 are in harvest (9 spruces, 4 pines, 3 birches), and 8 spruces in the control.

Sapflow is measured with a heat pulse velocity sap flow and stem water content sensor with SDI-12 output (Edaphic HPV-06). One sensor with radiation cover is installed to the southern side of the stem of each monitored tree, at 1.3 m height from ground. Sapflow monitoring commenced in the harvest site in 13.6.2020, and in the control site 3.9.2020.

Two Solartron AX-5 point dendrometers with radiation covers are attached to each tree to measure the stem diameter variation. Birch trees are not presently monitored for stem diameter variation. One sensor in each tree measures the diameter variation above phloem, and one above xylem. The sensors are attached to the trees with custom made temperature invariant frame. The monitoring stem diameter variation commenced fully in 16.6.2020. Temperature 4 cm above bark surface is continuously monitored with temperature logging i-buttons attached to the dendrometer frames from 13.7.2020 onwards.

Edaphic and Solartron sensors are attached to Campbell CR1000x data loggers, and multiplexer. Dendrometer datafiles, and the main sapflow data files is transmitted to Luke server daily. Ancillary sapflow datafiles are read manually at the site.

Additional Tomst point dendrometers are attached to 10 tree sample plots (22, 23, 31, 32, 33, 52, 53, 54, 63 and 64). The monitoring is made from 3 trees in each block, and each sensor also records air temperature. These dendrometers were installed in 15.9.2020. Tomst point dendromenters are manually read at the site.

2.6. Other measurements

For runoff quantity and quality monitoring, an earth embankment with an outflow pipe (diameter=20 cm) was established in the outlet ditch of each of the five sub-block areas (Figure 2). The 6th sub-block was excluded from the runoff monitoring because it has not the outlet ditch.

Water samples are taken from the outflow pipe of each catchment once a month and more often during high flows during spring snow-melt period and autumn heavy rainfalls. Runoff is measured concurrently with water sampling using a stopwatch and a bucket. Water samples are analysed at the laboratory of the Natural Resources Institute Finland for dissolved organic carbon (DOC), nutrients and heavy metals using the same methods as, e.g., Nieminen et al. (2020). The water quality and quantity data is aimed to be used to quantify DOC, nutrient and heavy metal exports in kg ha^{-1} $year^{-1}$ from each of the five sub-block areas (Figure 1) using modelled runoff using the hydrometeorological data collected at Ränskälänkorpi as model input data and the measured element concentrations in runoff as, e.g., Kaila et al. (2015). The runoff measured manually during water sample collection will be used as a verification data of the hydrological model.

Understorey vegetation survey was conducted by visually assessing the projection coverage of field layer species (dwarf shrubs, herbs, graminoids and tree and shrub seedling sand saplings up to 0.5 m height) and that of moss species, litter on the ground as well as a proportion of the surface covered by a tree or trump-root system. The percentage covers were recorded using scale 0.1, 0.2, 0.3, 0.5, 1, 2, 3, 5, 7, 10, 15, ...95, 97, 98, 100%. The species names for vascular plants and mosses followed the nomenclatures of Hämet-Ahti et al. (1998) and Ulvinen et al. (2002) respectively. For vegetation survey 10 permanent sample plots (1x1 m^2 size quadrats) were placed and their coordinates recorded in each block (Figure 19). The vegetation plots are arranged in two or three lines and distance between the plots may vary 30–50 depending on the shape and size and the variation of the vegetation type on each treatment site. Vegetation analyses was done in august 2020 on those treatments sites as well as in a systematic grid of 44 PSP- plots in each parallel site. The latter vegetation plots were located on the lines of the manual chamber GHG-measurement points, representing vegetation near the points. The number of vegetation plots was altogether 108 (Figure 18).

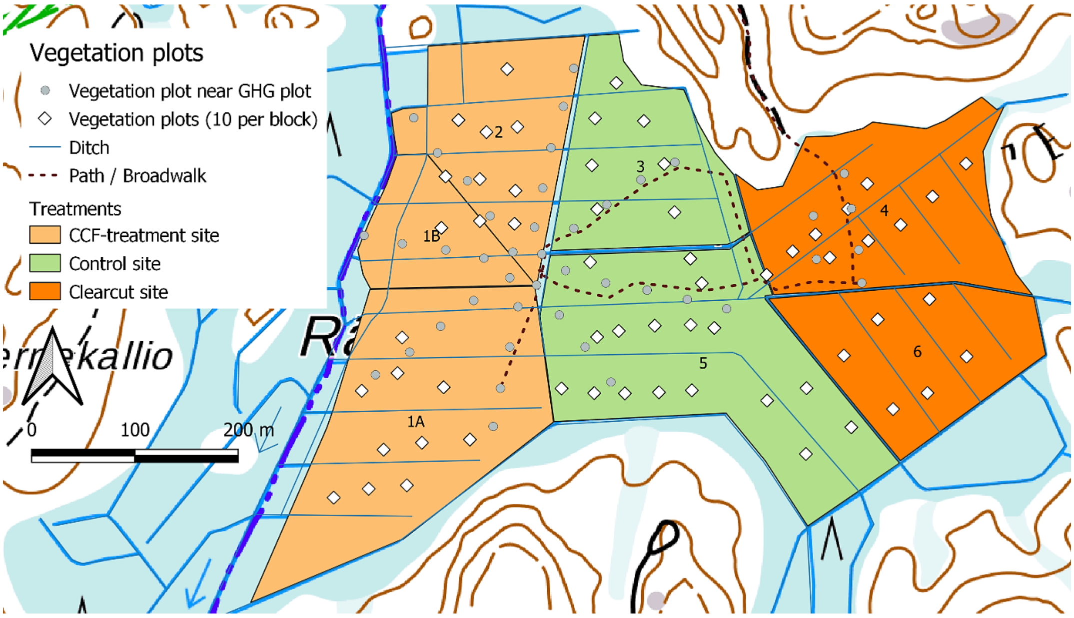

Figure 19. The permanent vegetation plots (n=60, marked with quadrats) located on three blocks and on the lines of gas measuring points (in a systematic grid of 43 PSP-plots in each parallel site, n=43) in Ränskälänkorpi study area.

In addition, vegetation survey was done on each biomass plot (30x30cm) which were also photographed before cutting the aboveground biomass samples near the GHG measurement points and each 1m^2 vegetation plot (representing same kind of vegetation) were collected.

Pre-harvest inventory of the tree seedlings was done from three small permanent circular seedling plots (4 m^2) established within each of the permanent measurement plots in in the CCF- and control blocks (together 120 seedling plots). Each of the seedling plot was placed at the distance of 5 m from the center of the permanent measurement plot (directions: south, north-west and north-east from the center). The seedling plots were marked with 30 cm long red plastic tube pushed to the peat so that about 10 cm of the tube was visible above the soil. In order to get estimate about the seedling number i.e. the regeneration potential, and their technical quality, all seedlings (< 1,3 m height) within the plots were invented. The seedlings were invented in autumn 2020.

Production of fine roots is measured using ingrowth cores, following Laiho et al. (2014). The cores were filled with local peat sieved through a 2-mm soil sieve to remove existing roots. Altogether, 20 cores per location were installed in the areas that will be later CC- or CCF-areas to capture their before-treatment fine-root production levels. Of these, 17 per location will be used for quantifying root production, and 3 for quantifying total bulk density following incubation. The cores will be recovered after 2-year incubation in the autumn of 2021.

In addition, **above-ground litter production** was measured with conventional litter traps. **Peat samples** (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm and 40–50 cm) were collected in November 2020 from the permanent measurement plots (n=43) and they were pooled according to sub-blocks (1–6) for the analyses of physio-chemical peat properties.

3. Lettosuo flagship demonstration and experimental site

3.1. Location and characteristics

Lettosuo peatland site is located in Tammela municipality in southern Finland (60°38' N, 23°57' E) (Figure 1). The total area of Lettosuo is ca 65 ha and it receives waters from large pristine Tervalamminsuo bog and surrounding mineral soil sites. Waters from Lettosuo discharge to small Mustijoki River, which is flowing through the southern part of the peatland (Figure 19). First sparse drainage was carried out in 1930's, but more intensive drainage was done in 1969 with the ditch spacing of 45 m. In pristine state, the site represented wet sparsely forested nutrient rich mire types. At present, the study site is a nutrient-rich drained peatland forest classified to *Vaccinium myrtillus* type II site (Mtkg II). Ground vegetation includes herbs like *Trientalis europaea* and *Dryopteris carthusiana* and dwarf shrubs such as *Vaccinium myrtillus* (Bhuiyan et al., 2017) and the moss layer is dominated by *Pleurozium schreberi* and *Dicranum polysetum* with some *Sphagnum*-mosses, such as *Sphagnum angustifolium* and *S. russowii* in moist patches.

Before a selection cutting (CCF), the average soil organic C content at the site was 58%, and the total soil N content averaged 2.3% in the 0–40 cm soil layer (Korkiakoski et al., 2019). The C:N ratio averaged 27, and the mean soil bulk density of the 0–40 cm layer was 0.14 g cm^{-3}. The peat thickness at Lettosuo varies mostly within 1.5 and 2.5 m. Assuming a mean thickness of 2 m results in soil organic C and N stock estimates of 156 ± 72 kg C m^{-2} and 6.4 ± 2.9 kg N m^{-2} (±SD), respectively.

The non-harvested tree stand consisted of a mixture of Scots pine (*Pinus sylvestris*) and pubescent birch (*Betula pubescens*) in the dominant layer, with a dense undergrowth of Norway spruce (*Picea abies*). The average stand volume before harvestings was about 278 m^3 ha^{-1} and in the CCF-treatment the average harvesting removal was about 208 m^3 ha^{-1}. Pine, spruce and birch accounted for 2%, 51% and 47% of basal area after CCF-treatment, whereas the shares before harvest were 60%, 20% and 20%, respectively.

The selection cutting (CCF) at Lettosuo was performed between 29 February 2016 and 16 March 2016 on a 13 ha area (Figure 19) where the dominant pine trees (ca. 75% of the tree biomass) were removed. After clear-cutting, the harvest residues were left at the site. All the ditches were left in their original state. In addition to the CCF-area, a non-harvested area (3.1 ha) located north-east of the selection harvested area were left as non-managed control, and an area of 2.3 ha was clear cut (CC) (Figure 20). After clear cutting in August 2016, the site was managed by mounding and Norway spruce seedlings were planted in summer 2017. The ground vegetation was partly destroyed at the CCF-area and completely destroyed at the CC-area by heavy harvesting machinery, harvest residue and the following increase in solar radiation. In the following summer, some species adapted to the open, well-lit conditions; for example, Rubus idaeus, *Carex canescens* and *Dryopteris carthusiana* were observed here and there within the CC-area (Korkiakoski et al., 2019).

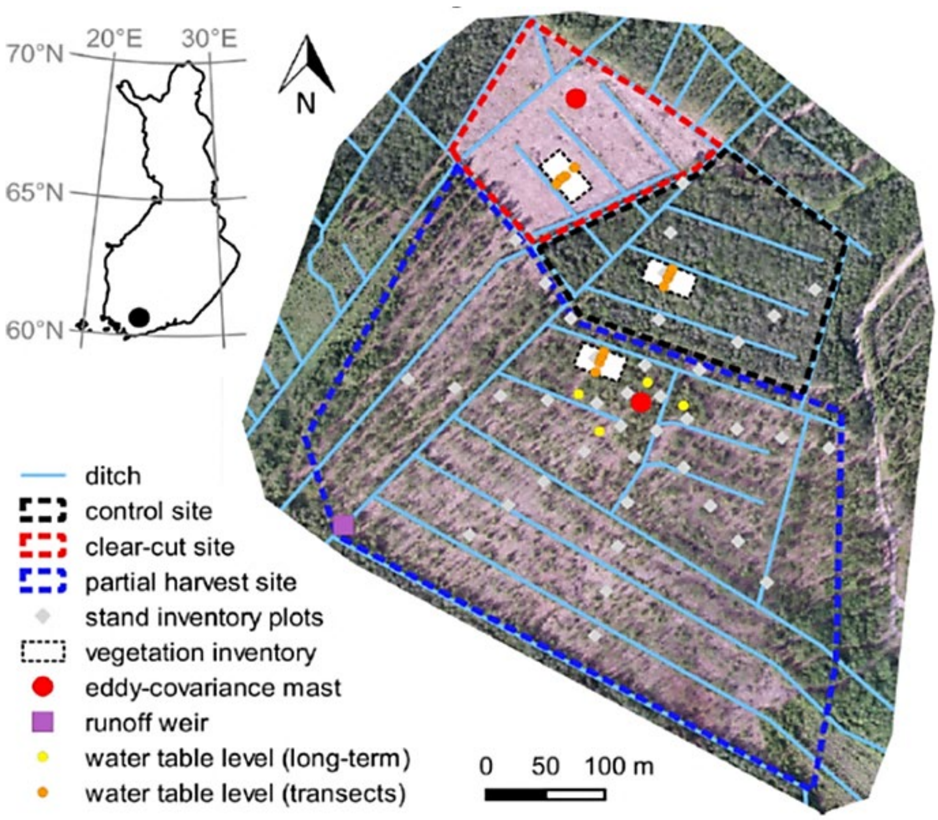

Figure 20. Experimental design of Lettosuo harvesting experiment on fertile drained peatland site in Tammela, southern Finland. Harvesting treatments were selection cutting (partial harvest site), clear cutting (clear-cut site), and non-harvested reference (control).

3.2. Tree stand and vegetation measurements

In Lettosuo, the **tree stands** were measured from 39 systematically arranged permanent circular sample plots. The plots were located on eight radial transects extending 160–200 m from the eddy-covariance mast and covering a total area of 4,000 m^2. Tree species were identified and stem diameter at the height of 1.3 m (DBH) was recorded for all trees with DBH > 25 mm before harvest in 2009 and 2014, and after harvest in 2016 and October 2020. In 2009, tree heights and crown lengths were recorded for a subset of trees to estimate standard stand parameters, such as standing stem volume and biomass distributions. These data consisted of 57 pine, 40 spruce, and 37 birch trees distributed evenly on the permanent inventory plots and covering the entire DBH ranges of each species. Trees in altogether 7 sample plots (W80, N80, N120, NW60, NW20, SE140, SW100) were also scanned by Terrestrial Laser Scanner (TLS) in 11.-12.10.2016 and 14.-15.5.2019.

The **understory vegetation** was monitored by visually assessing the projection coverage of field layer species (dwarf shrubs, herbs, graminoids, and tree and shrub seedlings and saplings up to 0,5 m height) and that of moss species and litter on the ground. The species names used for vascular plants and mosses followed the nomenclatures of Hämet-Ahti et al. (1998) and Ulvinen et al. (2002), respectively. Vegetation was surveyed from sample plots (50×50 cm^2 each, in years 2009 and 2015; in 2017–2018 and 2020 the size of sample plots was 1 m^2) which were placed in the permanent stand inventory plots, as well as in a systematic grid of 32 vegetation plots in each parallel site. The latter plots were located around the groundwater level sampling lines (Figure 20). Understory vegetation inventories were conducted in 2009, 2015, 2017, and 2018.

In year 2020, vegetation survey was done on part of the plots according to Life OrgBalt-project instructions. Vegetation survey was done on two vegetation plots nearest to the three GHG measurement points on each treatment site (6 vegetation plots (1 m^2) on each clear cut, control and selection harvest site). In addition, above ground biomass samples near the GHG measurement points and each 1 m^2 vegetation plot (representing same kind of vegetation) were collected on the size of 30x30 cm plots. The biomass plot was photographed, and vegetation survey was done before cutting the biomass sample. In addition, 4 more biomass samples were collected according to the instructions of ICOS. Altogether 18 vegetation plots and 22 biomass plots were surveyed in August 2020.

To evaluate **the physiological status of the foliage** of the remaining spruce undergrowth trees following the selection harvest, chlorophyll fluorescence (Fv/Fm) was measured from current and past year's needles. Altogether 70 trees ranging from 1 to 16 m in height: 20 in the control area and 50 in different parts of the selection harvested area were selected for these measurements. The measurements were done during the first and second post-harvest growing season, weekly during 10 June – 31 August 2016 and with varying intervals during 11 May – 16 August 2017. In each time, one lateral shoot in the upper third of the live canopy per tree was detached, placed in a plastic bag, and stored cool before the measurement (max. three hours). In the laboratory, the target needles (the two age classes separately for each shoot; current year's needles starting from 30 May) were first dark adapted for 30 min. using PPEA/LC dark adaptation leafclips (Hansatech Instruments, King's Lynn, Norfolk, UK). Measurements were done with a Pocket PEA continuous excitation chlorophyll fluorimeter (Hansatech Instruments; measure duration 1 second, illumination 3500 micromoles).

3.3. GHG measurements

3.3.1. Ecosystem level gas exchange measurements above canopy

Lettosuo flagship station consists of micrometeorological mast for eddy-covariance and ancillary measurements for continuous net CO_2, H_2O and energy fluxes at 27.2 m height (Figures 5 and 20). This system observes net fluxes of the 13 ha drained peatland forest managed based on continuous cover forestry.

The turbulent fluxes of CO_2, H_2O, sensible heat and momentum were measured with the eddy covariance technique on top of a 25.5 m telescopic mast. Fluctuations of wind velocity components were measured with a sonic anemometer/thermometer (USA-1 Scientific, Metek GmbH) and those of CO_2 concentration with a closed-path infrared CO_2/H_2O analyzer (LI-7000, LI-COR, Inc.). The heated inlet tube (3.1 mm i.d. Bevaline IV) for the LI-7000 was 21 m in length, and a flow rate of 6 l min^{-1} was used. CO_2-H_2O free air was generated by recycling the zero cell sample continuously through a closed soda lime – Magnesium perchlorate scrubber system. The mean CO_2 concentration ([CO_2]) was also observed at a height of 5 m with a LI-820 CO_2 analyzer, and at the 1 m height with a Picarro 1301 analyzer (see below). All analyzers were calibrated approximately 4–8 times per year with two known [CO_2] (0 and 460 ppm) and [H_2O].

The system including the mast, radiation components, precipitation gauge and high frequency eddy-covariance sensors were completely refurnished in 2019 (Figure 21). Carbon dioxide and water vapor fluxes are measured by eddy-covariance method using Metek USA-1 anemometer and LI-COR 7200RS gas concentration analyzer. Anemometer is in the end of a horizontal steel profile and LI-COR gas concentration sensor head is attached to the same boom at 1.10 m distance. Air is sampled via 4 mm i.d. steel tube with a rain cap in the inlet and Swagelok 2µm sinter between the tube and the sensor inlet. The tube is tilted so that the rain cap end is at lower level than the sensor inlet. Thomas 688CGHI piston pump is used for producing vacuum for sample flow which is about 12.5 l/min. It is monitored continuously by SMC PFM 725S-N01-C-M flowmeter with needle valve. Heating wire (HeathChem PFA coated constant resistance wire) is wrapped around the steel tube which is insulated by a foam tube. Heating power is about 14 W warming LI-COR sensor cavity temperature 4C above ambient. Upward and downward looking radiation sensors, PQS1 PAR Quantum Sensors, CNR4 pyranometer (solar radiation) and pyrgeometer (long-wave) combination are attached in the steel structure in the end of another boom.

Figure 21. The old forest scale eddy-covariance mast at Lettosuo was replaced by a new mast in spring 2019. Photo: Tuomas Laurila.

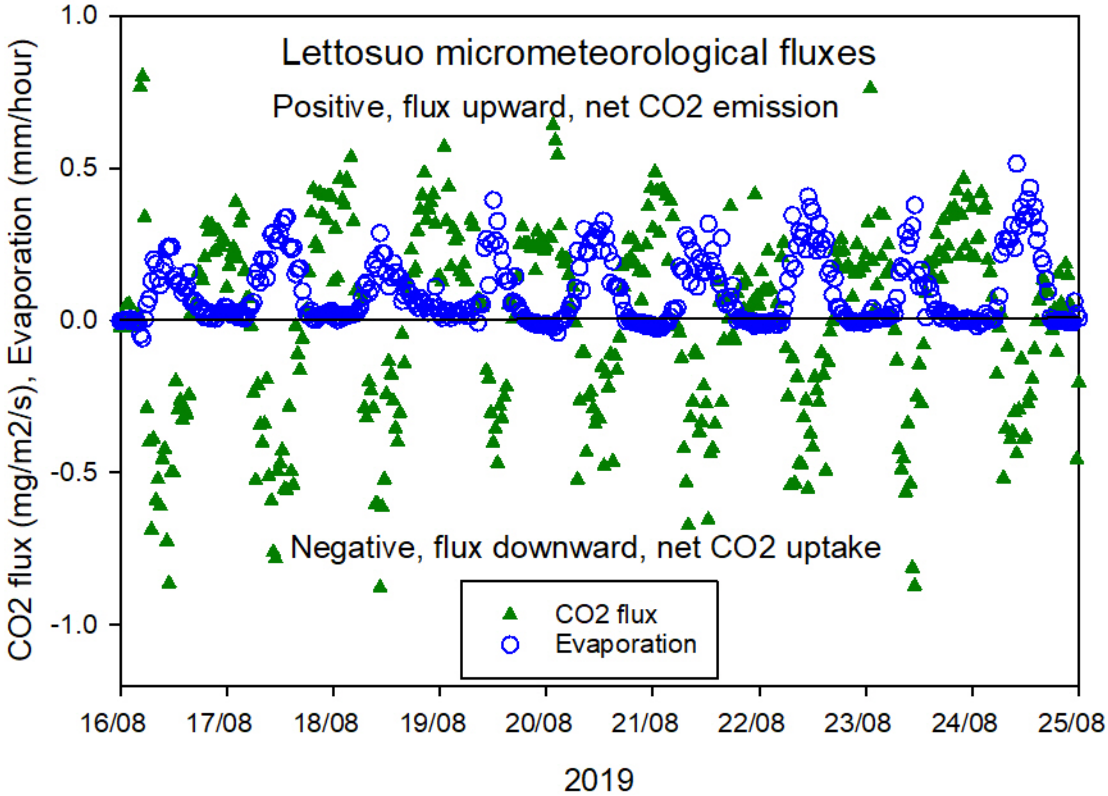

Figure 22. Micrometeorological flux observations (30 min averages) of forest scale CO_2 net exchange in August 2019, see also Figure 10 for average CO_2 fluxes. During daytime forest is net sink of CO_2 (negative values) and during night positive values indicate that the forest is net source of CO_2. Net H_2O flux, which is evaporation happens mainly during daytime driven by energy of solar radiation.

3.3.2. Automatic chamber measurements of soil GHG fluxes

Similar six-chamber system (Koskinen et al., 2014; Korkiakoski et al., 2017) as in Ränskälänkorpi continued operation at the Flagship station of Lettosuo, where we use a DLT100 (Los Gatos Research, Inc. U.S.A.) instrument for N_2O and CO soil flux measurements and a G1301 (Picarro, Inc. U.S.A.) gas analyzer for CO_2 and CH_4 (Figures 23 and 24). In each chamber there are temperature (Pt100, PT4T, Nokeval, Finland) measurements of air and soil (5 cm depth) and photosynthetically active solar radiation (PQS1, PAR Quantum Sensors).

Figure 23. Six automated chambers for forest floor GHG fluxes at Lettosuo. Photo: Tuomas Laurila.

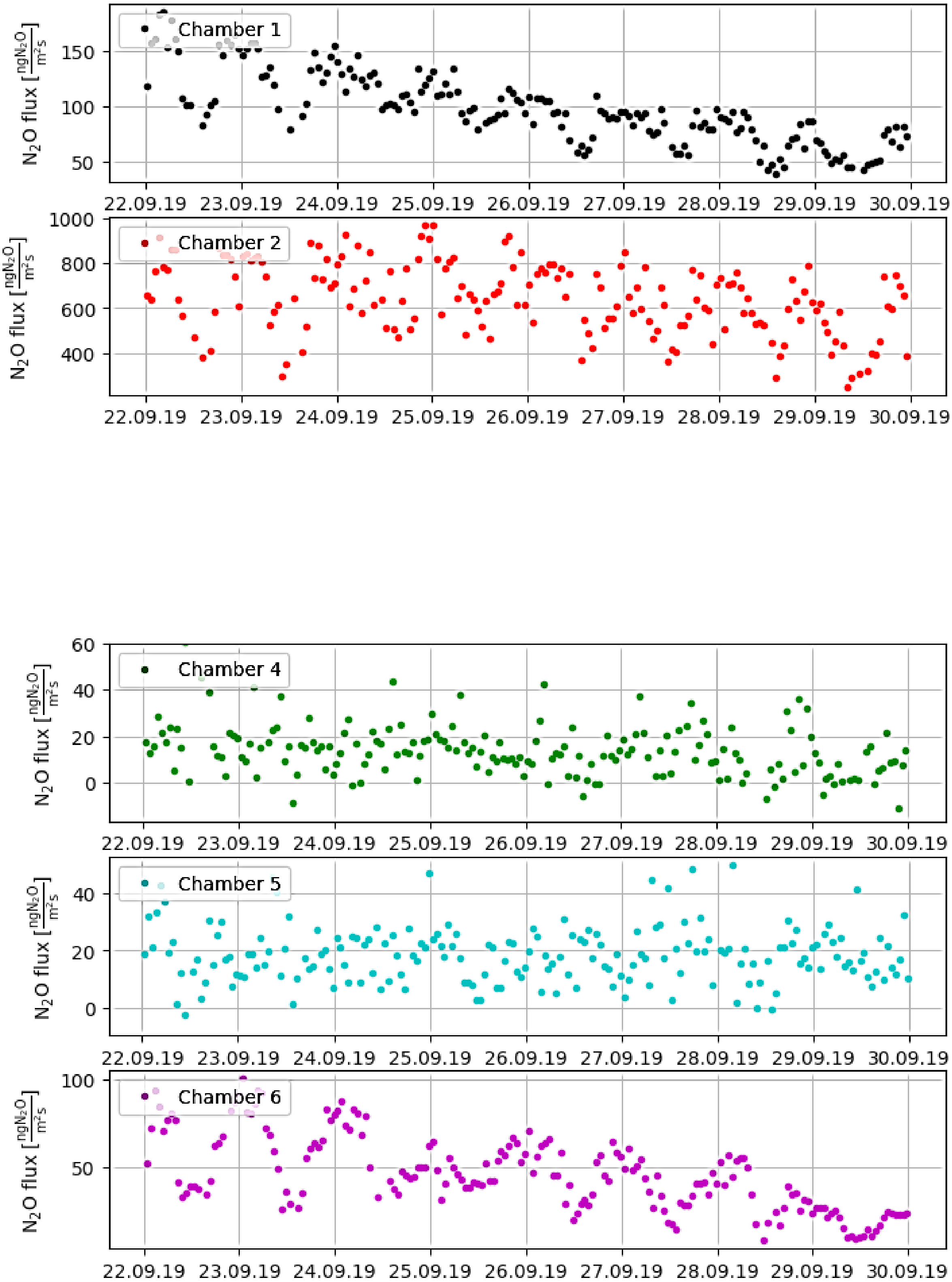

Figure 24. A period of N2O fluxes measured by automatic chambers (chambers 1–2 on selection harvested (CCF) and chambers 4–6 on non-harvested control site) at Lettosuo study area.

3.3.3. Ancillary data

Soil temperature profile (Pt100, PT4T, Nokeval, Finland) with sensors at 2, 5, 10, 20 and 30 cm depth were installed next to the measurement cabin containing the instruments used in the chamber measurements in 2011. In March 2020, the temperature sensors were replaced (Pt100 sensors) and installed at depths 5, 10, 20, 50. At the same time, soil moisture measurements were installed at 5 and 20 cm depths (DeltaT ML3 probes, Delta-T Devices, UK) with a ground heat flux plate (HFP01, Hukseflux Thermal Sensors, The Neatherlands) at 5 cm.

Water table levels next to the automatic chambers have been monitored with automatic loggers (TruTrack WT-HR, Intech Instruments Ltd, Auckland, New Zealand; Odyssey Capacitance Water Level Logger, Dataflow Systems Limited, Christchurch, New Zealand) since May 2010. When the chambers were close to each other, only one logger was installed between them.

Peat Eh was recorded at three points per treatment, using probes with four Pt electrodes placed at 5, 15, 25 and 40 cm depth and Ag-AgCl reference electrodes in KCl solution (PaleoTerra, Oijen, Netherlands).

3.3.4. Manual chamber measurements

The four transects around the mast

In addition to automatic chambers, manual chambers have been used to measure CO_2, CH_4 and N_2O fluxes at Lettosuo. In 2009–2011, GHG fluxes were measured from 16 plots, located in four transects (directions to the north, east, south and west) around the mast. All the plots included four treatments, where CO_2 efflux from peat (A), peat and litter (B), peat and litter and roots (C) and peat, litter, roots and above ground vegetation (i.e. all components, D) were measured. The treatments included the removal of above ground vegetation (A-C), the cutting of roots with 40 cm deep collars (A-B) and the removal and exclusion of incoming above ground litter with litter nets (A).

CO_2 efflux was measured with an opaque closed steady state chamber (diameter 31.5 cm, height 14.9 cm) attached to a portable infrared gas analyser (EGM-4, PP-Systems, Hitchin, UK; NSF11 in Pumpanen et al., 2004). Chamber closure time was 81 seconds. CH_4 and N_2O fluxes were measured from from the intact D-treatment points, with an opaque closed chamber (diameter 31.5 cm, height 30 cm). Four gas samples were taken with syringes during a chamber closure of 35 minutes and analysed with gas chromatograph. CO_2, CH_4 and N_2O measurements were conducted biweekly–monthly during the snow-free season from June 2009 to November 2011, and monthly–bimonthly during the rest of the year.

Soil temperatures at 5 cm were logged hourly at the center of each GHG measurement point, and in addition at 5, 10, 20, 30 and 40 cm depths at each transect (i-button, Dallas semiconductor Inc). Water table depth was also logged at each transect (TruTrack WT-HR, Intech Instruments Ltd, Auckland, New Zealand).

Harvest residue experiment

The impacts of logging trails and harvest residues on forest floor CO_2, CH_4 and N_2O fluxes were measured at the selection harvested area after cuttings in May 2016–Nov 2017. Opaque, closed chambers of 60*60*30 cm were used. The chambers were connected together with 60 m long tubing to the same instruments that were used for analysing automatic chamber fluxes. The measurements were done from five plots and at each plot from four differently treated surfaces (trail, trail compressed, trail side, outside) around logging trails (Poutamo 2019, Korkiakoski et al. 2020). The chambers were manually inserted on previously installed collars and the closure time was 5 min. WT and Tsoil were logged.

Spatial variation measurements

To study the spatial variation in soil respiration on the selection harvested (CCF) and non-harvested control sites, in May-August 2017 soil CO_2 efflux was measured with the same method and equipment as in 2009–2011, from 98 intact points in ten transects around the mast (Shamsuzzaman 2019)(Figure 25).

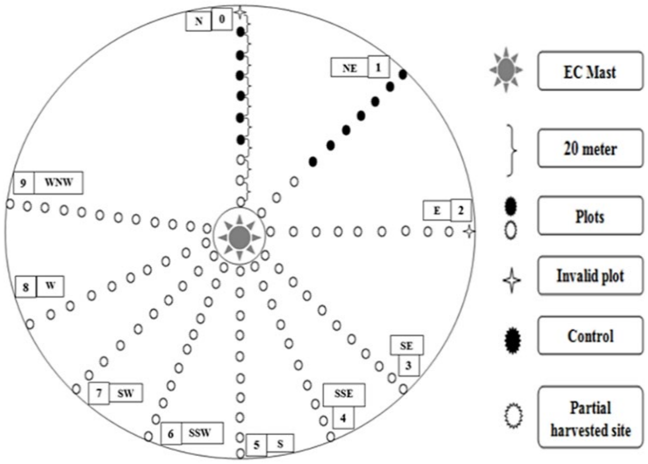

Figure 25. Soil CO_2 measurement points in ten directions around the EC mast. Open circles are for selection harvesting (CCF) and black circles are for non-harvested control.

3.4. Water table (WT) measurements

Water table (WT) at Lettosuo was monitored since May 2010 with four automatic loggers (TruTrack WT-HR, Intech Instruments Ltd, Auckland, New Zealand) located around the eddy-covariance mast. Additionally, four loggers (Odyssey Capacitance Water Level Logger, Dataflow Systems Limited, Christchurch, New Zealand) were installed on each site in December 2014 or July 2015 (CC-site). The four loggers were installed on sampling lines running from the mid-strip to ditch (Figure 14). All loggers recorded WT at an hourly interval.

WT was also monitored from 39 stand inventory plots located every 40 m from the EC mast in cardinal and inter-cardinal directions. WT monitoring started in June 2015 first by manual monitoring every 1–2 weeks during summer and at least once a month during winter. In June 2016, automatic WT sensors (Odyssey Capacitance Water Level Logger, Dataflow Systems Limited, Christchurch, New Zealand) were installed to 11 plots and 7 sensors more were installed in October 2016 while the rest of the plots were still monitored manually. The manual monitoring ended in September 2017.

3.5. Other measurements

Outflow water quantity and quality

Outflow water quantity from the partially harvested block is monitored from a V-notch weir (90°) installed in the southwest end of the area using a capacity water level logger (TruTrack WT-HR). Manual measurements of water level are taken regularly in the notch of the weir and the water level data produced by the logger is calibrated against these manual measurements. At the control and clear-cut blocks of Lettosuo, water quantity is measured similarly as at Ränskälänkorpi, that is by using a stopwatch and a bucket to measure water flow from a throughflow pipe of an earth embankment in the outlet ditch of the block area. To monitor outflow water quality from the three block areas, water samples are taken from the outflow water of the notch or pipe once a month and more often during high flow periods and analysed for DOC, nutrients and heavy metals as in, e.g. Nieminen et al. (2020).

Fine root production

Fine root growth, lifetime and production have been studied in Lettosuo with ingrowth cores (Bhuiyan et al. 2017) and minirhizotrons (Minkkinen et al. manuscript in preparation). In the study of Bhuyian et al. (2017), sixty ingrowth cores were installed in May 2010, just before the onset of the growing season, on two transects stretching across a strip between two ditches. They were recovered for analyses after three consecutive growing seasons in November 2010, 2011 and 2012; 20 cores were recovered each year. For the unpublished data, 18 ingrowth cores were installed in three of the minirhizotron plots, two per plot, in November 2015 and recovered in November 2017.

In August 2013, twelve acrylic tubes (minirhizotrons) were installed for photographing fine root growth, i.e. three tubes at four plots, close to the mast. Fine root growth was monitored until Nov 2017. One volumetric peat core (6,5×3,7×50 cm) was taken with a box corer near each MR tube for analysing fine root biomass.

Litterfall and biomass measurements

Litterfall from tree stands was collected at four transects (South, East, North, West), each transect having 14 collectors, each collector having area of 0.2*0.2 m^2. Litter collectors were placed at Lettosuo 1.7.2009 and the collection was continued until 2.5.2014. Litter was dried at 105 °C and separated into different compartments (tree species; needles, leaves, cones, bark, woody). Furthermore, periodic litter sampling for large on-ground litter collectors was set in 19.5.2020.

Biomass production of understorey vegetation was measured in 2020. Moss biomass production nets set were 9.6.2020 and biomass samples collected in December 2020. Biomass samples of herbaceous vegetation (annual plants) were collected in 28.8.–4.9.2020, and dwarf shrubs were sampled 28.8.–4.9.2020. Biomass of trees was sampled in 2014/2020. Fine roots/ soil samples were collected 21.–25.9.2020.

In addition, data on aboveground biomass of ground vegetation (vascular plants per species) before the selection harvesting (CCF) is available.

Decomposition experiments

Decomposition rates of roots of Scots pine, Norway spruce and the fern *Dryopteris carthusiana*, and several moss species have been quantified between 2009 and 2013. Some data exist also on decomposition of coarse root systems. In addition, decomposition experiments on peat and cellulose have been conducted before the selection harvesting.

Tree ring measurements for $\delta^{13}C$ ratios

Six suppressed spruce sample trees were selected from thinned and from control area of Lettosuo. The objective of the measurement was to analyse processes related to growth reaction of trees after thinning. Trees were selected outside from the last permanent sample plot of North-East transect and from the 2nd last plot of the South-East transect (looking from the EC tower). Trees were cored from Southern and Northern side of the trunk from the breast height. Thereafter ring widths were analysed for early wood and late wood thickness in the Viikki lab. Those tree rings were also analysed for intra-annual $\delta^{13}C$ ratios by laser ablation technique. During this analysis 10 $\delta^{13}C$ spots we measured from each tree ring.

In addition, **methane emissions from trees** were measured by Mari Pihlatie's research projects.

4. Experimental study sites for effects of varied thinning intensities on stand conditions and GHG on drained peatland forests

4.1. Location, characteristics and thinning experiments

Natural resources Institute Finland (Luke) has six stand scale replicated experiments, where effects of thinnings and thinning intensity on stand characteristics and GHG fluxes of drained peatland forests in transition to continuous cover forestry are studied (Figure 26). The sites represent mid-productive to fertile Norway spruce dominated peatland forests, where soil GHG emissions are high due to drainage that has exposed peat to decomposition in aerobic conditions.

Figure 26. Location of the experiments on continuous cover forestry (CCF) on drained peatlands. Replicated CCF experiments in red and flagship sites (see previous Chapters 2 for Ränskälänkorpi and 3 for Lettosuo) in blue.

The stand thinning experiment consisted of treatments with 1–3 thinning intensities of selection harvesting and parallel control sites that were left intact (Table 1). Study design included 2–5 replicates depending on the site. The size of the study plots varied from 970 m^2 to 2,000 m^2. Treatments were randomized to study plots as shown in Figure 27.

Table1. Characteristics of the experimental study sites, where varied thinning intensity of selection harvesting was tested on drained Norway spruce dominated peatlands. Site types are according to Finnish site type classification system for drained peatlands (Vasander & Laine 2008).

Site name	Location municipality	Coordinates, ETRS-TM35FIN	Site type	Selection cuttings	Pre-harvest BA, m2/ha	Post-harvest BA, m2/ha
Paroninkorpi	Hämeenlinna, Janakkala	6765901:378226	Rhtkg II	15.2.2017	22–31	12 or 17
Havusuo	Multia	6936709:375246	Mtkg I-Ptkg I	21.3.2016	25–31	13
Rouvanlehto	Heinävesi	6935618:581809	Mtkg I, MtkgII, Rhtkg I-II	21.2.2017	22–24	12 or 17
Vaarajoki	Juuka	7028814:588868	Mtkg I-Ptkg I	15.2.2017	19–24	12 or 17
Sinilammenneva	Orivesi	6853881:357383	Ptkg II	8.2.2018	29–40	0, 6 or 8
Lintupirtti	Tervola	7340122:439755	Rhtkg I	March 2015	22-32	9, 13, 17, 28

Table 2. Measurements on the experimental study sites. Measurements that have continued until 2020 are ongoing at the time of publication of this report.

Site name	GHG measurements, years	Water quality measurements	Ground water table (WT) measurements	Automatic WT monitoring	Tree stand measurements, years	TLS-scanning, tree stand	Inventory of tree seedlings, years	Vegetation survey, years
Paroninkorpi	2017-2020	2016-2020	2015-2020	2016-2020	2016, 28.10.-13.11.2020	20-23.11.2018 (plots 1-5); 6-13.5.2019 (plots 6-15)	2016, August 2020	2016, 2018, 2020
Havusuo	2016	-	2015-2020	2015-2020	2015		May 2017, September 2020	2016, 2018
Rouvanlehto	2018-2019	-	2015-2020	2017-2020	2016	30.10.2018	October 2017, August 2020	2016, 2018
Vaarajoki	-	-	2015-2020	2017-2020	2016	6.11.2018	October 2017, August 2020	2016, 2018
Sinilammensuo	2018-2020		2015-2020	2016-2020	2018		May 2019	2016, 2019
Lintupirtti	-	-	2014-2020	-	2015, 2019	26.10.2018	2015, 2017, 2019	-

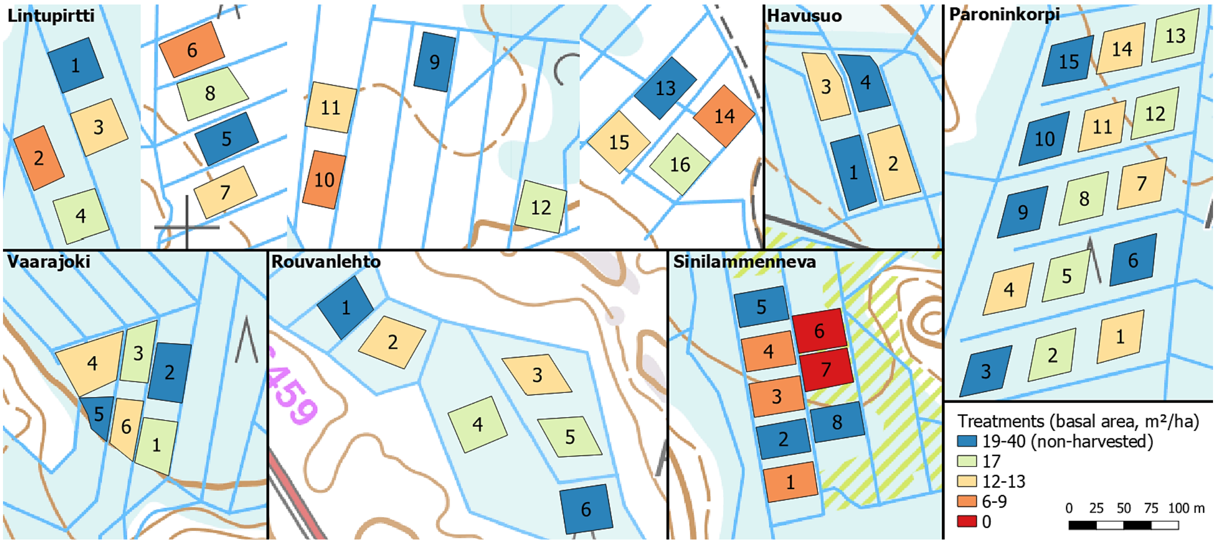

Figure 27. Layout of experimental control and thinning (categorized by remaining stand basal area) plots in the six CCF-sites.

4.2. Tree stand and vegetation measurements

4.2.1. Tree stand measurements

Trees of the study plots (in general 40*40m^2) were measured according to 'Kestokokeiden mittausohje'-guidance (Metsäntutkimuslaitos 1987). All trees higher than 1,3 m were marked (side indicates direction of first DBH measurement) and mapped (direction and distance from a reference point) and measured for variables shown in Supplementary (Table S1). In addition, a stratified (according to size class) sample of trees (n=20) were measured for tree and crown height. After stand thinning, new trees were added to this sample in order to maintain a total number of measured trees (n=20). In Sinilammenneva, trees were measured after thinnings. Therefore, also diameter of tree base was measured from stumps and with diameter data (base and DBH) from control plot DBH was modelled for harvested trees.

In addition, to tree measurements with conventional methods, we applied optical methods. Terrestrial laser scanning (TLS) data was obtained for all study sites (Table 1).

In Paroninkorpi, plots 1–5 were scanned in 20–26.11.2018 and plots 6–15 in 6–13.5.2019 by Luke. In Paroninkorpi, aerial laser (ALS) scanning was made on 14th of December 2018 by Vito-mittaus Oy. Scanner (Riegl VUX-1UAV) was carried with Riegl Ricopter (speed 3.5 m/s) and scanning elevation was 80 meters. Site was divided to 25 blocks (Figure 28) and resolution was max 40 million points per block. Blocks 1–15 represent study plots (see Figure 28) and for them resolution was 650 –7,500 points/m^2.

Figure 28. Study site (Paroninkorpi) was divided to 25 blocks for aerial laser scanning with Riegl Ricopter and Riegl VUX-1UAV scanner.

4.2.2. Monitoring of stand regeneration

Tree seedlings were measured on 4 m^2 circular plots (r=1,128 m) and all tree seedlings to the height of 1.3 m were recorded. A total of 15 circular seedling plots were systematically located on each selection harvesting treatment plot (Figure 29). Direction and distance of a circular plot to the permanent reference point was recorded in order to allow repeated measurements of the same plots. Measurements were repeated three or four growing seasons after the initial measurements (Table 1). Measured characteristics were

(1) Tree species (codes: 1=pine, 2=spruce, 3=silver birch, 4=downy birch, 5=aspen, 6=grey alder, 7=black alder, 8=other conifer, 9=other deciduous tree)
(2) Tree group (codes: 1=no specified, 2=remaining, 3=to be removed, 4=disappeared)
(3) Tree DBH for trees over 1.3 m height
(4) Tree damages (codes: 1=healthy, 2=standing dead tree, 3=tree with observed) decay, 4=stem damage, 5=top damaged or dead, 6=top displaced or multiplied)
(5) Cause of a damage (codes: 0=unknown, 1=wind, 2=snow, 3=other climate factors, 4=competition, 5=damaged due to harvesting, 6=other artificial, 7=vole, 8=moose,

9=*Tomicus*, ytimennävertäjä, 10=insect, 11=*Cronartium*, tervasroso, 12=*Gremmeniella abietina*, versosurma, ent. männynversosyöpä, 13=other fungi)

(6) Severity of a damage (codes: 0=recovered, 1=recovering, 2=damaged, 3=lethal or tree is already dead)

(7) Tree height (cm)

(8) Number of trees (if multiple seedlings in same height and diameter cohort)

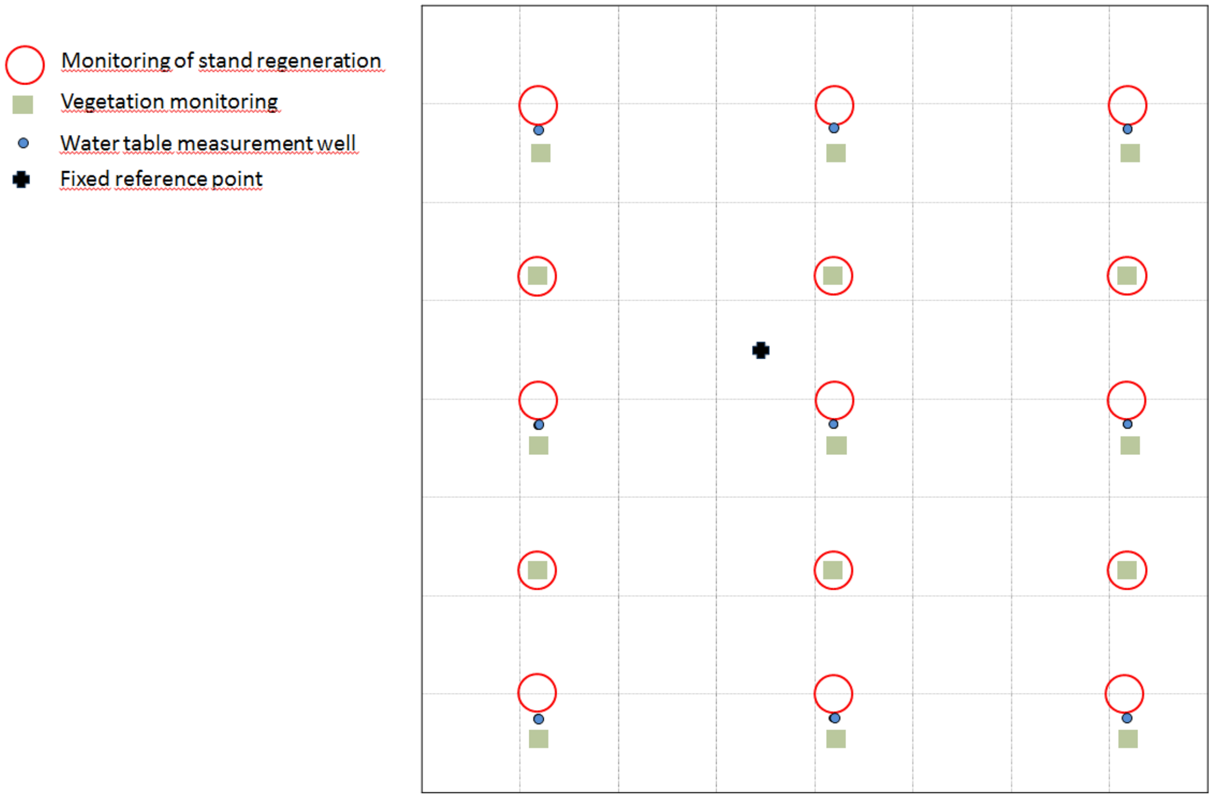

Figure 29. The disposition of the stand regeneration (4 m^2 circles) and understorey vegetation (1 m^2 squares) monitoring plots within the experimental treatment plot.

4.2.3. Vegetation monitoring and biomass sampling

Understorey vegetation was surveyed from 15 sample quadrats of 1 m^2 located systematically on each treatment plot (Figure 28). Species abundances were estimated visually. Covers (in % of surface) of bottom layer and field layer plant species were recorded using scale 0.1, 0.2, 0,3, 0,5, 1, 2, 3, 5, 7, 10, 15...95, 97, 98, 100%. In addition, a proportion of the surface covered by a tree, trump-root system or litter was estimated. *Rubus idaeus* was recorded as a field layer plant without height limit.

Covers of trees and bushes under 0.5 m were recorded as a part of field layer vegetation. Furthermore, the number of seedlings per tree species was recorded according to height classes <0.1 m and 0.1–1.3 m.

Site fertility level was estimated based on understorey vegetation (Laine et. al. 2012).

In august 2020, vegetation survey was done on part of the plots according to Life OrgBalt-project instructions. Vegetation survey was done on two vegetation plots (size 1 m^2) nearest to the three GHG measurement points on each treatment site (4 plots on clear cut, 4 plots on control and 8 plots on selection harvest sites). On clear cut site the vegetation survey was done first time. In addition, vegetation survey was done on each biomass plot (30x30 cm) which were also photographed before cutting the biomass samples near the GHG measurement points and each 1 m^2 vegetation plot (representing same kind of vegetation) were collected. Altogether vegetation survey was done on16 vegetation plots size 1 m^2 and on 16 biomass plots size 30x30 cm.

In addition, root ingrowth trials (root ingrowth meshes) were set on Paroninkorpi site in 30.11.2018, moss biomass production nets were set in 28.5.2020 and collected in December 2020, biomass samples of understorey vegetation were collected in 12.–13.8.2020 and tree biomass was sampled 2016/2020, fine roots - soil samples were collected 4.9.2020, periodic large on-ground litter collectors were set in 07/2019, litter material for decomposition trials was collected 29.9.2020.

4.3. GHG measurements

Greenhouse gas (CO_2, CH_4, and N_2O) fluxes are monitored for 1–3 years (Table 2) with manually operated chambers at four sites, where effects of selection (CCF) harvests are studied with replicated treatments.

Figure 30. Greenhouse gas (CO_2 and CH_4) measurements on Paroninkorpi site in October 2020 by Petri Salovaara with chamber and gas analyser LI-7810 (LI-COR Inc., Lincoln, NE, USA). In Paroninkorpi site, ongoing measurements of CO_2, CH_4, and N_2O fluxes started in 28.7.2017 and were continued in 2019 and 2020 over the snow free period. Heterotrophic respiration monitoring was appended by 4 new points in 20.5.2020. Photo: Raisa Mäkipää.

4.4. Water table (WT) measurements

Water table (WT) was monitored manually from 9 plastic tubes installed systematically in each sample plot of the experiments (Figure 28). The measurements were done beweekly during growing season. Furthermore, the WT was monitored automatically by data loggers (Tru Track WT-HR-loggers and Odyssey Capacitance Water Level Loggers) with one-hour measurement interval. The monitoring procedure was similar as in the Lettosuo and Ränskälänkorpi experimental sites.

4.5. Other measurements

4.5.1. Weather stations

In Paroninkorpi, Heinävesi, and Lintupirtti site, the meteorological conditions were measured with Vaisala at adjacent forest opening. In Paroninkorpi, the opening was the same where soil GHG measurements were conducted, otherwise the openings were in the immediate vicinity of the plots. Meteorological stations were identical VAISALA Automatic Weather Stations AWS310 Vaisala with WXT530 Weather Transmitters. Transmitters measure wind speed and direction, air temperature, relative air moisture, air pressure, and rain/hales. Additional Campbell CS320 Digital Thermopyle Pyranometers are installed to measure global radiation, and **Campbell 105T** temperarate probes are deployd to measure soil temperature at depths 5, 30 and 60 cm below the top of the moss layer. Data is logged in 10 min intervals by Campbell CR1000 datalogger. The weather stations are powered by 12 V/18 Ah gel batteries and ja 15 W solar panels. Data is transmitted to Luke server (G:\Luke\Saa-asemadata) through GSM network. Stations were deployed in Apr 2019, and data is measured only during the growing seasons (Apr-Nov).

4.5.2. Paroninkorpi soil GHG profile measurements

Soil gas collectors were installed in Paroninkorpi in two phases. Collectors were installed to three plots (1, 5, 6) during the 26–27.7.2018. Collectors were placed on top of each other to three horizons so that the concentration profile can be determined from one location in each plot. Each collector was made out of gas-permeable 220 cm silicone tube inside a hoover cover, total volume of tube being approximately 165 cm^3. Thin and non-permeable PTFE tube with valve was attached to the silicon tube and drawn to soil surface for sampling purposes (Figure 31). In 2.5.2019, three additional collector setups (now without hoover covers) were installed in plots 1 (1) and 6 (2). During these installations, the collectors were also installed to 2018 to measure gas concentrations between living moss layer and peat. In 2019, soil respiration plots were also established near each plot. Profile measurements cover the range 5–80 cm. During the samplings in 2019, air was collected from the living moss layer too.

Figure 31. Gas collector unit belowground (left) and setup with PTFE tubings and valves aboveground. Photos: Mitro Müller.

5. Host projects and research collaboration

These experiments were designed and established by Natural Resource institute Finland (Luke) jointly with collaborators Finnish Meteorological institute (FMI) and University of Helsinki (UH).

Lettosuo measurement site was established in 2009 in a project "Validating GHG emission factors for drained peatland forests with micrometeorological measurements (proj. 311134)", led by the University of Helsinki (Kari Minkkinen) and funded by the Ministry of Agriculture and Forestry. Instrumentation and measurements since 2018 were made by research projects "Novel Soil Management Practices - Key for Sustainable Bioeconomy and Climate Change Mitigation" SOMPA funded by the Strategic Research Council (SRC) at the Academy of Finland and "Towards Carbon Neutral Municipalities and Regions" CANEMURE Action A.1 Verification of cost effective GHG mitigation measures for cultivated and forested peatlands of the LIFE-IP CANEMURE-FINLAND project (LIFE17 IPC/FI/000002). Both projects are coordinated by research professor Raisa Mäkipää at the Natural Resources Institute Finland (Luke). The EU funded CANEMURE project will maintain instrumentation and measurements of the selected study sites for research and demonstration purposes until 2023. Manual-chamber measurements to characterize the peat soil GHG balance will be continued in 2020–2021 by the LIFE OrgBalt project (LIFE18 CCM/LV/001158) coordinated by Latvian State Forest Research Institute Silava; Finnish partner is Luke (Raija Laiho & Jyrki Jauhiainen).

The study sites Paroninkorpi, Havusuo, Rouvanlehto, Sinilammensuo and Vaarajoki were established in 2015–2016 by the project "New options for forestry on peat soils" funded by Luke (2015–2018; Raija Laiho) with cofunding from the Finnish Forest Industries in 2017–2018. The GHG measurements during 2016–2019 were done in the project "Continuous-cover forestry as an alternative to intensive silviculture in drained peatland forests and its associated environmental benefits" funded by Koneen säätiö (Meeri Pearson & Raija Laiho) and a part of supporting other measurements and instrumentation since 2019 by the SOMPA project funded by the SRC and by the CANEMURE project funded by the EU. GHG measurements in Paroninkorpi will be continued by the project LIFE OrgBalt during 2020–2021.

The established study sites are open for further measurements and instrumentation with research collaborators. CCFpeat project (funded by the Academy of Finland; Mika Nieminen) has enriched the research activities and runoff water quality measurements from the very beginning of the studies on these sites. Prof. Jukka Pumpanen's research group has conducted peat and water studies in Paroninkorpi site. In 2020, research project BiBiFe (funded by the Academy of Finland; coordinated by prof. Jaana Bäck) initiated further studies on ecosystem processes in Lettosuo and Ränskälänkorpi and prof. Petr Baldrian (Institute of Microbiology of the Czech Academy of Sciences) started his studies on microbial communities at Ränskälänkorpi in September 2020 by soil sampling and by installing Tomst point dendrometers and soil moisture sensors. In addition, Horizon 2020 project "Holistic management practices, modelling & monitoring for European forest Soils (HoliSoils)" will use the established study sites in 2021–2025.

6. References

Links to project's websites

www.luke.fi/sompa, "Novel Soil Management Practices - Key for Sustainable Bioeconomy and Climate Change Mitigation" SOMPA funded by the Strategic Research Council (SRC) at the Academy of Finland

www.hiilineutraalisuomi.fi, "Towards Carbon Neutral Municipalities and Regions" CANEMURE Action A.1 Verification of cost effective GHG mitigation measures for cultivated and forested peatlands of the LIFE-IP CANEMURE-FINLAND project (LIFE17 IPC/FI/000002)

www.orgbalt.eu, "Demonstration of climate change mitigation potential of nutrients rich organic soils in Baltic States and Finland" LIFE OrgBalt is funded by EU LIFE program, and coordinated by Latvian State Forest Research Institute Silava; Finnish partner is Luke (LIFE18 CCM/LV/001158 LIFE)

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Supplement

Table 1 Example data sheet for tree measurements

pvm:		mittaajat	ruutu m x m							linjan suunta					kp et 1-2		kp et 2-3			puita		167
30.-31.8.2016		MR,EP		40	40															koepuita		36
koe	koeala	Konepiste	Puu	Su	Et	Pl	Pr	lkerr			D1.3	D1.3			ia	syy	aste	kp	latvlev	pit	lraja	
Paroninkorpi	1	1	1	5	100	2	1	1			265	263						1		195	48	
	1	1	2	19	29	4	1	1			210	214						1		210	93	
	1	1	3	21	68	2	3	3			145	141										
	1	1	4	26	68	2	1	2			142	135										
	1	1	5	28	15	2	1	2			172	177										
	1	1	6	53	102	2	1	3			154	156										
	1	1	7	64	97	2	1	1			255	258						1		220	69	
	1	1	8	75	102	2	1	2			190	189										
	1	1	9	77	66	2	1	2			241	250										
	1	1	10	80	43	2	1	2			250	245										
	1	1	11	100	20	2	1	1			311	316										
	1	1	12	84	64	2	1	4			71	75						1		68	29	
	1	1	13	110	131	2	1	3			89	89										
	1	1	14	111	119	2	3	3			91	92										
	1	1	15	119	89	2	1	2			156	160										
	1	1	16	122	112	2	3	4			73	76										
	1	1	17	138	99	2	1	3			122	123										
	1	1	18	140	66	2	3	4			70	71										
	1	1	19	142	85	4	1	3			61	55			2	2	3					
	1	1	20	146	94	2	1	3			94	95										
	1	1	21	194	109	2	1	1			220	209										
	1	1	22	195	81	2	1	1			277	277						1		211	31	
	1	1	23	200	126	2	1	1			212	204										
	1	1	24	202	84	2	1	2			165	173										
	1	1	25	240	43	2	1	3			172	170										
	1	1	26	252	90	2	3	4			109	104										
	1	1	27	258	98	2	1	3			82	84										
	1	1	28	257	58	2	1	5			31	33						1		29	15	
	1	1	29	257	38	2	1	5			6	6						1		14	7	
	1	1	30	260	43	2	1	3			125	131										
	1	1	31	271	55	2	1	1			299	292										
	1	1	32	285	121	2	1	3			158	164			8	3	2					
	1	1	33	292	120	2	3	4			56	59										
	1	1	34	293	127	4	1	3			81	80						1		139	76	
	1	1	35	297	102	2	1	2			210	215										
	1	1	36	303	74	2	1	3			148	146										
	1	1	37	307	35	2	1	2			218	218										
	1	1	38	333	33	2	1	2			185	191										
	1	1	39	335	55	2	1	1			227	225										
	1	1	40	335	88	2	1	1			215	203						1		183	51	
	1	1	41	349	85	2	1	2			172	172										
	1	2	42	12	80	2	1	1			222	215										
	1	2	43	14	116	2	1	5			18	19										
	1	2	44	21	121	2	1	5			31	31						1		32	22	
	1	2	45	24	113	2	1	5			9	9										
	1	2	46	29	113	2	1	1			234	228										
	1	2	47	30	37	2	1	2			218	219										
	1	2	48	40	78	2	1	1			264	262										
	1	2	49	34	71	2	1	5			19	18										
	1	2	50	42	94	2	1	3			173	169						1		184	60	

S1 Guidance for tree measurements

Kaikki YLI 1,3 M PITUISET PUUT mitataan ja numeroidaan pysyvästi. Mitataan myös aiemmin mitatut puut, vaikka pituus olisi tällä hetkellä pienempi.

- Puun numero
- Puulaji
- Puustoryhmä
- Rinnankorkeusläpimitta, mm1
- -"- kohtisuoraan ed. mittausta vastaan

- Tekninen laatu (HUOM!)
- Tuhon ilmiasu2
- Tuhon syy
- Tuhon aste
- Pituus, dm
- Latvusraja, dm
- Lukumäärä, kpl3

1. Maalimerkki ensimmäisen mittaussuunnan rinnankorkeudella

2. Tuho: Tuhoista kirjataan vain vakavat tuhot (koodit 0-6).

3. Lukumäärä: Jos noin ½ metrin läpimittaisella alueella on useita suunnilleen saman pituisia, läpimittaisia ja ikäisiä lehtipuun vesoja, ne voidaan kirjata ryhmänä. Silloin läpimitta, pituus, latvusraja ja kantoläpimitta sekä koordinaatit kirjataan ryhmän silmämääräisesti arvioiden edustavan (keskimääräisen) puun mukaisesti. Lukumäärä kirjataan sille varattuun kohtaan.

Koepuut

Olemassa olevat koepuut säilytetään ja mitataan samat koepuut aina uudelleen.

Hakkuuta seuraavassa mittauksessa valitaan kuitenkin lisää koepuita, jotta niiden määrä palautuu tavoitetasolle. Koepuita tulisi olla vähintään 20 kpl/koeala. Niiden valinta tehdään 5 cm läpimittaluokittain. Ensin laitetaan läpimittaluokkiin olemassa olevat koepuut. Niihin luokkiin valitaan lisää koepuita, joissa on vajausta. Uudet koepuut arvotaan läpimittaluokan sisällä.

Koepuista lukupuutunnusten lisäksi mitattavat tunnukset:

- Koepuu = 1
- Kantoläpimitta, mm
- -"- ed. mittausta vastaan kohtisuoraan
- Latvuksen maksimi leveys, dm
- Leveys maksimileveydestä 90o myötäpäivään

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Natural Resources Institute Finland
Latokartanonkaari 9
FI-00790 Helsinki, Finland
tel. +358 29 532 6000