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Measurements of CO_2 exchange with an automated chamber system throughout the year: challenges in measuring nighttime respiration on porous peat soil

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Abstract

We built an automatic chamber system to measure greehouse gas (GHG) exchange in forested peatland ecosystems. We aimed to build a system robust enough which would work throughout the year and could measure through a changing snowpackin addition to producing annual GHG fluxes by integrating the measurements without the need of using models. The system worked rather well throughout the year, but it was not service free. Gap filling of data was still necessary.

We observed problems in carbon dioxide (CO_2) flux estimation during calm summer nights, when a CO_2 concentration gradient from soil/moss system to atmosphere builds up. Chambers greatly overestimated the nighttime respiration. This was due to the disturbance caused by the chamber to the soil-moss CO_2 gradient and consequent initial pulse of CO_2 to the chamber headspace. We tested different flux calculation and measurement methods to solve this problem. The estimated flux was strongly dependent on (1) the type of the fit (linear and polynomial), (2) the starting point of the fit after closing the chamber, (3) the length of the fit, (4) the speed of the fan mixing the air inside the chamber, and (5) atmospheric turbulence (friction velocity, u^*).

The best fitting method (the most robust, least random variation) was linear fitting with the period of 120–240 s after chamber closure. Furthermore, the fan should be adjusted to spin at minimum speed to avoid the pulse-effect, but it should be kept on to ensure mixing. If nighttime problems cannot be solved, emissions can be estimated using daytime data from opaque chambers.

1 Introduction

Climate change and international agreements to mitigate it have given rise to a need for understanding and quantifying greenhouse gas (GHG) exchange in all kinds of ecosystems and regions of the world. Chamber measurements are probably the most used method for doing this. A manual measurement with a closed chamber is an easy and inexpensive way to get a grasp of the instantaneous emission from any spot where a chamber can be inserted. For some gases like methane (CH_4) and nitrous oxide (N_2O), the measurement and its interpretation are rather straightforward. For carbon dioxide (CO_2), on the other hand, the picture is more complex, since carbon (C) fluxes are bidirectional and partly shift in organic form (e.g. litter from plants to soil).

It is essential to understand that the chamber measurement method has its limitations. One of these is that chambers can only be used to measure net ecosystem CO_2 exchange in systems where the vegetation can be closed inside the chamber. This works in low-vegetation ecosystems, such as open wetlands and grasslands, but excludes the biggest dry land biome, forests. In forests tower-based eddy covariance (EC) measurements must and have been extensively used to measure net ecosystem exchange (NEE) (Baldocchi and Meyers, 1991). However, the major limitation of the EC method is that it does not reveal any small scale spatial variation which is typically present in ecosystems. Unlike chambers, the EC method cannot be used to separate fluxes from different components, e.g. soil, litter, plants and roots. By using chambers, one can measure the responses of different treatments applied to the forest soil, e.g., certain C cycle compartments like root or litter respiration can be excluded. Thus, chamber measurements are an important tool for understanding the small-scale variation and functions in the ecosystem – even under the canopy.

Most commonly, measurements have been conducted with manual chambers, which offer great spatial but low temporal resolution. Because of this low temporal resolution, estimates of longer periods (seasons, years) are based either on linear interpolation or models, derived from only a few measurements (e.g. Ojanen et al., 2010). These gap-filling methods are likely to leave considerable uncertainty in the long-term estimates. Also short-term events, such as soil thawing (Bubier et al., 2002) and rainfall (Wayson et al., 2006) which may contribute considerably to annual GHG fluxes, can be missed on account of a sparse measuring schedule. For example, the N_2O flux from peatlands is highly dynamic with potentially large emissions during short freezing-thawing episodes (Maljanen et al., 2003; Pihlatie et al., 2010; Regina et al., 1996).

Furthermore, as an operator is needed, disturbance to the soil may occur, and measurement errors due to soil compression cannot be ruled out when making measurements with manual chambers. Also, it is very difficult to measure CO_2 exchange manually between forest floor and atmosphere under a canopy frequently enough so as to account for rapidly changing light and temperature conditions (Badorek et al., 2011). This in turn impedes attempts to understand and model the functioning of ecosystems in various present and future situations.

In the boreal region, snowpack during winter poses a major challenge to measuring gas emissions from the ground. Thus, this justifies the need for a year-round operating automated chamber system which functions in freezing as well as sweltering temperatures and adapts to changes in the thickness of the snowpack. Further, the chamber system should affect the measurement plots as little as possible, both during and between measurements.

Ideally, an automated chamber system that operates in all seasons, day and night, with a high measuring frequency would allow the integration of long-term gas balances, directly from the measurements without modelling. In practice, data gaps always occur and gap-filling is needed. However, with high frequency data it is possible to examine the response of forest floor gas exchange to rapid temporal changes in environmental conditions more effectively. The use of automated chamber systems should therefore greatly improve the accuracy of GHG exchange models and consequently decrease the uncertainties in seasonal and long-term estimates compared to those gained using manual chambers.

It has, however, been demonstrated that the chamber method poses a number of challenges. For example, even a simple measurement of CO_2 efflux from soil gives different results depending on seemingly small differences in chamber design and techniques (Pumpanen et al., 2004).

Soil type may also have a great impact on the results. In chamber measurements on vegetated, porous peat soil, Lai et al. (2012) showed that the flux estimate was greatly affected by the chamber closure time. The problems occurred during nighttime

CO_2 measurements, which are rarely made using manual chambers. To overcome the observed problems they suggested far longer closure times, ∼ 30 min, than usually applied in CO_2 measurements. On the other hand, the flux calculation method has been shown to markedly affect the results. Some papers emphasize the importance of non-linear fitting when calculating the flux from the concentration time series (Kroon et al., 2008; Kutzbach et al., 2007; Pihlatie et al., 2010), while linear fitting is used in several other papers (e.g. Ojanen et al., 2010; Maljanen et al., 2003; Lai et al., 2012). Pihlatie et al. (2013) compared linear and exponential regressions in CH_4 flux calculation and found that the linear fit systematically underestimated the flux, whereas the exponential one both over- and underestimated it. On the other hand, Levy et al. (2011) analysed nearly one thousand chamber measurements on six sites and found the linear fit to be better than the alternatives in many cases.

The problems and considerations associated with chamber measurements in general have been well summarized in the introduction of Kutzbach et al. (2007).

Our aim was to study the differences in gas exchange between two drained peatland sites, with a high temporal resolution. To achieve this we built a robust, year-round functioning, high-frequency chamber system for the measurement of gas exchange between the forest floor and atmosphere. In principle, this would enable unbiased measurements in rapidly changing light conditions under the tree stand canopy, and interfere minimally with the measuring plot. The design of the structure was driven by the principle that it should be simple with as few moving parts and movements as possible but nonetheless capable of lifting the measurement chamber away and aside from the measurement plot when measurement was not in progress. An important aim was also to make the system operable throughout the winter with a changing snowpack. It was also necessary to make the chambers wide and tall enough to fit the shrubs typical for peatlands inside them. Data-wise we hoped that the high temporal resolution would enable us to calculate the yearly net gas exchange directly from the measurements. Additionally, we sought more detailed information on the soil-related reasons underlying the different carbon fluxes of the two forestry-drained peatlands (Lohila et al., 2011).

In this article we (1) describe an automated chamber system capable of high temporal resolution gas exchange measurements of the forest floor throughout the year, (2) examine the technical problems we encountered and present our solutions to them, and (3) examine technical and environmental factors that affect the respiration measurements made with automated closed chamber systems on porous organic soils.

2 Material and methods

2.1 Measurement sites

We built the measurement system in two peatland forests that had been drained by ditching in the beginning of 1970s, Kalevansuo and Lettosuo (60°38′ N , 24°21′ E and 60°38′ N , 23°57′ E , respectively). The sites are located at the same latitude, only 20 km apart from each other. Both of the sites were Scots pine-dominated (*Pinus sylvestris*) peatlands before drainage, but differences in site fertility have led to different outcomes. Kalevansuo, which is a nutrient-poor site, is a virtually pure pine stand, while Lettosuo, a nutrient-rich site, is a mixture of pine, Norway spruce (*Picea abies*) and birch (*Petula pubescens*), and much denser than the tree stand at Kalevansuo. Because of higher shading in Lettosuo, the ground vegetation is patchy and very variable depending on the level of shading and moisture. Herbs like *Dryopteris carthusiana* and shrubs like *Vaccinium myrtillus* are common. The moss layer is also patchy, and dominated by *Pleurozium schreberi*, *Dicranum majus* and *D. polysetum*. *Sphagnum girgensohnii*, *S. russowii* and *S. angustifolium* are present in moist patches. The moss species are similar at Kalevansuo, but their coverage there is almost 100 % (Badorek et al., 2011). The sparse tree stand causes much less shading than at Lettosuo and the ground vegetation is therefore vivid. Mire shrubs like *Ledum palustre* and *Vaccinium uliginosum* are abundant together with *V. vitis-idaea* and *V. myrtillus*. *Eriophorum vaginatum* is also abundant in moist patches.

We selected six plots from both sites representing the different plant communities and empty patches in the peatlands. To analyse the impact of the moss layer and soil surface structure on the fluxes and to better characterise the gas measurement plots, the fresh and dry bulk densities of the living moss layer and peat soil below it were determined by taking volumetric samples of the top 22 cm from separate plots similar to the gas measurement plots and dividing them into the living moss layer and different peat layers, if applicable. The divided samples were dried at 70 °C until their weight did not change measurably during 8 h in the oven. The peat (0...22 cm) bulk density was on average 0.09 g cm^{-3} at Lettosuo and 0.03 g cm^{-3} at Kalevansuo, but there was high variation between the plots (Table 1).

At both sites, the NEE of CO_2 and H_2O have also been measured in a tower using the EC technique. At Kalevansuo the measurements lasted from 2004 to 2009 (Lohila et al., 2011). At Lettosuo, the fluxes have been measured since autumn 2009. This measurement setup provided us with the supporting meteorological data such as wind speed and friction velocity (u^*) on a half-hourly basis. On both sites, the tower was located about 50 m from the instrument cabin of the chamber system, while the chambers themselves were located at a maximum of 15 m from the cabin.

2.2 Description of the chamber system

The basic structure of our chamber system consisted of a frame made of stainless steel L- and U-beams to which a polycarbonate chamber was attached with two hinges. (Fig. 1). The lower frame was supported by five legs on which it could be vertically moved to keep it above the snowpack. The legs rested on wooden 2 × 4″ poles driven into the soil at Kalevansuo, where the peat was less dense compared to Lettosuo. Under the frame, a 5 cm and 10 cm collar at Lettosuo and Kalevansuo, respectively, connected the frame to the soil surface. The collar extended circa 2 cm into the surface moss layer, thus leaving most of the roots uncut. The connection between soil and collar was sealed with peat and moss. During winter, the frame was raised on top of the snowpack and 1 to 2 extension collars (height = 16 cm) were installed between the soil and lower frame to block the gases from moving horizontally in the snowpack. As a result, we could adjust the height of the collar along the growth of the snowpack. The attachment of the chamber to the upper frame was sealed with a sealant tape. On the down position, the upside-down U-beam frame (width = 1 cm) surrounding the chamber on the upper frame sat on a protrusion on the lower frame, and this connection was sealed with silicone D-tape. To prevent frost and snow from sticking to the connection, the tape was treated with a silicone paste.

The chamber was a 57 × 57 × 30 cm ($l \times w \times h$) transparent polycarbonate box with a 12 cm fan attached to the ceiling. The gas outlet and inlet tubes were led through the chamber wall at the rear upper corners. The gas inlet tube was placed in the stream of the fan to evenly mix the returning gas to the chamber airspace and prevent it from going straight back to the outlet. To enable daytime opaque chamber respiration measurements, two-layered shrouds of polyester cloth meant for sunblock curtains were made for the chambers.

The chambers were opened and closed by linear actuators (Linak Techline LA-35, Linak, 2009) attached to the lower and upper frames. Precise control of the closed position was achieved by connecting the actuator to the upper frame with a bolt so that the connection point could be moved back and forth relative to the upper frame with a precision of 2 mm. The actuators were controlled by separate relay cards in turn controlled with ADAM 4069 relay modules (Advantech). The actuators relay cards featured a current-limited failure mode, which was monitored by an ADAM 4055 8-channel digital I/O module (Advantech).

Gas from the chambers was transferred to a measurement cabin through 15 m polyurethane tubes (FESTO, OD = 6 mm, ID = 4 mm) . The selection of the gas source was made with a solenoid valve array. From the array, the gas was sucked through the instruments either by a Thomas membrane pump or by the built-in pumps of the instruments. After going through the instruments, the gas was returned to the chambers. The solenoid valves were controlled by ADAM 4069 relay modules (Advantech).

For measuring the CO_2 concentrations, a Li-840A (LI-COR, Inc.) CO_2/H_2O analyser was used. At the Lettosuo site, CH_4 concentration and delta $^{13}CO_2$ were also measured with Picarro instruments G1301 and G1101-i, respectively (Picarro, Inc.) (the data is excluded from this paper). The Picarro instruments featured their own gas pumps which sucked their samples before the gas entered the Li-840A and returned the gas to the main stream after the Li-840A, before the main pump. Utilizing this configuration, additional instruments could be attached to the system as needed.

Supporting meteorological data from chambers and their immediate surroundings were obtained by Nokeval 680-loggers. Temperatures were monitored with pt100 temperature probes. Soil temperature profiles with probes at 2, 5, 10, 20 and 30 cm depth were installed in a lawn surface at Lettosuo, which is the dominant microtopographical feature there. Since the Kalevansuo site had much more microtopographical variation, profiles were installed in two places there, a hummock and a lawn. Air temperature at 30 cm height was measured inside the chambers next to the fan under a sheet metal heat shield to prevent direct sunlight from skewing the measurements. Soil surface temperature probes were installed in every chamber just below the moss surface or peat surface if no mosses were present.

The whole system was controlled by a PC running a Linux operating system, which was also used for obtaining and storing data from the Licor and Nokeval loggers. The Picarro instruments featured their own hard drives and programs for data logging. The CO_2 concentration was logged every second, the CH_4 concentration was logged every 4 to 5 s, and delta $^{13}CO_2$ every 10 s. Also the meteorological data from the Nokeval loggers was read every 10 s.

The airflow through the system at both sites was maintained at circa 1 L min^{-1}. To flush the tubes, air was sucked from a chamber from right when it started to close, which took 30 s. This was enough to flush all the old air from the tubes, as it took about 20 s for the air to reach the instruments from a chamber. A post-measurement flush was also made by keeping the air source unchanged as the chamber was opened. This pre- and post-measurement data was discarded in post-processing. When all the chambers were open, the air source was ambient air. The hourly median ambient CO_2 concentration was used in flux measurement filtering.

2.3 Measurement period and flux calculation

The measurements began in October 2010 at the Lettosuo and in December 2010 at the Kalevansuo site.

We applied several different chamber closure times from 120 to 1200 s during the course of our study, and tested the calculation of the CO_2 flux using concentration data of different lengths and starting points after the closing of the chamber.

All calculations were done with R software (R Core Team, 2012) using the additional packages zoo (Zeileis and Grothendieck, 2005), caTools (Tuszynski, 2011) and Lattice (Sarkar, 2008).

The change in CO_2 concentration over time (dCO_2/dt) was calculated by fitting a simple linear regression to a chosen data range averaged into 5 s values. A polynomial fit was also tested. The flux (F) was calculated, based on the ideal gas law, as follows:

$$F = \frac{T_0}{T} \cdot \frac{M}{V_{NTP}} \cdot V/A \cdot 3600 \frac{s}{h} \cdot \frac{a}{10^6} \tag{1}$$

where T_0 is 273.15 °K, T is the mean air temperature in the chamber during measurement (°K), M is the molar mass of CO_2 (44.01 g mol^{-1}) V_{NTP} is the volume of one M of normal gas under normal pressure and temperature (0.0224 m^3), V is chamber headspace volume (m^3), A is ground area under chamber (m^2) and a is the slope of the linear regression (ppm s^{-1}). The unit of the flux was g CO_2 m^{-2}h^{-1}. Changes in chamber headspace height (because of snow and moss growth) were monitored and V was corrected accordingly. The pore space in the soil and snow was not considered part of the chamber headspace.

Chamber height was measured at the start and end of the growing season on 16 evenly spaced points inside each collar with a tape measure and level. The end of the measure was gently placed on top of the surface mosses for taking the readings. The height was then linearly interpolated towards the whole growing season. During th winter, snow depth was approximated visually with the aid of a solid measure. The observed changes in snow depth were manually coincided with snowfall events and melting periods recorded by an observatory of the Finnish Meteorological Institute in Jokioinen, which is located ∼ 35 km from the Lettosuo site and ∼ 60 km from the Kalevansuo site.

For testing the polynomial fit, we fitted second-degree polynomial functions to the whole measurement period as well as to the first 100 s of the measurement period. The "measurement period" in this case excluded the first 30 s to remove disturbances caused by the closing of the chamber. 960 s net exchange measurement data from the summer 2012 was used for this test.

Choosing the best time interval for the fit depends on two opposing effects. A shorter time period in principle provides a more linear concentration curve; in theory, the CO_2 concentration evolution during the chamber closure is saturated due to the decreasing concentration difference between the soil and the atmosphere, driving the flux (so-called saturation). However, a short fitting period is susceptible to even small disturbances in the evolution of the CO_2 concentration due to, e.g., a sudden, strong wind gust. On the other hand, the concentration change over a longer time period is less affected by minor disturbances, but drastic changes in the ambient conditions such as the sky changing from clear to overcast or increasing moisture and temperature affecting the biological processes during the period become more probable. Hence, a short interval is more desirable.

To minimise the effect of saturation on the CO_2 concentration change in the chamber airspace, we applied as short a flux calculation period and discarded as little data as possible during the first year of operation. From the concentration data curves we visually estimated that the disturbances caused by the closing chamber were finished after 30 s. Therefore, we calculated the flux from a data segment of 30–90 s after the closing of the chamber (s). During the second year we tested various fitting periods and lengths of initial discarded data and their effects on flux calculation. We examined the effect of the positioning of the fitting period on the flux value and stability of the calculated flux from one data segment to another. These were reflected by the running mean (flux value) and standard deviation (SD, stability of flux) of five consequent 60 s flux calculations overlapping by 30 s. We assumed that if disturbances were present in the longer closure period, they would be reflected as an increase in the SD of the flux values in the moving window.

The effect of the length of the fitting period on the linearity of the concentration change and the value of the calculated flux was also tested by calculating the root mean square error of fits of different lengths to the same measurement.

2.4 Flux filtering

After the flux calculation, a number of filters were applied to the results to remove cases where the system had malfunctioned in one way or another. The filtering conditions were as follows:

1. If the initial CO_2 concentration in the chamber was >100 ppm higher than the hourly median ambient CO_2 concentration measured between measurement runs, the chamber was considered to be stuck closed;
2. If the flux was negative or zero (i.e., showing CO_2 uptake) during winter or night time (defined as a time when PAR level was close to zero), it was assumed the chamber was stuck open;
3. If the licor cell pressure was <83 kPa, it was assumed the gas inlet tube was frozen and thus stuck.

2.5 Respiration modelling

In addition to estimating respiration from nighttime fluxes, we measured daytime respiration during the second summer by shrouding the chambers with hoods for two to five days at a time, approximately two times per month in order to observe any differences between the night- and daytime respiration measurements. Additionally, a longer campaign (15 and 24 days at Kalevansuo and Lettosuo, respectively) of respiration measurements was performed in early autumn during which several methodological tests were made (described in Sect. 3.3).

To enable gap-filling of respiration data, we fitted an exponential model (Eq. 2) to the daytime respiration measurement data (Lloyd and Taylor, 1994):

$$F = ae^{b\left(\frac{1}{T_{\mathrm{ref}}-T_0}-\frac{1}{T-T_0}\right)} \qquad (2)$$

where parameter a controls the base level of the flux F ($\mathrm{g\,m^{-2}\,h^{-1}}$) and parameter b the temperature sensitivity. T_{ref} is the reference soil temperature at 5 cm depth, 10 °C, T_0 is the temperature at which no respiration takes place, −46.02 °C and T is the soil temperature during measurement. The fixed values for T_{ref} and T_0 are from Lloyd and Taylor (1994). The value of parameter b was limited to positive values.

To account for the changing vegetation conditions in the plots, we fitted the model to two subsets of the data; one representing early summer and the other late summer–early autumn. For the modelling, we combined the data from all of the chambers.

3 Results and discussion

3.1 Mechanical operation of the chamber system

The automatic chamber system worked well most of the time, but data gaps did exist on both sites. At the Kalevansuo peatland, 75 % or more of potential measurements were achieved on 65 % of the days after filtering. Over half of the daily measurements failed on 22 % of the days, and on 15 % of the days, no acceptable measurements were performed at all. At the Lettosuo site, the system operated better, achieving 75 % of potential measurements on 75 % of the days.

The main reasons for missing data from single chambers were the deterioration of the electrical leads of the linear actuators, temporary malfunctions of the linear actuators due to cold weather or breaking of their attachment to the upper frame. Two actuators out of twelve in total broke down permanently during two years of almost hourly operation. The hourly mean temperature range measured by the sensors in the chambers at Lettosuo during the campaign was from −32 °C on 18 February 2011 to +30 °C on 10 June 2011. At Kalevansuo, the temperatures ranged from −33 °C on 18 February 2011 to +32 °C on 2 July 2011.

Transparent chambers are often considered subject to rising air temperatures during measurement (Unsworth, 1986). To counter this, some systems are equipped with cooling devices to keep the temperature and air humidity close to the ambient values. We did not encounter any problems with rising temperature inside the chamber during measurement even with the longest measurements of 1200 s.

Near-freezing and slightly below zero temperatures proved difficult for the gas tubes, which were clogged with ice several times during the first winter.

During the first summer, thunderstorms caused power surges which broke instruments and loggers on both sites. Storms also caused power outages which in some cases lasted for a few days.

We attempted to find solutions to the various problems faced. To prevent physical breaking of the power leads we switched the motor leads to more durable rubber cables and turned the motors around so that the motor lead moved less during operation. To prevent ice from clogging the gas tubes we insulated the cable and tube bundles running from the cabin to the chambers and installed heating elements inside the insulation. The elements were automatically turned on one at a time if a drop in Li-840A cell pressure was observed during the measurement, indicating that the inlet tube had frozen. In the wintertime, the sample air was released into the cabin as the return tubes froze inside the chamber where the heating elements did not reach. We installed optical isolators between the computer and the Licor unit to prevent power surges from destroying the electronics inside the instrument. After our improvement measures, the system at Kalevansuo was more operable during the second winter and summer, achieving on average 67 % of maximum daily measurements in 2010–2011 and 78 % in 2012 (Fig. 2a), whereas no particular trend was observed in the operation at Lettosuo (Fig. 2b), achieving on average 75 % and 77 % of maximum daily measurements in 2010–2011 and 2012, respectively.

Several articles describing different automated chamber systems for flux measurement have been published (e.g. Bubier et al., 2002; Drewitt et al., 2002; Goulden and Crill, 1997; Liang et al., 2003; Savage and Davidson, 2003). However, few examples exist of automated chamber measurement systems that operate during the boreal winter. In any case, a mechanical reliability analysis similar to ours has not been previously published to our knowledge. Bubier et al. (2002) had built a system that operated on a peatland in the temperate zone from November to March, with a minimum air temperature of −21 °C. They also used separate collars to raise the chamber above the snowpack. Their fan was set to a speed high enough to create channels in the snow. In contrast to our system, their pneumatically operated lid was only 15 cm tall and air was circulated between the chamber and the CO_2 sensor at 5 L min^{-1}. They reportedly discarded 36 % of obtained measurements as unreliable on the basis of r^2 values being lower than 0.8.

Another approach to automated measuring of winter emissions through the snowpack was applied by Seok et al. (2009), who installed a tower with sampling tubes at various heights from 0 to 245 cm on their research site and measured the gas gradients inside the snowpack. Fluxes were calculated with a diffusion model. The system produced apparently unreliable results, as the calculated fluxes at a given time varied tenfold when calculated using data from different heights. Wind speed also had a large effect on the apparent flux.

Wintertime chamber measurements have also been done by removing the snow and measuring directly from the soil surface (Alm et al., 1999). The validity of this method can be questioned because of the chimney-effect it may create between soil and atmosphere. Sometimes chambers have been inserted directly on top of the snow without the use of collars. This method is not recommendable because wind easily blows through the underlying snowpack, thus disturbing the measurements. Also, the insertion of the chamber into the snow will change the CO_2 concentration gradient inside the snowpack because it locally blocks the air from escaping upwards, decreasing the diffusion of CO_2 from soil to the chamber and making it go around the chamber, unless collars prevent this. For these reasons collars should extend from soil surface to the snow surface, and they should be inserted without disturbing the snowpack.

3.2 First year – flux anomaly during calm nights

During the first year of operation we used as short a closure time as possible in order to minimise the chamber-induced disturbance on the measurement plot. Since previous research has pointed out thay the concentration change in a closed dynamic chamber is subject to saturation (e.g. Kutzbach et al., 2007), we wanted to calculate the flux from as close as possible to the moment the chamber was closed with as short a fitting period as feasible. Therefore the calculations were done with a 60 s linear fit, skipping only 30 s of data from the beginning. We considered this to be sufficient for removing the artefacts caused by the possible pressure disturbance (Fig. 3) from the closing chamber, and for preventing small-scale concentration fluctuations on the one hand and saturation on the other from skewing the results.

However, we found that nighttime fluxes at Kalevansuo during the first growth season were exceptionally high compared to previous manual measurements from the same site (Fig. 4). During these periods of high fluxes there appeared to be an initial flush of CO_2 from the soil and the concentration curve was clearly bent (Fig. 5).

The phenomenon of CO_2 accumulation in the air layer close to the surface during calm summer nights has been well recognized in papers reporting EC measurements

(Baldocchi, 2003; Aubinet, 2008). Lai et al. (2012) also found an enrichment of CO_2 on the soil surface and moss layer during still nights and coinciding high fluxes in their automated chamber measurements on porous peat soil. This layer of CO_2 is apparently disturbed by the fan-induced turbulence inside the chamber and mixed into the chamber headspace air. This causes a high apparent flux as the CO_2 concentration in the chamber headspace rapidly increases. In daytime respiration measurements an initial flush is not apparent, probably because even on still days, turbulence caused by thermal differences adequately mixes the air on the soil surface.

In EC measurements, the effect is opposite to that in chamber measurements. CO_2 storage is not disturbed by the measurement, thus the measured flux is lower than the biological production of CO_2 during nighttime and high in the morning when turbulent transport is induced thereby dispersing the storage.

These results prompted us to conduct a series of experiments testing the sensitivity of the measured and calculated flux to various environmental and technical factors.

3.3 Sensitivity of the flux to measurement and calculation methods

We tested the sensitivity of the measured and calculated flux to several factors: (1) the starting point of the fit after the closing of the chamber, (2) the type of the fit (linear and polynomial), (3) the length of the fit, (4) the speed of the fan mixing the air inside the chamber, and (5) atmospheric turbulence (friction velocity, u^*).

In theory, the starting point and length of the fit affect the result as follows: at the beginning, initial disturbance caused by the closing chamber may have a significant effect on the apparent flux. Later on, saturation of the chamber airspace decreases the concentration gradient between the soil and air which is the main driving force behind the soil CO_2 flux (e.g. Lai et al., 2012). A longer fitting period makes the measurement less sensitive to instrument noise, as the concentration change compared to the noise becomes larger, but disturbances due to wind gusts outside the chamber become more probable (Bain et al., 2005).

In principle, linear fitting will underestimate flux if there is saturation or leakage, whereas polynomial (quadratic) fitting would overcome these effects (Kutzbach et al., 2007). However, polynomial fitting is very sensitive to initial disturbances and may give extremely biased results. It is thus sensitive to the starting point. Linear fitting is strongly dependent on the length of the fit but less dependent on the starting point. Hence, the calculated flux is potentially strongly dependent on the selected fitting procedure.

The speed of the air-mixing fan inside the chamber has been noted to affect the measurement results in a laboratory setup (Pumpanen et al., 2004). In addition, wind speed outside the chamber may affect the measurements because it can cause pressure differences between the chamber airspace and surrounding atmosphere. On porous soils, such as peatlands, this may cause either over- or underestimation of the flux, depending on whether an under- or overpressure condition is induced (Bain et al., 2005).

3.3.1 Effect of the starting time and length of the fit

In this experiment, we used 960 s-long nighttime measurements made during the summer 2012. First, we made 60 s-long linear fits over the measurements, moving the fit starting time by 30 s between fits. With this data we aimed at determining the best period for calculating the flux by looking at the mean and standard deviation (SD) of the flux estimates from five consecutive fits to a single measurement with a moving window of 30 s.

We noticed that with later starting times the flux decreased asymptotically. However, the decrease did not cease during the 960 s measurement (Fig. 6a). Thus based on the mean alone it was impossible to determine the best period for flux calculation. Instead, the SD of five consequent fits initially decreased until about 120 s after closure and in several cases started to rapidly increase again after 240 s (Fig. 6b). This was true on both sites. This result suggested the optimal period for flux calculation to be between 120 and 240 s after closing the chamber.

Thus, the optimal period for flux calculation was determined, on the basis of minimum standard deviation between subsequent fits, to be between 120 and 240 s after closing the chamber. Secondly, we tested the effect of the length of the fitting period by calculating the flux with a fitting period of 30, 60, 120, 240 and 360 s, starting from 120 s after closing the chamber.

In our case, the mean flux did not seem to change significantly with fits longer than 120 s, but the nonlinearity and random disturbances in the concentration change, indicated by an increased root mean square error (RMSE) of the fit, became significantly higher after that (Fig. 7). Therefore we decided to calculate the fluxes using the concentration data measured 120–240 s after chamber closure; this is the fitting period used in the later tests unless stated otherwise.

Our optimal fitting period was the same as that used by several others (Davidson et al., 2002; Goulden and Crill, 1997). In contrast, Lai et al. (2012) found that the best period for nighttime flux calculation was between 10 and 15 min after closing the chamber. They found the flux to be most stable during this period, whereas we found in several cases that the flux became erratic after ∼ 300 s. The reasons for our different results on somewhat similar sites are uncertain. We are concerned that the long chamber closure time could cause underestimation of the flux because the CO_2 concentration gradient between soil and air becomes smaller as the CO_2 concentration in the chamber airspace rises. In principle one could select as low a flux value as desired, down to zero flux, by extending the chamber closure time. In our case, the difference between calculating the flux with our chosen range (120–240 s) and with data from 830–950 s after closing the chamber was 43 % at Kalevansuo and 41 % at Lettosuo (opaque chamber data, summer 2012). However, the nonlinearity of the concentration change during the calculation period reflected as RMSE of the fit also rose significantly between the periods, suggesting the effect of wind gusts and CO_2 saturation in the chamber headspace. Our results suggest that on our sites, a short measuring period of 240 s of which data from 120–240 s is used for flux calculation is optimal.

Deciding the best time period for flux measurement and calculation is a compromise. With a longer measurement time possible storage effects are mitigated somewhat but the increasing CO_2 concentration in the chamber headspace eventually lowers the

CO_2 gradient between soil and air so much that it affects the flux from the soil to the chamber. In order to obtain comparable data from different sites and times of day and seasons, one must select a fitting procedure and period that works well on every occasion.

3.3.2 Type of fit

The second-degree polynomial fits we tested gave net CO_2 exchange and respiration values with a slightly wider range but nearly the same median and mean as the linear fit (Table 2). When the fitting period was short (30–130 s), polynomial fitting yielded unrealistically high maximum and low minimum respiration values. This was caused by poor fitting in cases with initial disturbances that were still effective, lasting even longer than 30 s after closing the chamber (Fig. 3).

However, the polynomial fit to the whole measurement period (30–960 s) produced very similar values compared to the linear fit (120–240 s). Thus, we could apparently use shorter chamber closure times with the linear fit. Since the polynomial fit did not prove to be better than the linear fit in general and may in fact produce unrealistic estimates in certain cases (Figs. 3 and 5), we chose to use the more simple and robust linear fit for flux calculation.

Our findings contrast several previous studies, most notably Kutzbach et al. (2007), in which the linear fit was found to greatly underestimate the flux. It should be noted that in the aforementioned work, measurements with photosynthesis were also included in the data. Photosynthesis occurring in a closed airspace quickly becomes limited by the decreasing CO_2 concentration. Therefore, a nonlinear function is arguably better in reflecting the concentration dynamics than a linear one. In our sites, soil respiration is usually higher than photosynthesis and dominates the net fluxes. For that reason and since our main problem was nighttime respiration, we used dark respiration data in our tests (measured either during night or daytime with opaque chambers). Furthermore, we suggest that some of the respiration measurements used by Kutzbach et al. (2007, Figs. 2c and 3c) in fact included a similar initial flush of CO_2 stored in the surface layer as Lai et al. (2012) and we have described in Sect. 3.2. Hence, the curvature of the concentration data could be a measurement artefact.

Our results suggest that using a linear fit is a viable approach to calculating respiration fluxes from automated chamber data. Our stance is supported by Levy et al. (2011), who found that the linear model yielded the best fit in almost half of the cases. Although their results concerned CH_4 and N_2O, the general dynamics are similar to CO_2 respiration.

3.3.3 Effect of fan speed and friction velocity

The effect of fan speed on the soil temperature sensitivity of the measured respiration was clear (Fig. 8). We compared the nighttime measurements from the year 2011 when the fan speed was high and year 2012 when the fan speed was low (1 June–30 September) by using 30–90 s data for the fit to get comparable results. Respiration was clearly higher at corresponding soil temperature with the higher fan speed setting.

The effect of fan speed on the apparent flux was tested in September 2012 by switching the fan speed from high to low on consequent measurement runs, and comparing the resulting fluxes. The high fan speed was achieved by running the fans at ~ 12 V and the low speed by running them at ~ 5 V out of the rated 24 V. On both sites, the higher fan speed resulted in significantly higher fluxes, a difference of 0.17 g (35 %) and 0.08 g (18 %) $CO_2\,m^2\,h^{-1}$ on average on Kalevansuo and Lettosuo, respectively (Fig. 9).

As a separate test we alternated the fan speed from low to off in subsequent measurements. Surprisingly, this had no statistically significant effect on the measured flux; however, the r^2 value of the fits with the fan turned off was much lower especially when there was wind outside the chamber than when the fans were turned at least to low speed. (Data not shown).

The effect of u^* was to lower the measured respiration flux. This effect was most significant in nighttime measurements regardless of the fan speed setting (Fig. 10). In daytime respiration measurements, however, the effect was in most cases insignificant.

Our results were contrary to some previously reported results. Dantec et al. (1999) reported lower measured fluxes with a higher fan speed. On the other hand, they found that when the wind speed outside the chamber was higher than the fan-induced wind speed inside the chamber, the measured flux was lower. This supports our finding that a higher u^* yields lower measured fluxes. Their measurements were made on a humus-covered gleyic luvisol in the temperate region using small manual chambers and a higher fan-induced wind speed compared to our system. Lai et al. (2012) reported similar results to ours on highly porous peat soil in Canada. The use of a fan with minimum speed was enough to mix the air, whereas turning the fan off caused a gradient in the CO_2 concentration within the chamber headspace, thus spoiling the measurements (Lai et al., 2012, N. Roulet, personal communication, 2013).

To address the problem of the chamber-induced disturbance of the CO_2 gradient, we tried several approaches. In addition to reducing the spinning speed of the fans as described above, we lengthened the chamber deployment period to 960 s. We also tried venting the plots before measurements to break the CO_2-enriched layer by closing and opening the chambers four times with the fans spinning at high speed. Lowering the fan speed during measurement significantly decreased the flux (Figs. 8 and 10) but did not completely remove the sensitivity to u^*. Lowering the fan speed and measuring respiration during the daytime, however, lessened the effect and significance of u^* on the measured flux. The other measures did not have any significant effect on the u^* sensitivity of the flux. Consequently, if certain nighttime measurements are unreliable, daytime respiration measurements could be used to construct a model to replace them.

The problems associated with high nighttime fluxes were much bigger at Kalevansuo than Lettosuo. In the case of Kalevansuo, the measured nighttime respiration was higher at corresponding soil temperatures than daytime respiration (Fig. 8), whereas no such difference was observed at Lettosuo (Fig. 11). The Kalevansuo site is characterized by higher coverage of dwarf shrubs, mosses and hummocks than Lettosuo, where the ground layer is often barren. The bulk density of the surface peat layer is also smaller at Kalevansuo (Table 3). Therefore, we tested if the density of the moss-layer vegetation and surface peat explained the differences between plots and sites. We compared the plot-wise fresh and dry bulk densities of the living surface layer (Table 3) to the effect of fan speed (high and low) on the flux (Fig. 12). At Kalevansuo, the higher fresh bulk density of the living surface moss layer resulted in a clear correlation: greater effect of fan speed on the flux. At Lettosuo, on the other hand, no correlation whatsoever was found. The dry bulk density or the difference between the dry and fresh bulk densities of the surface mosses did not correlate with the fan speed effect better than the fresh bulk density of the surface mosses on either site. At the Kalevansuo site, the moss layer is thick and high in density while the density of the underlying peat is low; all these factors indicate high porosity of the soil surface. Apparently, a surface layer with higher porosity is more susceptible to pressure and turbulence caused by the fan. At the Lettosuo site, the living moss layer is thin and the underlying peat dense, which could consequently explain the observed insensitivity.

3.4 Respiration modelling

We fitted four Lloyd–Taylor respiration models to the Kalevansuo data. For two of these the data was limited to daytime (9 a.m.–5 p.m.) respiration measurements made with opaque chambers during the respiration measurement campaigns to emulate manual chamber data and two used normal operation nighttime (11 p.m.–4 a.m.) measurements limited to hourly mean u^* values of over $0.4\,\mathrm{m\,s^{-1}}$. A model for spring (1 June–19 July) and autumn (20 July–30 September) were made with both limitations. The temperature used was the 5 cm depth soil temperature.

We hoped to replace the unreliable still night measurements using a respiration model fitted to non-still night measurements. The models using daytime respiration measurements fitted better to previous manual respiration measurements from Kalevansuo than the u^*-limited models (Fig. 13). The u^*-limited models yielded higher flux values at corresponding soil temperatures than the manual data as well as the daytime limited models. In both automated data models fitted to the autumn dataset, the value of the temperature sensitivity parameter b (Eq. 3) was low. All the parameters in the models were highly significant, the standard errors being in the range of 1–10 % of the parameter estimates.

4 Conclusions

4.1 Structure, function and reliability of the system

Our automated chamber system proved to be quite reliable. No only did it deliver enough measurements for linear interpolation on most days when the system operated, but it also covered most of the variation in environmental conditions so that the missing days could realistically be modelled with ambient supporting environmental data. Generally speaking, most missed individual measurements occurred during winter when the actuators sometimes randomly malfunctioned. Longer gaps with no chambers working occurred during summertime and were due to power outages and instrument breakage by thunderstorms.

We conclude that a robust, frame-based chamber structure, such as ours, is a reasonably reliable tool for gas exchange measurements during wintertime in the boreal region. Generally, chamber systems should be better described and their reliability characterized in articles concerning automated chamber measurements.

4.2 Flux estimation

Low friction velocity during summer nights may result in a strong CO_2 gradient in surface peat and moss layers. Chamber closure may disturb this gradient and cause a rapid increase in headspace CO_2 concentration. Use of such data may cause large overestimation of nighttime emissions. This effect must be recognised and fitting procedure solved, before data can be used.

We tested and developed flux measurements and calculation methods to overcome these problems.

We conclude that the most important methodological and material factors affecting the measured flux are fitting interval, fan speed and the physical properties of the sampling plot surface.

We also conclude that linear fitting is a viable approach to calculating respiration fluxes from automated chamber data. Polynomial fitting, which is also often used, will overestimate nighttime emissions.

Since the fitting interval has a major effect on the resulting fluxes, it should be fine-tuned and selected for each measurement campaign based on the properties of the measurement plots. It is not possible to determine the best interval solely from CO_2 concentration data due to the mixed effects of initial disturbance and CO_2 saturation within the chamber headspace. Hence, not only the flux value but also the stability of the flux should be considered when choosing the optimal fitting interval. At our sites, the best interval was 120–240 s after chamber closure. Furthermore, we conclude that the lowest possible fan speed should be used to avoid overestimation of the flux via disturbance of the CO_2 gradient between soil and air.

Surface soil structure affects the sensitivity of a measurement plot to the disturbances caused by the measurement method. Thus, further assessment of the effect of the air-mixing fan and the soil structure of the measurement plots on the measured flux is necessary. Future studies should always test for the effect of fan speed on the measurements to see if it is significant on the study site in question. Methods to match the wind speed inside and outside the measurement chamber during measurement should be explored.

We also propose that the effect of the flux measurement chamber on the CO_2 concentration gradient in the soil and the near-ground airspace should be studied.

If nighttime measurements from still nights cannot be used, fluxes may be modelled using respiration data from nights with higher u^* or preferably from daytime respiration measurement campaigns with opaque chambers.

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References

Alm, J., Saarnio, S., Nykänen, H., Silvola, J., and Martikainen, P. J.: Winter CO_2, CH_4 and N_2O fluxes on some natural and drained boreal peatlands, Biogeochemistry, 09, 163–186, 1999. 14210

Aubinet, M.: Eddy covariance CO_2 flux measurements in nocturnal conditions: an analysis of the problem., Ecol. Appl., 18, 1368–78, 2008. 14211

Badorek, T., Tuittila, E.-S., Ojanen, P., and Minkkinen, K.: Forest floor photosynthesis and respiration in a drained peatland forest in southern Finland, Plant Ecology & Diversity, 4, 37–41, 2011. 14198, 14200, 14229

Bain, W. G., Hutyra, L., Patterson, D. C., Bright, A. V., Daube, B. C., Munger, J. W., and Wofsy, S. C.: Wind-induced error in the measurement of soil respiration using closed dynamic chambers, Agr. Forest Meteorol., 131, 225–232, 2005. 14211, 14212

Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, Glob. Change Biol., 9, 479–492, 2003. 14211

Baldocchi, D. D. and Meyers, P.: 1. Evaporation and CO_2 Efflux, J. Geophys. Res., 96, 7271–7285, 1991. 14197

Bubier, J. L., Crill, P. M., and Mosedale, A.: Net ecosystem CO_2 exchange measured by autochambers during the snow-covered season at a temperate peatland, Hydrol. Process., 16, 3667–3682, 2002. 14197, 14209

Dantec, V. L., Epron, D., and Dufrêne, E.: Soil CO_2 efflux in a beech forest: comparison of two closed dynamic systems, Plant Soil, 214, 125–132, 1999. 14216

Davidson, E. A., Savage, K., Verchot, L. V., and Navarro, R.: Minimizing artifacts and biases in chamber-based measurements of soil respiration, Agr. Forest Meteorol., 113, 21–37, 2002. 14213

Drewitt, G. B., Black, T. A., Nesic, Z., Humphreys, E. R., Jork, E. M., Swanson, R. V., Ethier, G. J., Griffis, T., and Morgenstern, K.: Measuring forest floor CO_2 fluxes in a Douglas-fir forest, Agr. Forest Meteorol., 110, 299–317, 2002. 14209

Goulden, M. L. and Crill, P. M.: Automated measurements of CO_2 exchange at the moss surface of, Tree Physiol., 17, 537–542, 1997. 14209, 14213

Kroon, P. S., Hensen, A., Bulk, W. C. M., Jongejan, P. A. C., and Vermeulen, A. T.: The importance of reducing the systematic error due to non-linearity in N2O flux measurements by static chambers, Nutr. Cycl. Agroecosys., 82, 175–186, 2008. 14199

Kutzbach, L., Schneider, J., Sachs, T., Giebels, M., Nykänen, H., Shurpali, N. J., Martikainen, P. J., Alm, J., and Wilmking, M.: CO_2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression, Biogeosciences, 4, 1005–1025, doi:10.5194/bg-4-1005-2007, 2007. 14199, 14210, 14212, 14214

Lai, D. Y. F., Roulet, N. T., Humphreys, E. R., Moore, T. R., and Dalva, M.: The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in an ombrotrophic peatland, Biogeosciences, 9, 3305–3322, doi:10.5194/bg-9-3305-2012, 2012. 14198, 14199, 14211, 14213, 14216

Levy, P. E., Gray, A., Leeson, S. R., Gaiawyn, J., Kelly, M. P. C., Cooper, M. D. A., Dinsmore, K. J., Jones, S. K., and Sheppard, L. J.: Quantification of uncertainty in trace gas fluxes measured by the static chamber method, Eur. J. Soil Sci., 62, 811–821, 2011. 14199, 14215

Liang, N., Inoue, G., and Fujinuma, Y.: A multichannel automated chamber system for continuous measurement of forest soil CO_2 efflux., Tree Physiol., 23, 825–32, 2003. 14209

Lloyd, J. and Taylor, J.: On the temperature dependence of soil respiration, Funct. Ecol., 8, 315–323, 1994. 14207

Lohila, A., Minkkinen, K., Aurela, M., Tuovinen, J.-P., Penttilä, T., Ojanen, P., and Laurila, T.: Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink, Biogeosciences, 8, 3203–3218, doi:10.5194/bg-8-3203-2011, 2011. 14200, 14201

Maljanen, M., Liikanen, A., Silvola, J., and Martikainen, P. J.: Nitrous oxide emissions from boreal organic soil under different land-use, Soil Biol. Biochem., 35, 689–700, 2003. 14197, 14199

Ojanen, P., Minkkinen, K., Alm, J., and Penttilä, T.: Soil–atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands, Forest Ecol. Manag., 260, 411–421, 2010. 14197, 14199

Pihlatie, M. K., Kiese, R., Brüggemann, N., Butterbach-Bahl, K., Kieloaho, A.-J., Laurila, T., Lohila, A., Mammarella, I., Minkkinen, K., Penttilä, T., Schönborn, J., and Vesala, T.: Greenhouse gas fluxes in a drained peatland forest during spring frost-thaw event, Biogeosciences, 7, 1715–1727, doi:10.5194/bg-7-1715-2010, 2010. 14197, 14199

Pihlatie, M., Christiansen, J. R., Aaltonen, H., Korhonen, J. F., Nordbo, A., Rasilo, T., Benanti, G., Giebels, M., Helmy, M., Sheehy, J., Jones, S., Juszczak, R., Klefoth, R., Lobo-do Vale, R., Rosa, A. P., Schreiber, P., Serça, D., Vicca, S., Wolf, B., and Pumpanen, J.: Comparison of static chambers to measure CH_4 emissions from soils, Agr. Forest Meteorol., 171–172, 124–136, 2013. 14199

Pumpanen, J., Kolari, P., Ilvesniemi, H., Minkkinen, K., Vesala, T., Niinistö, S., Lohila, A., Larmola, T., Morero, M., Pihlatie, M., Janssens, I. A., Yuste, J. C., Grünzweig, J. M., Reth, S., Subke, J.-A., Savage, K., Kutsch, W., Østreng, G., Ziegler, W., Anthoni, P., Lindroth, A., and Hari, P.: Comparison of different chamber techniques for measuring soil CO_2 efflux, Agr. Forest Meteorol., 123, 159–176, 2004. 14198, 14212

R Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0, 2012. 14204

Regina, K., Nykänen, H., Silvola, J., and Martikainen, P. J.: Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity, Biogeochemistry, 35, 401–418, 1996. 14197

Sarkar, D.: Lattice: Multivariate Data Visualization with R, Springer, New York, availabale at: http://lmdvr.r-forge.r-project.org, 2008. 14204

Savage, K. and Davidson, E. A.: A comparison of manual and automated systems for soil CO_2 flux measurements: trade-offs between spatial and temporal resolution, J. Exp. Bot., 54, 891–899, 2003. 14209

Seok, B., Helmig, D., Williams, M. W., Liptzin, D., Chowanski, K., and Hueber, J.: An automated system for continuous measurements of trace gas fluxes through snow: an evaluation of the gas diffusion method at a subalpine forest site, Niwot Ridge, Colorado, Biogeochemistry, 95, 95–113, 2009. 14209

Tuszynski, J.: caTools: Tools: moving window statistics, GIF, Base64, ROC AUC, etc., available at: http://CRAN.R-project.org/package=caTools, r package version 1.12, 2011. 14204

Unsworth, M. H.: Principles of microclimate and plant growth in open-top chambers, Commission of the European Communities Air Pollution Research Report, 5, 16–29, 1986. 14208

Wayson, C., Randolph, J., Hanson, P., Grimmond, C., and Schmid, H.: Comparison of soil respiration methods in a mid-latitude deciduous forest, Biogeochemistry, 80, 173–189, 2006. 14197

Zeileis, A. and Grothendieck, G.: zoo: S3 Infrastructure for Regular and Irregular Time Series, J. Stat. Softw., 14, 1–27, 2005. 14204

Table 1. Surface peat and moss layer (total) and living moss layer (moss) fresh and dry bulk densities ($\mathrm{g\,cm^{-3}}$) and surface layer thickness (cm) at the Kalevansuo and Lettosuo sites.

Plot	total fresh	total dry	moss fresh	moss dry	moss thickness
Lettosuo					
1	0.38	0.09	0.097	0.014	5.5
2	0.47	0.12	0.041	0.009	4
3	0.57	0.13	0.291	0.063	2
4	0.19	0.04	0.05	0.01	4.5
5	0.43	0.1	0.367	0.088	1
6	0.22	0.03	0.1	0.011	5.5
mean	0.38	0.09	0.16	0.03	3.75
Kalevansuo					
1	0.273	0.027	0.233	0.02	3
2	0.167	0.034	0.156	0.018	4
3	0.148	0.035	0.093	0.013	6
4	0.192	0.043	0.085	0.018	4.5
5	0.201	0.031	0.099	0.011	4.5
6	0.141	0.017	0.242	0.028	2
mean	0.19	0.03	0.15	0.02	4

Table 2. Minimum, maximum and quartiles of NEE and respiration (*R*) values (g CO_2 $m^{-2}h^{-1}$) calculated with linear (120–240 s) and polynomial (30–130 s, 30–960 s) fits for Lettosuo, June–September 2012. The data used in NEE includes all day- and nighttime measurements, while the data used in R respiration measurement campaign measurements. Filtered cases were excluded from both datasets.

Type	Min	1st Q	Median	Mean	3rd Q	Max
NEE						
Linear 120–240 s	−0.46	0.36	0.47	0.48	0.60	0.99
Poly 30–960 s	−0.51	0.37	0.48	0.48	0.61	1.03
Poly 30–130 s	−1.96	0.37	0.48	0.49	0.62	2.94
R						
Linear 120–240 s	0.14	0.34	0.43	0.45	0.55	0.90
Poly 30–960 s	0.24	0.45	0.57	0.56	0.66	0.95
Poly 30–130 s	−0.10	0.42	0.60	0.55	0.73	1.3

Fig. 1. Photographs of the chamber system in **(a)** summer position at the Lettosuo site and **(b)** winter position with additional collars installed at the Kalevansuo site. The frame is lifted by bolts on the five threaded rod legs. Insulation of the cables and tubing is visible in the winter position. Original direction of motors is visible in the summer position, adjusted direction in the winter position.

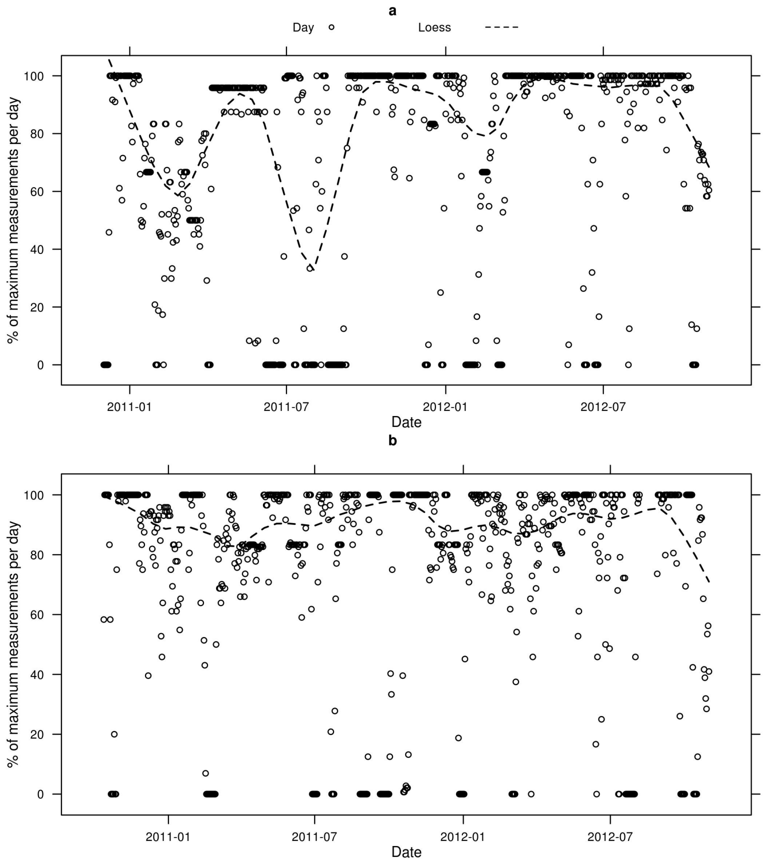

Fig. 2. Time series of achieved percent of maximum measurements per day at Kalevansuo **(a)** and Lettosuo **(b)**. Loess smoothed local average uses span value of 1/7.

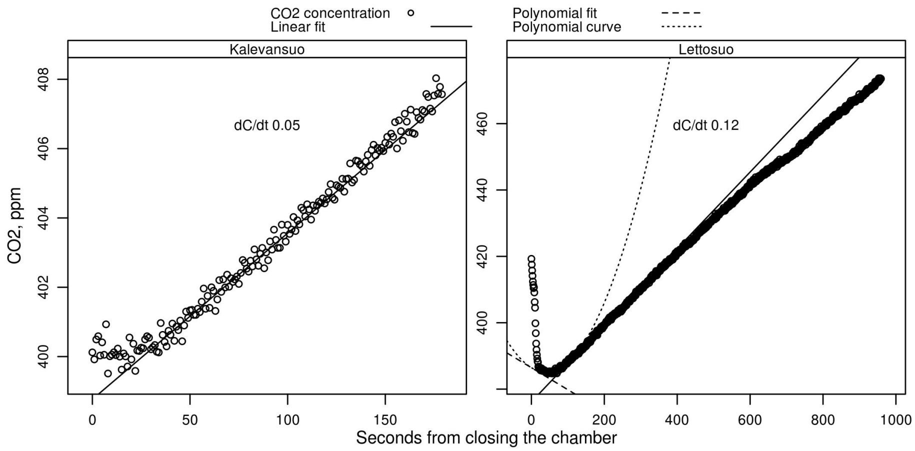

Fig. 3. Example of a CO_2 concentration curve measured at Kalevansuo on 10 December 2010 and at Lettosuo on 19 June 2012. Notice the large variation during the first 30 s, due to disturbance caused by chamber closure. Linear fit made to 30–90 s data from Kalevansuo, 120–240 s data from Lettosuo; polynomial fit is the initial dCO_2/dt of a polynomial fit to 30–130 s data. Notice the differing scales on both axes. Given dC/dt value is the slope of the linear fit.

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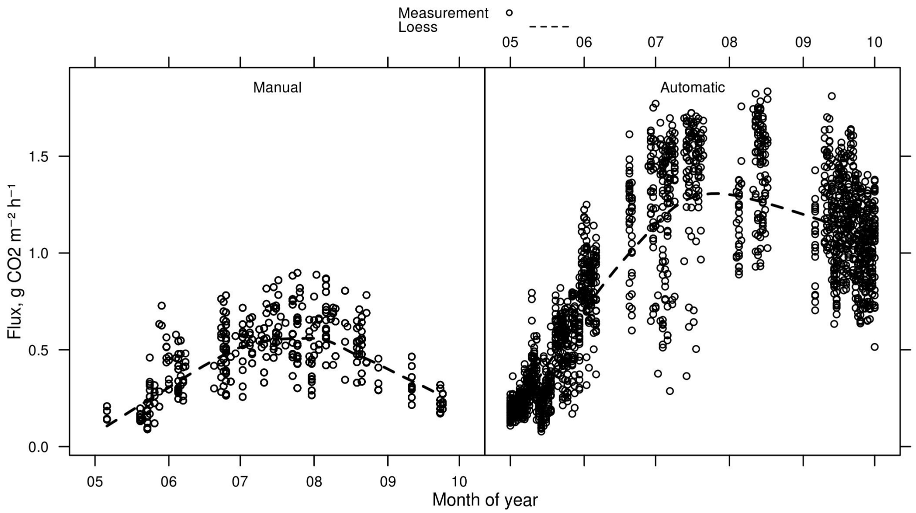

Fig. 4. Exceptionally high nighttime respirations observed in the first year (2011) at the Kalevansuo site (“automatic”). For comparison, dark respiration fluxes from previous years (2007–2009) (“manual”) (Badorek et al., 2011) from the same sites. Loess-smoothed line included for clarity (span = 1/7). Automatic fluxes calculated with 30–90 s data.

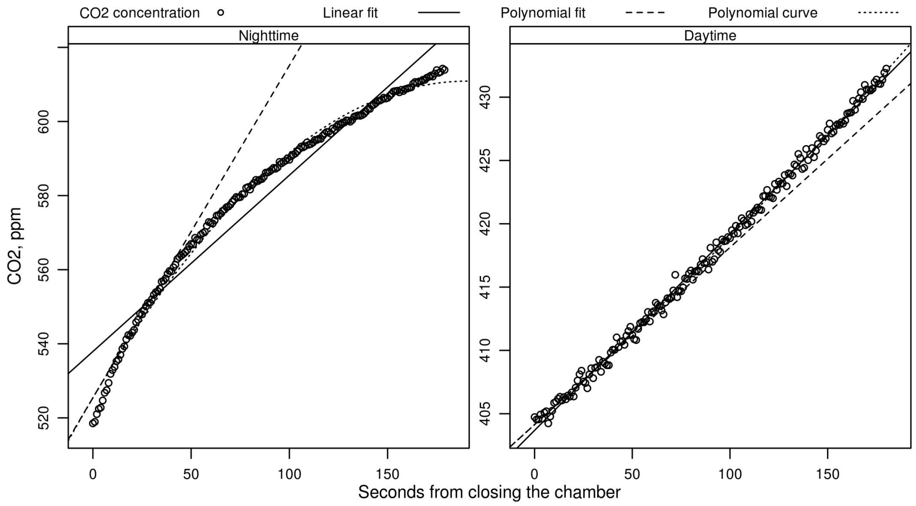

Fig. 5. Example of high initial flux in nighttime versus normal daytime respiration measurement in CO_2 concentration development at the Kalevansuo site. Nighttime measurement from 29 June 2011, daytime respiration measurement from 19 June 2012. Note the differing y-axis scales. Both fits are made to all visible data.

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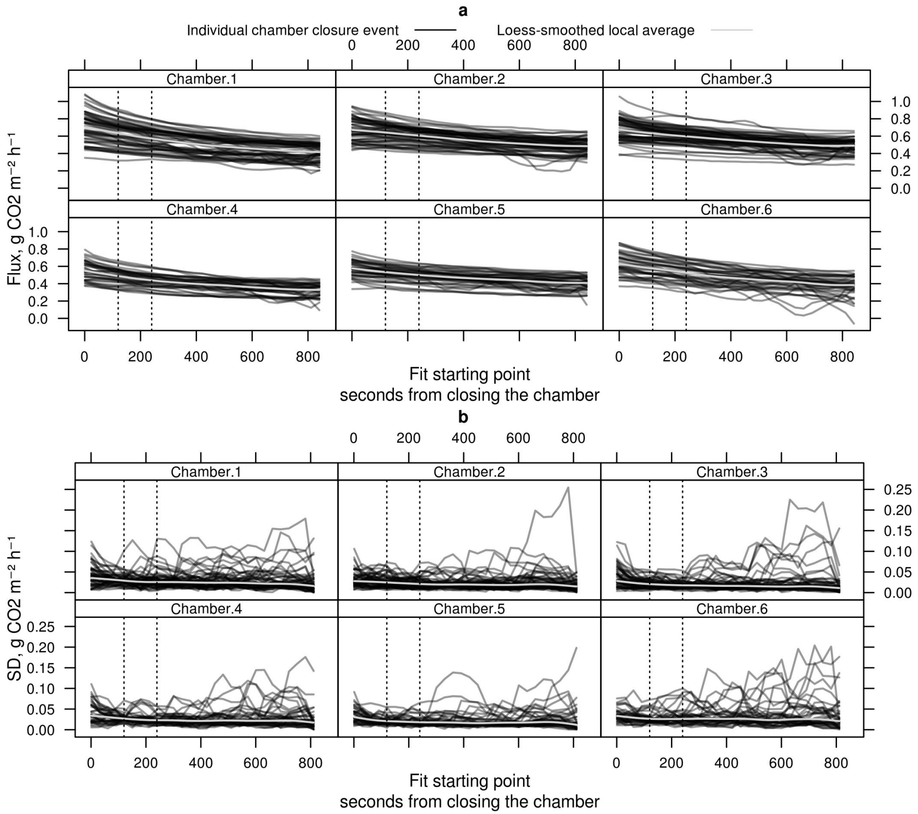

Fig. 6. Running **(a)** mean and **(b)** SD of respiration values ($\mathrm{g\,CO_2\,m^{-2}\,h^{-1}}$) calculated with consecutive overlapping 60 s fits (moving window of 5 fluxes) vs. calculation starting point at the Kalevansuo site, June–August 2012. Opaque chamber respiration measurements. Dashed vertical lines delineate the 120–240 s range we chose for flux calculation.

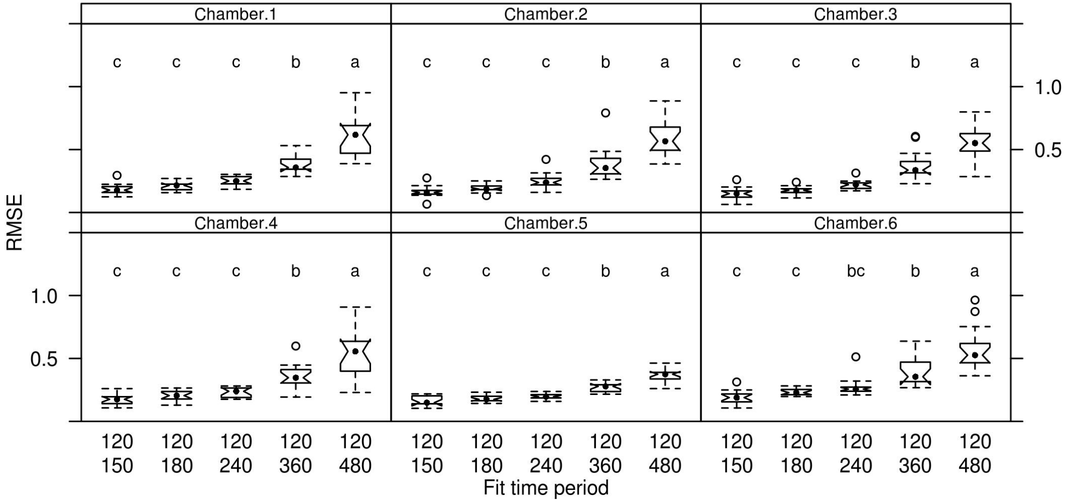

Fig. 7. Root mean square error (RMSE) of linear fit of CO_2 concentration vs. fitting interval (seconds after closing the chamber). Nighttime data in June 2012 from Kalevansuo with linear fittings is shown. Notches indicate 95 % confidence interval of the median indicated by the black dot. Box indicates 25–75 % quantiles. Dashed lines indicate 25 % and 75 % quantile ±1.5 interquartile ranges. Circles indicate outliers. Letters above boxes indicate groups with significant differences ($P < 0.001$) according to Tukey's Honestly Significant Difference test.

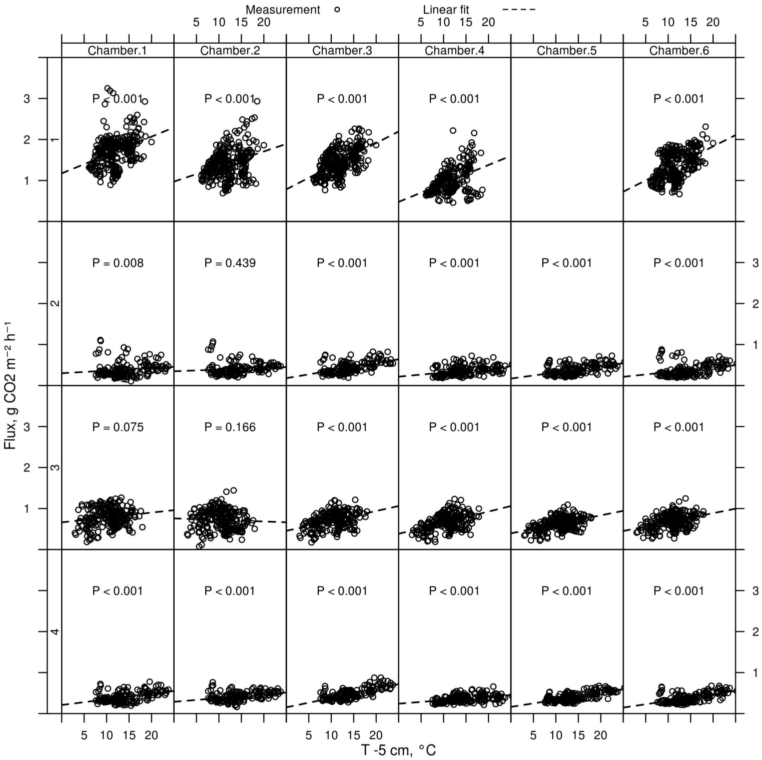

Fig. 8. Sensitivity of flux (flux, $g\,CO_2\,m^{-2}\,h^{-1}$) to soil temperature at 5 cm depth (T −5 cm, °C) measured at the Kalevansuo site. All fluxes were calculated with 30–90 s data unless stated otherwise. Row 1 indicates nighttime measurements from June–September 2011; row 2 nighttime measurements from June–September 2012; row 3 opaque chamber daytime (9 a.m.–5 p.m.) respiration measurements from June–September 2012; row 4 the same measurements as on row 3 but with data spanning 120–240 s. P values mark significance of T −5 cm parameter in a linear fit against the flux value.

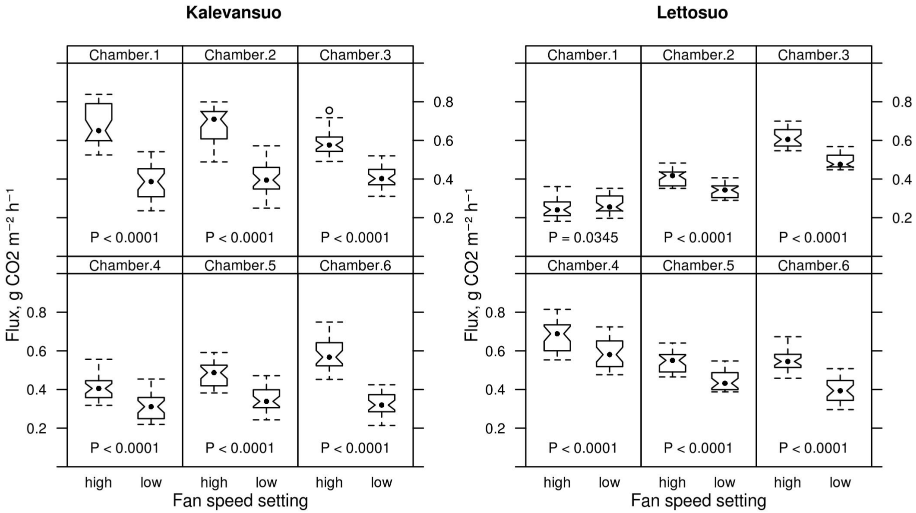

Fig. 9. Effect of fan speed (high vs. low) on nighttime flux at the Kalevansuo and Lettosuo sites. Measurements made between 21 and 24 September 2012. Fluxes calculated with 120–240 s data. For explanation of the plot elements, see Fig. 7. Given P values indicating significance of differences in flux between the fan speeds were calculated using Student's *t* test.

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Automated chamber CO_2 exchange measurements

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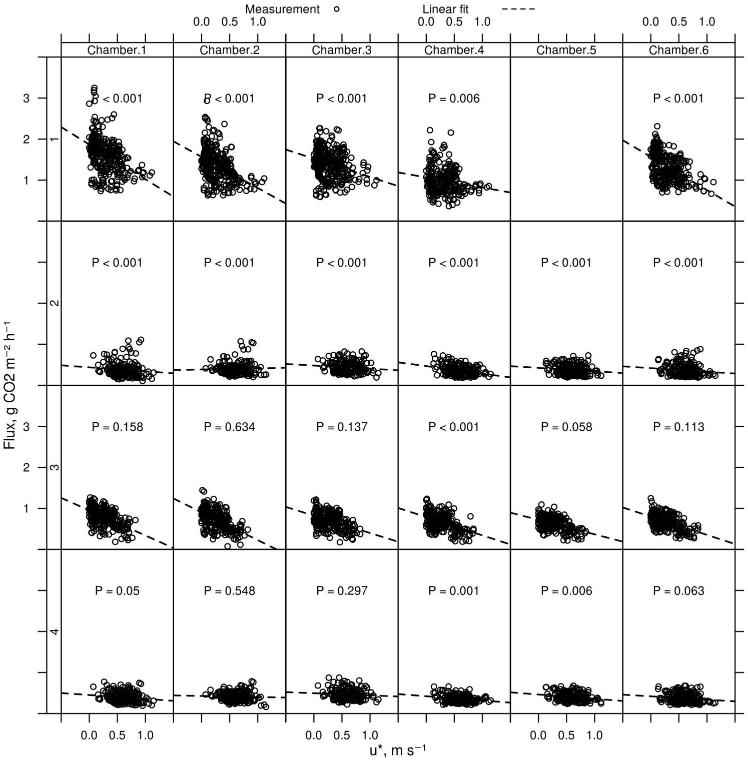

Fig. 10. Sensitivity of flux (flux, $g\,CO_2\,m^{-2}\,h^{-1}$) to atmospheric turbulence (u^*, $m\,s^{-1}$) measured at the Kalevansuo site. All fluxes were calculated with 30–90 s data unless stated otherwise. Row 1 indicates nighttime measurements from June–September 2011; row 2 nighttime measurements from June–September 2012; row 3 opaque chamber daytime (9 a.m.–5 p.m.) respiration measurements from June–September 2012; row 4 the same measurements as on row 3 but with data spanning 120–240 s. *P* values mark significance of u^* parameter in a linear fit against the flux value.

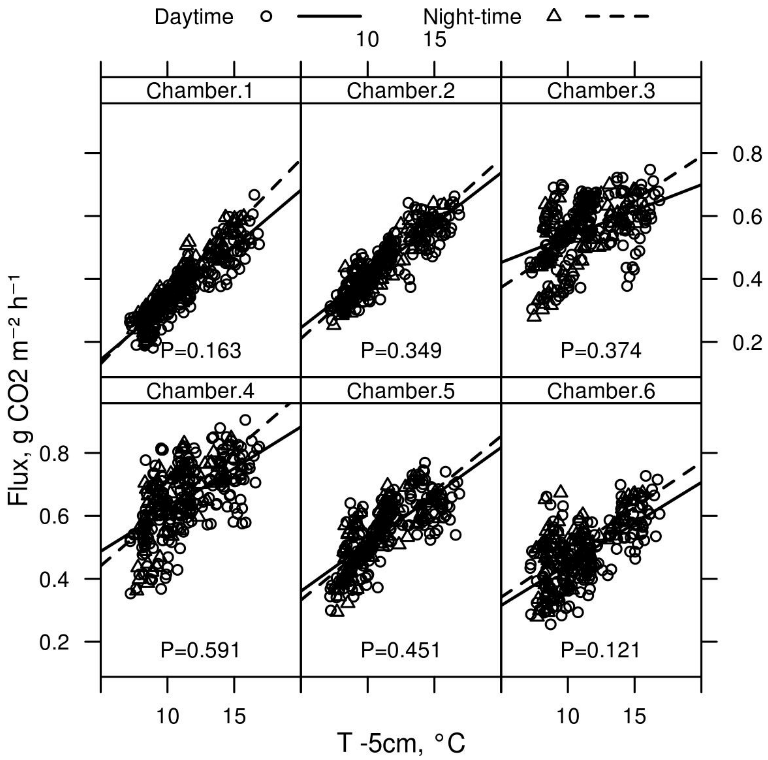

Fig. 11. Sensitivity (actual measurements and linear fit) of day- and nighttime (flux, $\mathrm{g\,CO_2\,m^{-2}\,h^{-1}}$) respiration measurements to soil temperature at 5 cm depth (T −5 cm, °C) at the Lettosuo site in Summer 2012 (June–September). Fluxes calculated with 120–240 s data. *P* values indicating the significance of differences between night- and daytime measurements were calculated with Student's *T* test.

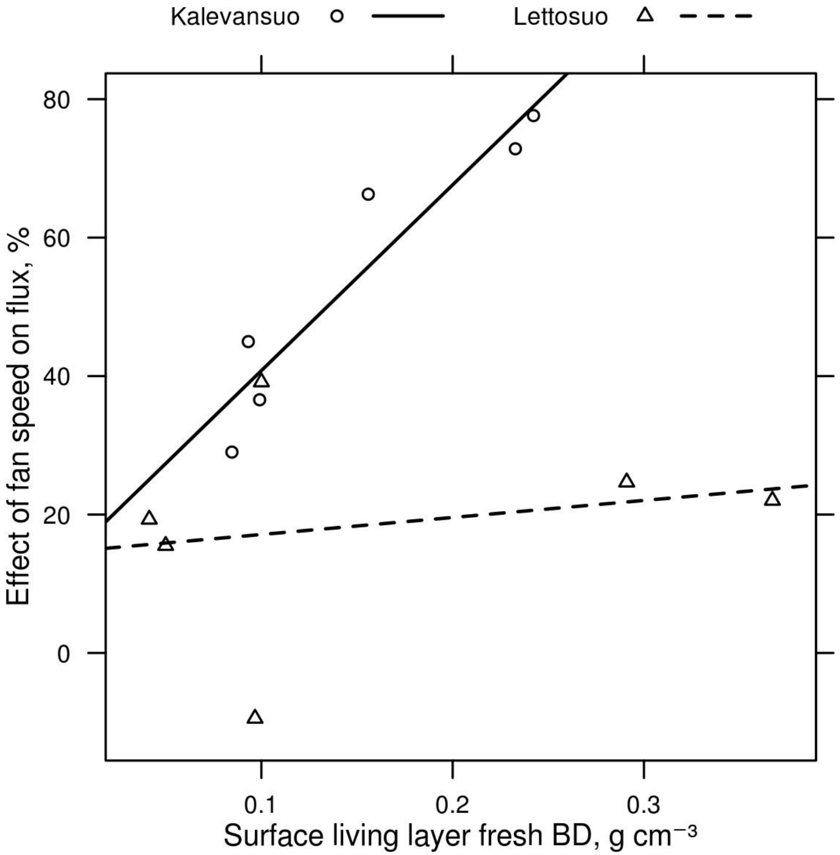

Fig. 12. Relationship between fresh bulk density (BD, g cm^{-3}) of living moss layer and effect of fan speed on the CO$_2$ flux((flux$_{high}$ – flux$_{low}$)/flux$_{low}$ · 100 %) at th eKalevansuo and Lettosuo sites.

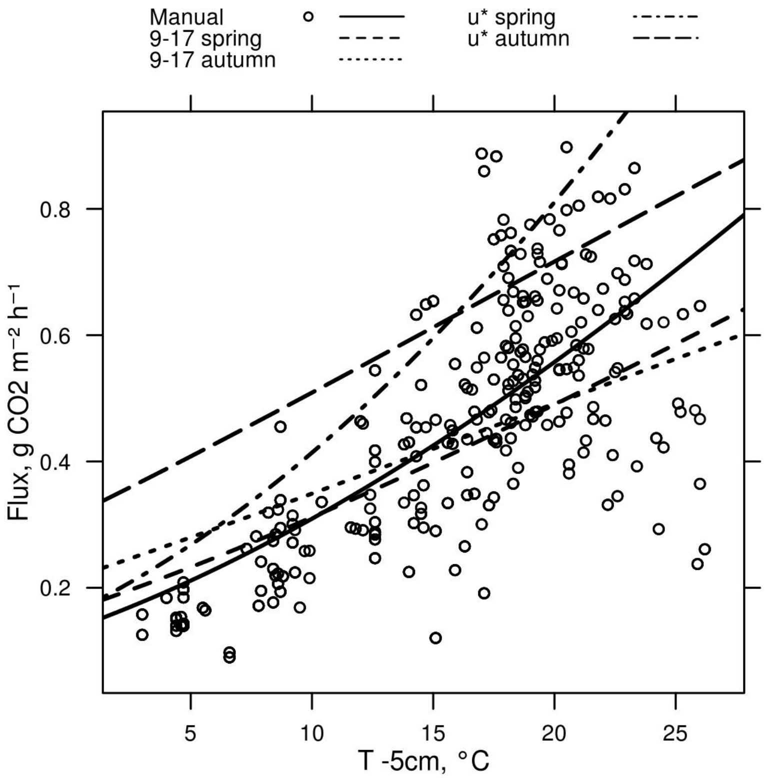

Fig. 13. Soil temperature sensitivity of manual respiration measurements (flux, $\mathrm{g\,CO_2\,m^2\,h^{-1}}$) from 2007–2009 and Lloyd–Taylor respiration models fitted to manual data (manual) and automated daytime (9–17) and u^*-limited (u^*) data. Automated daytime dataset limited to hours 9 a.m.–5 p.m., u^*-limited dataset limited to u^* values over $0.4\,\mathrm{m\,s^{-1}}$. Spring datasets from 1 June to 19 July 2012; autumn datasets from 20 July to 30 September 2012.