Pro Gradu

Meteorology

METHANE FLUXES FROM TREE STEMS AT A DRAINED PEATLAND IN SOUTHERN FINLAND AND ERROR SOURCES USING CLOSED CHAMBER MEASUREMENT TECHNIQUES

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The boreal forest zone covers approximately 3% of Earth's non-frozen land area and contains large quantities of carbon. Methane (CH$_4$) emissions originating from the forested peatlands are not large but their contribution can change due to future’s climate change. This makes it important to study how boreal forests respond to changing climatic conditions. Methane-producing archaea present in these ecosystems produce CH$_4$ under anaerobic conditions. Soil CH$_4$ emissions are controlled by the depth of the anaerobic and aerobic layers, which are affected by variations in water table level (WTL).

Here I addressed the role of trees, growing in drained peatland forests, on the CH$_4$ balance, and discussed what could be the driving environmental variables affecting tree CH$_4$ exchange. The Lettosuo site is a nutrient rich drained peatland forest in southern Finland. The measurement setup: 1) control plot 2) partially harvested plot without Scots pines to decrease evapotranspiration, which leads to higher WTL. The partial harvest at Lettosuo simulates real world selective cutting giving more value to this study. Tree stem fluxes were measured over two summers (May-Sept 2016 and 2017). All the species emitted CH$_4$ from the stems and the emissions decreased in the order: downy birches, Scots pines, Norway spruces. According to the linear mixed-effects model, WTL significantly affected the CH$_4$ emissions from the stems of downy birches ($p<0.05$). Also different chamber designs (box-shaped and cylinders) were used during the measurement campaign. We found that observed CH$_4$ fluxes differ from each other largely depending on the chamber design.

Avainsanat – Nyckelord – Keywords
peatland, wetland, methane, greenhouse gases, chamber, chamber measurements, downy birch

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1 Introduction

1.1 Background and significance

Methane (CH_4) is a strong greenhouse gas that has a global warming potential of 28 (Hartmann et al. 2013), which means that over a 100-year period it traps 28 times more heat than carbon dioxide (CO_2) per mass unit. Methane has both natural and anthropogenic sources. Natural sources make up about a third of the global CH_4 emissions and of this third, about a fourth comes from boreal wetlands (borealforest.org, 2017). The boreal wetlands constitute an important and interesting research topic because of their relatively big contribution to the global CH_4 budget and the relatively big land area they cover which is 49.8 million square kilometres (borealforest.org, 2017). These areas might be susceptible to future climatic changes such as changes in precipitation and temperature (Van Oldenborgh et al. 2013). A common general expectation is that as the water table level (WTL) is higher, microbes produce more CH_4 anaerobically in the soil which is further brought up to the atmosphere by wetland trees and vegetation (e.g., Pangala et al. 2013; Terasawa et al. 2015). As will be discussed later in this thesis, trees can both consume and emit methane through the bark or their shoots (Machacova et al. 2016; Pangala et al. 2017; Sundqvist et al. 2012). For example if a boreal wetland area were to receive more precipitation which would make the WTL of this area rise, this could lead to an increased anaerobic production of CH_4 in the soil and lead to a larger transport of CH_4 from the soil to the tree roots and further to the atmosphere. On the other hand some regions are predicted to get drier (Van Oldenborgh et al. 2013), which could lead to an increase in the area of dry forest floor that is a CH_4 sink(e.g., Castro et al 1994; Singh et al 1997). From these examples one can easily see that the research topic requires a lot more research because the different sources and sinks of CH_4 create a complex puzzle that is under constant influence of changing environment.

The global atmospheric CH_4 concentration has been on the rise since the early 1800s and the rise has been particularly strong after 1980s apart from the steady plateau (figure 1). The reason to this is currently quite unclear.

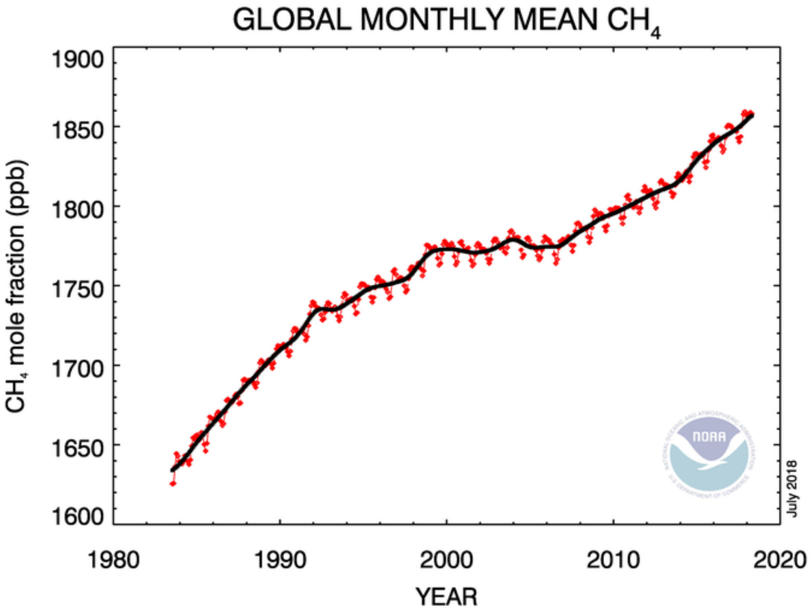


Figure 1: Evolution of CH$_4$ concentration from 1980s to 2018 (NOAA, Earth System Research Laboratory, 2018)

The steady period during 1998-2007 has been under heavy discussion after which the CH$_4$ concentration began to rise again (e.g. NOAA, Climate.gov, 2018). Scientists are debating whether it is the higher anthropogenic emissions of methane that are to blame or if a possible decrease in atmospheric hydroxyl radical (OH) during the last decades could play a big role in perceived higher concentrations of methane. In addition to research done on peatlands, wetlands and plants, as an example Rigby et al. (2017) arrived to a conclusion that a decline in global OH concentrations can be attributed to the post-2007 methane rise with a probability range of 64-70% although they could not give a reason to the decline. They used a computer model and atmospheric observations of 1,1,1- trichloroethane (CH_3CCl_3) to estimate OH-levels. Trichloroethane is mainly lost in reactions involving OH, and the uncertainty in the measurements of the compound have previously limited the accuracy of estimating OH concentrations. It is currently very hard to take direct measurements of hydroxyl radical hence its contribution to global methane concentration remains very uncertain.

Carbon dioxide is the most significant greenhouse gas produced by mankind because its emissions are high and its lifespan in the atmosphere is long compared to other greenhouse gases. According to a model study by Archer et al. (2009) 20-35% of CO_2 remains in the atmosphere after having equilibrated with the ocean (2-20 centuries). As a result of mankind's activity, fossil fuel combustion produces about 35 Gt of CO_2 per year, which accelerates climate change (Myhre et al. 2013). Carbon dioxide is natural in the atmosphere because it is part of the naturally occurring carbon cycle, where plants take up CO_2 from the atmosphere in photosynthesis and turn it into their biomass. A part of this biomass is respired back to the atmosphere, eaten by animals or consumed by bacteria and archae which release CO_2 and CH_4 back to the atmosphere. Carbon dioxide also dissolves into oceans and other bodies of water such as lakes and rivers (Ciais et al. 2013). People have interfered with the natural carbon cycle by releasing more CO_2 to the atmosphere than would normally be present, which has also increased the carbon sink (marine acidification) of the sea (Ciais et al. 2013), and has changed carbon storage capacity of the forests as a result of land use change and increased fire frequency (Hartmann et al. 2013). Carbon dioxide concentration in the atmosphere has risen from pre-industrial 280 ppm to 410 ppm. This addition can with high confidence be attributed to human activities during the last few centuries (Myhre et al. 2013).

1.2 Boreal natural and drained peatlands

Peatlands cover about 3% of the earth's non-frozen area and their carbon storage is very large (peatsociety.org, 2018). Natural peatlands store 400-500 Gt of carbon (Roulet, 2000) As stated by Ciais et al. (2013) CH_4 emissions from anaerobic soils in natural wetlands and rice paddies taken together contribute significantly, at least 25%, to the total global emissions of 542 - 852 Tg CH_4 year^{-1}, wetlands being the largest individual source with an approximate 20% contribution to the total. Wetland is a more general term referring also to mineral soils that are under water, whereas peatlands consist of peat forming vegetation, sphagnum mosses (Limpens et al. 2011; Maltby and Immirzi, 1993). In Finland most of the wetlands are peatlands (e.g. Minkkinen et al.

2002). Methanogenic (methane producing) archae of these ecosystems produce CH_4 in anaerobic conditions (Ciais et al. 2013). Some of these peatlands are drained for forestry and there is a potential for increased vegetation growth in regions where climate change may lead to a lowering of the WTL (Laiho et al. 2004). Peatlands are globally considered as a carbon sink due to peat forming vegetation and low decay, but they are susceptible to varying weather conditions and climatic changes. Several studies (e.g. Moore et al. 2005) have found that large losses of carbon in the form of CO_2 from pristine mires followed as a consequence of extended summer droughts. According to different climate change scenarios annual precipitation and seasonal precipitation patters are predicted to change in the boreal zone which can alter carbon balance of peatlands around the world (Van Oldenborgh et al. 2013). Contrary to the general expectation that more precipitation would lead to more CH_4 emissions due to an elevated WTL and increased anaerobic production, some studies have drawn an opposite conclusion (Gorham 1991; Gitay et al. 2001; Hogg et al. 1992). The regions where precipitation is expected to decrease during the growing season WTL of some peatlands could lower which could further lead to increased CH_4 emissions because of initiated forest succession in which organic matter and nutrient cycles shift to being dominated by arboreal vegetation (Gorham 1991; Gitay et al. 2001; Hogg et al. 1992).

Majority of peatland area in Finland has been drained for forestry in the 1960s and 1970s because the drainage lowers WTL and allows for the trees to grow better (Heikurainen and Paivanen, 1970; Macdonald and Yin, 1999). The drained peatlands have been investigated for possible long-term effects of climate change on carbon cycling (e.g. Strack et al 2004). This type of research is especially important in Finland where 20% of the total area and 28% land area is covered with peatlands (luonnontila.fi, 2014). Of these more than half are drained forested peatlands (Geology department, Finland 2018). In Finland, the most common forms of land use in peatlands are forestry and agriculture, protection of peatlands and peat production (Geology department, Finland 2018). This has provided a motive for economic and climate perspectives to study these forested peatlands. For example Minkkinen et al. (1999)

found that lowered WTL in the long-term enhances forest growth given there is enough nutrients in the mineral soil. Peat soils have very different temperature and moisture regimes compared to mineral soils and both of these regimes are under gradual change as the forest keeps growing after a lowered WTL (Minkkinen et al. 1999). Thermal conductivity is low in peat soils due to litter and peat itself which keeps the unfrozen layer shallow. In mineral soils thermal conductivity is higher. (Abu-Hamdeh et al. 2000). The shallower the unfrozen layer the less volume there is for methanogenes to act.

Methane of wetland origin can be released to the atmosphere by three different pathways: ebullition, soil/water-atmosphere molecular diffusion and plant-conducted transport via vascular plants stems (Walter and Heimann, 2000). Ebullition is a process in which bubbles of CH_4 reach the surface of a water body and the gas is released to the atmosphere. Bubbles form as a result of methane building up over time in the soil (Glaser et al. 2004). Molecular diffusion explains the net flux of molecules from a region of higher concentration of molecules to one of lower concentration. If regions are capable of exchanging molecules with each other, particles will flow from the region of higher concentration to the region of lower concentration until the concentrations in both regions are equal.

The capability of wetland trees to emit CH_4 is to a great extent governed by CH_4 production in peatland (Segers et al. 1998). The amount of carbon per mass unit in peatland depends on the peatland type, and the potential for CH_4 production is enhanced by higher soil moisture (Segers et al. 1998; Woodland et al. 1998). The more moisture and carbon per unit mass in the soil the more potential for CH_4 production (Segers et al. 1998; Woodland et al. 1998). Soil moisture may vary in different layers of soil and thus it might be crucial for stem-emitted methane at which depth the majority of the roots are. Wetland trees that are periodically or permanently flooded tend to develop features that help them adapt to wetter conditions (Pangala et al. 2014; Rusch et al. 1998). As they also stated, these include features such as enlarged lenticels and hollow aerenchyma tissue; as internal pathways for air transport enlarge so to facilitate root oxygenation, it will also become easier for soil-originated CH_4 to be emitted to the atmosphere. Many studies have stated that plant-conducted transport has the biggest contribution to the total soil flux of CH_4 Of these three pathways in some ecosystems (Carmichael et al. 2014; Joabsson et al. 1999; Shannon et al. 1996) However ecosystems can be very different; as an example, a wetland of which a substantial area is water-logged with little vegetation.

1.3 Methane cycle in peatlands

Net CH_4 flux to the atmosphere depends on the rate of production and consumption of CH_4 in soil. The production happens in anoxic soil layers and consumption in oxygenation process of CH_4 into CO_2 in oxic soil layers (Bellisario et al. 1999). Water table level largely determines the thickness of these layers in peatlands (Bubier and Moore, 1994) because its depth controls the available oxygen in the peat. Some of the Northern peatlands emit CH_4 to the atmosphere which is thought to originate from methanogenic archaea (Cao et al. 1996; Conrad et al. 1998). The most important substrates for methanogenesis are acetate and $H_2 - CO_2$ (Zinder, 1993). The processes of CH_4 production and consuption are called methanogenesis and methanotrophy, respectively. The availability of organic substrates with low redox potential values controls the production rate of CH_4 which is further affected by soil pH and soil temperature (Koskinen, 2016; Wang et al. 1993). Redox potential (also known as reduction potential or oxidation potential) is a measure of a chemical compounds' tendency to acquire electrons and thereby be reduced in the process (Tochner and Likens, 2009). All chemical species have their own values of redox potential. The more positive the redox value, the more effeciently the species acquires electrons and the faster the redox potential is reduced. The potential is used to describe a system's oxidizing capacity (Tochner and Likens, 2009). Methane oxidation occurs closer to the surface of peatland in the oxic conditions. The process is governed by soil water content, soil temperature, available nutrients, soil pH and concentration of oxygen and CH_4 in the peat (Dunfield et al. 1993; Scheutz and Kjeldsen, 2004)

In upland forest soils with low production of CH_4 strong uptake of CH_4

by methanotrophic mircrobes usually leads to negative net flux of CH_4 from the atmosphere (Megonigal and Guenther, 2008). A peatland commonly turns from a net producer of CH_4 to a net sink of CH_4 after a successful drainage operation that results in a WTL drawdown, increased CH_4 oxidation and decreased CH_4 production (Lohila et al. 2011; Minkkinen et al. 2007). Because CH4 production and consumption are microbial processes, soil temperature is also an important controlling factor affecting the fluxes (Melling et al. 2005, Pangala et al. 2015).

1.4 Methane emissions from vegetation

A study by Keppler et al. (2006) showed for the first time that CH_4 can also be produced in aerobic conditions in living and dead plant tissue. Their global up-scaling of aerobic emissions from biome yielded a range of 62–236 Tg CH_4year $^{-1}$. They found that CH_4 emissions from dead and alive plant material was stimulated by light and temperature. It was assumed that CH_4 emission rates are directly linked to net primary production (NPP) of different plant types. They estimated new plant tissue growth in a year based on NPP, which they thought could be equated with the biomass in the systems they used in their experiments. In the calculations they assumed that the emission rates are constant during the whole growing season and that there is no difference in emission potential between the different parts of a plant. Among others Kirschbaum et al. (2006) responded on the paper with their comment claiming that Keppler et al. (2006) likely overestimate the aerobic CH_4 production due to their over-simplistic assumptions. Kirschbaum et al. (2006) stated that different parts of biome emit CH_4 at different rates, and of the total NPP a large part goes to roots that cannot be stimulated by sunlight. Metabolically active and light-exposed tissue, such as leaves and needles, also likely emit more CH_4 than woody material, such as bark. Furthermore the period during which CH_4 can be emitted is likely to shorter than estimated by Keppler et al. (2006) because some of the plant tissue might be consumed by herbivores or fall on the ground in senescence. Kirschbaum et al. (2006) suggested two new methods for estimating aerobic production from biome.

They assumed that leaves are the most important part of a plant for aerobic CH_4 production. The emission rates per unit dry mass from Keppler's study were used and they multiplied these by estimates of intact biomass in different biomes. The second method assumes that the ratio of aerobic CH_4 emissions to the ratio of photosynthesis is constant so that global aerobic methane emissions can be estimated from the estimates of photosynthesis. According to the alternative calculations they presented, they estimated global aerobic plant CH_4 emissions as 10-60 CH_4year $^{-1}$. According to Garmichael et al. (2014) currently the best estimate is probably 8-60 CH_4year $^{-1}$ using methods that include measurements of NPP above-ground to for upscaling to the landscape level (Kirschbaum et al. 2006; Parsons et al. 2006; Butenhoff and Khalil, 2007).

In the boreal forest zone the trees growing on peatlands remain understudied and also the mechanisms responsible for CH_4 emissions from tree stems and canopies remain unknown. This is in contrast to herbaceous plant-meditated emissions that have been thoroughly investigated for longer than two decades at locations of different vegetation and soil types (e.g. King et al.1998; Shannon et al. 1996). The work done on plant-conducted CH_4 transport has led to a relatively good understanding of the differences between plant species (excluding trees) seasonal variability of emissions and conditions controlling CH_4 emissions. (e.g. Shannon et al. 1996). Most studies of tree-mediated CH_4 published up to year 2015 have concentrated on emissions from tree stems or trees in laboratory conditions and the results might not be applicable or scalable to field in different climatic zones and varying environmental conditions. (e.g. Garnet et al. 2015; Rusch et al. 1998).

In 1998 Rusch et al. found that *Alnus glutinosa* significantly emit CH_4 from stem. They also found that there is a relationship between how much carbon is available in the top soil and flux strength. After their finding other researches (e.g. Garnet et al. 2005; Gauci et al., 2010; Pangala et al., 2014; 2015; 2017; Terazawa et al., 2015, Machacova et al., 2016) have measured stem emissions from other tree species. The work done on this field has led to research trying to estimate the role of trees in CH_4 emissions from wetlands. In 2010 Rice et al. estimated that 10% of the CH_4 emissions from wetlands globally come from trees that grow in these areas.

Recent studies have indicated that trees are capable of transporting CH_4 that has been anaerobically produced in the soil to the atmosphere from tree stem and shoots (Terazawa et al. 2007; Rice et al. 2010; Gauci et al. 2010; Pangala et al. 2015; Machacova et al. 2016). Among other studies Pangala et al. have found out that CH_4 might be actively transported inside of trees via transpiration stream and according Terazawa et al. (2007) the passive transportation can happen through aerenchyma tissue. So far there's only a few studies that have looked into the methane fluxes from trees in the boreal forest zone. The tropical and temperate vegetation zones remain better studied due to their easier accessibility and higher fluxes but also boreal forests are important because of their large area, 48.2 million km^2 in the Northern hemisphere. More research is needed to understand the mechanisms and environmental drivers behind the CH_4 fluxes from boreal forest trees.

1.5 Different methods for measuring greenhouse gas fluxes

There are several methods to measure CH_4 emissions from terrestrial ecosystems. The most widely used is the closed chamber method (Pihlatie et al. 2013) which is applied to quantify surface fluxes at atmosphere-biosphere interface. A static soil chamber consists of a permanently fixed soil collar and periodically closed box with known dimensions. A trace gas accumulates (in case of emission) or decreases (in case of uptake) in the head-space of a chamber, and flux from a surface can be calculated using concentration change data and specifications of the chamber's dimensions and measured area. Some chamber designs have a vent tube attached to its wall to stabilize for pressure changes between the atmosphere and the air inside of the chamber (Hutchinson and Livingston, 2001; Xu et al. 2006; Venterea et al. 2018). The chambers need to be sealed gas-tight and usually the chamber frames are placed into the soil or onto tree stems. The principle of this technique is to observe concentration changes inside of a chamber over time and use different mathematical methods for flux calculation. Gas sampling can be conducted either by taking gas samples from chamber headspace using syringe and vials, a continuously operating laser- or infrared-based measurement device with manual chambers, as has been done with the measurements for this thesis, or by setting up an automatic system with high temporal resolution.

Pihlatie et al. (2013) assessed the problem: what is the optimal design for a static chamber. In their study they only focused on soil chambers which immediately leads to thinking that tree chambers would require a similar assessment. Various different kind of chamber designs exists and they tested 15 different chamber designs of various dimensions. They arrived to a conclusion that an increase in area and volume of a chamber leads to a significant reduction in the flux underestimation ($p < 0.05$), and also the usage of non-linear method in flux calculation improves accuracy of flux estimation but this also led to bigger uncertainty.

Another flux measurement technique for measuring CH_4 and other greenhouse gases is Eddy Covariance (EC) technique. It is a direct micro-meteorological flux measurement method which can be used to determine fluxes of greenhouse gases or other trace compounds of interest at ecosystem scale, typically over an area of several hundreds of meters around the measurement point. (Aubinet et al. 2012). It is also useful due to its high temporal resolution of 30 minutes. In EC technique data are measured at high frequency (10 or 20 Hz) at a certain height above surface or canopy by using sensors that measure gas concentration as a scalar quantity, and wind and air temperature in three dimensions (three dimensional sonic anemometer). Long time series of flux data can be used to deduce meteorological and soil parameters that could have an effect on these fluxes such as cloudiness, precipitation, soil moisture and vegetation. This method is one of the best for measuring turbulent fluxes and doesn't require many assumptions (Aubinet et al. 2012).

Other methods to measure greenhouse gases from terrestrial ecosystems include satellite measurements of greenhouse gases in an air column. Spaceborne observations of atmospheric methane concentrations are very important a resource for assessing global methane emissions because of the continuity and high-frequency in the data they provide (Kuze et al. 2009). The shortwave infrared (SWIR) instruments measure air column greenhouse gas concentrations with vertical sensitivity that is nearly uniform in vertical direction from the top of the atmosphere to the surface. GOSAT (Kuze et al. 2009) was launched in January 2009 by the Japan Aerospace Agency. It determines CH_4 concentration by analysis of the spectrum that forms from backscattered solar radiance in infrared regime near 1.6 μm. GOSAT circles the Earth in Sun-synchronous low earth orbit. GOSAT has a resolution (0.6% and 10 km × 10 km vs. 1.5% and 30 km × 60 km). Taking use of GOSAT's machinery with higher spatial resolution, researches have been able to map sources of CH_4 more reliably because the CH_4 emissions can have high spatial variability. One example of such study that benefited from newer, higher-resolution instruments is the study conducted by Turner et al. (2015). They used three years (2009–2011) of GOSAT data to map global and North American methane emissions. The validity of GOSAT retrievals was evaluated using GEOS-Chem chemical transport model. The model data was used to identify and correct a bias that occurred between the model and GOSAT data in high-latitudes. They used GOSAT and model data to map CH_4 sources at 4° x 5° resolution globally. These results were further used as boundary conditions to optimize methane sources in North America with an even higher 50 km x 50 km resolution.

1.6 Research questions

In this Pro Gradu master thesis, I will address the question of whether trees growing in a drained peatland forest might have a role on methane balance of this ecosystem and assess the underlying factors affecting tree CH_4 exchange. The measurements were conducted during the growing season (May to October) in 2016 and 2017. Lettosuo site has two study plots: one control plot where all the pines have been harvested and one control plot. The measurements of these two study plots are compared here. The partially harvested plot has constantly a higher WTL because of reduced evapotranspiration.

As increased WTL is expected to increase anaerobic CH_4 production in the soil and lead to higher CH_4 emissions from trees, the following research questions are raised: 1) does WTL have a significant effect on the CH_4 emissions from tree steams, 2) whether the selection of the chamber design has a measurable effect on stem CH_4 fluxes.

2 Methods and materials

2.1 Site description

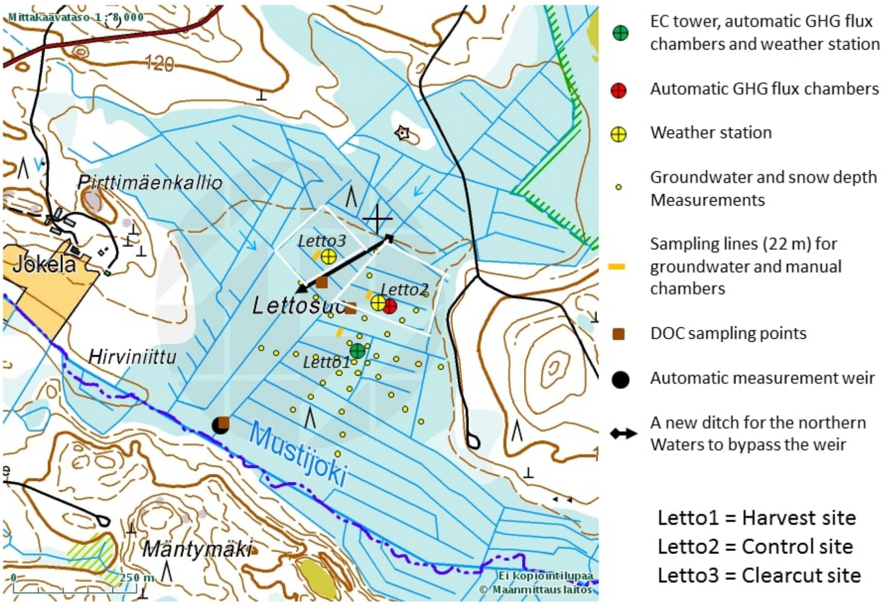


Figure 2: Map of Lettosuo (FMI, 2018)

The measurement site is Lettosuo (figure 2), a drained, nutrient rich peatland forest in Tammela, southern Finland (60°38' N, 23°57' E) about 90 kilometers north-west of Helsinki (Korkiakoski et al. 2017). The forest has been fertilized with potassium and phosphorus after its draining in 1969. After this the tree stand consists mainly of downy birch (*Betula pubescens*), Scots pine (*Pinus sylvestris*) and some scattered Norway spruce (*Picea abies*) in the canopy, and Norway spruce in the forest understorey (Korkiakoski et al. 2017). As Korkiakoski et al. (2017) also stated canopy is quite dense which results in highly varying light conditions on the surface. This in turn leads to variable ground vegetation with some places having almost no vegetation at all. Herbs such as *Trientalis europaea* and *Dryopteris carthusiana* and dwarf shrubs such as *Vaccinium myrtillus* are common in Lettosuo (Bhuiyan et al. 2017). The distribution of moss layer is uneven and is mainly dominated by *Dicranum polysetum* and *Pleurozium schreberi* and *Sphagnum spp.* (Korkiakoski et al.

2017). Koskinen et al. (2014) conducted measurements in Lettosuo to determine carbon-to-nitrogen ratio (C:N ratio). They sampled surface peat at four locations at a distance of 20-50 meters from the tree and soil chambers. They found an average C:N ratio of 24 for the 0-20 cm layer. This is a relatively low value typical for fertile peatland forests such as Lettosuo site.

There are two measurement plots at Lettosuo (figure 2), the control plot (Letto 2) and the partially harvested plot (Letto 1). All the Scots pines were harvested at the partially harvested plot to make the WTL rise due to expected decreased evapotranspiration, to change the lighting conditions and to simulate real-world harvest and the changes it might cause in general (Korkiakoski et al. 2017). In total the harvest removed 75% of the biomass. At the partially harvested plot the tree species of interest are mature downy birch and Scots pines, and in control plot there's Scots pines, downy 12 birches and Norway spruces. There is a total of 25 sample-trees and both study plots have 5 replicates of each species. At the partially harvested plot there are also 3 birch trees with 3 chambers attached to different heights of the trees to study CH4 flux variation in vertical profile of the trees.

The climate in Lettosuo is cold and temperate and has both continental and maritime influences. Lettosuo is classified as Warm-summer humid continental climate (Dfb) by Köppen and Geiger climate classification. According to Pirinen et al. (2012) the average annual temperature of 1981-2010 is 4.6 °C, July being the warmest month and February the coldest. Average annual rainfall is around 627 mm and precipitation falls mainly during the summertime with August being the rainiest month (Pirinen et al., 2012). But even in winter, December to March, monthly precipitation exceeds 25 mm on average (Pirinen et al. 2012).

2.2 The chambers and flux measurements

The chamber measurements were conducted during the summertime, May to October, in 2016 and 2017. In 2016 measurements were conducted in each plot one to two times a week and in 2017 approximately once every two weeks. I personally conducted about 80% of the flux measurements at Lettosuo. In

2017 the stem chambers at the partially harvested plot were measured using Picarro (figure 6; chapter 2.3). Three types of chambers were used for flux measurements at both plots:

Figure 3: box-shaped static plastic chamber (width: 8.6 cm, height: 13 cm, depth: 6 cm) (lowest in the figure). Also illustrates the profile measurement setup.

Figure 4: Older type cylindrical chamber without plastic wrap and plate (height: 40 cm, width 4-6 cm).

Figure 5: Newer type cylindrical chamber (height: 30 cm, width 2.3 cm)

The cylinder chambers narrow from the middle to the ends where they were attached to the tree stem using neoprene and silicone for sealing. The body of the chamber is of plastic wrap wrapped around the chamber supported by iron wires. The older type of cylinder chamber (figure 4) has a fan for internal air mixing, and the The newer type chamber (figure 5) has two. The new cylinder chamber is a little smaller than the old chamber the size of which varies a little due to the installation. The support bars in this chamber are thicker and made of stainless steel. The in- and outlet tubes are on different sides of the chamber (figure 5). These type of chambers hold their form a lot better than the older type chambers (figure 4). chambers and usually require less plastic wrap for the installation

2.3 Gas analysis

Static chambers of the form cylindrical and box were used in the measurements and the concentration measurements were conducted using laser technology. UGGA (Ultraportable Greenhouse Gas Analyzer, Los Gatos Research Inc. California). The device measures CH_4 concentration (in addition to H_2O and CO_2) by calculating concentration from absorption spectra produced by change in the laser's luminous intensity as it is reflected thousands of times between highly-reflective mirrors in the cavity before entering the photodetector. The method creates an extremely long optical path of many kilometers that increases the sensitivity of the device and creates strong absorbtion peaks as the light beam interacts with the gas (Los Gatos Research, 2018). The software for UGGA used in the field constantly plots concentration versus time graph on the screen of a tablet device. One tree was measured at a time using UGGA with a chamber closing time of 10 to 20 minutes depending on whether a concentration change inside of the chamber was close to zero (a shorter closing time) or bigger than 2 ppb (detection limit for the measurement frequency of 1 Hz).

Picarro G1130 (Picarro Inc., Santa Clara, CA, USA) cavity ring-down spectroscopy gas analyzer was used to measure concentration changes inside of the chambers at the partially harvested plot in 2017. The method of the device is based on small molecules, CO_2, H_2O CH_4, having unique near-infrared absorption spectra. At typical sub-atmospheric pressure, the spectra consist of narrow, distinct and sharp peaks, each of them located at a characteristic wavelength. Because the locations of these absorption peaks are well-spaced and well-known, the concentration of any trace gas can be quantified by measuring the absorption strength. "In contrary to conventional infrared spectrometers, CRDS - Cavity Ring-Down Spectroscopy uses an effective path length of many kilometers enabling the concentration changes to be monitored in seconds with precision of up to the parts per billion level." (CRDS, Picarro.com, 2018). In this technology the beam from a single-frequency laser diode enters a cavity with two or more highly-reflecting mirrors. In Picarro analyzers there's three mirrors to enhance a continuous traveling light wave. When the laser is on, the cavity is filled with laser beams. A fast photodetector senses the small amount of light that one of the mirrors lets through, which produces a signal that is directly proportional to the light intensity in the cavity (CRDS, Picarro.com, 2018).

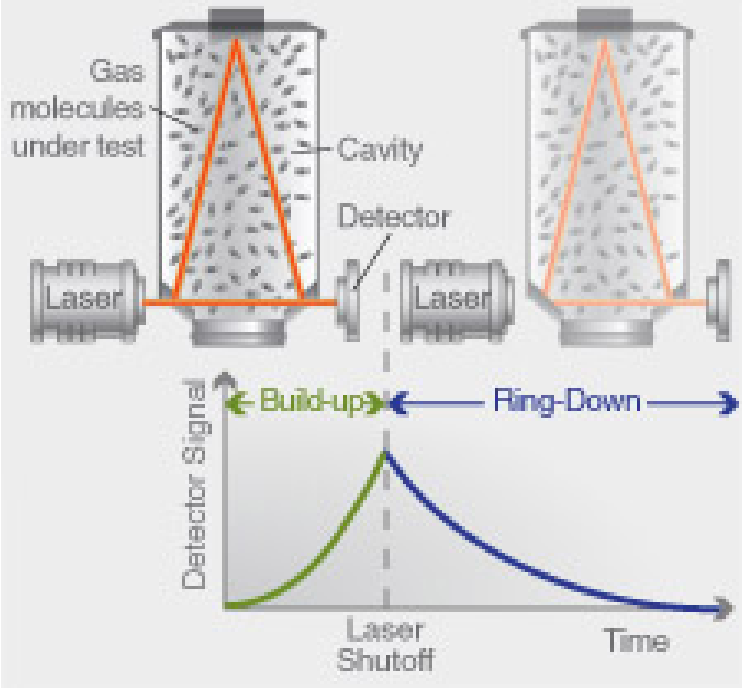


Figure 6: Schematic presentation of a ring down measurement with Cavity Ring-Down Spectroscopy method (CRDS, Picarro.com, 2018)

In the analyzer, when a threshold level for the photodetector signal is reached, the continuous laser wave is turned off (figure 6). The beam in the cavity continues to be reflected between the mirrors (about 100,000 times) but because the mirror are only 99.999% reflective, the light intensity steadily decays to zero exponentially. The intensity decay is called "ring down" and it is measured in real-time by the photodetector. The amount of time for a ring down is solely determined by the mirror reflectivity if the cavity is empty. A gas species in the cavity accelerates the ring down time. The ring down time is the faster the bigger is the concentration in the cavity. The instrument automatically calculates and compares the ring down time with and without absorption caused by the gas species of interest. The continuous comparison allows for very robust concentration measurements because it takes into account possible absorption losses that could be due to wearing of the mirrors.

2.4 Flux calculations and filtering

The fluxes of CH_4 and CO_2 were calculated according to Pihlatie et al. (2013). Here a linear fit was used. The flux value (F_0) at chamber closure (t=0) can be calculated:

$$F_0 = S\frac{V}{A}\frac{M}{V_m}\frac{273.16}{273.16+T}3600, \tag{1}$$

where S is the slope of the linear (S_{lin}) fit as time derivative ($\mathrm{ppms^{-1}}$), A chamber volume ($\mathrm{M^3}$), A chamber area ($\mathrm{m^2}$), M molecular mass of CH_4 ($16.042\ \mathrm{gmol^{-1}}$), V_m ideal gas mole volume ($0.0224\ \mathrm{m^3mol^{-1}}$), and T headspace temperature (°C) inside the chamber (Pihlatie et al 2013).

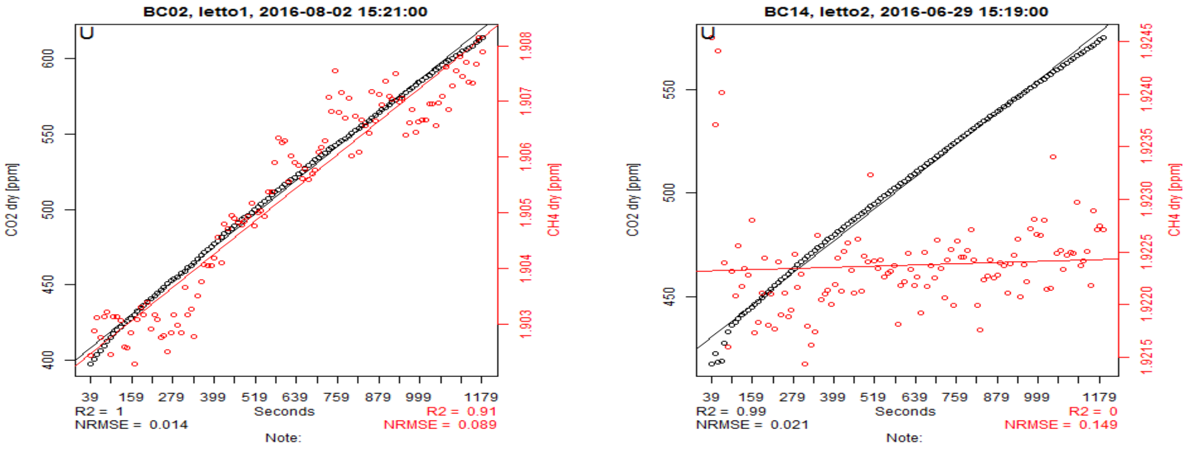
According to Pihlatie et al. (2013) linear evolution of chamber headspace concentration as a function of time can be expressed as

$$C(t) = C_0 + F_0\frac{t}{h}, \tag{2}$$

where C_0 is the gas concentration at the time of chamber closure, F_0 is the constant flux (equation 1), $h=V/A$ the effective chamber height (m). Slope (S_{lin}) as time derivative ($\mathrm{ppms^{-1}}$) is

$$S_{lin} = \frac{F_0}{h} \tag{3}$$

After linear flux calculations, filtering was conducted using goodness-of-fit parameters: normalized root mean square error (NRMSE) (Christiansen et al. 2011) and coefficient of determination (R^2). The former is the root-mean-square-error (RMSE) of the linear fit divided by the range of gas concentration during the whole closure time. It is a relative measure of how far individual measurement points lie from the fit used. The latter, R^2-value (also coefficient of determination), is the fraction of the variance in the dependent variable that can be predicted based on the independent variable(s). It is a measure of how well observed outcomes are described by the model, based on the fraction of total variation of outcomes explained by the model (Glantz et al. 1990). In another words it gives one information of how close the analyzed data are to the fitted regression line.



(a) (b)

Figure 7: Examples of two different chamber closures from 2016 using linear-fit: Non-zero CO_2 and CH_4 flux with both goodness of fit parameters having acceptable values (a) A zero flux of CH_4 with R^2-value 0 (b).

The outliers were filtered from the data according to NRMSE ≤ 0.2 for CH_4 and by looking at each individual chamber closure with its linear-fit and R^2-value. Figure 7a shows an example of non-zero flux for CO_2 and CH_4 with NRMSE < 0.2 and CH_4 concentration changes more than 2 ppb during the closure. All the fits in which the CH_4 concentration in the chamber headspace was changing within the detection limit (2ppb for 1 Hz measurement frequency) were regarded as zero fluxes regardless of the NRMSE or R^2 values. By looking at many different linear fits, it became very clear that R^2-value cannot be used if one wants to account for zero or near-zero fluxes. This makes sense because, as seen in figure 7b, the majority of the individual measurement points fall within this detection limit and R^2 value is zero. All the closures during which the CO_2 concentration grew too high (many thousands of ppm, mainly a problem in old type cylinder chambers) were filtered out. At times the CO_2 concentration grew very high in the measurements conducted using the cylinder chambers because their area to volume ratio is bigger than that of box chambers.

2.5 Ancillary measurements

Automatic soil chambers at Lettosuo measure CO_2, CH_4 and N_2O. The measurements of CO_2 have been going on since autumn 2010 and CH_4 measurements since March 2011. In total there are 12 transparent soil chambers, 6 at each plot. These chambers are connected to the gas analyzers in the cabins. The cabin at harvest plot is located around 30 m away from a 25.5 m tall EC tower (Koskinen et al. 2014) where the wind speed above the canopy is measured. The chambers have been placed so to maximize the number of different ground vegetation composition within a radius of 15 m from the cabins (Korkiakoski et al. 2017). Soil chamber dimensions are 57 cm x 57 cm x 30 cm. A steel collar was installed (height 5 cm, inserted at depth of 2 cm) below the chambers to minimize soil disturbances and for better air-tightness. A 24 V fan (Maglev KDE2408PTV1, Sunon Ltd, Kaohsi-ung, Taiwan) (size 8 cm × 8 cm) was used for headspace air mixing inside of the chamber. The fan voltage was regulated to keep the mixing constant, but kept as low as possible (Koskinen et al. 2014). Carbon dioxide, CH_4 and H_2O concentrations were measured every 4 s using Picarro G1130. The tubes (Festo Oy, Vantaa, Finland) used here were of polyurethane with inner and outer diameter of 4 and 6 mm, respectively. Before each chamber closure, the tubes were flushed with ambient air. Ambient air was measured when all the chambers were open. A more detailed description of the soil chamber system can be found in Koskinen et al. (2014)

Air and soil temperatures were measured by Pt100 probes (PT4T, Nokeval

Oy, Nokia, Finland) and Nokeval 680 loggers (Nokeval Oy, Nokia, Finland) every 10 s. One probe was positioned under a metal heat shield, to prevent direct sun light exposure, next to the fan at height of 30 cm inside of each chamber. One soil temperature probe was placed just below the moss and litter layer on the surface. Additionally, a temperature profile with probes at depths 2, 5, 10, 20 and 30 cm was installed near the chamber. Water table level was monitored hourly at 4 locations using a data logger (TruTrack WT-HR data loggers, Intech Instruments Ltd, Auckland, New Zealand). In October 2017 in total 24 WTL measurement tubes were installed next to each sample tree to determine changes in WTL. WTL sample-taking using these tubes was carried out 4 times between October and November 2017 and the seasonal variability in WTL at each sample tree location was calculated using the average of these measurements. The precipitation data were acquired from and observatory in Jokioinen (around 15 km northwest of Lettosuo) maintained by Finnish Meteorological Institute.

In addition to the tree CH_4 measurements also characterization of microbial communities, quantification of methanogenic and methanotrophic functional genes, measurements of soil and wood CH_4 concentration and measurements of potential CH_4 production and consumption from peat profile and forest floor moss samples were carried out to understand the underlying mechanisms of methane flux dynamics in Lettosuo. On top of this intermittent sample taking, there are continuous measurements of environmental variables such as temperature, water table depth, soil moisture content. However, there is no EC system that could be used to account for the fluxes within the canopy nor are the shoots directly measured.

2.6 Statistical analysis

Linear-mixed effects model on Matlab B2017a was used to analyse the effect of environmental parameters on tree CH_4 fluxes. "Linear mixed-effects models are extensions of linear regression models for data that are collected and summarized in groups" (Mathworks, Linear Mixed-Effects Models, 2018). These models characterize the relationship between independent variables and a response variable, where the response variable in this case CH_4 flux from either tree stem or soil, and the independent variable is for example water table level. It is possible to use many independent variables in a model when trying to explain the behavior of the response variable, but it is important that they are independent of each other (Mathworks, Linear Mixed-Effects Models, 2018); for example air temperature at 2m and soil temperature measured at 10cm depth are not independent of each other when measured at the same experimental plot. The models use coefficients that can vary with respect to different grouping variables (Mathworks, grouping variable, 2018). A grouping variable sorts data within data files into categories or groups; examples of grouping variables are categorical, binary and numerical variables (Mathworks, grouping variable, 2018). A mixed-effects model consists of two parts: fixed and random effects. Fixed-effects terms are typically the linear regression part, such as CH_4 versus WTL, and the random effects are associated with individual measurements, such as each sample tree, randomly selected from a population (Mathworks, Linear Mixed-Effects Models, 2018). The standard form of a linear mixed-effects model can be expressed as (Mathworks, Linear Mixed-Effects Models, 2018) with modifications:

$$y = X\beta + Zb + \epsilon \tag{4}$$

where:

- y is the n-by-1 response vector for number of observations,n

- X is an n-by-p fixed-effects design matrix.

- β is a p-by-1 fixed-effects vector.

- Z is an n-by-q random-effects design matrix.

- b is a q-by-1 random-effects vector.

- ϵ is the n-by-1 observation error vector.

- The first term on the right contains the fixed effects and the second is for the random effects. ϵ is the error or the residual. This stands for the variability that's not due to any of the fixed or random effects in the model; the part that is out of the scope of the model.

- Here: p is the number of fixed-effects predictor variables and q is for the

random-effect predictor variables
The assumptions for the linear mixed-effects model are:
- Random-effects vector, b, and the error vector, ϵ, have the following prior distributions:

$$b \sim N(0, \sigma^2 D(\theta)), \epsilon \sim N(0, \sigma^2 I). \tag{5}$$

where $\boldsymbol{D}$ is a symmetric and positive semidefinite matrix, parameterized by a variance component vector θ, $\boldsymbol{I}$ is an n-by-n identity matrix, and σ^2 is the error variance.
- Random-effects vector, b, and the error vector, ϵ, are independent from each other.

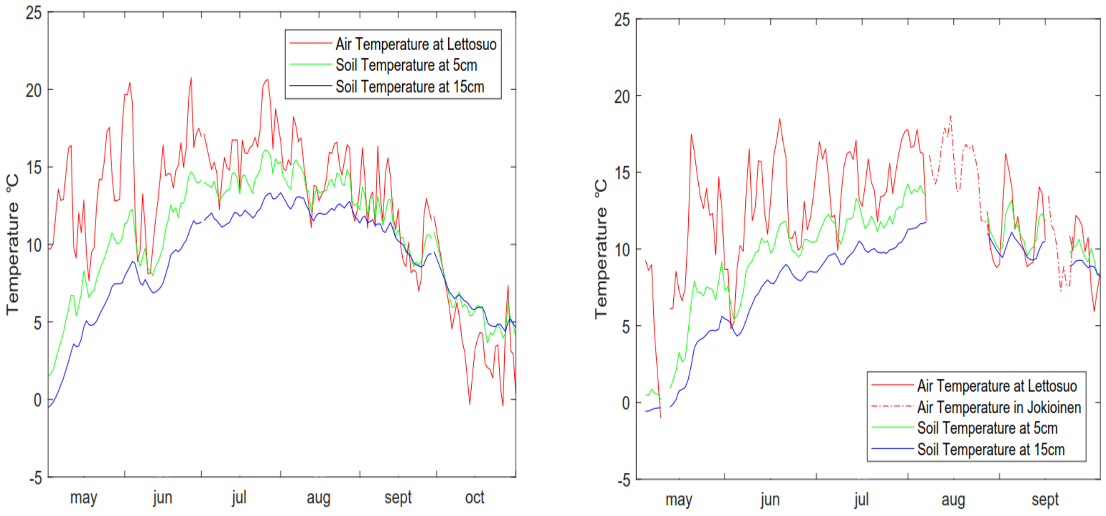
Linear mixed-effects models need at least one random effect and here the logical choice is tree ID corresponding to different sample trees. This random effect can be thought as something that is expected to have a non-systematic or unpredictable effect on the data. On the other hand, fixed effects are expected to have a predictable influence on the data. Compare function (Mathworks, "compare", 2018) was used to compare whether the presence of different fixed effects in the model is significant. Under the null hypothesis, H_0, the observed log likelihood ratio test statistic has an approximate chi-squared reference distribution with degrees of freedom that equals the number of different parameters in the models (Wilks, 1962). Further, when comparing two models, compare-function computes the p-value for the likelihood ratio test by comparing the observed likelihood ratio test statistic with this chi-squared reference distribution (Winter, 2013). In other words the idea in the likelihood ratio test is to compare how likely the two models differ from each other. The two models are: 1) The null-model (H_0) is a model without the attribute you are interested in 2) a model with the attribute, such as WTL here. In conclusion, difference between these two models, using the compare function, is considered significant if the p-value is less than 0.05.

3 Results

3.1 Environmental data

The average temperatures in 2016 (figure 8a) and 2017 (figure 8b) were quite typical, but in 2017 May and the beginning of July were relatively cold. There are quite a lot of data missing in year 2017, but using the measurements available the average temperature at the nearby weather station in 2016 and 2017 during the measurement periods was 12.4 °C and 11.0 °C, respectively. Precipitation during the measurement period May to October was 44% higher in 2017 (406 mm) than in 2016 (282 mm).

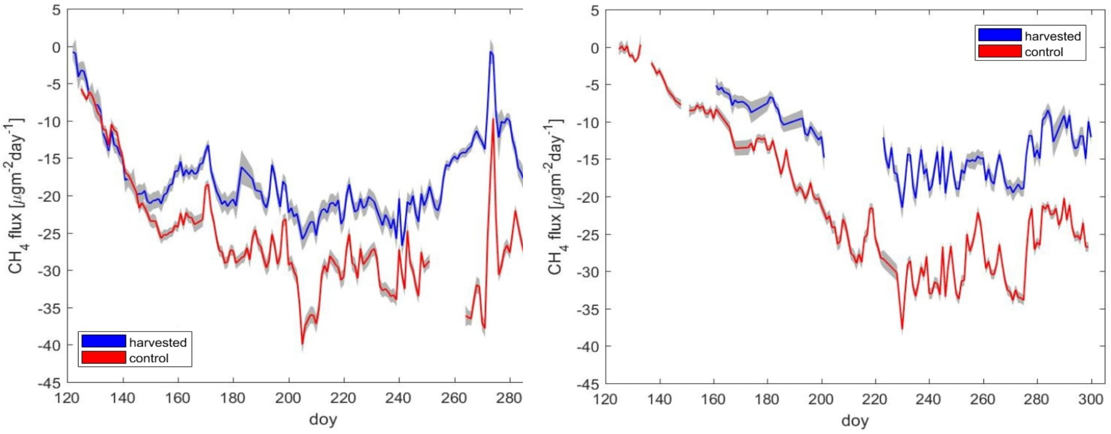
Water table level varies between the two plots, the partially harvested plot having higher WTL on average. Due to varying micro-topography the differences in water-table level measured near individual sample trees can be up to 15 cm. The WTL next to each sample tree was calculated afterwards by subtracting the average difference of three to four WTL measurements next to each sample tree from the automatic WTL measurements at both plots at the time of when individual measurements were conducted (Appendix 1). In both plots WTL was at all times at depths 30-70 cm.



(a) 2016 (b) 2017

Figure 8: Air and soil temperatures at Lettosuo in 2016 (a) and 2017 (b). For the figure b, supporting data from near-by Jokioinen weather station has been used due to gaps in temperature and precipitation data from Lettosuo.

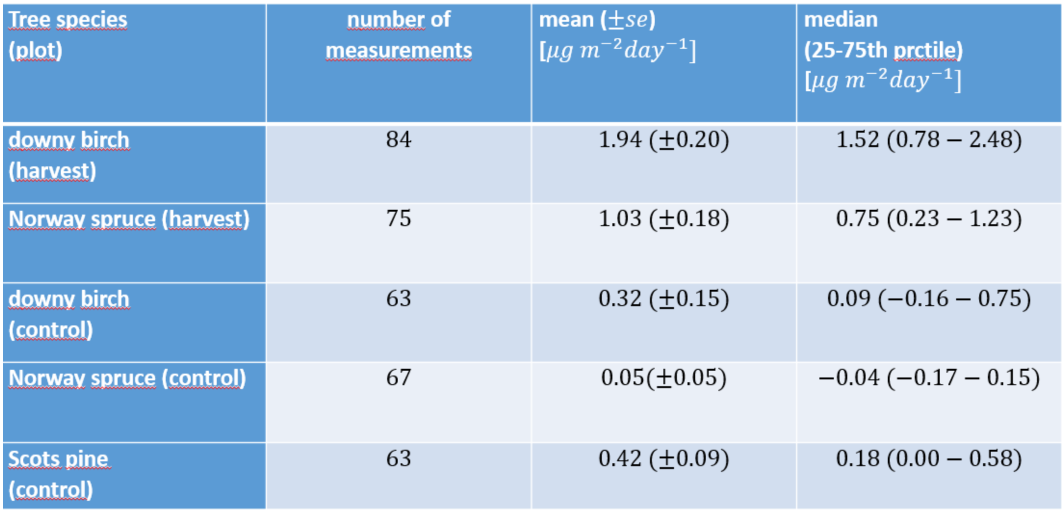
3.2 Soil and tree fluxes



(a) 2016 (b) 2017

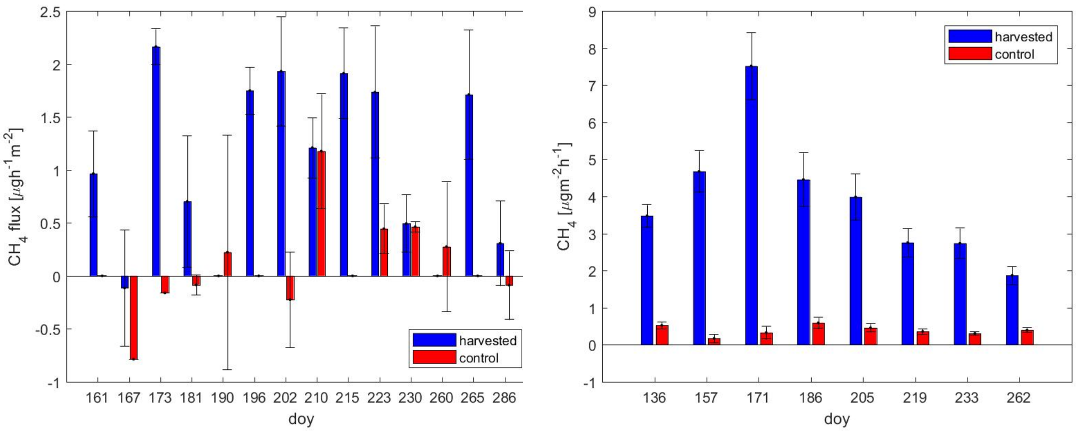
Figure 9: Daily CH_4 soil fluxes at the harvested and the control plot in a) 2016 and b) 2017. Only the time during which also the sample-taking of trees was conducted is shown here. Errorbars represent standard error of the mean (SEM). Doy (day of year) lies on the x-axis r. For these measurements 6 automatic soil chambers were used at both plots.

The results from automatic soil chambers in years 2016 (figure 9a) and 2017 (figure 9b), May to October, are presented here. The figures show that the soil is a bigger CH_4 sink at the control plot than at the partially harvested plot in both years.



Tree species (plot)	**number of measurements**	**mean $(\pm se)$ $[\mu g\ m^{-2} day^{-1}]$**	**median (25-75th prctile) $[\mu g\ m^{-2} day^{-1}]$**
downy birch (harvest)	84	1.94 (±0.20)	1.52 (0.78 – 2.48)
Norway spruce (harvest)	75	1.03 (±0.18)	0.75 (0.23 – 1.23)
downy birch (control)	63	0.32 (±0.15)	0.09 (−0.16 – 0.75)
Norway spruce (control)	67	0.05(±0.05)	−0.04 (−0.17 – 0.15)
Scots pine (control)	63	0.42 (±0.09)	0.18 (0.00 – 0.58)

Table 1: Methane fluxes from tree stems in 2016 and 2017.

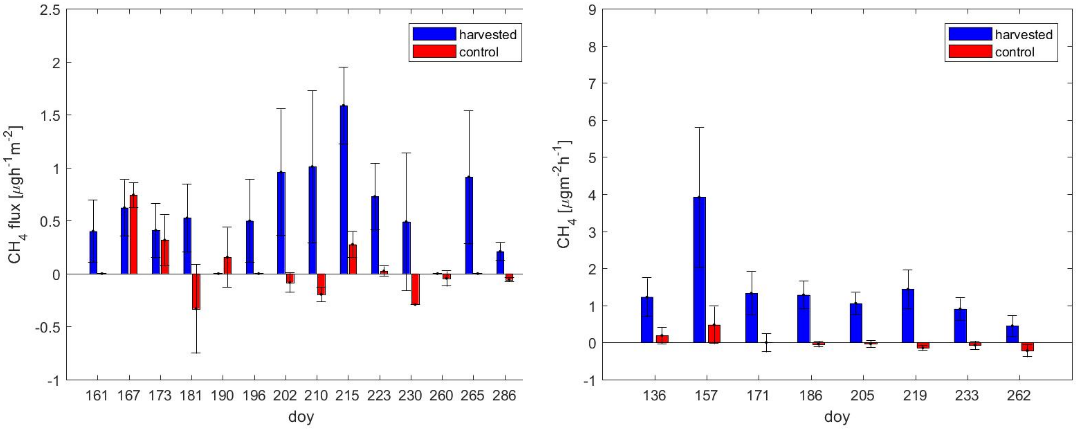


(a) 2016

(b) 2017

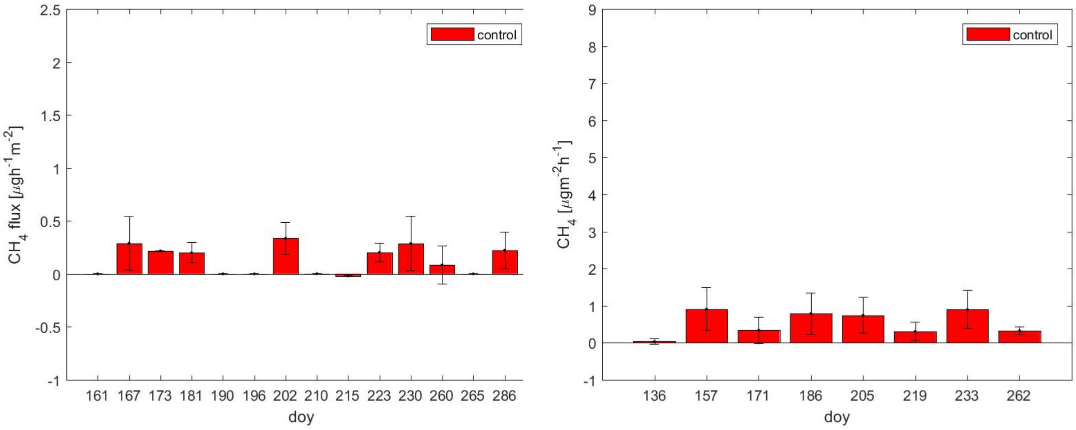
Figure 10: Weekly mean CH_4 fluxes of downy birches at the harvested and control plots in a) 2016 and b) 2017. Errorbars represent standard error of the mean (SEM). Doy (day of year) on the x-axis represents the last sample-taking day of each week as day of year. There are 5 box chambers for birches at both the harvested and control plot.

The CH_4 fluxes in general were higher at the harvested than at the control plot in both years (figure 10). There also seems to be a seasonality in the flux strength in year 2017. The fluxes from Norway spruces (figure 11) and Scots pines (figure 12) are shown below. The CH_4 fluxes on average are smaller than from downy birches in both years.



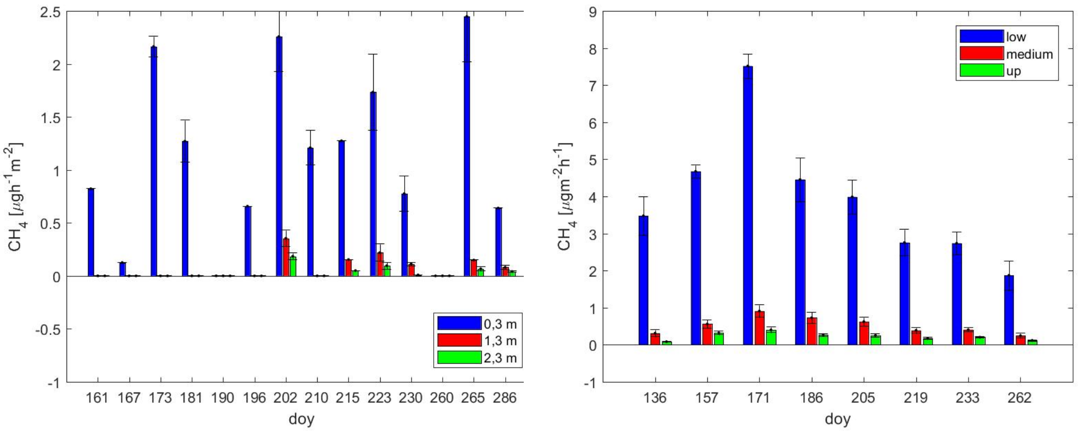
(a) 2016 (b) 2017

Figure 11: Weekly mean CH$_4$ fluxes of Norway spruces at the harvested and control plots in a) 2016 and b) 2017. Errorbars represent standard error of the mean (SEM). Doy (day of year) on the x-axis represents the last measurement day of each week as day of year. The partially harvested plot has 3 box chamber and 2 older type cylinder chambers for spruces. The control plot has one box chamber and 4 older type cylinder chambers.



(a) 2016 (b) 2017

Figure 12: Weekly mean CH$_4$ fluxes of Scots pines at the harvested and control plots in a) 2016 and b) 2017. Errorbars represent standar error of the mean (SEM). Doy (day of year) on the x-axis represents the last sample-taking day of each week as day of year. The partially harvested plot has one box chamber and 4 older type cylinder chambers for pines.

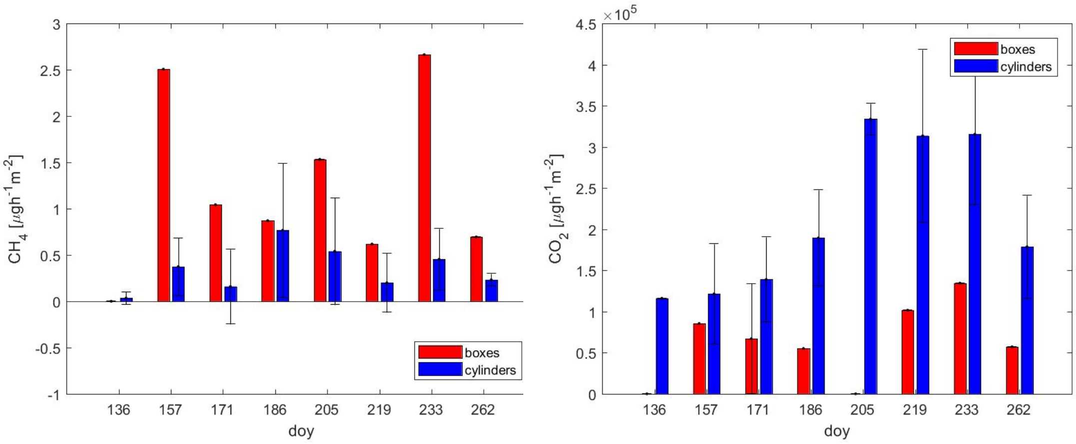


(a) 2016

(b) 2017

Figure 13: Weekly CH$_4$ fluxes of profile measurements of downy birches at Letto1 in a) 2016 and b) 2017. Errorbars represent standard error of the mean (SEM). Doy (day of year) on the x-axis represents the last sample-taking day of each week as day of year. There are 3 birches to which profile measurement has been set up. The lowest chamber is always a box chamber and the two upper ones are newer type cylinder chambers.

Figure 13 shows CH$_4$ fluxes from profile measurements of downy birches in 2016 (a) and 2017 (b). Here a profile consists of a box chamber that is attached to the tree stem at height of 0.3 m and two newer type cylinder chambers attached to the stem at heights 1.3 and 2.3 m, respectively. The newer type cylinder chambers were installed in mid-July 2016. The CH$_4$ fluxes were larger at the bottom of the tree stem in both years (figure 13).



(a) (b)

Figure 14: Comparison between box and older type cylinder chambers using measurements of pine trees at the control plot in 2017. (a) weekly CH_4 fluxes for both chamber types (b) weekly CO_2 fluxes for both chamber types. Errorbars represent standard error of the mean (SEM). The control plot has one box chamber for pine trees and 4 older type cylinder chambers. Numbers on the x-axis represent the last measurement day of each week as day of year.

A comparison of resulting CH_4 and CO_2 fluxes obtained using box and older type cylinder chambers was made for pine tree replicates at the control plot in 2017 (figure 14). The figure (a) shows that the CH_4 fluxes from box chambers were larger than the CH_4 fluxes from older type cylinder chambers and vice versa for the CO_2 fluxes (b).

3.3 Results from linear mixed-effects model

Working with the data it became quite evident that the best tree species for any kind of comparison between the environmental parameters and CH_4 flux is downy birch, since the fluxes from them in both 2016 and 2017 are the greatest. Testing different formula for the model, rainfall and soil temperature at 5 cm proved to be insignificant = high p-values, thus the focus here is in WTL. The following mixed-effects model was used:

$$Flux = B_0 + B_1 WTL + e_i \tag{6}$$

where Flux is CH_4 flux from birches, $\boldsymbol{B_0}$ is the intercept parameter for the model, $\boldsymbol{B_1}$ is the parameter value for WTL (a fixed effect) and e_i is the random effect for tree i (tree ID). The model (equation 6) yields that WTL is significant factor affecting CH_4 flux with a p-value 0.03.

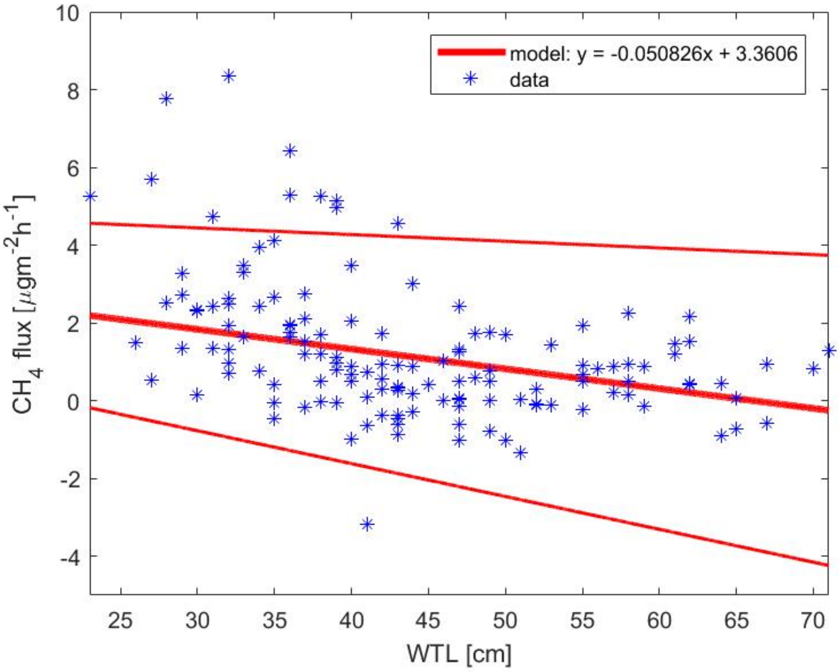


Figure 15: The result of linear mixed-effect model illustrated. The thickest line is the model with the best estimate for the intercept and slope. The two other lines represent the same model with 95% confidence intervals for the intercept and slope. The data are single measurements from the lowest chamber height of all downy birches at both plots in 2016 and 2017.

Here the results of linear mixed-effects model are illustrated; how well the model explains the sampled CH_4 based on the WTL data (figure 15). It looks like that there is some correlation between the WTL and flux strength.

To determine the significance of the CH_4 emissions between the two plots the following linear mixed-effects model was used:

$$Flux = B_0 + B_1 plot + e_i \tag{7}$$

where Flux is CH_4 flux from birches, B_0 is the intercept parameter for the model, B_1 is the parameter value for plot (a fixed effect) and e_i is the random effect for tree i (tree ID). According to the model (equation 7) with the plot as the only fixed variable, CH_4 fluxes from downy birches were statistically different ($p < 0.05$) between the harvested and control plots in both years.

In addition to these, according to linear mixed-effect model (the general form is the same as in equations 6 and 7), with the chamber type as the only fixed variable and tree id as a random variable, the difference in CH_4 fluxes from different chambers is not significant ($p = 0.099$). This was used for the chamber comparison before (figure 14).

4 Discussion

4.1 Factors driving tree-CH_4 fluxes

The CH_4 fluxes from all three tree species were larger in 2017 than in 2016. This difference is mainly evident at the partially harvested plot where the WTL is on average approximately 15 cm higher and fluxes larger than at the control plot. The difference in CH_4 fluxes between the two years is especially distinct from downy birches growing at the partially harvested plot (figure 10). As stated before, the precipitation during the sample-taking months in 2017 was around 40% larger than in 2016. During the summertime in Finland a big fraction of the total precipitation falls as rain showers which can lead to big differences in local precipitation accumulations (Pirinen et al. 2012). Since the closest weather station is 15 km away from Lettosuo, it makes more sense to use the WTL data from the site than to use the precipitation data from the weather station for data analysis. As the mixed-effects model showed (figure 15), it is possible that the higher WTL led to larger CH_4 fluxes from downy birches at both plots in 2017 in comparison to 2016. It also seems like that the largest CH_4 fluxes that occur when the WTL is high are not well represented by the model which might mean that the correlation between the stem CH_4 flux and the WTL is non-linear. The plot (partially harvested/control) was also found to be a significant factor ($p = 0.002$) affecting stem CH_4 fluxes from downy birches when the fluxes from both years were pooled together (equation 7). The important role of WTL in regulating the CH_4 emissions is further supported by smaller soil uptake of CH_4 at the partially harvested plot in both years (figure 9). In general the fluxes from downy birch were the greatest of all three tree species at the partially harvested plot during 2016 and 2017 (figures 10, 11, 12). The fluxes at the control plot were very small, and possibly more noisy given the accuracy of the measurement devices (table 1).

The CH_4 fluxes were larger at the bottom of the stem (figure 13), which has also been shown by other research (e.g. Pangala et al. 2015). It might be that the aerenchyma structure of trees offers a transport pathway for CH_4

after which diffusion through the bark is the main mechanism that transports CH_4 to the atmosphere (Terazawa et al. 2007; Pangala et al. 2015). Pangala et al. (2015) found that that tree specific density of different tree species increases with height and it is negatively correlated with stem CH_4 emission rates at different heights. Tree specific density might also be an important factor explaining differences in CH_4 fluxes between tree species. However, for example according to Repola J. (2006) downy birch, that emit the most CH_4 of the three tree species in this study, has the largest specific density of these species. This suggests that there are surely some other features the trees have, such as amount of lenticels for gas exchange in the bark, that might affect their capability of functioning as emission pathways or emitters for CH_4.

In general the CH_4 fluxes measured in this study and in Machacova et al. (2016) from tree stems of the trees growing in the boreal forest zone are orders of magnitude smaller than those measured in the tropics (Pangala et al. 2017). This can be due to higher temperature and higher soil CH_4 production rates at low-latitude wetlands (Pangala et al. 2015). As an example, Pangala et al. (2017) measured fluxes from the stems of 2,357 individual sample trees from 13 floodplain locations across the central Amazon basin. They found that these fluxes were up to 200 times larger than emissions measured from temperate forests. The fluxes they measured are reported in $\mathrm{mgm^{-2}h^{-1}}$ and in our study at Lettosuo the suitable unit is $\mu\mathrm{gm^{-2}h^{-1}}$. Pangala et al. (2015) also conducted measurements from temperate forest wetland in Flitwick, UK ($52^o0'$N, $0^028'$W), about 70 kilometers north of London. The species measured were black alder (*Alnus glutinosa*) and downy birch. The study was conducted between April 2011 and April 2012. During the period May to September in 2011 the fluxes from both species were in the range 150-200 μg $\mathrm{m^{-2}h^{-1}}$ which is about 15-25 higher than the CH_4 fluxes measured at Lettosuo. Soil temperature at the time of their study was a few degrees higher than in Lettosuo in 2016 (figure 8a) but Lettosuo fluxes were larger in 2017 than in 2016 when soil temperature was even smaller (figure 8b) and WTL higher than in 2017. In Lettosuo soil temperatures at different depths were found to insignificantly affect CH_4 flux strength. In other words higher CH_4 fluxes followed higher soil temperatures in Pangala's study whereas in Lettosuo the more decisive factor was WTL. This is yet another example of that more research is needed in this field.

4.2 Error sources in tree-flux measurements

Possible sources of experimental error with the chamber method are among others disturbances of concentration gradient by e.g. introducing CO_2 through the chamber's edges and CH_4 emitting chamber materials. It is also possible for chambers to leak but the possible leakages were monitored by blowing air to the edges of the chambers during the sample-taking. The chamber materials (glues and boxes) used in Lettosuo were tested in laboratory conditions and they were found not to emit CH_4 (unpublished data). Before closing a box chamber the chamber was dried from the excess water and all the extra material inside the chamber headspace was removed such as brown needles, living and dead insects, leaves etc. Upon closing a chamber before each measurement, one needed to hold the breath to avoid breathing into the chamber. In the case of box shaped plastic chambers, airtightness was ensured by blowing in the sealing of a closed chamber observing if a sudden peak forms in the plot for carbon concentration. In general, it was noticed that these kind of box chambers are very durable and weatherproof. In the case of cylindrical chambers, airtightness is harder to ensure because of their bigger volume. Ambient air was pumped into the chamber, outlet was closed and the chamber observed whether the it properly fills with air and there are no sounds of leakage, visible holes or other signs of severely worn-off materials. Before taking a sample one the straps wrapped around the neoprene in loops around the tree stem were tightened because they may loosen in time. The older type of cylindrical chambers also tend to change their form as the plastic foil wrapped around them loses its elasticity. This kind of deformation changes the volume of chambers and one needs to consider this when analyzing the results. It is important to learn to estimate when the deformation of a chamber is big enough so that it is worth of a remark. In this study the measurement analyzers allowed for a relatively short chamber closing time which is beneficial because during a closure the concentration inside of the chamber does not get very high which would have an effect on the flux from the stem. Long closure times and build-up of trace gas inside the chamber by diffusive flux typically leads to decreased concentration gradients, which decreases the fluxes and may lead to underestimated flux rates (Pihlatie et al. 2013)

The most unexpected result from this measurement campaign was the big difference in measured CH_4 flux from Scots pines at the control plot in 2017 measured using different chamber designs (figure 14). Using box chambers the CH_4 fluxes from Scots pines are around four times bigger than using older type cylinder chambers. For CO_2 the result was opposite, the fluxes obtained by using cylinder chambers were around 2.5 times larger than those by box chambers. Various reasons may explain these differences, such as the difference in size and speed of CH_4 and CO_2 molecules (Joos and Freeman, 1958), different elasticity of the chamber materials and the sealing technique of a chamber. The size of a CH_4 molecule is smaller than that of a CO_2 molecule (Greenwood and Earnshaw, 2012) and it might escape easier from cylinder chambers than from box chambers because their gas-tightness is harder to ensure than that of box chambers. If CH_4 escapes from cylinder chambers the same happens with CO_2 but to lesser extent, and the effect might be negligible because the fluxes of CO_2 are many orders of magnitude larger than the CH_4 fluxes (figure 14). Also a different number of cylinder and box chambers in the comparison, 4 cylinder chambers versus 1 box chamber, may distort the validity of this comparison. In general box chamber are more sturdy in the sense that the chambers walls do not bend due to pressure changes inside of the chamber, and it is also easier to seal them gas-tightly. In addition some cylinder chambers were quite worn-out at the time the measurements were stopped, and they certainly collected more moisture inside of them than newer type cylinder chambers and box chambers that were open whenever gas sampling was not conducted using them. Thus, there is a possibility that some CH_4 oxidizing bacteria developed inside of the cylinder chambers that would have decreased the CH_4 fluxes and increased the CO_2 fluxes calculated using the cylinder chambers. The reasons to this difference are probably many, but the fact is that no perfect chamber design exists, one only needs to strive to find the most suitable one.

When measuring greenhouse gases in different locations the most important question one needs to address is: What is the ecosystem like one is about to measure and what factors could possibly contribute to its greenhouse gas balance? This question leads to thinking that it is not certainly enough to only measure the greenhouse gas of interest in a few locations (such as tree stems, soil floor, wetland's water-atmosphere interface etc.) but also that it is very crucial to measure important environmental variables such as soil moisture, temperature, PAR (photo-synthetically active radiation), WTL etc. After knowing your ecosystem one needs to think of the budget of the measurement campaign and find answers to the following questions: How often do I need to conduct the sample-taking and measurements so that the results could possibly be valid for answering the research questions? How many people need to be hired to conduct the measurements often enough? What is the research question and is the emphasis of the research more about the magnitude of different greenhouse gas emissions or also the underlying mechanisms behind the emissions? What kind of analyzing techniques are going to be used and what is the budget of the campaign (for example a portable Nitrous oxide lasers cost around 100 000 euros). After these questions have been addressed, it would also be a good idea to do some comparison between different measurement techniques to obtain an idea of the best possible technique for the campaign at hand. As an example if the research area consists of a boreal wetland, one could compare the fluxes measured from soil and stem chambers to eddy covariance measured fluxes. If these two techniques produce results close enough to each other, one could possibly make a choice between these two techniques based on human resources, time and money available for the campaign.

5 Conclusions

At the Lettosuo drained peatland forest the soil was in general a sink of CH_4 and the trees a small source of CH_4. In both years the soil was a larger CH_4 sink at the control plot than at the partially harvested plot which is most likely attributable to the higher WTL, and thus likely increased anaerobic methanogenic activity, at the partially harvested plot. Similarly, the CH_4 emissions from trees were larger at the partially harvested plot in comparison to the control plot. Also tree emissions were likely controlled by the changes in WTL as could be seen from the results of linear mixed-effects model. The CH_4 emissions from downy birches were in general larger than those from Scots pines and Norway spruces possibly due to structural differences between the tree species.

The comparison of different stem chamber designs using data from Scots pines showed that the CH_4 fluxes obtained using box chambers were larger than those using older type cylinder chambers every week when the data are available for comparison. On the contrary CO_2 fluxes measured using the cylinder chambers were larger than the CO_2 fluxes using the box chambers. Reasons to this could be: CH_4 being a quicker gas than CO_2 and its molecular size is also smaller making it possibly easier for CH_4 to escape from cylinder chambers. In conclusion, it cannot be taken for granted that different chamber designs give out the same results. To enhance the reliability of a measurement campaign, all the chamber design that one plans to use should be tested under appropriate laboratory conditions prior their use in the campaign.

Judging whether trees growing at Lettosuo have an effect on the CH_4 balance of the ecosystem, one must acknowledge that no flux data from the canopy is available. For this purpose canopy chambers or an EC system would need to be set up at the plot. To assess the role of trees growing on a peatland more accurately, I would suggest a similar measurement set-up to this campaign, but using automatic stem chambers that measure fluxes every day along with automatic and continuous WTL measurements next to each sample tree. I would also like to have a profile installed to more tree stems to make up-scaling of fluxes possible for the ecosystem scale.

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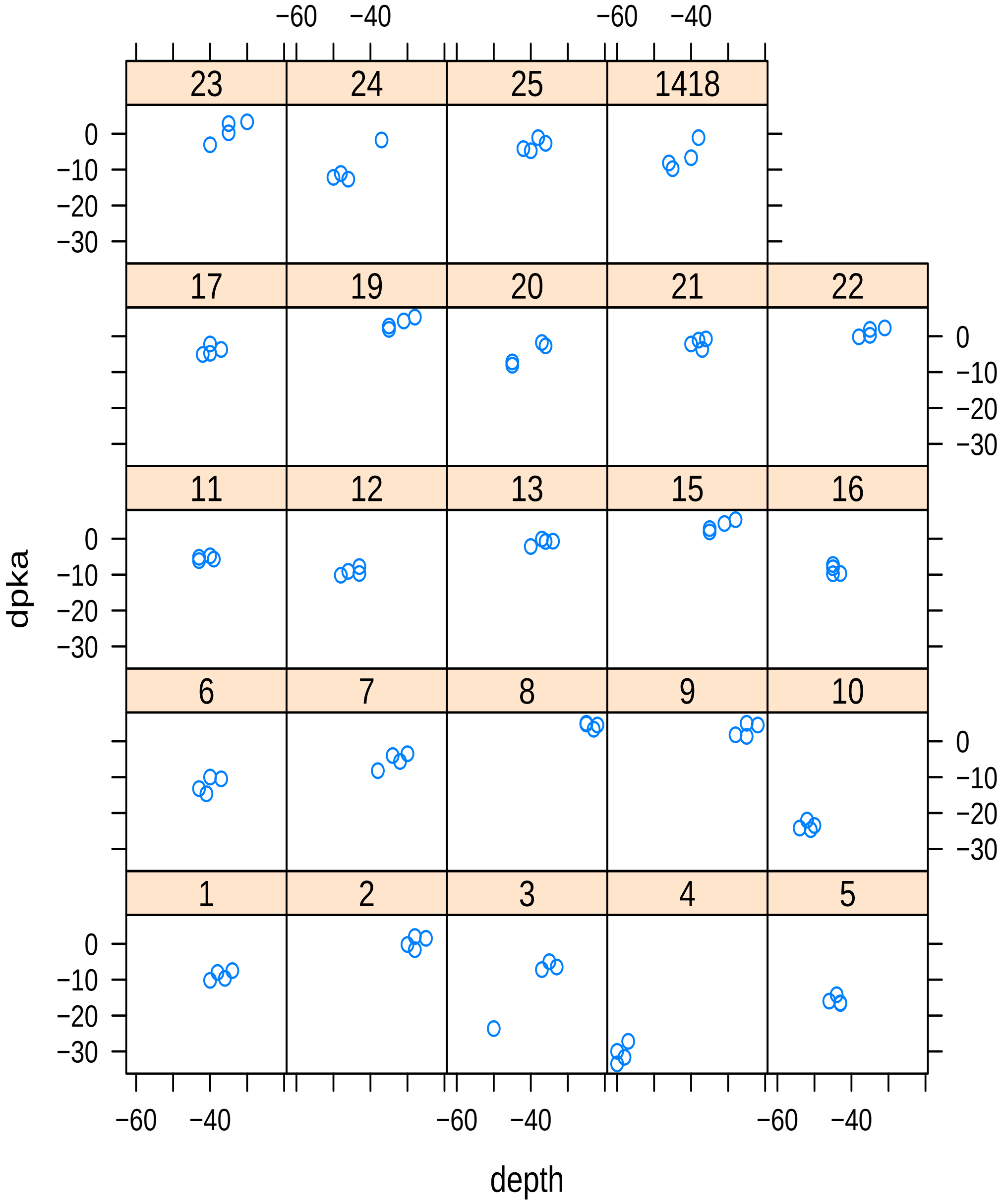
Appendix



Appendix 1: Difference in WTL between individual measurements at each sample tree and WTL measured in one point at both plots expressed as centimeters. Please note negative values in both axis. Depth in the x-axis depicts the individual measurements taken using a blow tube. The difference between each individual measurement and daily average of respective plot is on the y-axis. Positive integers: 1-5 downy birches and 6-10 Norwegian spruces at the partially harvested plot; 11-15 downy birches, 16-20 Norwegian spruces and 21-25 Scots pines at the control plot.