Dead associate editor,

We have now carefully studied the comments from the reviewers and revised the manuscript accordingly. Some critical corrections were applied to the data analysis, which caused major changes to the results. Therefore, in addition to the comments given by the reviewers, we have made some significant changes to the text. We have also changed the title of the manuscript and added two new co-authors.

We thank you for the opportunity to revise our manuscript and hope that you and the reviewers find the changes satisfactory.

Response to reviewer #1

The authors present two years of CH4 flux data from a drained peatland forest site which have been collected with an automated chamber system consisting of six chambers connected to a high resolution gas analyser. The aim of the study is twofold. First, the flux data series is used to test whether CH4 fluxes from these chamber measurements are better analysed with linear or non-linear regression. As conclusion, the authors recommend to first calculate all fluxes by linear regression and then to recalculate high fluxes with an exponential regression. High CH4 fluxes were defined by a site-specific threshold. Second, the study analyses the variation in CH4 flux rates from the forest floor at various scales (diurnal, seasonal, inter-variation) and annual balances are presented as well.

The manuscript is very well written and this study provides an important flux dataset. High resolution gas analysers for CH4 measurements are a recent development and the number of studies combining automated chambers and these analysers for long-term measurements are still scarce. This study has the potential to result in an excellent paper providing new insights into CH4 flux dynamics and the methodological challenges associated with gathering these data. However in my opinion, the manuscript has two major flaws. On the one hand, the authors do not fully explore the potential of the dataset from a methodological standpoint and should expand this part of the manuscript more.
On the other hand, they provide a lengthy description of the flux differences between the single chambers, but the experimental design does not really allow a proper discussion of the fluxes from an ecological standpoint.

Thus, I recommend major revision and will detail my concerns below.

General comments
− I find the threshold of 3.5 µg CH4 m–2 h–1 quite arbitrary. Based on the data presented here, I am not convinced to use such a threshold as decision for which regression to use. Why should this method be more appropriate than using a statistical criterion like e.g. AIC and to decide based on that criterion for each flux measurement separately which regression method to use?

1. To answer this point, we have to start by briefly explaining that there was a flaw in our flux calculation and the results reported in the original manuscript. We have now recalculated all fluxes, and they are approximately 3 times as high as in the previous version. In addition, we have performed a dilution correction for CH4 concentrations, which also had an impact on the fluxes, and used a longer closure time to determine the fluxes (see comments below).

   To get back to the original comment of the referee, we tested the method (AIC) suggested by him/her. However, an AIC-based selection of the regression form proved to be partly inconsistent and resulted in increased noise in the calculated fluxes. Particularly during the low-flux period (winter, spring), the flux variability was higher than when using our 'Flux limit method' (see Figure 1A.)

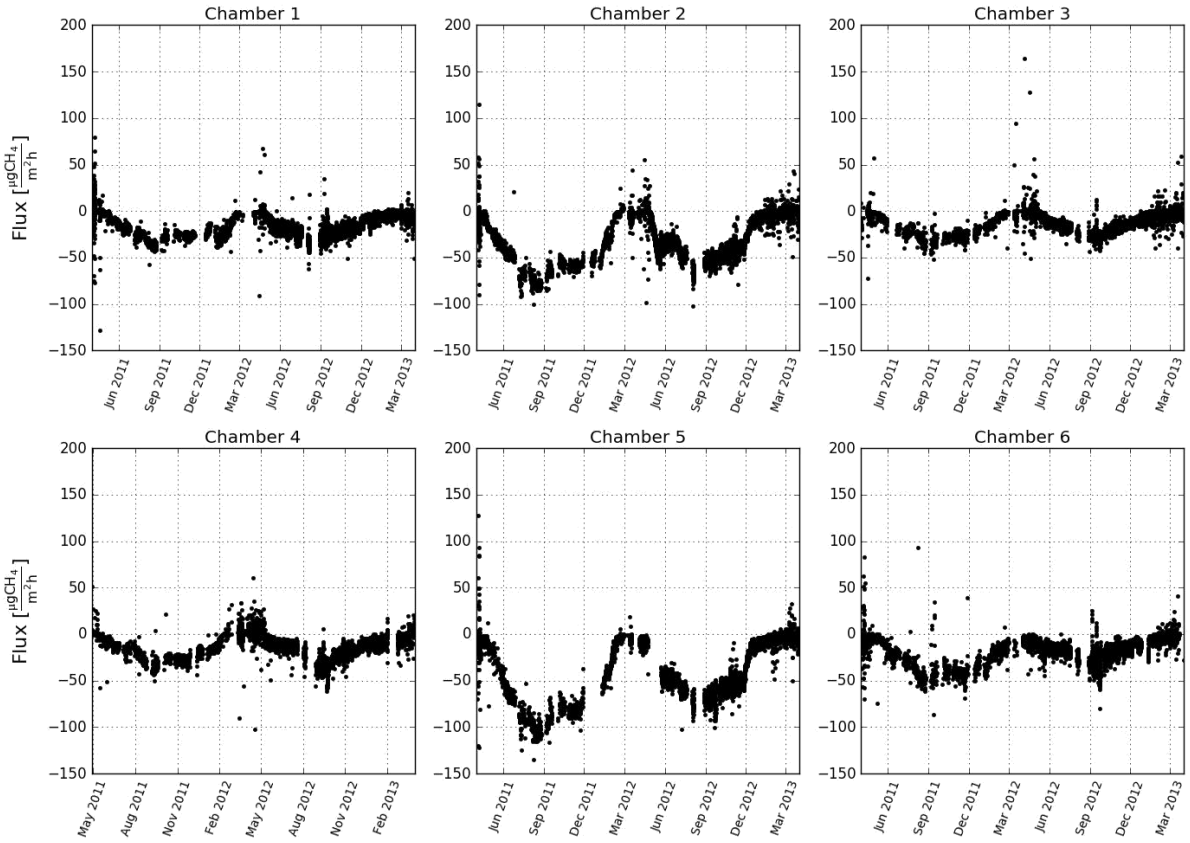

Figure 1A. Time series of CH4 flux in 2011-2013 in each of the six chambers, calculated using the 'AIC method'.

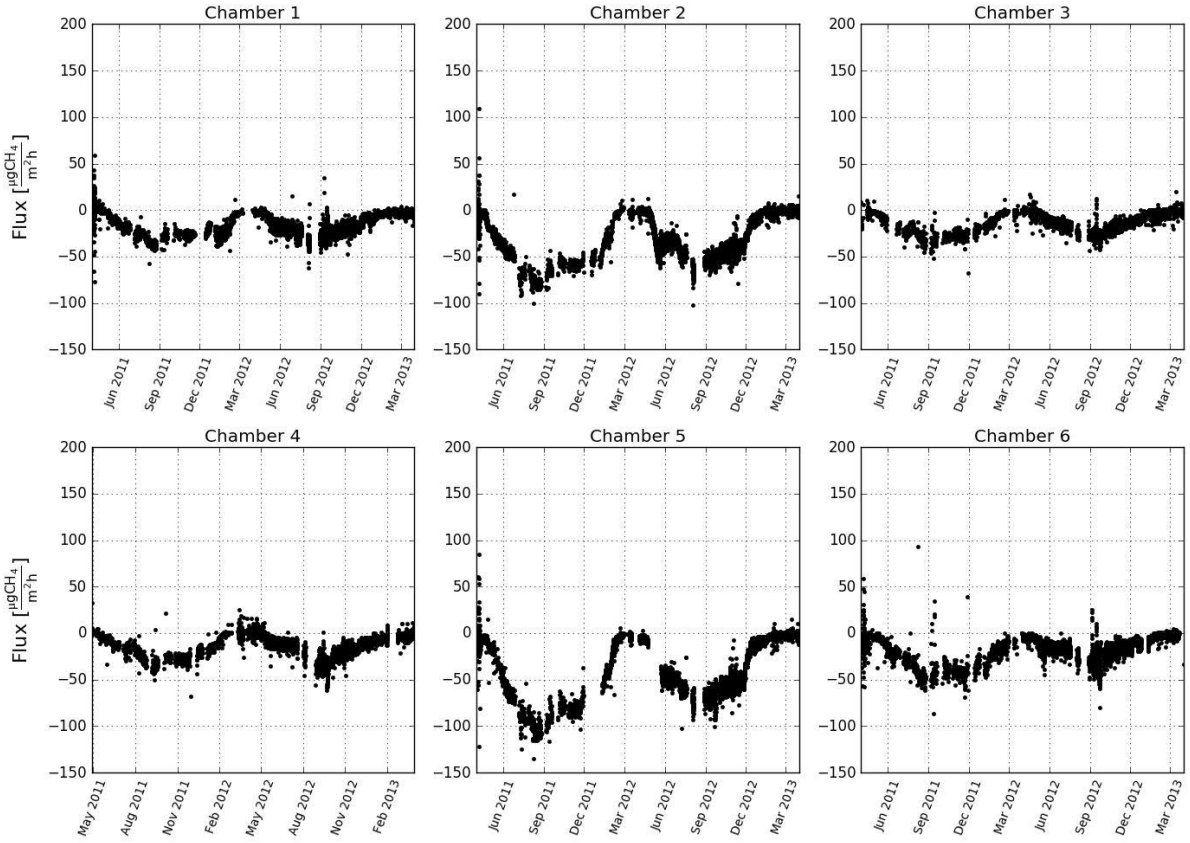

Figure 1B. Time series of CH4 flux in 2011-2013 in each of the six chambers, calculated using the 'Flux limit method'. Both figures 1A and 1B include only 6 minute closures, therefore there are only 4 measurements/day in 2011 – March 2012.

Therefore we decided to keep our approach. However, we revised the criterion based on which the flux limit was chosen: we calculated bin averages of the linear and exponential fluxes of the whole data set and plotted them against each other (Fig. C). From that plot we estimated the value of the linearly calculated flux after which the flux variation (=noise) in the exponential fit increased and the shape of the relationship changed. The new flux limit is 2.5 µg CH4 m-2 h-1, which is about 20-25% of the limit presented in the original manuscript. We think that using this revised limit provides a more accurate and robust estimate of very low CH4 fluxes. Below this limit the concentration variations from which the flux is derived become increasingly affected by measurement noise and the exponential fitting becomes more prone to random perturbations to individual concentration data points and does not result in realistic flux estimates anymore.

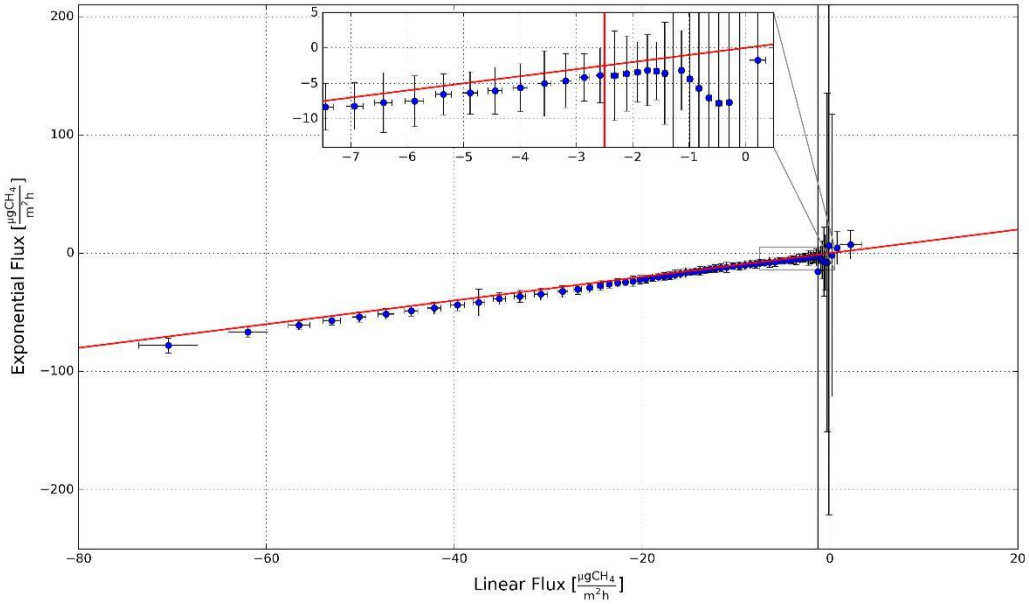

Figure 1C. Bin averages (n=500) of the linear and exponential fluxes of the whole data set plotted against each other. In the small zoom figure the red vertical line denotes the selected flux limit of 2.5 µg CH4 m-2 h-1. (this Figure will be included in the revised paper)

− I am missing more details (including figures) about the effect of different closure times on the flux calculation results.

2. We tested different fitting windows by increasing the fitting period from the beginning (changing fitting length) (Fig. 1D) and by moving the start of the fit further (constant fitting length) (Fig. 1E). In this analysis we used data from summer 2012 when measurements were done with 16 min closure times. From this analysis it is clear that the closure time (or fitting period length) has an impact on the fluxes, particularly with closure times less than about 200 s. Therefore, instead of using the 120 s closure (and fitting) time, as done in the original manuscript, we decided to use 6 min closure time, as the noise in the fluxes was significantly reduced (this can be seen by comparing Fig.

1B above to Fig. 3 in the original manuscript). A closure time of 6 min was selected because it was used for most of our data. On the other hand, for studying the inter-annual variation, we then had to correct the 2011 fluxes (which were mostly measured with 2 min closure times) to correspond to the 6-min closure time. For this, we estimated the correction factor for each day separately by using the 6-min closure measured four times a day in 2011. The correction factor was then smoothed by using a moving average with a 2-week window. It varied between 0.9 and 1.2, being mostly 1.05, meaning that the 2011 measurements were increased about 5% due to the correction.

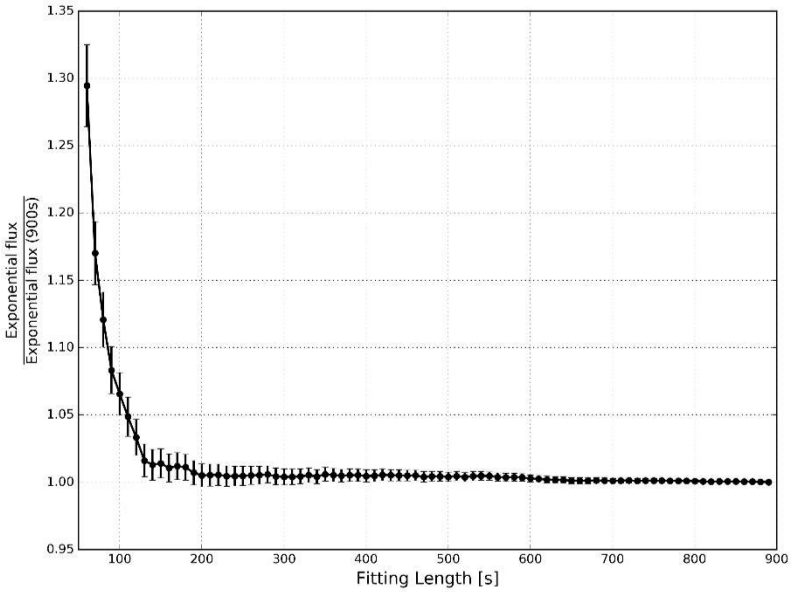

Figure 1D. Flux calculated with the increasing fitting length (shown in x-axis) plotted against the flux calculated with the 900 s fitting length. For example, the first point of the graph, showing a ratio of 1.29, is based on 60 s fitting length from the beginning, the second on 70 s long fitting, and so on. Data is from summer 2012. (This Figure will be included in the revised paper)

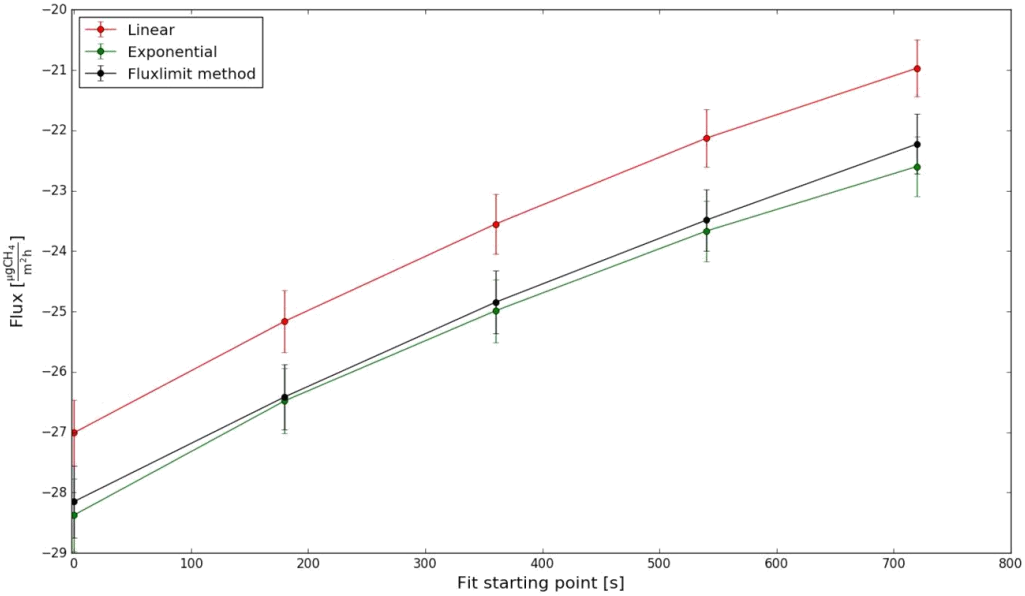

Figure 1E. Fluxes calculated with linear, exponential and 'Flux limit' methods using a 3-minute window and five different starting points. The data are from summer 2012.
(This Figure will be included in the revised paper)

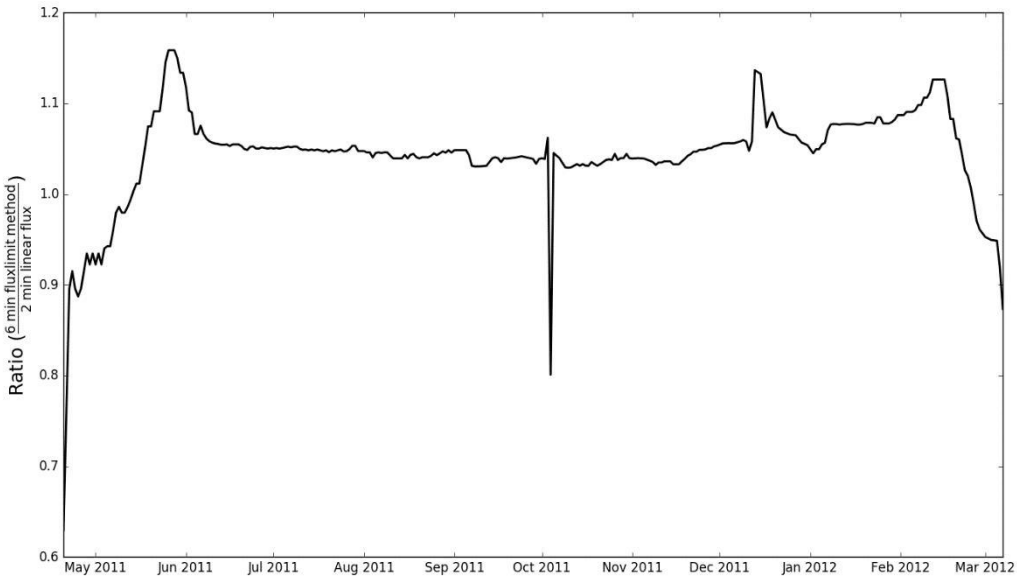

Figure 1F. Smoothed correction factor for converting 2-min fluxes to the 6-min closure time (Will be included as a Supplement)

− You have only one replicate per vegetation type. Based on this setup, it is not really possible trying to understand the differences between the chambers from an ecological standpoint. Furthermore, as additional data besides vegetation composition, you only seem to have soil temperature for the single plots. Why wasn't the water table measured at each chamber? Do you have any knowledge about the soil profiles at the different locations? How has the porosity of the soil changed due to the drainage? Are your six

locations really representative for the chosen vegetation types and the soil conditions at the site?

3. We realize that the use of "vegetation type" has been misleading and simply wrong. Because of the limitation of having only one gas analyzer for the six chambers, the chambers had to be located rather close to each other. Thus, the chambers were within a radius of 10 m from the measurement cabin (this information is now added to the manuscript). The locations are of the same vegetation type (Vaccinium myrtillus II type, information added to the manuscript) and being this close to each other on a well-drained, even (no hummock-hollow patterns) peatland they are unlikely to have markedly different water tables, soil temperatures deeper than at the soil surface, or soil conditions. The comparison of different vegetation types is not the aim of this study and not possible with this setup.

   We did not expect that the rather close locations on the even, well-drained site would have very different fluxes, but by placing the chambers on locations with different vegetation composition we wanted to get as much between-location variation in flux dynamics as possible for the analysis of daily/seasonal dynamics. The observed differences in ground vegetation composition mainly result from irregular shading of the tree stand (mentioned in the first paragraph of Chapter 2.1. Site description), and definitely do not indicate different vegetation types.

   To clarify the text, "vegetation type" has been changed to "vegetation composition".

   Soil profile description for the site (bulk density, CN ratio) is now added to the manuscript. This key background information was accidentally left out of the manuscript. The peat has definitely compacted due to the drainage (leading to lower porosity as well).

− **Despite the number of replicates, the dataset is very suitable to study diurnal variations in CH4 fluxes. This should be a separate section in the discussion and be more focused on the underlying processes causing these variations. Right now, this part has good references, but is mainly descriptive. In general, the manuscript has a good reference list, but often you only write which correlations were found in other studies. You need to go a step further and discuss more the processes involved. Process descriptions often stay too vague and general.**

4. After all the corrections applied in the flux calculation we found that 1) the variation originally found to take place in 2012, showing higher uptake at midday, disappeared, mainly due to the dilution correction; 2) the diurnal variation found after the dilution correction, and found to take place in both 2011 and 2012, showing lower uptake in the daytime, was mainly explained by wind speed variations (Fig. 1G). On the other hand, the air or soil surface temperature showed no or only a weak correlation with the CH4 flux (data not shown but will be added to supplement). Furthermore, inspired by Pirk et al. 2016 (see comments by referee #2), we tested the connection between the curvature parameter C in the exponential equation (see Eq. 2 in the original manuscript) and the wind speed and found, contrary to Pirk et al., that with a higher wind speed the curvature typically decreased (data will be shown in supplement). Our conclusion is that the relationship of CH4 flux with wind speed may be related to chamber leaking, as shown by Pirk et al., but also to other wind-driven processes, such as changes in the

concentration gradient within the soil that before the chamber closure is controlled by the wind speed. Thus there is no need to discuss the biological processes, as our evidence shows that these do not play a significant role or cannot be detected.

Pirk N., Mastepanov M., Lund M., Crill P. R.. Christensen T. 2016. Calculations of automatic chamber flux measurements of methane and carbon dioxide using short time series of concentrations. Biogeosciences. Vol. 13(4) s. 903–912.

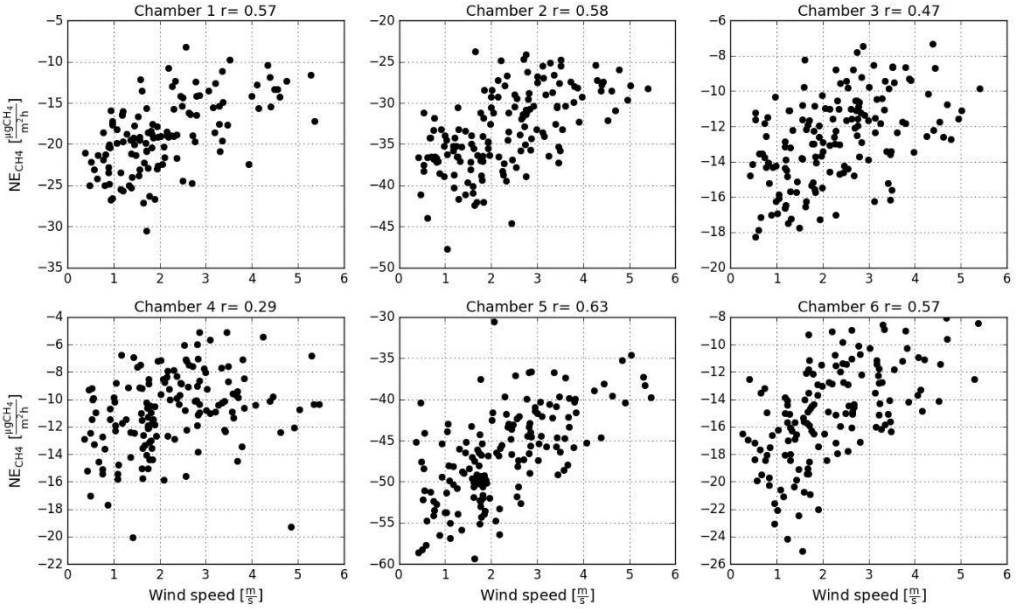

Figure 1G. Hourly CH4 fluxes plotted against the wind speed measured above the canopy in June 2012. (This Figure will be included in the revised paper, but only for the chamber #2, the data from which were used in Figure 7 and 8 in the original MS. The rest of the wind speed relation figures for all chambers and for other time periods will be included as a Supplement).

Specific comments

− **Page 1, line 17: CH4**

5. Corrected.

− **Page 2, line 14: „…thus turning in particular well-drained peatlands…”**

6. Corrected.

− **Page 2, line 22: Methane oxidation rates are also strongly controlled by the methane concentration in the soil, not only the oxygen concentration.**

7. Corrected.

− **Page 3, line 19: Add that exponential regression is especially sensitive to disturbances at the beginning of the measurement.**

8. Corrected.

− **Page 3, lines 19-20: It is not generally true that you need more than five data points to fit an exponential regression. It depends on the flux strength. See for example the paper**

by Pedersen et al. (2010) and Forbrich et al. (2010) which you cite in your manuscript. Thus, it is not uncommon to perform non-linear regression on datasets derived from syringe sampling. A high resolution gas analyser is not typically required. The great advantage of the high resolution gas analyser is that is reduces the uncertainty of the estimated slope of the flux curve, it does not necessarily change the mean estimate.

9. Corrected.

− **Page 3, line 23: Specify 'high temporal resolution'. You probably mean both the sampling rate during one chamber measurement, and the total number of chamber measurements you can perform per day.**

10. Yes we do. Corrected.

− **Page 3, line 31: Do you know how much fertilizer was applied?**

11. The fertilizer contained 10.5% of P as raw phosphate and 12.4% of K as potassium salt. We have no documentation of the dosage used but an application of ca. 400–500 kg/ha, according to contemporary forest fertilization practices (Huikari & Paavilainen, 1968), would result in approximately 40 kg of P and 50 kg of K per hectare.

    Huikari, O. and Paavilainen, E.: Metsänlannoitus (”Forest fertilization”). Kirjayhtymä, Keskusmetsälautakunta Tapion julkaisuja, 1968.

− **Page 4, line 7: For the first species in the brackets write the full name. The way you have written it now, "S." stands for Sphagna and not Sphagnum.**

12. Corrected.

− **Page 4, line 20: Specify the type of fan used. What was the volume turnover inside the chamber?**

13. We assume that the "volume turnover" refers to the rate at which the air inside chamber volume is fully changed. One could calculate this as a relationship between the chamber volume (0.097 m3=97 L) and the flow rate of the sample gas (on average 0.9 L/min). This would give a turnover time of 108 min. However, in fact the chamber air is not replaced by ambient air, since the sample air is returned back to the chamber from the analyzers.

    The fan type was added to the text. The speed of the fan (Sunon Maglev, 1.7 W, 24 V, size: 8 cm x 8 cm) was regulated by adding a resistor into the circuit (see details in Koskinen et al. 2014). This information was added to the newly written chapter 2.2 (as requested by referee 2). It must be noted here, that there was a typo in Koskinen et al. concerning the size of the fan (8 x8 cm, not 12 x 12 cm).

− **Page 4, line 31: What does "w = 1 cm" mean?**

14. The whole chapter was rewritten by the suggestion of the other referee and this part was removed (see also the previous answer #13).

− **Page 5, line 1: Is "Linak, 2009" a reference? If yes, it is not in your reference list. In general, be more consistent when mentioning product names. Include the company name as well as the associated city and country.**

15. This reference was removed while the chapter 2.2 was rewritten. We also checked all the product and company names and made them more consisted as suggested by the referee.

− **Page 5, line: Wasn't the flow rate quite low? What was the actual tubing length and tubing diameter for the chambers?**

16. The flow rate was originally adjusted following the recommendations in the Li840 manual. For Li840, a maximum flow rate is 1L/min. Thus, we have aimed to maintain the flow rate at about 0.8-0.9 L/min. This flow rate is also useful to avoid significant regimes of under/overpressure inside the chamber, which would probably result from significantly higher suction and blowing rates of sample gas. We do not see that this flow rate would cause any problems. There was a certain lag time (typically less than 10 s) between the chamber closure and the observable analyzer response, which is accounted for during the data treatment.

    Tubing length and id/od have been reported in Chapter 2.2. The actual length and diameter do not differ from the reported ones.

− **Page 5, line 7: Specify the type of sensor you used for soil temperature measurements.**

17. PT4T, Nokeval Oy, Nokia, Finland. This information was added to the text.

− **Sections 2.3 & 2.4: Which software did you use for the flux calculations and data analysis?**

18. All the calculations were made with the Python programming language (Python Software Foundation, version 2.7, https://www.python.org) using libraries: NumPy (http://www.numpy.org/), SciPy (http://www.scipy.org/), Pandas (http://pandas.pydata.org/) and matplotlib (http://www.matplotlib.org). Also, most relevant methods (e.g. fitting) are now explained in more detail in the text.

− **Page 5, line 13: "bihourly" = twice per hour or every two hours?**

19. Every two hours. This is now clarified in the text.

− **Page 5, line 14: If I understand correctly, you did not discard any data points from the measurement start. Why was it in your case justified to not apply a deadband to the flux data? How can you be sure that you had proper headspace mixing immediately after chamber closure?**

20. We actually discard the first 4 points, which is equivalent to 18 seconds. This is now added to the text. The fan was working all the time, even when the chamber was open.

− **Page 5, line 17 – page 6, line 1: I don't quite understand this part. What exactly is the purpose of equation 3? Are these parameter estimates inserted into equation 4? Also, is the Kutzbach model applicable to CH4 since it was developed for CO2?**

21. The parameters in equation 3 (a2,b2 and c2) are used as an initial guess for the parameters (a17, b17 and c17) in equation 4. If this is not done, then fitting the equation 4 typically fails. However, we now removed the equations 3 and 4 from the text and only mention that the initial fit is done. We do not know any reason, why the Kutzbach model would not be applicable to CH4. Our data show similar behavior (although mostly opposite in sign) and the same laws of physics apply for CH4 as for CO2.

− **Page 7, line 1: insert "CO2" in front of "concentration"**

22. Corrected.

− **Page 7, line 10: Were these hardware problems of the gas analyser? If yes, it might be interesting information for other users.**

23. The hardware problems here mean the problems with the chambers not working correctly. This was mentioned on Page 6, lines 26-27. The gas analyzer worked fine for the whole two year measurement period. This information was added into the text.

− **Page 8, line 2: insert "it" before "usually".**

24. Corrected.

− **Page 8, lines 4-12: You base a lot of the following sections on these results. Provide example figures of single flux concentration curves so that the reader can judge for himself/herself.**

25. Two example figures, showing closures with 'high' and 'low' uptake fluxes are now added to the revised manuscript (see also answer #7 for referee 2).

− **Page 8, line 9: How do you know that it is an underestimation?**

26. Thank you for pointing this out. We actually do not know. The term "underestimation" is replaced with the word "lower" or similar when occurring in the text. See also the answer #6 for referee 2.

− **Page 8, line 16: Shouldn't it be "<"?**

27. Corrected.

− **Page 8, lines18-19: This sentence is mainly a repetition of the previous sentences. And is the data removal really the only reason for the observed differences?**

28. This section was mostly rewritten after the new data analysis. We also removed Table 2b and recalculated the data shown in Table 2a.

− **Page 8, lines 21-23: I am not convinced of this based on the presented data.**

29. See the reply 30 above

− **Page 10, line 30: Friction velocity is an important parameter, but it has not been mentioned at all before this section. I assume, u* is based on the eddy tower measurements?**

30. Yes, u* is based on the eddy tower measurements. As discussed above, wind speed (which is correlated to u*) had an important role in explaining the flux dynamics. As wind speed is already discussed using other Figures and the Table 3, we decided to remove the u* figure and replaced u* with the wind speed measured above the canopy.

− **Page 12, line 5: I don't see a reason for mentioning the CO2 data here.**

31. We decided to remove the comparison to Koskinen et al. since they did not compare same subjects.

− **Page 12, lines 10-11: This is an obvious observation when using relative differences.**

32. This chapter was rewritten after the new data treatment, and these lines are not relevant anymore.

− **Page 13, line 1: Also discuss the importance of the water table depth. The low temperature does reduce metabolic activity, but methanogens are favoured by the increasing soil moisture content.**

33. Yes, this is true. However, during winters 2011 and 2012, the water level was not high during the whole winter. Instead, it reached a local minimum in February-March. Still, the soil moisture can be high beneath the snowpack and the frozen soil surface. We added soil moisture as one possible driver of methane production.

− **Page 13, lines 14-23: This section is a very good example of the weakness in your study. You are lacking data on (potentially) important environmental variables and are just speculating here.**

34. It is true that we did not measure WTD separately beside each chamber. This cannot be changed afterwards, as in the beginning of 2016 the site was harvested and thus changed. We have installed more WTD sensors within the area, but these data cannot be used for this older CH4 exchange data owing to the harvest.

    Explaining the spatial variation was not the original purpose of the study. Instead, we wanted to cover, as much as possible, the varying ground vegetation composition with the current setup to get an average estimate of the soil CH4 exchange. It would have been of course ideal to have much more ancillary measurements; however, we consider reporting the flux dynamics of a forested peatland interesting as such and worth publication. This has also been discussed in the reply 4.

    We first considered removing lines 14-23. However, the sentence about the temperature is not speculation, as it is based on measured soil temperatures. Also, removing all this discussion would give an impression of not considering the possible reasons for the observed differences at all. Therefore we decided to keep these lines, but change the wording of "… we cannot confirm its role…" to "…we can only speculate its role…".

− **Page 15, line 5: Could the lack of correlation be due to a lack of grass species (e.g. root exudates as food source for microorganisms) in comparison to the other study?**

35. This lack of correlation was likely caused by the fact that the measuring points at Lettosuo do not have plant species growing roots to anoxic layers, that would be capable of directly providing root exudates as substrate to anaerobic decomposition.

− **Table 1: Do you have a reference for VGAmax? Include more details about the sampling method and the sampling time.**

36. We do not have a reference for VGAmax as it is based on unpublished data. We added a short description of the sampling method and time to the table text.

− **Table 3: Did you also perform correlation tests on the entire dataset without dividing it into seasons?**

37. Yes we did. We also calculated correlations for monthly and annual periods, which was mentioned in the text (Page 10, line 18). We decided to show only the results of the seasonal dataset because showing the monthly data would have resulted in a vast table that would not add any significant information.

− **Figure 1: At what height was air temperature measured? What were the standard errors of the average water table depths? How far were the chambers away from the WTL measurement points? Maybe provide a map of the experimental site setup as a supplement.**

38. The height was 25.5 m, which was added to the text. SE of WTL was added to Fig. 1. One of the WTL loggers was located between the chambers #1 and #2 and the rest were located about 50 m from the chambers. We have added a map of the site as a Supplement.

− **Figure 2: Did you also check the relationship for each year separately?**

39. Yes we did. They looked quite similar except for the fact that 2012 had fewer measurement points and a lower sink. This figure was removed and replaced by another one (see Figure 1C above)

− **Figure 3: It looks a bit like CH4 uptake sometimes was even higher than -40 µg CH4 m2 h-1 and the fluxes just went off scale. Also, what was the uncertainty of the single fluxes on average?**

40. Thank you for noticing the problem with the y-axis of the figure. It is now updated. The uncertainty of single fluxes mainly varied within 2-3 %; however, for very small fluxes (such as in a cold winter of 2012-2013) it was higher, about 10%. This was added to the text.

− **Figure 5a: This bar chart is quite meaningless without some indication of the uncertainty for each bar. Do you also have a cumulative error estimate for Figure 5b?**

41. An uncertainty analysis was added to the text. We estimated the uncertainty for three most important sources: 1) random error, 2) gap-filling and 3) correction of the fluxes measured using the 2-min closure time in 2011.

− **Figure 6: Is the daily flux just upscaled from the average hourly flux or does it represent the cumulative hourly fluxes per day? Also, I find it really difficult to distinguish between the black and blue points. It would be nice to have these plots for the other five chambers as supplement.**

42. The daily flux is upscaled from the average hourly flux. The colours were changed. The plots for the other five chambers are included as a Supplement.

Response to reviewer #2

The manuscript is based on the continuous two years CH_4 flux dataset obtained by automatic chamber measurement at a forestry-drained fen. The use of high-resolution gas analyzer let the authors to document low and variable fluxes, and continuity of the measurements together with their high temporal resolution allowed to estimate longtime net CH_4 exchange and judge the variability of the fluxes. The site chosen for the study is not an easy one for CH_4 flux measurements: the net result of both methanogenic and methanotrophic activities can change from small negative to small positive flux, being dependent on a combination of different factors. I highly appreciate the value of the obtained dataset, and would really like to see this study eventually published.

Unfortunately, within a number of comments following below, at least one seems to be critical and enforces me to ask for a major revision (followed by an additional review):

Equation 5 (page 6) seems to be incorrect, or, at least, has been presented incorrectly. If the time derivative is expressed in ppm/h, and the resulting flux F is also per hour, why the multiplier 3600 s/h is used? Then, I do not see a reason for a multiplier 273.15 in the numerator of the temperature fraction: the universal gas law with constant R in J mol-1 K-1 in the denominator implies temperature in K (273.15 + T in C) also in the denominator. Another way of expression for this type of flux equations (for example, Koskinen et al., 2014) operates with the standard molar volume of ideal gas instead of the universal gas constant (R), in this case ratios between the standard and the actual temperature and pressure are used. The equation 5 as it is stated in the manuscript is a mixture of these two correct approaches, and is mathematically incorrect. Formally, in the result of these two mistakes, the F values obtained with Eq.5 must be overestimated by six orders of magnitude. However, the reported fluxes seem to be of a realistic order of magnitude, while million times lower fluxes are absolutely undetectable by this type of measurements. Thus, I suppose the authors did not use the Eq.5 as it stated in the manuscript, but I can not exclude a chance that the actually used formula was also somewhat incorrect.

1. Thank you for the important observation, and apologies for this crucial error in the manuscript, which we were not aware of. The error was in the temperature fraction of the equation, which was actually used in the calculation. Also, in the text, the derivative was said to be ppm/h when the actually used derivative was ppm/s. This explains why the reported fluxes were only three times lower, not six orders of magnitude. After the correction, the flux rates are now about three times higher as originally reported. This affected for example the annual balances but did not affect the dynamics of diurnal variation or correlations. Everything in the paper to which this error affected (figures, values, comparisons to other studies) have been updated accordingly.

Talking about flux calculations, I would also ask the authors to describe what software and how was used; I can not imagine such amount of data was processed without some automated scripts/programs. Then, the description of these scripts/programs and their settings might be crucial to evaluate possible weaknesses of the calculations. How, for example, the moment of the chamber closure (t=0, page 5 line 25) was recognized by this program? As I understand from Koskinen et al. (2014), the chambers were controlled from a separate Linux PC, so operated according to its internal clock; the Picarro analyzer recorded the measured concentrations with the time stamp from its own clock – had those two being synchronized, and how often? Was the delay in gas lines between the chamber and the analyzer properly addressed?

2. All the calculations were made with the Python programming language (Python Software Foundation, version 2.7, https://www.python.org) using libraries: NumPy (http://www.numpy.org/), SciPy (http://www.scipy.org/), Pandas (http://pandas.pydata.org/) and matplotlib (http://www.matplotlib.org). Also, most relevant methods (e.g. fitting) are now explained in more detail in the text.

   Unfortunately the Picarro and the PC were synchronized only after September 2012. Therefore we had to manually synchronize the Picarro data afterwards. After September 2012, the Picarro analyzer was connected to and synchronized with the Linux PC, so the problem of different time stamps was avoided. Linux PC acted both as a time (NTP) client fetching time from Finnish Meteorological Institute's time server ca. once a day, and as a time server for the Picarro analyzer.

   Example of how the system works during one chamber measurement:
   (min:sec)
   00:00 chamber lid starts to close, and the valve is switched to the chamber line. Fan has been running all the time.
   00:30 chamber is fully closed
   00:50 a flag is added to data stream indicating the source of gas (e.g. 'Chamber1'). There was a certain lag time (up to 20 sec, depending on the flow rate) between the chamber closure and the observable analyzer response, and to ensure that all the data having the flag was usable for flux calculation this higher lag was used. In addition, during the post-processing four Picarro data points, representing about 20 s, were removed from the beginning.

More about the setup: was it the same as described by Koskinen et al. (2014), just with the Picarro analyzer connected in parallel to the Licor CO_2 analyzer? In the current manuscript it is stated (page 4 line 25): "The polycarbonate chamber was attached to a stainless steel frame (see description in Koskinen et al., 2014)." – not clear for the reader, is the reference about the frame, or the whole chamber, or the whole setup. Then some setup features are described, almost exactly in the same words as in the 2014 publication, but others (like valves, fan, etc.) are skipped. As the result, the description looks somewhat

sleazy: for example (page 4 line 20), "A gas inlet tube made of polyurethane (FESTO, OD = 6 mm, ID = 4 mm)" – but wasn't the outlet tube made of the same material and size? I would strongly suggest the authors to completely rethink section 2.2 – clearly state in the beginning, that the setup was described in details by Koskinen et al. (2014), repeat only key elements of that description without details, then clearly state what in the described measurement system is different from 2014 publication (here with all the details).

3. Thanks for this comment. It is true, that the chapter was in some parts copied from Koskinen et al., but it was not clearly stated that the system is exactly the same. Now, the whole chapter 2.2. has been rewritten with these suggestions taken into account.

My next group of comments is related to the fact that the majority of the fluxes reported in the current study have a really low value (Fig.3). According to my back-of-the-envelope calculations, a net uptake of 20 µg CH_4 m^{-2} h^{-1} equals to CH_4 concentration change in the chamber of about 3 ppb over 2 minutes! Being amazed by the quality of the study, which made possible to justify such small fluxes, I have to stress the authors about the extra precaution with such data processing, interpretation and discussion.

For example, was the effect of water vapor dilution properly addressed? In CO_2 study (Koskinen et al., 2014) it was stated "The CO_2 concentration values were not corrected for water vapor dilution as the change in air humidity during measurement was small (data not shown)". In the current study, when CH_4 concentration in the chamber changes so tiny (3/1850=0.16%), even a small change of humidity inside the chamber during the measurement can strongly influence the result. Was H_2O concentration in the gas sample measured by the same Picarro G1130 analyzer (page 4, line 24 – unfortunately, I was unable to find any information about this model in the Internet)? Was the wet or the dry mixing ratio used in the calculations? I think the water vapor dilution should be both addressed in the calculations, and discussed in the manuscript.

4. Picarro G1130 gas analyzer measures also H_2O concentration, so the dilution correction is possible and it is also automatically made by the analyzer. By the referee's suggestion, we are now using the dilution corrected data, which in some cases had a very small impact on fluxes, but in some cases even the sign of the flux was changed. The correction changed the annual balances a little and some correlations with CH4 flux and meteorological and soil quantities. However, its impact to the diurnal variations was in some cases very significant. For example, we cannot see diurnal variation showing higher CH4 uptake during the daytime any more as observed in June 2012 (Fig.8 in the original manuscript). The diurnal variation did not vanish, but it is now similar to the ones observed in spring and summer 2011. This phenomena came, as the referee suggested, purely from the concurrent variation in H2O concentration. So now all the diurnal variation we see, shows lower uptake during the midday. As a whole, this was a very important comment by the referee and crucial for the quality of this study and we thank him for that, and apologize for neglecting it in the original manuscript.

In opposite, with such small change in the chamber headspace CH_4 concentration, I think the discussion about "distortion of the vertical concentration gradient" between the soil and the headspace (mentioned many times throughout the whole manuscript) and the concentration feedback on the microbial oxidation rate (page 11 line 29) is virtually not applicable to the current study. Undoubtedly, both can be discussed, but with a clear note, that the change in the headspace concentration from 1850 to 1847 ppb CH_4 should practically not affect either gradient or methanotrophic activity.

In this context, I do not agree with the reasoning (for example, page 11 line 20) that the distortion of the vertical concentration gradient is the main reason for non-linearity of the concentration change in the closed chamber and the difference between the linear and exponential flux estimations. In my opinion much more important reasons are water vapor dilution (see above) and leakages (both through chamber construction and through the soil). The possible leakages are not discussed at all in the manuscript; even the fact that "when the wind speed increased, the uptake of CH_4 decreased" (page 15 line 8) does not seem suspicious for the authors. However, such fact often can be very clearly explained by small leaks in the chamber – see for example Pirk et al., 2016 (doi:10.5194/bg-13-903-2016), where the non-linearity of detected fluxes is directly related to the wind speed and the material of chamber sealing.

5. We agree with the referee in this subject. After performing the dilution correction as suggested by the referee, the closures where the H2O concentration changed significantly, became more linear. We considered and examined the wind speed impact on fluxes, and found that the observed diurnal variation was mainly explained by the wind speed (see also answer #4 for referee 1). However, as pointed out in the answer #4, the wind speed dependency is not necessarily fully attributed to leakage, but can be related to the distortion of the soil concentration gradient by wind before the chamber closure. We also studied the curvature parameter c in relation to wind speed and found that the curvature was typically smaller with higher wind speeds (see also answer #4 for referee 1). The discussion has now been modified accordingly.

Another point I do not agree with, is an intransigent statement that "use of linear regression systematically underestimated CH_4 flux rates" (page 1 line 14, and many times later in the manuscripts). Such statement implies that one knows the "true" flux values, and compares them to the ones obtained by a linear regression. This is not the case in the current study (but is the case for example in Pihlatie et al., 2013, where the flux was pre-set). Instead, the fluxes were estimated with two different mathematical methods (linear and exponential), and the results were somewhat different (Fig.2). Then the authors propose, that the linear estimation is more correct for low fluxes, and exponential – for high fluxes. This should be phrased as a proposal, as an assumption, supported by theoretical arguments and other studies, but still not as a statement, proven by this study.

6. We agree with the referee that it was wrong to use the statement "underestimation" in case of linear regression and this is now corrected in the text (see also the answer #26 for referee 1). Our intention was not to prove that the linear estimation is more correct for low fluxes, but to find a method by which the high noise in the small fluxes produced by exponential fitting could be reduced. Therefore we are suggesting, that for our data a flux limit of 2.5 µg CH4 m-2 h-1 would be an appropriate limit, and that in the forthcoming studies a similar approach could be applied, but the limit need to be estimated individually for each case. By referring to comment #2 for referee1, we think that using this limit provides a more accurate and robust estimate of very low CH4 fluxes. Below this limit the concentration variations from which the flux is derived become increasingly affected by measurement noise and the exponential fitting becomes more prone to random perturbations to individual concentration data points and does not result in realistic flux estimates anymore.

Still having in mind very low magnitude of the fluxes, I would ask the authors to add, either in the main paper or in the supplementary material, a figure with two typical examples of concentration data during flux measurements – one with a high flux (over 3.5 µg CH_4 m^{-2} h^{-1}), and one with a low flux – with lines for the linear and the exponential approximation over each. That will be a very sensible for the reader illustration of the measurement precision, signal-to-noise ratios, etc.

7. Figures of concentration data of 'high' and 'low' flux cases have been added to the revised version of the manuscript (see also answer #25 for referee 1).

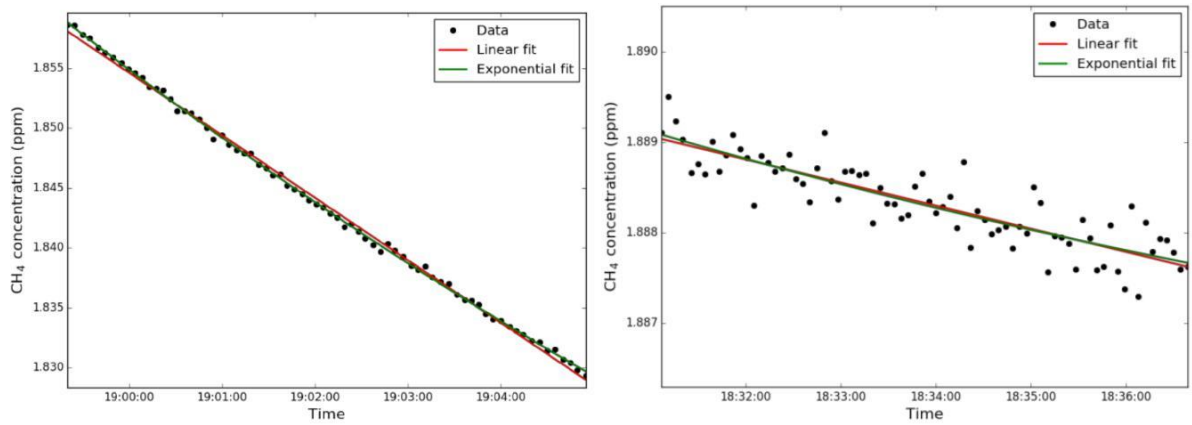

Figure 2A. Concentration data during one chamber closure for a case with a higher (left: linear and exponential: -90 and 104 µg CH4 m-2 h-1, respectively) and lower (right: lin -3.5, exp -4.3 µg CH4 m-2 h-1) flux.

And the last general comment. Unfortunately, I have to mention somewhat careless formulations and citations in the introduction:

Page 2 line 10: "In peatlands, the net CH_4 flux between the soil and atmosphere is the sum of CH_4 production and oxidation (Dunfield et al., 1993)" – the word "sum" is never used in this publication; it was a great detailed study of both processes, but the authors never stated that they sum up to the flux. There are more processes – lateral transport (applicable to the

current study with drainage ditches), subsurface storage – which affect the net fluxes as well.

Page 2 line 20: "…a lack of electron acceptors other than acetate and hydrogen are a precondition for the production of CH_4 (Segers, 1998; Kotsyurbenko et al., 2004)." Acetate and hydrogen are not electron acceptors! Hydrogen is the donor (in reaction with CO_2), acetate decays formally without donor-acceptor interaction. The publication by Segers is mentioning "alternative electron acceptors" a lot, but never stated that acetate and hydrogen are electron acceptors; the publication by Kotsurbenko et al. does not contain the words "electron" or "acceptor" in any form.

Page 2, lines 22-23: "The rate is mainly controlled by oxygen concentration, temperature and soil moisture (Boeckx and Van Cleemput, 1996)." The study by Boeckx and Van Cleemput was focused on experimental evaluation of three factors affecting methane oxidation: soil moisture, soil temperature and nitrogen (NH_4^+, NO_3^-) addition. Neither oxygen concentration nor CH_4 concentration were examined (were set the same in all samples); their importance for the methanotrophic oxidation was supposed to be obvious because they are reagents. Boeckx and Van Cleemput have never stated which factors are "main", but mentioned soil compaction and pH as well. So this citation is also incorrect and misleading: oxygen concentration, as well as methane concentration (as stated at page 11 line 29) and methanotrophic potential (amount and oxidation capacity of bacteria) are the factors, directly influencing CH_4 oxidation; temperature, moisture etc. are the factors of indirect action.

Page 2, line 25: "Closed chambers are commonly used in the measurement of greenhouse gas exchange between the forest floor and the atmosphere (e.g. Livingston and Hutchinson, 1995; Christensen et al., 1995; van Huissteden et al., 2005; Alm et al., 2007; Denmead, 2008; Forbrich et al., 2009, Koskinen et al., 2014)." The publication by Livingston and Hutchinson has only one mentioning of a forest floor (an example of study in Brazilian rain forest), but does not say how common such studies are; the publications by Christensen et al. and by van Huissteden et al. are focused on tundra and never mention "forest".

I do not clearly remember all the publications cited in the current manuscript, and do not have enough time to check every reference. The four examples above warn me that the authors are not careful enough in their citations, so I really suggest them to check meticulously every citation in the manuscript: did the publication really state or show that? It is a big work, indeed, but it had to be done much earlier in the manuscript preparation stage.

8. We apologize for our carelessness. We went through the citations and either corrected the text or removed the references.

At this stage I will not go for more specific comments and technical corrections related to the current manuscript text, as I imagine the text will be strongly changed before the

resubmission. Still wish the authors to continue their work and bring their study to publication in a more carefully written form.

9. As a general comment we want to notice that due to the recalculations and other changes and corrections in the manuscript the discussion part was in most parts rewritten. For example, the comparison to other studies will be changed, since the fluxes in the new version will be three times as high as previously. We also included two additional coauthors in the paper.

~~CH_4 –~~ Methane exchange at the peatland forest floor – automatic chamber system exposes the dynamics of small fluxes~~of a forestry-drained fen: low flux rates but high temporal variation~~

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Abstract. We measured methane (CH_4) exchange rates with automatic chambers at the forest floor of a nutrient-rich drained peatland in 2011–2013. The fen, located in southern Finland, was drained for forestry in ~~the 1970s~~1969 and the tree stand is now a mixture of Scots pine, Norway spruce, and pubescent birch. Our measurement system consisted of six transparent ~~polycarbonate~~ chambers and stainless steel frames, positioned on a number of different field and moss layer ~~types~~compositions. Gas concentrations were measured with an on-line cavity ring-down spectroscopy gas analyzer. Flux ~~rat~~es were calculated with both linear and exponential regression. The use of linear regression resulted in systematically ~~underestimated~~ smaller CH_4 flux ~~rat~~es by ~~20~~10–45~~50~~ % when compared to exponential regression. However, the use of exponential regression with small fluxes (< ~~3~~2.5 µg CH_4 m^{-2} h^{-1}) typically resulted in anomalously large absolute flux ~~rat~~es and high hour-to-hour deviations. ~~We t~~Therefore, we recommend that flux ~~rat~~es are initially calculated with linear regression to determine the threshold for "low" fluxes and that higher flux ~~rat~~es are then recalculated using exponential regression. The exponential flux was clearly affected by the length of the fit when the fitting length was < 190 sec, but stabilised with longer periods. Thus, we also recommend to use of a fitting period of several minutes to stabilise the results and decrease the flux detection limit. There was clear seasonal dynamics in the CH_4 flux: the forest floor acted as a CH_4 sink particularly from early summer until the end of the year, while in late winter the flux was very small and fluctuated around zero. However, the magnitude of fluxes was relatively small throughout the year, ranging mainly from –130 ~~40~~ to +100 ~~50~~ µg CH_4 m^{-2} h^{-1}. CH_4 emission peaks were ~~occasionally~~ observed occasionally, ~~particularly in spring during the snow melt, and~~mostly in summer during heavy rainfall events. Diurnal variation, showing a lower CH_4 uptake rate during the daytime, ~~was~~ observed in all of the chambers, mainly in the summer and late spring, particularly in dry ~~and warm~~ conditions. It was attributed more to changes in wind speed than air or soil temperature, which suggest that physical rather than biological phenomena are responsible for the observed variation. The a~~A~~nnual net CH_4 exchange among the six chambers varied from –104±30~~31~~ to –505±39~~155~~ mg CH_4 m^{-2} yr^{-1}; with an average of –219~~67~~ mg CH_4 m^{-2} yr^{-1} over the two-year measurement period.

Keywords: methane uptake, methane emission, high resolution flux measurement, automatic chamber, peatland forest, drained peatland, linear regression, exponential regression

1 Introduction

Methane (CH_4) is one of the most important atmospheric ~~trace~~ greenhouse gases due to its capability to absorb thermal radiation and warm the climate (IPCC, 2014). One of the main sources of CH_4 globally are peatlands (e.g. Denman et al., 2007) where CH_4 is produced by the decomposition of organic matter in anaerobic conditions. ~~(Waddington and Roulet, 2000; Rinne et al., 2007; Leppälä et al., 2011).~~ Around 3 % (ca. 4 000 000 km^2) of the Earth's land surface is covered by peatlands ~~(4 000 000 km^2)~~ (Clarke and Rieley, 2010) and the majority of ~~peatlands~~ these are located in the boreal region (Fischlin et al., 2007). About one third (104 000 km^2) of European mire and peat resources are located in Finland (~~Joosten and Clarke, 2002;~~ Montanarella et al., 2006) and more than half (55 000 km^2) of this area has been drained for forestry (~~Lappalainen, 1996;~~ Päivänen and Hånell, 2012).

~~In peatlands, the net CH_4 flux between the soil and atmosphere is the sum of CH_4 production and oxidation (Dunfield et al., 1993).~~ Methane can be both produced and consumed in soil so that the net CH_4 flux depends on the rate of CH_4 production in anoxic soil layers and on the rate of CH_4 oxidation in the oxic soil layers. In peatlands, the thickness and depth of CH_4 producing and oxidizing layers are largely determined by the water table (Bubier and Moore, 1994), which controls the vertical distribution of oxygen in the soil profile. CH_4 is produced under anaerobic conditions by microbes known as methanogens. The production rate is dependent on the availability of organic substrates at low redox potential (Eh) values, and is controlled by soil temperature and pH (Dunfield et al., 1993; Wang et al., 1993; Segers, 1998; Kotsyurbenko et al., 2004). On the other hand, oxidation of CH_4 occurs in the oxic soil layer closer to the surface and potentially also in the moss layer (Larmola et al., 2010). Like the production rate, the oxidation rate is controlled by soil temperature and pH (Dunfield et al., 1993; Scheutz and Kjeldsen, 2004; Boeckx and Van Cleemput, 1996), but also many other factors affect oxidation processes, such as soil water content, soil texture, nutrients and CH_4 and oxygen concentration (Boeckx and Van Cleemput, 1996; Ridgwell et al., 1999; Scheutz and Kjeldsen, 2004). In addition to the direct control of production and oxidation rates, there are other phenomena which may affect the observed net CH_4 flux above the soil surface, including lateral CH_4 transport in the soil (Christophersen and Kjeldsen, 2001) and subsurface storage.

In environments with low soil CH_4 production, such as upland forest soils, grasslands and tundra, uptake of atmospheric CH_4 by the methanotrophic microbes dominates (Dutaur and Verchot, 2007). This is also what commonly happens after ~~T~~the drainage of peatlands, which results in water level drawdown and increased oxic layer thickness. Thereby, CH_4 production is decreased and the fraction of oxidized CH_4 increased (e.g. Moore ~~&~~ and Knowles, 1989; Roulet et al., 1992). Consequently, the CH_4 oxidation rate in the aerated surface soil and mosses typically exceeds ~~that of~~ CH_4 production that occurs deeper in the soil, thus turning in particular well-drained peatlands ~~in particular~~ into net CH_4 sinks (Martikainen et al., 1995; Minkkinen et al., 2007; Ojanen et al., 2010; Lohila et al., 2011). However, poorly drained sites may remain to act as CH_4

sources ~~in many cases~~ (Ojanen et al., 2010). In addition, the drainage ditches even at well-drained sites typically continue to emit CH_4 at rates similar to pristine boreal peatlands (Minkkinen et al., 1997; Minkkinen and Laine, 2006; Luan and~~&~~ Wu, 2015).

~~CH_4 is produced under anaerobic conditions by microbes known as methanogens. The rate of production is mainly controlled by soil temperature, pH and redox potential (Eh) (Dunfield et al., 1993; Wang et al., 1993; Kotsyurbenko et al., 2004). Low Eh values and a lack of electron acceptors other than acetate and hydrogen are a precondition for the production of CH_4 (Segers, 1998; Kotsyurbenko et al., 2004). Oxidation by methanotrophic microbes occurs in the oxic soil layer closer to the surface and also in the moss layer (Larmola et al., 2010). The rate is mainly controlled by oxygen concentration, temperature and soil moisture (Boeckx and Van Cleemput, 1996). In environments with low soil CH_4 production, uptake of atmospheric CH_4 by the methanotrophic microbes also takes place.~~

Closed chambers are commonly used in the measurement of greenhouse gas exchange between the forest floor and the atmosphere (e.g. ~~Livingston and Hutchinson, 1995; Christensen et al., 1995; van Huissteden et al., 2005; Alm et al., 2007;~~ Denmead, 2008; Forbrich et al., ~~2009~~2010, Koskinen et al., 2014). Unlike the eddy covariance (EC) method, which is more suitable for measuring fluxes at the ecosystem level, the chamber method permits the investigation of ~~small~~ small-scale processes, such as the gas exchange of different microtopographic~~al~~ surfaces, and enables the quantification of spatial variation (Keller et al., 1990; Singh et al., 1997). However, there are ~~several~~ various details related to~~in~~ the chamber ~~structure~~ design and the deployment of this measurement technique in practice that may have a significant impact on the ~~observed~~ flux that is estimated from the observed concentration change in the chamber headspace. ~~rate~~ , ~~and hence should be taken into account.~~ For example, ~~increasing chamber size, especially height, seems to have an effect on the flux~~the flux estimate seems to depend on the dimensions of the chamber (Pihlatie et al., 2013). In addition, ~~it has been suggested that~~ chambers should include a fan to evenly distribute the air in the chamber headspace (Pumpanen et al., 2004; Christiansen et al., 2011) ~~as it decreases uncertainty in the flux,~~ although the rotational speed of the fan should be kept low to avoid excessive turbulence (~~Pumpanen et al., 2004; Christiansen et al., 2011,~~ Koskinen et al., 2014). A ~~second significant~~major source of uncertainty is the impact of the chamber itself on the gas concentration gradient in the soil ~~and in the boundary layer just above it~~ (Healy et al., 1996; Hutchinson et al., 2000; Conen and Smith, 2000; Davidson et al., 2002; ~~Conen and Smith, 2000;~~ Livingston et al., 2005) and in the boundary layer just above it. The concentration gradient is critical as it ~~is the main factor driving~~drives the soil-atmosphere ~~CH_4~~ gas exchange and thus any aerodynamic disturbance may ~~therefore have a severe~~ impact ~~on~~ the observed flux.

The gradient between the soil and the air inside the chamber changes when the gas concentration inside the chamber changes during the measurement. This changes the flux ~~rate~~, which makes the concentration change ~~in time~~ non-linear in time. However, non-linearity of the concentration during the chamber closure may also result from chamber leaking. For example, Pirk et al. (2016) demonstrated that the degree of convex curvature in the increasing methane concentration correlated

positively with wind speed outside the chamber. Furthermore, in the case of soil acting as a methane sink, the methane consumption by soil methanotrophs obeys the first-order reaction kinetics which should lead to curvilinear concentration dynamics in the chamber (e.g. Sabrekov et al., 2016). However, the different processes responsible for the curvature in the concentration time series may be difficult to separate from each other (Kutzbach et al., 2007).

There are many studies that have recognized that the use of linear regression in flux calculation can cause significant underestimation of the flux (e.g. Healy et al., 1996; Hutchinson et al., 2000; ~~Pedersen et al., 2001; Welles et al., 2001;~~ Nakano et al., 2004; Livingston et al., 200~~5~~6; 2006; Kutzbach et al., 2007; Kroon et al., 2008; Pedersen et al., 2010; ~~Pihlatie et al., 2010;~~ Pihlatie et al., 2013) ~~and that the error caused by using linear regression is systematic, not random (Hutchinson et al., 2000; Livingston et al., 2005; Livingston et al., 2006; Kutzbach et al., 2007)~~. However, many studies have used linear regression (e.g. ~~Reth et al., 2005;~~ Laine et al., 2006; ~~Wang et al., 2006;~~ Alm et al., 2007; Jones et al., 2011; Bergier et al., 2013; Fassbinder et al., 2013), because under field conditions it is more robust to random measurement errors than non-linear methods. Moreover, the use of linear regression is preferred when comparing measurement sites as it is not as sensitive as non-linear models to small differences in soil properties (Venterea et al., 2009). The selection of the optimal fitting method is important as it can be ~~the~~ a large~~st~~ source of uncertainty in flux calculations (Levy et al., 2011; Venterea et al., 2013). ~~However, the use of exponential regression is problematic as it is sensitive to disturbances during the measurement and it requires more than five measurement points. As such, a high resolution gas analyzer is typically required instead of traditional syringe sampling (Kroon et al., 2008).~~

Although several studies have examined the different fitting methods for calculating fluxes from chamber data, there exist only a few papers exploring the dynamics of CH_4 flux data that mainly consist of small uptake fluxes and are measured with automatic chambers coupled to a high-resolution gas analyzer (e.g. Savage et al., 2014; Ueyama et al., 2015). In this study, we measured the CH_4 flux between ~~the~~ a forest floor and the atmosphere continuously throughout ~~for~~ 2 years ~~in~~ at a ~~relatively~~ boreal nutrient-rich forestry-drained peatland site with typically small CH_4 exchange rates. We used six automatic soil chambers and a cavity ring-down spectroscopy analyzer, which allowed us to measure with a relatively high sampling rate during each chamber closure and to perform multiple daily measurements with each chamber. ~~sample with relatively high temporal resolution.~~ Our particular aims with this set-up ~~was~~ were to determine:

1. What is the optimal fitting method for calculating the CH_4 flux~~How large is the difference between fluxes calculated from linear and exponential regression, and which regression method should be preferred~~?
2. How large ~~is~~ are the diurnal, seasonal ~~or~~ and inter-annual variations in the CH_4 flux?
3. What is the annual CH_4 balance ~~in~~ of the study~~ied~~ site?

2 Materials and methods

2.1 Site description

The measurements were made in southern Finland at Lettosuo ~~in southern Finland~~ (60°38' N, 23°57' E) (Fig. S1a), which is a ~~nutrient~~ nutrient-rich peatland forest that was drained in 1969 and fertilized with phosphorus and potassium soon after~~at the beginning of the 1970s~~. The open ditches, located in approximately 45 m intervals (Fig. S1b), were originally about 1 m deep but have since been partly filled with new vegetation. Before drainage, the tree stand was dominated by Scots pine (*Pinus sylvestris*) with some pubescent birch (*Betula pubescens*). After drainage, the ~~site~~ stand has ~~become~~ developed to a mixture of Scots pine and~~,~~ pubescent birch in the dominant canopy layer, with an understorey of~~, and~~ Norway spruce (*Picea abies*) with some scattered small-sized pubescent birch~~understory vegetation~~. The s~~S~~tem volumes ~~during 2011–2012 were estimated at~~at the time of this study equaled to 174, 46, and 28 m^3~~/~~ ha^{-1} for Scots pine, pubescent birch, and Norway spruce, respectively. The tree stand is quite dense, which ~~and this~~ results in irregular shading and consequently, patchy and variable ~~which makes the~~ ground vegetation layer ~~patchy and variable~~. For example, herbs such as *Dryopteris carthusiana* and *Trientalis europaea*, and dwarf shrubs such as *Vaccinium myrtillus* are common in the ground vegetation (~~Koskinen et al., 2014~~Bhuiyan et al., 2016). In addition, the moss layer is patchy and is dominated by *Pleurozium schreberi* and *Dicranum polysetum* with some *Sphagna (Sphagnum~~.~~ girgensohnii*, *Sphagnum~~.~~ angustifolium* and *Sphagnum~~.~~ russowii)* appearing in moist patches ~~(Koskinen et al., 2014)~~.

CN ratio of the surface peat, sampled at four points located at a 20–40 m distance from the chamber plots, averaged 24 for the 0–20 cm layer (Table 1). The relatively low CN ratio is typical for fertile peatland forests and reflects the fen history of the site. The bulk density of these samples was 0.11 and 0.17 g cm^{-3} for the 0–10 and 10–20 cm layers, respectively, while the average bulk density of the 0–20 cm layer below each chamber varied from 0.03 to 0.13 g cm^{-3} (Koskinen et al., 2014). The ash content of the peat varied from 3.4 to 6.5 %.

The vascular green area (VGA) was estimated for each chamber and vascular plant species every two weeks during the growing seasons 2011 and 2012 (Ojanen, unpublished data). This was done by estimating the number and dimensions of leaves within each chamber and calculating green area by species-specific regression models between leaf dimensions and green area. For *Vaccinium myrtillus*, also the surface area of the green stems was included into VGA. The coverages of the mosses was estimated visually. The maximum VGA and the coverages for each chamber are shown in Table 2.

~~The climate at the site has both continental and maritime influences. The long-term (1981–2010) annual mean temperature and precipitation at the nearby weather station are 4.6 °C and 627 mm, respectively (Pirinen et al. 2012). Continuous EC measurements of carbon dioxide (CO_2) and latent and sensible heat fluxes have been running at the site since 2009. At the same time, measurements of meteorological variables, such as air temperature, relative humidity, global radiation, net~~

~~radiation, photosynthetically active radiation (PAR), soil temperature profile, soil moisture, precipitation and soil heat flux have also been continuously recorded.~~

2.2 ~~Measurement~~ Flux measurement system and ancillary measurements

The automatic chamber measurement system is the same as used for CO_2 exchange by Koskinen et al. (2014). The CO_2 flux measurements started in autumn 2010, and the CH_4 analyzer was added to the system in March 2011. Here we report the CH_4 fluxes measured since then until April 2013. ~~The measurements of forest floor CH_4 exchange started in March 2011 and continued until April 2013. CH_4~~ Forest floor gas exchange, including the tree roots, was monitored ~~with~~ using six transparent soil chambers connected to an instrument cabin. The cabin was located ~~placed~~ at a distance of about 30 m from the 25.5 m tall EC mast (Koskinen et al., 2014) from which the wind speed above the canopy was measured. The locations of the chambers were selected ~~so that they were close to each other but represented~~ to maximize the number of different ground vegetation ~~types~~ compositions (Table ~~2~~1) within a circle of ca. 15 m radius around the cabin.

The details of the chamber system can be found in Koskinen et al. (2014), and thus here we only describe the main features of the system. The size of the ~~each~~ chamber boxes ~~was~~ were 57 cm x 57 cm x 30 cm (length x width x height). We used a permanently installed steel collar (height 5 cm, inserted at a depth of 2 cm) below each chamber to minimize the disturbance to the soil, and to enhance the sealing between the soil and the chamber. There was a U-profile at the bottom of the chamber edges, insulated with a foam tape, to further improve the sealing. In winter, the whole chamber frame was raised above the snow level by placing one or two extension collars (height 16 cm) between the frame and soil.

A 24 V fan (Maglev KDE2408PTV1, Sunon Ltd, Kaohsiung, Taiwan) (size 8 cm x 8 cm) was used to mix the air inside the chamber headspace. The voltage of the fan was regulated to keep the mixing steady, but as low as possible (Koskinen et al., 2014). Sample gas was drawn from the chamber typically once an hour (with some exceptions explained below) at a flow rate of about 1 L min^{-1}, and returned back to the chamber from the gas analyzers. CH_4, CO_2 and water vapor concentrations were ~~A gas inlet tube made of polyurethane (FESTO, OD = 6 mm, ID = 4 mm) was positioned in the stream of the fan to mix the returning gas from the pipeline and prevent it returning to the outlet. Tubes (15 m in length) were used to transfer the gas to and from a measurement cabin where the mixing ratio of the gas was~~ measured approximately every 4 s~~four seconds~~ with a Picarro G1130 cavity ring-down spectroscopy gas analyzer (Picarro Inc., Santa Clara, CA, USA). The inlet and outlet gas tubes (FESTO Oy, Vantaa, Finland) were made of polyurethane and were 15 m in length and had an inner and outer diameter of 4 mm and 6 mm, respectively.

~~The polycarbonate chamber was attached to a stainless steel frame (see description in Koskinen et al., 2014). The lower frame included five vertically movable legs, which could be used to keep the frame and chamber at snow level. A collar (height=5 cm) was used to connect the steel frame to the soil surface. Most of the roots in the area were left uncut as the collar was only installed to a depth of 2 cm in the moss layer. Peat and moss were used to seal the connection between the~~

~~collar and soil. To prevent the gases from moving horizontally in the snow during winter, the steel frame was raised above the snow level by placing one or two extension collars (h=16 cm) between the frame and soil. When the chamber was closed, the connection between the frame (w=1 cm) and the chamber was sealed with silicone D-tape.~~

~~Linear actuators (Linak Techline LA-35, Linak, 2009) were used to open and close the chambers. The flow rate of the sample gas in the system was kept at or slightly below 1 L min^{-1}.~~ The tubes were flushed with ambient air just before the chamber was closed. When all the chambers were open, ambient air was sampled. The delay in the analyzer response caused by the long tubing was taken into account using a flagging system in the computer program collecting the data, which labelled each data point with the respective chamber number using a 20 s lag. However, as the flow rate varied slightly in time, some points were removed from the data before the flux calculation (Sect. 2.4).

~~Meteorological~~ Air and soil temperature data ~~was~~ were collected every 10 s~~econds~~ using Pt100 probes (PT4T, Nokeval Oy, Nokia, Finland) and ~~from the chambers and adjacent areas with~~ Nokeval 680-loggers (Nokeval Oy, Nokia, Finland). ~~Temperatures inside the chambers were measured with pt100 temperature probes. The~~ One probe was ~~installed~~ located inside each chamber at a height of 30 cm and positioned next to the fan under a metal heat shield to prevent direct solar radiation from affecting the measurements. Furthermore, soil surface temperature~~s were~~ was monitored inside each chamber just below the surface of the moss or litter layer. In addition, soil temperature probes were placed at depths of 2, 5, 10, 20 and 30 cm at one location near the chambers. Water table level (WTL) was monitored every hour ~~from~~ at four different points at the site (TruTrack WT-HR data loggers, Intech Instruments Ltd, Auckland, New Zealand). The air pressure, precipitation and snow depth data were acquired from the nearby Finnish Meteorological Institute observatory at Jokioinen (~35 km northwest of Lettosuo).

2.3 Meteorological conditions

The climate at the site has both continental and maritime influences. The annual mean temperature and precipitation at the nearby weather station in 1981–2010 were 4.6 °C and 627 mm, respectively (Pirinen et al., 2012). During this study, the first measurement year (4/2011–3/2012) was significantly warmer (annual mean temperature 5.8 °C) than the second measurement year (4/2012–3/2013) (1.4 °C) (Fig. 1). The first year was slightly warmer and the second year was significantly colder than the long-term mean recorded at the nearby weather station (4.6 °C). Both the summer (JJA) (17.6 °C) and winter (DJF) (2.7 °C) temperatures in 2011 were warmer than those of 2012 (12.1 °C and –2.3 °C). In particular, the beginning of summer 2012 was much colder than the same period in 2011.

Annual precipitation during the first (976 mm) and second (780 mm) measurement years was higher than the long-term mean (627 mm). Summertime precipitation was 9% higher in the first (309 mm) year as compared to the second (284 mm) year, while in winter the difference was 18 % (577 mm and 490 mm in the first and second winters, respectively). The first snow appeared on 5 December in 2011 and 25 October in 2012, and the first permanent snow was recorded on 7 January in

2012 and 28 November in 2012. In spring (MAM) 2011, the snow had melted by 13 April. For spring 2012, we do not know the exact day of snowmelt due to missing data, although the snow had melted at latest by 4 April. From the temperature data we estimate that the snow cover disappeared sometime in mid-March.

WTL varied from –8 to –59 cm from the soil surface (negative sign denotes WTL below the surface) and was highest in the spring and late autumn (SON). The lowest (i.e. deepest) values were recorded at the end of summer. The average WTL in summer 2011 was –47.2±7.4 cm (±SD) and –49.1±7.1 in summer 2012. Occasional sudden increases in WTL were observed after rainfall events and it usually took 1–2 weeks to reach the WTL observed prior to the event.

2.~~3~~ 4 Flux calculation

During the study period, the chambers were operated with varying closure times ranging from 2 to 16 minutes. In 2011, 2 min closures were used with the exception of 6 min measurements made four times per day. After mid-March 2012, the minimum closure time was 6 min. Thus, ~~E~~each chamber was typically sampled ~~usually~~ once an hour ~~with a closure time of 2, 5 or 8 minutes~~, with the exception of summer 2012 (JJA) when a longer closure time of 16 min~~utes~~ was tested~~. Then,~~ and each chamber was sampled every two hours~~at bihourly intervals~~. For the analysis of CH_4 exchange dynamics (Sects. 3.3–3.4), we used the fluxes calculated with a 6 min closure time (as justified in Sect. 3.2). In addition to removing 20 s from the start of the measurement due to lag caused by long tubing (Sect. 2.2), 18 s were discarded from the start of a measurement to ensure that the air inside the chamber was properly mixed. Dilution and spectral corrected CH_4 concentrations reported by Picarro G1130 were used to calculate the fluxes. ~~For consistency between the measurements with different closure times, only the first 120 seconds of the concentration data from these measurements was used. However, data from longer closure times were utilized when testing the effect of different closure time (see 3.3).~~

Two different regression~~s~~ types were fitted to the data: linear and exponential. The linear function describing the change in the concentration, C, as a function of time ~~[C(t)]~~was:

$$C(t) = a_{lin} + b_{lin} \times t, \quad (1)$$

where a_{lin} and b_{lin} are parameters and t is the time from the start of the closure. In this model, the slope b_{lin} equals t~~T~~he concentration change in time ~~is b_{lin} and the slope is assumed to be constant over the whole chamber closure~~.

The exponential function we fitted was:

$$C(t) = a_{exp} + b_{exp} \times \exp(c_{exp} t), \quad (2)$$

where a_{exp}, b_{exp} and c_{exp} are parameters. When differentiating Eq. (2) with respect to time and inspecting the moment when the chamber closes (t=0), it follows that the concentration change with time is the product of parameters b_{exp} ~~b~~ ~~and~~ and c_{exp} ~~c~~. It is generally considered that this initial rate of concentration change best represents the flux ~~rate of~~at that time. However, when fitting the exponential function to the data using the least squares approach, the fitting ~~usually~~ frequently

fails due to local minima. To overcome this and to avoid over-parameterisation, ~~a second-order polynomial is initially fitted to the data:~~

~~$C(t) = a_2 t^2 + b_2 t + c_2$,~~ ~~(3)~~

~~where a_2, b_2 and c_2 are parameters. A~~a Taylor power series expansion ~~of the 17th order~~ (Kutzbach et al., 2007) was fitted to the data to determine ~~the~~ initial estimates ~~of~~for the parameters of the exponential regression.~~:~~

~~$C(t) = a_{17} + b_{17} t + c_{17} t^2 + \sum_{i=3}^{17} \frac{2^{i-1} c_{17}^{i-1}}{i!\, b_{17}^{i-1}} t^i$,~~ ~~(4)~~

~~where a_{17}, b_{17} and c_{17} are the initial estimates of parameters a_{exp}, b_{exp} and c_{exp} for Eq. (2).~~

The exponential regression should capture the flux better than the linear regression as it takes into account the change in the gradient between soil and chamber headspace during chamber closure, which is evident when diffusion flux is decreasing the concentration difference. However, exponential regression is very sensitive to possible disturbances to the data at the beginning of chamber closure. In our study, we attempted to minimize these disturbances by closing the chamber slowly and smoothly, which seemed to prevent pressure ~~peaks~~/fluctuations related to chamber closing. For the analysis of CH_4 exchange dynamics (Sects 3.3–3.4), we used flux data that are based on a combination of linear and exponential fits: first all fluxes were calculated using the linear regression, and below and above a limit of 2.5 µg CH_4 m^{-2} h^{-1} the fluxes were calculated with the linear and exponential method, respectively (for justification see Sect. 3.1).

The CH_4 flux (F, µg CH_4 m^{-2} h^{-1}) was calculated according to ~~the~~ Eq. ~~5~~3, which is based on the ideal gas law:

$$F = \left(\frac{dC(t)}{dt}\right)_{t=0} \cdot M \cdot \frac{P}{RT} \cdot \frac{273.15}{273.15\,°C + T} \cdot \frac{V}{A} \cdot 3600 \frac{s}{h}, \quad (5\text{~~5~~3})$$

where $\left(\frac{dC(t)}{dt}\right)_{t=0}$ is the time derivative (ppm~~/~~ s^{-1}~~h~~) of a linear (b_{lin}) or exponential ($b_{exp} \times c_{exp}$) regression at the beginning of the closure, M is the molecular mass of CH_4 (16.042~~×10^6~~ ~~µ~~g mol^{-1}), P is ~~the~~ air pressure (Pa), R is the universal gas constant (8.31446 J mol^{-1} K^{-1}), T is the mean chamber headspace temperature during closure (~~°C~~K), and V and A are the volume (m^3) and the base area (m^2) of the chamber headspace, respectively. ~~Air pressure, precipitation and snow depth data were acquired from the nearby Finnish Meteorological Institute observatory at Jokioinen (~35 km northwest of Lettosuo).~~

Here, a micrometeorological sign convention is used: a positive flux indicates a flux from the ecosystem to the atmosphere (emission) and a negative flux indicates a flux from the atmosphere into the ecosystem (uptake).

When estimating the volume of the chamber headspace, the height of the moss and snow surfaces ~~were~~ was assumed to represent the interface between the soil and air. In other words, the pore space in the soil and snow was ignored from the headspace volume. The error caused by this in flux calculations ~~is~~ was estimated to be only a few percent (Koskinen et al., 2014). To create a continuous data set of snow depth, the manual measurements carried out irregularly at the site were combined with those measured daily at the Jokioinen observatory. In addition to snow depth, the height of the chamber

headspace was measured at the start and end of the growing season from 16 points inside each collar by gently placing the end of a tape measure on top of the surface mosses (Koskinen et al., 2014). The height of the chamber headspace between these manual measurements was determined with linear interpolation.

All the calculations and analyses were made with the Python programming language (Python Software Foundation, version 2.7, https://www.python.org) using the following libraries: NumPy (http://www.numpy.org/), SciPy (http://www.scipy.org/), Pandas (http://pandas.pydata.org/) and matplotlib (http://www.matplotlib.org). All the Python scripts were developed specifically for this study. For the fits, the least squares method was used through the 'polyfit' function of NumPy library for the linear regression and the 'curve_fit' function of SciPy library for the non-linear fits.

2.4 5 Filtering of the flux data

After the fluxes were calculated, several filters were applied to remove cases ~~when~~ where the measurement system did not work adequately. The most common reason for discarding data ~~were~~ was due to the problems with the chamber operation~~associated with the hardware~~, for example, for the improper functioning of a linear actuator, which caused the chambers to remain stuck either ~~stuck~~ open or closed. These cases were detected by monitoring the simultaneously measured CO_2 concentration data during the closure. The g~~G~~oodness of fit was checked by calculating the normalized root mean square error (NRMSE) (e.g. Christiansen et al., 2011; Pihlatie et al., 2013) for each fit ~~using Eq. 6~~:

$$NRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(C_{fit,i}-C_i)^2}}{C_{max}-C_{min}}, \quad (\text{~~6~~4})$$

where n is the number of measurement points, $C_{fit,i}$ is the CO_2 concentration calculated from the fit, C_i is the measured CO_2 concentration and C_{max} and C_{min} are the highest and lowest concentrations measured during closure. ~~The numerator is also known as the root mean square error (RMSE).~~ If the NRMSE was larger than 0.05, the CH_4 data from that closure ~~was~~ were discarded. It should be noted that the application of this criterion~~a~~ removes closures with no change in ~~A~~CO_2 concentration~~=0~~, which may result when photosynthesis rate equals respiration rate. Here we found < 20 of such cases meaning that this criterion~~a~~ could be applied without removing a significant amount of potentially suitable data.

In addition to NRMSE filtering, ~~a~~ the running mean of CH_4 flux (F_{CH4}) with a time window of 14 days (shifting one day at a time) and the corresponding standard deviation (σ) ~~was~~ were calculated to remove random spiking in the data. The data points that failed to fall within F_{CH4}±10σ were removed iteratively. In total, ~~75923~~ 71229 closures were recorded from which 1~~9~~49 % (n=998~~7~~14345) were discarded due to large NRMSE values (~~hardware~~ problems with the chambers) and ~~7~~ <0.001 % (n=40~~4999~~) were removed with the σ-filter as outliers.

~~Cumulative CH_4 flux was calculated by summing all the hourly measured fluxes for each chamber over one year of measurements. Possible gaps were filled with linear interpolation. As our measurements started in April 2011 and ended in~~

~~March 2013, exactly two years, we decided to call the time period 4/2011–3/2012 the first year and 4/2012–3/2013 the second year.~~

~~A 95 % confidence interval was used to show the uncertainty of the results unless otherwise specified.~~

2.6 Detection limit

The Minimum Detectable Flux (MDF) was estimated by using the metric originally developed by Christiansen et al. (2015), which was modified by Nickerson (2016) to make it more suitable for high-frequency measurements:

$$\mathrm{MDF} = \left(\frac{P_I}{tc\sqrt{\frac{t_c}{p_s}}} \right) \left(\frac{VP}{ART} \right) M \quad (5)$$

where P_I is the analytical precision of the instrument (ppm), t_c is the closure time of the chamber (h), and p_s is the sampling periodicity (h). The P_I for the Picarro G1130 analyzer, tested and reported by the manufacturer for this specific instrument used in this study was 0.256 ppb and p_s was 5 s. On a typical summer day (T=20 °C), the MDF of the system was about 0.06 μg CH_4 m^{-2} h^{-1}. However, during winter the MDF was higher due to lower temperatures and the use of the extension collars which together about double the headspace volume (without snow) and therefore also the MDF.

2.7 The annual balance and its uncertainty

The annual balance of CH_4 was estimated for each chamber by first calculating the daily flux sums from the hourly fluxes and then summing these over a year. The gaps in the data were filled by using linear interpolation between the existing hourly and daily fluxes. As most of the fluxes in 2011 and in the first quarter of 2012 were measured with a 2 min closure time, which was considered too short for the exponential regression (Sect. 3.2), we corrected the fluxes calculated with linear regression from the 2 min closures to correspond to those measured using a 6 min closure available four times a day during this period as a reference. This correction was implemented by calculating the daily median ratios between the fluxes from 6 min and 2 min closure times, which were smoothed by a running median with a moving window of 14 days. Finally, the 2 min data from 2011 to March 2012 were multiplied by this ratio (Fig. S2).

The uncertainty of the CH_4 balance estimate derived from the measurements was evaluated by identifying three key error sources: (1) the random error of regression, (2) the error caused by gap filling and (3) the error caused by the correction of the fluxes measured using the 2 min closure time during the first measurement year. First, because the annual balance of each chamber was calculated from the mean daily fluxes, we estimated the daily random error as the squared sum of the uncertainties of the hourly flux data of each day. Assuming that the goodness of fit reflects all the uncertainties related to a

single flux measurement, the standard deviation of the slope estimate obtained ($\left(\frac{dC(t)}{dt}\right)_{t=0}$, Eq. 3) provides a measure of this uncertainty.

Next, the error caused by the gap filling procedure was estimated by removing one month of flux data from different parts of the whole data set and inspecting how this affected the annual balance of the different chambers. The average value of the effect of these monthly gaps was calculated and downscaled to represent the effect of one missing day. Multiplying this value by the number of missing days during the year gives an estimate of the gap-filling error. It must be noted that the length of the removed period was similar to the longest gap observed in our data.

Last, the error estimate related to the ratio used to transform the fluxes calculated from 2 min closure to represent the 6 min closure was estimated from the median absolute deviation assuming normally distributed medians. Finally, these three error estimates were added together by using the standard accumulation principle of independent errors.

As our measurements started in April 2011 and ended in March 2013, exactly after two years, from now on in this paper the expressions 'first year' and 'second year' denote the time periods of 4/2011–3/2012 and 4/2012–3/2013, respectively.

3 Results

~~3.1 Meteorological conditions~~

~~The first measurement year was significantly warmer (annual mean temperature 5.8 °C) than the second measurement year (1.4 °C) (Fig. 1). The first year was slightly warmer and the second year was significantly colder than the long-term mean recorded at the nearby weather station (4.6 °C). Both the summer (17.6 °C) and winter (2.7 °C) temperatures in 2011 were warmer than those of 2012 (12.1 °C and −2.3 °C). In particular, the beginning of summer 2012 was much cooler than for the same period in 2011.~~

~~Annual precipitation during the first (976 mm) and second (780 mm) measurement years was higher than the long-term mean (627 mm). Summertime precipitation was 9% higher in the first (309 mm) year as compared to the second (284 mm) year, while in winter the difference was 18% (577 mm and 490 mm in the first and second winters, respectively). The first snow appeared on 5th December 2011 and 25th October 2012, and the first permanent snow was recorded on 7th January 2012 and 28th November 2012 in the first and second measurement years, respectively. In the first spring, the snow had melted by 13th April 2011. For spring 2012, we do not know the exact day of snow melt due to missing data, although the snow had melted by 4th April. From the temperature data, we would estimate that the snow cover had disappeared sometime in mid-March.~~

~~WTL varied from −8 to −59 cm from soil surface and was highest in the spring and in late autumn. Lowest (i.e. deepest) values were reached at the end of summer. The average WTL in summer 2011 was −47.2±7.4 cm (±Standard deviation) and~~

~~49.1±7.1 (± Standard deviation) in summer 2012. Occasional sudden increases in WTL were observed after rainfall events and usually took 1–2 weeks to reach the WTL prior to the event.~~

3.1~~2~~ Flux calculation method

Examples of typical concentration development inside a chamber during one measurement are shown in Fig. 2, for both 'high flux' case in summer (Fig. 2a) and a 'low flux' case in winter (Fig. 2b). In summer and autumn, when the fluxes were the highest, the concentration development inside a chamber usually was not adequately approximated by a linear function and thus the slope calculated with the linear regression (Eq. 1) did not properly represent the initial 'undisturbed' slope from which the flux should be calculated. As a result, linear regression resulted in lower flux estimates for these cases than exponential regression (Eq. 2). However, during the periods when the flux approached the detection limit and the concentration data became noisier, the use of exponential regression resulted in noisier flux data. Often, exponential regression created a sharp slope at the beginning of the fit in the concentration time series that resulted in unphysically high fluxes. To be able to reliably estimate the CH_4 exchange for the whole range of fluxes, we determined the flux limit below which the exponential regression resulted in unreliable flux estimates and the linear fit should be preferred. This limit was estimated by comparing bin (n=500) averages of linear and exponential fluxes for the whole data set (using a 6 min closure time) (Fig. 3). When the linearly calculated fluxes fell below ca. 2.5 μg CH_4 m^{-2} h^{-1}, the noise in the flux calculated using the exponential regression increased steeply and the shape of the relationship changed (Fig. 3). Therefore, we decided to first calculate the flux with the linear regression and to recalculate all the fluxes exceeding the limit of 2.5 μg CH_4 m^{-2} h^{-1} with the exponential regression. Henceforth, all the data shown in this paper have been calculated in this way unless stated otherwise.

The whole 2-year data set showed that the CH4 fluxes calculated with linear regression (Eq. 1) were systematically and significantly lower than those calculated with exponential regression (Eq. 2) (Table 3). The seasonal average flux difference between the linear and exponential regressions varied within 10.9–44.4 % (average over 2 yr 27.5±0.3 %, ±95 % confidence interval). The mean relative difference was dependent on the time of the year: it was largest during the winter and spring (24.9–44.4 %) when the soil CH4 sink was at its lowest, and smallest in summer and autumn (10.9–14.4 %) when the sink was at its highest. When comparing individual measurements, the average relative difference between the linear and exponential regression was slightly smaller in 2012 compared to 2011. Also, the uncertainties associated with the fluxes were slightly larger in 2011 probably due to the fewer measurements available with 6 min closure time.

~~The CH_4 fluxes calculated with linear regression (Eq. 1) were systematically and significantly lower than those calculated with exponential regression (Eq. 2) (Table 2a). At very low flux rates, the exponential regression resulted in increased variation in fluxes due to decreased signal-to-noise ratio in the gas mixing ratio time series. Typically, exponential regression created a sharp slope at the beginning of the time series that resulted in high variation in fluxes. We found that, on average,~~

~~when the linear CH_4 flux values were below 3.5 µg CH_4 m^{-2} h^{-1} (Fig. 2), the use of the exponential fit resulted in noisy flux values. When the fluxes exceeded this value, linear regression resulted in an underestimation of the flux rates. Therefore, we decided to use the flux values estimated with the linear regression method when that method estimated fluxes lower than 3.5 µg CH_4 m^{-2} h^{-1}. If the flux was higher, we used the flux calculated from the exponential regression. Unless otherwise specified, the fluxes shown hereon have been calculated with this method.~~

~~When the data below and above the limit of 3.5 µg CH_4 m^{-2} h^{-1} was examined, the difference between the linear and exponential fits mainly varied between 20–50 % (average 35.3±0.3 %). The relative difference was dependent on the time of the year: it was largest during the winter (DJF) and spring (MAM) when the temperature and the soil CH_4 sink were at their lowest, and smallest in summer and autumn, varying from 19.0 to 23.8 %. For fluxes > 3.5 µg CH_4 m^{-2} h^{-1}, i.e. when the exponential regression did not work reliably, the overall difference between the linear and exponential fits decreased from 35.3±0.3 % to 22.1±0.2 % (Table 2b). Seasonally, the greatest effect was seen in the winter and spring data, as a large amount of data with fluxes below the limit were removed from this period.~~

~~The underestimation (in %) caused by using the linear regression was slightly smaller in 2012 compared to 2011. However, the uncertainties associated with the fluxes were slightly larger in 2012. Comparison of the fitting methods for the winter periods was meaningless as the exponential regression did not give reliable results in winter 2012–2013 as almost all the fluxes were < 3.5 µg CH_4 m^{-2} h^{-1}.~~

~~3.3~~ 3.2 Effect of closure time on fluxes

The effect of the different fitting time windows was tested by both increasing the fitting period from the beginning of the closure with 10 s steps and by keeping the fitting window constant but moving its starting point. For these tests, we used the data from summer 2012, when the measurements were made with a 16 min closure time. The flux from the exponential fit was clearly affected by the length of the fit when the fitting period was < 190 s (Fig. 4b). After that, the mean difference was mostly statistically insignificant ($p > 0.05$), as compared to the flux calculated with the 900 s period. On the other hand, the estimated linear flux stayed about the same for the first 140 s resulting in 16.2±0.6 % higher fluxes than obtained with the 900 s fitting window (Fig. 4a). However, further increase of the fitting period systematically decreased the estimated flux by about 1.3 % per 60 s. A decrease of 17.3±3.0 % and was also observed when the starting point of the fit was delayed by 530 s, but the fitting period was kept constant at 6 min (Fig. 5).

Even though the results above might support the selection of a fitting period of 190 s, a 6 min fitting period was applied in further analysis. This was selected based on three arguments: (1) it made the exponential regression results more stable; (2) we wanted to use the same fitting period in both linear and exponential regressions, and (3) a longer fitting period decreases the detection limit (Eq. 5). The last point was mainly related to winter measurements when the detection limit was increased by lower temperatures and the use of extension collars (increasing the effective volume before the collars were filled with

snow). However, in 2011 and in the first quarter of 2012, a 2 min closure time was mostly used, which proved to be too short for accurate estimates with the exponential fit. As a result, the results from these shorter measurements were corrected to correspond to those obtained with the 6 min closure time (Sect. 2.7).

~~No significant differences between the fluxes calculated with 2- or 5-minute closure times were detected. When the whole measurement period was examined, the average relative difference between the 2- and 5-minute closure times was 4.2±0.1 %, with the 2-minute closure always producing larger fluxes. However, the use of only linear regression to calculate the fluxes produced a larger difference for the whole measurement period (7.4±0.1 %). The differences were also checked annually and seasonally. The second year had a smaller difference (1.9±0.1 %) between the closure times than the first year (9.1±0.2 %), although it should be noted that in the first year most of the measurements were made with the 2-minute closure time and only 4 measurements per day had 5-minute closures. As such, there were fewer measurements available for the analysis for the first year. Seasonal comparisons revealed that the differences between the closure times were smallest in autumn and summer when the fluxes were largest, slightly larger in winter and largest in spring.~~

3.~~3~~4 ~~ ~~Seasonal dynamics of CH_4 flux and comparison between the chambers

During the 2-year measurement period, CH_4 flux~~-rat~~es varied mainly between –120 ~~40~~ and +20~~50~~ µg CH_4 m^{-2} h^{-1} (Figs. ~~3~~ 6 ~~&~~ and ~~Fig. 4~~7). Higher uptake rates ~~(70 µg CH_4 m^{-2} h^{-1}) of uptake~~ were measured more often during the first year (Fig. ~~4~~7a) and during summer 2011 (Fig. ~~4~~7b) than in the second year and in summer 2012.~~,~~ T~~although t~~he number of ~~cases indicating~~ emission cases~~s~~ ~~were~~ was low in both years and~~.~~ ~~Although~~ the soil acted as a CH_4 sink for most of the time in all chambers, although a few emission peaks of up to ~~90~~200 µg CH_4 m^{-2} h^{-1} were recorded during and following heavy rainfall events. The data filtering (Sect.~~see~~ 2.~~5~~5) ~~used for the data~~ was ~~deliberately~~ designed to be flexible to prevent the removal of these short-lasting CH_4 bursts from the ~~soil~~accepted data set. While some emission peaks were ~~observable~~ observed in ~~all~~ most of the chambers, the peaks were largest in chamber #6. However, the peaks did not necessarily occur at the same time in different chambers.

CH_4 fluxes showed a clear seasonal variation. In spring, when the snow melted and thawing of the soil surface had started, CH_4 emissions ~~fluctuating~~ fluctuated around ~~3~~2 µg CH_4 m^{-2} h^{-1} ~~were observed~~ in all chambers (Fig. 6~~3~~). As the temperature rise continued, ~~chambers showed~~ increasing CH_4 uptake was observed. In both years, CH_4 uptake was largest in August, ~~with~~ when fluxes ~~varying~~ varied between –30~~15~~ and –130~~40~~ µg CH_4 m^{-2} h^{-1}. In September, the uptake decreased and by the end of November it had dropped to half of that ~~observed~~ in the summer. However, the soil acted as a sink until the soil surface froze, after which CH_4 fluxes fluctuated around zero.

Considerable ~~and~~ systematic differences in fluxes between the chambers were detected. The largest two-year average ~~values~~ sinks were measured in chambers #5 and #2 (Fig. 8~~5~~), which were dominated by forest mosses *Pleurozium schreberi* and *Dicranum polysetum* (Table 2). The third largest sink was observed in chamber #6 (Fig. 8~~5~~) with a *Sphagnum* ~~girgensohnii~~

sp. carpet, while the remainder of the chambers showed similar flux ~~rat~~es. Annual net CH_4 exchange rates were on average –26~~78~~4±55~~33~~ and –172~~51~~±31~~18~~ mg CH_4 m^{-2} yr^{-1} (±Standard error of the mean) in 2011–2012 and 2012–2013, respectively. ~~However, t~~The forest floor sink was ~~21~~10–44~~54~~ % lower during the second than first annual period ~~compared to the first~~and this difference was statistically significant ($p < 0.05$) for all the chambers except chamber #4. The largest absolute year-to-year ~~drop~~ reduction in annual CH_4 exchange was observed in the two chambers dominated by *Pleurozium schreberi* and *Dicranum polysetum* (#5 and #2), followed by the chamber dominated by *Sphagnum* ~~girgensohnii~~ sp. (#6). However, the largest relative decrease in net CH_4 exchange happened in chamber #6 (44 %) while in the rest of the chambers the decrease varied within 10–37 %.

~~In four of the chambers (#2, #3, #5 and #6), a statistically significantly (Student's t-test, $p<0.05$) larger sink was observed in summer 2011 than in summer 2012. Moreover, t~~The sink period, i.e. the period when all chambers acted as CH_4 sinks (daily mean flux < –2 µg CH_4 m^{-2} h^{-1}), was slightly longer in the first than in the second year. In the first year, all chambers acted as sinks from ~~9~~14~~th~~ May~~June~~ 2011 to ~~31~~20~~st~~ February~~January~~ 2012, a total of 282~~236~~ days. During the second year, the sink period lasted for 269~~191~~ days from ~~22~~10~~nd~~ May 2012 until ~~29~~3~~th~~ February~~November~~ 2013~~2~~. ~~Among some chambers, a difference of six weeks was detected in the length of the sink period between years.~~ In addition, chamber #6 acted as a sink over the whole winter and spring in 2012, while from chambers #2 and #5 daily mean fluxes of < –2 µg CH_4 m^{-2} h^{-1} were measured already at the start of the study in April 2011.~~The difference between the mean winter and summer fluxes was about 5–10 µg CH_4 m^{-2} h^{-1}; larger in 2011 than in 2012.~~

3.~~5~~ 4 Factors controlling the short- and long-term variations in CH_4 exchange

3.4.1 Seasonal cycle

There was an observable, exponential relationship between the mean daily CH_4 fluxes and the deeper soil temperatures when the data from the spring and summer ~~data~~ of 2011 were pooled (Fig. ~~6~~9a). Splitting these~~is~~ data into shorter periods showed that the relationship was rather strong in April–May and in June–early~~start of~~ July, but after that, when the soil temperature at 30 cm depth exceeded 12°C, the relationship was ~~rather weak~~absent. ~~Since i~~It is evident ~~likely~~ that there is ~~a~~ some co~~-correlation~~variation between soil temperature and WTL with typically higher CH_4 uptake taking place at~~at~~ lower WTL. The plot between the residuals of the temperature response against WTL (Fig. 9b~~6b~~) suggests that the variation in~~, we plotted the residuals of Fig. 6a against WTL (Fig. 6c). This plot suggests that~~ the ~~high~~ CH_4 uptake during the latter half of July and August was better explained by the WTL than temperature. ~~cannot be solely explained by higher temperatures, or by the lower WTL. This increase of residuals usually started when the WTL was between ~35 and ~40 cm and when the WTL decreased even more, the oxidation was larger than acquired from the exponential model (Fig. 6a).~~ All the chambers recorded similar behaviour in~~when~~ 2011 and 2012~~ were compared~~, although in 2012 the data ~~was~~ were noisier and ~~this~~ the ~~phenomenon~~ relationships observed in 2011 were~~as~~ not as clear.

3.4.2 Diurnal cycle

In addition to seasonal dynamics, diurnal variation was observed in CH_4 flux ~~rates was observed~~ at least occasionally in all chambers, mostly in May and in the first half of June. Such variation was more common in 2012 and was observed in all of the chambers, while in 2011 the variation occurred mostly in chambers #2, #5 and #6. For example, during the first two weeks of June 2011 a clear diurnal cycle coinciding with the variation in air temperature was observed (Figs. 10 and 11a–b). Higher CH_4 uptake was observed during the night and morning hours, while the sink decreased towards the midday and started to grow again towards the night (Fig. 11a). This particular 2-week period was associated with high daytime air temperatures, reaching almost +30°C, and a relatively low WTL (Figs. 10 and 11a–b). After that, at about mid-June, the weather type changed to cool and wet and the diurnal variation was diminished or absent (Figs. 10 and 11d–e). Such behaviour, illustrated in Fig. 10, was typical for the rest of the growing season data: diurnal variation occurred more often with dry weather, while during and after the rain the variation ceased for a while. However, WTL itself did not have an impact on the diurnal cycle.

Pooling the data of these 2-week periods into hourly means implies that the soil temperature may exert a strong control on the CH_4 exchange (Fig. 11). However, as temperature often – though not always – tends to correlate with wind speed, particularly in the summer, it is necessary to consider the effect of both these variables. The correlations calculated from hourly data indicate that it was the wind speed (Fig. 12a) and not the temperature (Fig. 12b) which played the major role in causing the diurnal variation in CH_4 flux (see also Figs. S6-S27). However, this relationship was not comprehensive, as the correlation with wind speed was absent during some periods. In qualitative terms, we observed that the drier the soil was, the greater was the impact of wind speed.

To explain this correlation, we investigated the relationship between the parameter c_{exp} (Eq. 2) and ambient wind speed, in 2-week to one month periods to diminish the possible impact of seasonality (Fig. 13, Figs. S28-S40). c_{exp}, represents the curvature of concentration time series during each chamber closure. For example, the c_{exp} determined for chamber #2 became less negative when wind speed exceeded 2 m s^{-1} (Fig. 13). This means that the curvature was weaker for cases of high wind speed. ~~Most of this short-term variation was observed in summer (Fig. 7), with a few cases in spring 2011. At the beginning of June 2011 in particular, a strong diurnal cycle that coincided with the variation in air temperature was observed: Relatively high CH_4 uptake was observed during the morning hours (Figs. 7 and 8a) whereas the sink strength decreased towards afternoon. This period was associated with high daytime air temperatures and relatively low WTL (Fig. 7). However, during the latter half of June 2011 when there was lower ambient air temperatures and higher WTL, the diurnal variation was absent (Fig. 8b). However, in summer 2012 the largest uptake occurred in the afternoon and uptake was lowest at night (Fig. 8c). Similarly to the previous summer, the periods with diurnal variation had relatively low WTL, although daytime temperatures were generally 5–10 °C lower.~~

3.4.3 Correlation between the flux and meteorological variables

To understand the general driving factors behind all the variation, either diurnal or~~and~~ seasonal~~ variation~~, Pearson correlation coefficients~~s~~ ~~(Pearson)~~ between the hourly CH_4 flux and key environmental variables were ~~checked~~ calculated for different seasons, averaging the correlations determined separately for each chamber ~~using monthly, seasonal and annual data~~(Table 4)~~. Only in the cases of insignificant correlations (usually |r|<0.1), the p-value reached values higher than 0.01. In some cases, a number of chambers showed positive and some chambers negative correlations of similar strength during the same season, for example, in the case of surface temperatures in spring and autumn 2011. The correlation coefficients in Table 3 have been classified accordingly.~~

There was a highly significant negative correlation between CH_4 flux and soil temperature (i.e. higher uptake at higher temperature). The deeper soil temperatures (at 20 cm and 30 cm depths) showed the best correlation in all seasons. ~~In general, soil temperatures at 20 cm (T20) and 30 cm (T30) depths correlated negatively with CH_4 flux rates (i.e., higher uptake at higher temperatures) in each of the eight seasons during the two study years. In addition, soil temperatures at 5 cm (T5) and 2 cm (T2) depths~~ Also, T5 and T2 often correlated with CH_4 flux. The highest correlations were observed in springs, winters and in autumn 2012, and all these correlations were significant in all the chambers with the exception of summer 2011. Also, the correlations of ambient (AirT) and soil surface temperature (ST) were systematically lower than those of the deeper soil temperatures. The correlation with surface soil temperatures was absent or very low in summer 2011, when only the deeper soil temperatures showed a significant correlation.~~, however a marked difference was observed between summers 2011 and 2012: in 2011 the most significant correlation was observed with the deeper soil temperatures (T20 & T30) and with friction velocity (u^*), in 2012 the air and surface soil temperature, as well as T2 and T5 showed the best correlation with the flux. Interestingly, the soil temperature at 10 cm (T10) had the poorest correlation with the CH_4 flux, with significant correlation in all the chambers observed in only two seasons.~~

~~There was a positive correlation between~~ WTL and CH_4 flux correlated positively in both summers (i.e. the~~ deeper~~ deeper the WTL, the higher the uptake), while~~. A~~ a negative correlation~~ with CH_4 flux~~, (i.e. the ~~lower~~ deeper the WTL, the higher the emission) was ~~found for the winters~~only observed in winter 2011–2012~~. The correlation between the flux ~~rate~~ and PAR was always low (|r|<0.2) or absent.

A significant ~~(~~positive~~)~~ correlation between wind speed (WS) ~~u~~u^* and the flux ~~rate~~ was ~~only~~ found in both summers and autumns and in spring 2012, meaning that the estimated sink decreased when wind speed increased. This correlation was especially clear in the time periods when there was diurnal variation in the flux (e.g. Fig. 12a), but it was non-existent when no diurnal cycle was observed, which is consistent with the result reported above. However, even though the correlation was high in autumn 2011, no statistically significant diurnal variation in the flux was observed at that time (data not shown). Of all the inspected quantities, wind speed was the best explanatory factor of the diurnal cycle of CH_4 flux; this was followed by temperature quantities.~~ 2011. However, apportioning the flux data into u^* bins (interval 0.05 ms^{-1}) resulted in a steady CH_4~~

~~exchange rate with u^* of <0.25 ms^{-1} with a decreasing rate after that value (Fig. 9). This effect was also observed in shorter time periods, for example, in summer and autumn, although the results were not always significant. However, lengthening the inspected time period increased the statistical significance. Even though u^* was found to correlate with CH_4 flux when diurnal variation in the flux was observed (Fig. 8), we were not able to explain the variation with u* due to simultaneous correlation with ambient, soil surface, T2 and T5 temperatures.~~

4 Discussion

4.1 ~~Impact of~~ Chamber closure time and flux calculation method ~~on fluxes~~

In this study, we found that using the linear regression method in flux calculations resulted in 20–50 % lower flux ~~rate~~ estimates~~values~~ for most of the time, in comparison to flux ~~rat~~es calculated with an exponential fit. ~~In contrast~~ On the other hand, in winter and early spring, i.e., at the time of low absolute CH_4 fluxes (< ~~3~~2.5 µg CH_4 m^{-2} h^{-1}), linear regression gave more reliable results with clearly lower hour-to-hour noise in the fluxes. The uncertainty associated with exponential regression with low fluxes was caused by the decreased signal-to-noise ratio in the concentration data, leading to more or less arbitrary values of the concentration change ~~over time~~estimated at t=0. This ~~unreliability~~ explains why the difference between the fluxes estimated by the linear and exponential models was highest during winter and spring.

The use of exponential regression ~~may be~~can be considered especially justified during summer and autumn when the concentration development ~~distortion of the vertical concentration gradient occurs~~ inside the chamber is strongly non-linear. ~~In this~~During these periods, linear regression gave significantly ~~underestimated the~~ lower flux estimates with~~by~~ an average difference of~~by~~ ~~21.5~~12.8±1.8~~1~~ %. In winter and spring, however, the average seasonal ~~underestimation~~ difference was as high as ~~60~~44 %. Concerning the annual balance, it should be noted that this difference has a greater influence during summer and autumn when the fluxes are up to two orders of magnitude larger. The mean difference~~underestimation~~ during the whole measurement period (~~35.3~~27.5±0.3 %) is in agreement with many previous studies~~;~~, for example, Anthony et al. (1995) and Pedersen et al. (2010) reported a 35 % and 34 % decrease in flux values, respectively, when using linear regression instead of exponential regression. Kutzbach et al. (2007) ~~noted~~ reported that underestimations for multiple sites varied mostly ~~between~~ within 20–60 % ~~on multiple sites in their study~~, while Pihlatie et al. (2013) found~~under laboratory conditions at different flux levels reported~~ an average underestimation of 30 % under laboratory conditions at different flux levels. However, the above-mentioned studies focused on either CH_4 and CO_2 emissions or CO_2 uptake and did not include measurements related to a small soil sink of CH_4. Since the exponential fit results in larger uptake estimates, which we consider to better represent the correct flux at the time of the chamber closure, we agree with the previous studies that recommend the use of exponential regression in flux calculation. However, due to the considerable noise generated for small fluxes, ~~For clarification, the distortion of the vertical concentration gradient in this case describes the effect where the~~

~~concentration difference between the soil and the chamber headspace decreases during chamber closure, which causes the flux to change over time. This occurs every time that a vertical concentration gradient exists between the chamber headspace and the soil. In addition, the microbial oxidation rate is proportional to the CH_4 concentration in the soil (e.g. Ridgwell et al., 1999), which may have an effect on CH_4 concentrations within the chamber headspace.~~

~~Therefore,~~ we recommend that in the future studies ~~with~~ employing temporally high-resolution data, the fluxes should be calculated initially with both methods to determine the threshold for "low" fluxes. As this threshold value is ~~always~~ dependent on the measurement system and method, it cannot be generalized. ~~We are not aware of any publications where this would have been tested.~~

We found that increasing the fitting period up to 15 min from the beginning of the concentration time series systematically decreased the flux estimated by the linear regression model, but only after this period exceeded 140 s. On the other hand, the flux estimated by the exponential regression decreased until the fitting window covered 190 s after which the estimated flux was stabilized. To disentangle whether these anomalous patterns in the beginning of both curves were caused by an initial disturbance to the measurement or if they represented a real phenomenon affecting the flux, we removed 2 min of data from the beginning of concentration time series. This removed the plateau with large variation from the linear fit results, but did not change the shape shown for the exponential fit in Fig. 4b (results not shown). This suggests that the concentration data during the first minute of measurement are perturbed by chamber closure and that the linear fit is more sensitive to this than the exponential fit, when using a short fitting period. On the other hand, the exponential fit seems to overestimate the flux if the fit is limited to a short time window, but this overestimation is not related to a possible disturbance in the beginning of the data.

Because the concentration development is non-linear, it is not only the length of the fitting period, but also the start of this period which is important for the flux estimate. The more data are removed from the beginning, the smaller the estimated CH_4 uptake becomes, as illustrated in Fig. 5. Ueyama et al. (2015) noticed that the flux estimates by linear and exponential regressions both decreased with increasing closure time. Their slopes of linear regression (14±2 % over 5 min) decreased faster than those in our study (16.2±0.2 % over 13 min), suggesting that their concentration data were more non-linear. The difference could be partly explained by the fact that Ueyama et al. (2015) used smaller chambers and measured higher fluxes which both result in a faster decrease of the vertical concentration gradient between the soil and the chamber headspace.

~~We also found that the length of the closure time had a small effect on the calculated CH_4 flux; the mean difference in the flux measured with the 2- or 5-minute closure times was 4.2±0.1 %. Koskinen et al. (2014) also tested how the length of the fit might affect CO_2 flux and found that with the linear fit the mean flux did not change significantly, although the RMSE and non-linearity increased. However, in their study the first 120 seconds of the closure were always removed before the start of fitting, and it is likely that using all the data would have resulted in significant differences between the different closure times. In this study, we noticed that the difference between the closure times was larger when using only linear~~

regression to calculate the fluxes (7.4±0.1 %), which further supports the observation of increasing non-linearity with longer closure time. In addition, we noticed that the relative difference between the 2- or 5-minute closures was largest in winter and spring when CH_4 fluxes were lowest. Even though absolute differences in fluxes were slight, the small non-linearity in low fluxes, which became apparent over longer closure times, caused higher relative differences between the different dataset lengths in winter and spring. It is also possible that in the case of low fluxes, the use of longer closure times may be needed to increase the concentration change in chamber headspace to make the measurement less sensitive to the instrument noise. However, it should be noted that an increased closure time makes the measurements more prone to disturbance by wind gusts, especially if the chamber has a vent tube or if the measurements are made on soils with high porosity (Bain et al., 2005).

4.2 CH_4 exchange dynamics in a peatland forest

4.2.1 Annual balances

The measurement site (excluding the ditches) was a small annual CH_4 sink (50–80 mg varying from 172±31 to 267±55 mg CH_4 m^{-2} yr^{-1}, ±Standard error of the mean) over the two-two-year measurement period. While we do not have measurements prior to drainage, it is possible to roughly estimate the pre-drainage fluxes from measurements conducted at similar sites. Asthe Lettosuo site was originally a herb-rich tall sedge birch-pine fen, it can be considered similar and is similar to a the site reported by Nykänen et al. (1998). That site has with high CH_4 emissions of (25 g CH_4 m^{-2} yr^{-1}), so it is obvious that the . Therefore, assuming similar emissions at Lettosuo before drainage of Lettosuo has turned, the peat soil from has obviously turned from a CH_4 source to a small CH_4 sink. Other studies in drained peatland forests have reported uptake that varied between 10 and 970 mg CH_4 m^{-2} yr^{-1} (Alm et al., 1999; Minkkinen et al., 2007; Ojanen et al., 2010; Lohila et al., 2011), while the average uptake in boreal upland forests is about 200 mg CH_4 m^{-2} yr^{-1} (Dutaur and Verchot, 2007). Thus, the CH_4 sink of Lettosuo soil was smaller than the average CH_4 sink in boreal upland forests. However, it should be noted that our calculations of annual and daily CH_4 exchange do not include the emissions from the ditches, which have been found to be highly variable: from 0 to 600 mg CH_4 m^{-2} day^{-1} (e.g. Minkkinen et al., 1997; Minkkinen and Laine, 2006; Luan and& Wu, 2015). At Lettosuo, where the ditches cover 2–3 % of the area, we estimated, based on 41 manual chamber flux measurements from six points made in the latter half of 2011, that CH_4 emissions (per m^2 peatlandditch) from the ditches averaged (±standard error of the mean) 242 (±5838, ±SD) g CH_4 m^{-2} yr^{-1} (unpublished data). This would suggest that even with a very small ditch area, Simple upscaling suggests that, when ditches are accounted for, Lettosuo is a small annual source of CH_4 to the atmosphere, although the very high uncertainties associated with this calculation should be noted.

Previous studies of drained peatland forests in Finland have reported uptake rates varying between 10 and 970 mg CH_4 m^{-2} yr^{-1} (Alm et al., 1999; Minkkinen et al., 2007; Ojanen et al., 2010; Lohila et al., 2011). The average annual uptake in boreal upland forests typically varies from about 100 to 500 mg CH_4 m^{-2} yr^{-1} (Smith et al, 2000; Dutaur and Verchot, 2007; Lohila

et al., 2016), but also annual net emissions from upland forests have been reported (e.g. Sundqvist et al., 2015; Lohila et al., 2016). Thus, the net annual CH_4 exchange measured at Lettosuo (excluding the ditches) was well within the typical range of the average CH_4 sinks reported for boreal upland forests.

4.2.2 Emission peaks

~~Many drained peatland sites have been shown to act as CH_4 sources over a year due to poor drainage and high water table levels (e.g. Nykänen et al., 1998; Minkkinen and Laine, 2006; Ojanen et al., 2010). At our site, A small CH_4 emissions (< 30 µg CH_4 m^{-2} h^{-1}) were recorded during winter and spring when the soil temperature was close to zero. These low temperatures are likely to slow down the activity of methanotrophic bacteria (e.g. Boeckx and Van Cleemput, 1996) and low temperatures also decrease the rate of microbial CH_4 production (e.g. Dunfield et al., 1993). In addition, a~~ few larger CH_4 emission peaks were observed during and after heavy rainfall events in summer, but not all chambers responded to the same rainfall events. The largest number and magnitude of these short bursts of CH_4 were recorded with the *Sphagnum*-dominated chamber (#6), which was expected as *Sphagnum* mosses favor wet spots. These rainfall events turned the soil from a sink to a ~~small~~ source (up to 200 µg CH_4 m^{-2} h^{-1} in chamber #6) for a short period ranging from a few hours to few days. This was~~,~~ possibly due to increased water saturation and decreased air-filled pore space leading to reduction in oxygen diffusion~~ oxic space~~, which could promote methanogenic activity and suppress methane oxidation.

Similarly to our results, Nykänen et al. (1995) ~~also~~ observed that a drained peatland soil can switch to a CH_4 source (up to ~~0.2~~200 ~~m~~µg CH_4 m^{-2} h^{-1}) during ~~increased~~ water saturation event. However, the emission peaks at Lettosuo were relatively small when compared to ~~some~~ upland mineral soil forest sites, where emissions of up to 3.7 mg CH_4 m^{-2} h^{-1} have been observed in wet conditions (e.g. Savage et al., 1997; Lohila et al., 2016). Similarly, the maximum hourly uptake in summer at Lettosuo was ~~slightly lower than~~ rather similar to the fluxes reported for the ~~above~~ above-mentioned upland forests (from ~~on average 2~~ –50 to –120 µg CH_4 m^{-2} h^{-1} at Lettosuo vs. –40 to –80 µg CH_4 m^{-2} h^{-1} at ~~the~~ upland forests).

4.2.3 Spatial variation

There were relatively large differences in the annual net CH_4 exchange rates between the chambers (~~largest uptake~~from ~~154~~104 mg CH_4 m^{-2} yr^{-1} in chamber #3, to~~smallest uptake~~ ~~32~~505 mg CH_4 m^{-2} yr^{-1} in chamber #5; Fig. 8), even though all the chambers were located within a maximum distance of about 15 m ~~only a few meters apart~~ from each other. ~~In our measurements, t~~The difference in the soil surface temperature between the chambers was usually less than 2 ~~degrees~~K, which ~~would~~ indicates that the soil temperature was not the main factor determining the observed spatial variation in fluxes. ~~Moreover~~ S~~, s~~ince we do not have WTL data for ~~below~~ each of the chambers separately, we cannot ~~confirm~~ quantitatively evaluate its role in ~~explaining the difference~~the spatial variation of fluxes. ~~However, i~~It is unlikely that the variation in the WTL solely could explain the difference: even though chambers #4 and #5 were located at the same distance from~~closest to~~

the a ditch, and probably had the deepest WTL. Indeed, chamber #5 showed the highest uptake, while although chamber #4 was one of the smallest sinks. Hence, although WTL is likely to explain part of the spatial variation in in the spatial variation of the CH_4 fluxes, there are potentially many other factors, such as the vegetation compositiontype or and small-scale soil properties. The smallest sink was observed in chambers #1, #3 and #4, which were characterized with the lowest (#3) and highest (#1, #4) vascular green area (VGA_{max}) values (Table 2). Thus it seems that it was not the amount of ground vegetation which affected the sink, but a more relevant factor could have been the coverage of mosses vs. that of vascular plants within the collar, especially that of the forest mosses *Pleurozium schreberi* and *Dicranum polysetum*, which were particularly abundant in the highly oxidizing chambers #2 and #5. Due to the small number of chambers, however, the relationship between the forest floor vegetation and the CH_4 exchange may be coincidental and can only be speculated.

4.2.4 Diurnal variation

All the chambers recorded diurnal variation in CH_4 flux at some time in during the study period with most of the variation observed during late spring and early summer. In the beginning of June 2011 Typically, CH_4 uptake was at its highest during the early morningnight, and decreased towards while in June 2012 it was highest in the afternoon (Figs. 7 and 118). The diurnal variation was more common and occurred more often in all chambers in 2012, while in 2011 it occurred mostly in chamber #2. This variation usually ceased or was at least greatly diminished during and after rainfall events (Fig. 10), but usually appeared again after a couple of days. WTL as such, however, did not have an impact to the cycle, which suggests that the conditions in the soil surface were much more important for this phenomenon. The first half of June 2011 was dry and warm, whereas June 2012 was cooler (Fig. 8). In the first half of June 2011 the daytime temperatures reached as high as 30 °C and a strong diurnal pattern was observed with the highest uptake values observed early in the morning and the lowest in the afternoon. This diurnal variation ceased after mid-June 2011 with increased rainfall and decreased temperatures. In the beginning of June 2011, CH_4 oxidation in the afternoon might have been hindered due to high daytime temperatures, which likely resulted in a drier surface soil layer. In contrast, drying of the soil surface did not occur in summer 2012, and the CH_4 oxidation peaked in afternoon simultaneously with the soil temperature maximum. The cycle in summer 2012 had a similar pattern in regard to the highest and lowest uptake rates as has also been observed by Wang et al. (2013) in a Canadian mixed forest. In CH_4 emitting ecosystems, such as natural and experimental wetlands and in lakes, CH_4 emissions have been reported to peak in afternoon and reach their minimum at night (e.g. Mikkelä et al., 1995; Duan et al., 2005; Morin et al., 2014, Sun et al., 2014).

Although the diurnal variation seemingly followed the patterns in the air and soil surface temperatures, it was best explained by wind speed (WS) measured above the canopy (below canopy WS is not available). To study further this relationship, we tested the correlation between the parameter c_{exp} (Eq. 2) and WS. c_{exp} represents the curvature in the exponential fit, being negative whenever the concentration increase during a chamber closure shows a slowing shape. As we only selected

negative, i.e. uptake, fluxes here, it follows that a more negative c_{exp} indicates a higher curvature in the concentration evolution. Should leaking be responsible for the smaller CH_4 uptake during daytime as the observed relationship between WS and CH_4 exchange implied, it would be logical to find higher curvatures with higher WS. Such a relationship was recently found by Pirk et al. (2016) for CH_4 emission chamber flux data from pristine peatlands. However, we did not observe such a relationship in our CH_4 uptake data. For example, in chamber #2, in which the diurnal cycle was most explicit, an increasing c_{exp} was determined for most of the studied periods (Figs. S28-S40). There were only a few chambers and periods when c_{exp} decreased with increasing WS. Thus we must conclude that the diurnal variation in our data is related to the technical operation of the chamber rather than environmental conditions. Nevertheless, as the temperature and WS correlated strongly, it is possible that some of the observed pattern was due to some microbial or environmental factor.

We hypothesize that, rather than chamber leaking, the main underlying factor for the clear negative correlation between wind speed and CH_4 uptake is related to changes in the soil storage and thus the changes imposed by chamber closure to the concentration gradient within the top soil and the adjacent air layer. Prior to the closure, this gradient is controlled by atmospheric mixing and hence strongly affected by the ambient wind speed. During a calm night with a cool soil surface, turbulent mixing is strongly suppressed and molecular diffusion gains importance, while windy and sunny conditions result in much smaller vertical gradients due to vigorous turbulence that is also able to perturb the top-soil pore space. After the chamber is closed, the concentration gradient adjusts to the constant mixing generated by a fan. Thus, the change in concentration gradient depends on the mixing conditions that prevail above the target surface just before the chamber is introduced and how these relate to the mixing rate of the chamber headspace air. In the nocturnal case outlined above, mixing is enhanced after the chamber closure, resulting in a higher CH_4 uptake in the chamber.

The absence of the diurnal cycle in winter, and during and after the rain in summer, can be explained by the increased soil moisture content, which decreases the air-filled pore space in soil, thus hampering the wind-induced mixing effect at the soil–atmosphere interface and by slowing down the diffusion rate (Pirk et al., 2016).

It should be noted that the situation is different when CH_4 exchange is measured above a forest canopy with the EC method. In that case, the measurement does not significantly disturb atmospheric mixing and increased mechanical turbulence potentially enhances vertical gas exchange. Such positive correlation between the downward CH_4 flux and wind speed, with higher sinks during the daytime, has been reported by Wang et al. (2013). This is consistent with the results of our fan-speed test, described in Koskinen et al. (2014) who measured CO_2 respiration by the same chamber system. The CH_4 flux data from the same test showed a higher CH_4 uptake with higher fan speed (data not shown).

A wind-induced diurnal cycle suggests that the chamber construction could be improved by making the fan speed vary as a function of the ambient wind speed, so as to mimic the variations in atmospheric mixing. However, we can expect that the systematic bias resulting from the wind response is minimized when employing automated sampling that facilitates continuous measurements. Our results imply that sporadic sampling with manual chambers, which is typically limited to the

daytime, would have resulted in lower uptake estimates for this site than the extensive data collected with our automatic system.

~~During periods of a discernable diurnal cycle, the daily range of observed fluxes could vary by as much as 20 μg CH_4 m^{-2} h^{-1}. This would suggest that determining CH_4 exchange for longer periods from only daytime measurements using, for example, manual chambers, could cause a significant bias in annual balance calculations. However, when the flux is correlated with temperature, the flux can be modeled with temperature as an explanatory variable to decrease the bias (e.g. Ojanen et al., 2010). If measurements take place only during the growing season and these are then used to estimate annual CH_4 exchange it may result in an overestimation of the sink. We tested this by taking one daytime measurement from each chamber every second week, allowing a few days and a few hours of random variation around this two week time step. This provided a selection of multiple datasets for the same time period. Annual CH_4 exchange was calculated using linear interpolation between the points, as is often done when using manual chamber data. The resulting values were compared to CH_4 exchange calculated from our automatic chamber measurements (Fig. 3). The decreased measurement interval underestimated CH_4 uptake by 11–54 % (average 30±3 %) depending on the chamber.~~

4.3 Driving factors for the CH_4 efflux

~~In this study,~~ The seasonal CH_4 fluxes correlated best with ~~the~~ soil temperatures ~~measured~~ at the depths of 20 cm and 30 cm~~, and WTL~~, but significant correlations occurred also ~~-~~with ~~air, soil surface and~~ soil temperatures at other depths for most of the study period (Table 4). The correlations with air and soil surface temperatures were lower. ~~of 2 cm and 5 cm during summer and autumn.~~ The correlations were always negative, indicating that higher temperatures promoted the soil CH_4 uptake. This observation could be attributed to increased consumption of CH_4 by methanotrophs in higher temperatures that enhance methanotrophic activity (e.g. Mohanty et al., 2007). However, it is likely that in addition to – or even instead of – the increased methanotrophic activity, there are other reasons behind this relationship. The covariation of temperature with other variables, such as ground water level and phenology, all typically peaking in July–August, may lead to spurious correlation between temperature and CH_4 flux. Indeed, the flux was also correlated with WTL, the correlation being significantly positive (higher uptake with lower WTL) in spring, summer and autumn, but negative in winter. At our site, the soil layers most favourable for methane production and oxidation are located at clearly different depths in the soil, the first being found below the water table and the latter much closer to the soil surface (A. Putkinen, unpublished data). Both of these have distinct temperature and moisture responses, which are practically impossible to disentangle by examining the net CH_4 flux observed at the surface.

In addition to the correlations found in the hourly data, we found evidence that lowering WTL increases the daily CH_4 uptake in the latter part of summer, when WTL < –40 cm (Fig. 9). In the beginning of the summer, the daily fluxes were

better explained by the soil temperature, while after the mid-July the WTL overshadowed the temperature as a control of the daily fluxes.

In pristine peatlands, temperature has been shown to correlate positively with the CH_4 emission rate (e.g. Mikkelä et al., 1995; Bellisario et al., 1999; Mastepanov et al., 2013). In drained peatland forests, significant correlations between CH_4 flux and temperature have been found in CH_4-emitting ecosystems (Nykänen et al., 1998; Minkkinen and Laine, 2006), although the direction of the correlation has been found to differ between fens and bogs. In contrast, no significant correlations with temperature were found in peatland forests that mainly showed CH_4 uptake (Ojanen et al., 2010; Wang et al., 2013). Both CH_4 emission and uptake have been found to correlate with WTL (e.g. Bellisario et al., 1999; Ojanen et al., 2010).~~CH_4 fluxes (both emission and uptake) have been found to correlate with WTL in many studies (Mikkelä et al., 1995; Bellisario et al., 1999; Ojanen et al., 2010; Mastepanov et al., 2013). Here we found evidence that WTL controls the CH_4 flux, particularly when WTL < 40 cm, showing increased CH_4 uptake rates with deeper WTL. Due to the likely co-correlation of WTL and soil temperature, both typically peaking in July, determination of the exact contribution of these variables on CH_4 flux is not straightforward. However, from the analysis shown in Figs. 6a–c it seems likely that the influence of WTL in controlling the CH_4 exchange is more pronounced at deeper WTL. First, this might be attributed to a decrease in CH_4 emissions from the deeper layers; a logical consequence of the drawdown of the anoxic peat layer suitable for CH_4 production. On the other hand, increased net CH_4 uptake could be caused by increased CH_4 oxidation due to the increase of the oxic peat layer. The observed negative correlation between the flux rate and soil temperature suggests increased consumption of CH_4 by methanotrophs as it is known that increasing soil temperature enhances methanotrophic activity (e.g. van den Pol-van Dasselaar et al., 1998; Mohanty et al., 2007). In other studies, significant correlations between CH_4 flux and temperature have typically been found in ecosystems that display CH_4 emissions (Nykänen et al., 1998, Minkkinen & Laine, 2006), although the direction of the correlation has been found to differ in fens and bogs, respectively. In contrast, no significant correlations with temperature have been found in peatland forests that mainly show CH_4 uptake (Ojanen et al., 2010; Wang et al., 2013). In pristine peatlands, temperature has been shown to correlate positively with the CH_4 emission rate (e.g. Mikkelä et al., 1995; Bellisario et al., 1999; Mastepanov et al., 2013). As the net CH_4 flux is a result of production and oxidation, which both show a positive temperature response and a variable response in respect to WTL; it is not evident how the net CH_4 flux should respond to changing environmental conditions. At our site, the increasing temperature seemed to favor CH_4 uptake, and WTL had an additional control on the net uptake after the WTL had dropped below a certain threshold.~~

In addition to temperature, WTL and WS, CH_4 flux~~uptake~~ has been found to correlate with ~~wind speed (Wang et al., 2013) and~~ tree stand volume (Ojanen et al., 2010; Minkkinen et al., 2007), which is, on the other hand, an indirect measure of the WTL. Also, PAR has ~~also~~ been observed to correlate positively with CH_4 emissions in a *Sphagnum*-dominated mixed mire (Mikkelä et al., 1995). In this study, however, the correlations with PAR were low or absent., ~~although u* correlated~~

~~positively with the flux in some chambers in summer 2011 and also with the longer time periods when the flux data was grouped into u* classes of 0.05 m s^{-1}. This correlation with u* means that when the wind speed increased, the uptake of CH_4 decreased, which is in contrast to the findings of Wang et al. (2013) in Ontario, Canada. At our site, it is likely that there is CH_4 production deep in the soil (Pihlatic et al., 2010), but the CH_4 is oxidized by methanotrophic bacteria at the soil surface for most of the year and, additionally, are able to consume atmospheric CH_4. It is possible that with stronger winds the concentration gradient is mixed deeper in the soil, thus bringing more CH_4 from the deep soil layers to the atmosphere more rapidly, and the produced CH_4 is able to bypass oxidation by the bacteria.~~

5 Conclusions

In this paper, we have presented a two-year data set of CH_4 exchange measured at the forest floor of a boreal forestry-drained fen. These results show that automated chamber measurements with an accurate on-line gas analyzer make it possible to observe small CH_4 fluxes even during the winter with snow cover. Although the fluxes at our site were relatively low throughout the year, we succeeded in catching the annual cycle in the CH_4 uptake. Our results indicate that the forest floor of this peatland site acted as a small annual CH_4 sink (mean balance –0.22 g CH_4 m^{-2} yr^{-1}), although completing the balance with the emissions from ditches indicates that the site is likely to be a small CH_4 source.

In spite of the low flux detection limit of the measurement system, our results indicate that it is necessary to pay attention to the flux calculation methods, and instead of choosing between linear and exponential fits we decided on a combination of both. Even though the fit based on linear regression was observed to typically result in a smaller flux than an exponential fit, its use was justified for low fluxes by showing that it produced more robust estimates when the concentration change during chamber closure was small and thus more affected by measurement noise. In addition, we demonstrated that both the length of the fitting period and the starting time of this window had a significant effect on the flux estimates and thus cannot be selected arbitrarily.

The CH_4 uptake, measured with closed chambers, was observed to correlate with wind speed, and caused a corresponding diurnal cycle. However, this was partly attributed to aerodynamic effects due to chamber closure, which are dependent on atmospheric mixing prior to the closure. Thus, the chamber construction could be potentially improved by adjusting the chamber fan speed according to the ambient wind speed. As this variation is partly related to changes in the soil CH_4 storage, the error introduced in the annual balance estimated from short-term fluxes can be diminished by continuous measurements fully covering the diurnal cycle. Continuous long-term measurements also facilitate the analysis of the environmental factors that control CH_4 exchange. However, in order to understand the biological processes involved in CH_4 production and oxidation, i.e. the processes behind the net CH_4 flux observed, additional measurements are necessary, focusing on the production and oxidation potentials and the within-soil gas gradients.

Since the considerations of the measurement system performance are site- and system-specific, we recommend that any future study should address the procedures involved in flux calculation, including the fitting method and the length and delay of the fitting period, based on the analysis presented above. In particular, we recommend using the flux limit method applied in this study, i.e. using linear regression for low fluxes and exponential regression for fluxes above a threshold to be determined. ~~This study presents two years of CH_4 exchange data measured by six soil chambers in a forestry drained peatland. With the use of an accurate and precise gas analyzer, we were able to observe small CH_4 fluxes even during winter. Over the two year period, CH_4 exchange from the different chambers varied from −31.8 to −154.2 mg CH_4 m^{-2} yr^{-1} (average −67 mg CH_4 m^{-2} yr^{-1}). The site acted as a small annual CH_4 sink, although the effect of CH_4 emissions from the ditches was uncertain and it is possible that the site could be a small annual CH_4 source. There was clear seasonal variation in CH_4 flux and the site acted as a sink in summer. The sink decreased towards winter, and in early spring small periods of CH_4 emissions were recorded. In addition, diurnal variation was observed in summer, and the shape of the variation pattern varied between years. In summer 2011, the uptake was highest in the morning, but was highest in the afternoon in summer 2012. Net CH_4 uptake correlated best with soil temperature, especially at 20 and 30 cm depths, and also with WTL, showing increased CH_4 uptake with higher temperatures and lower WTL. Both linear and exponential regressions were used to calculate CH_4 fluxes, and like many studies before, we found that linear regression gave systematically lower flux estimates than the exponential regression. However, exponential regression was less useful for the estimation of low fluxes (sink/source < 3.5 μg CH_4 m^{-2} h^{-1}) due to the sensitivity of that regression method to signal to noise ratio. Therefore, we recommend using the flux calculated from linear regression on these low fluxes and the flux calculated from exponential regression when the flux is higher than the threshold. This threshold is dependent on the measurement system and cannot be generalized.~~

Data availability

The measured flux and meteorological data will be made available through European Fluxes Database Cluster (http://gaia.agraria.unitus.it/home).

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Table 1. CN ratio, bulk density and ash content (±SD) of the peat at Lettosuo (n=4).

	C/N ratio	Bulk density (g cm^{-3})	Ash content (%)
Humus	29.2 ± 1.8	0.005 ± 0.003	3.1 ± 0.4
0–10 cm	23.9 ± 1.0	0.107 ± 0.014	6.5 ± 1.5
10–20 cm	24.3 ± 0.7	0.170 ± 0.011	3.4 ± 0.4

Table 21: Ground vegetation in each chamber and , all-sided maximum vascular green area (VGA_{max}, m^2 vascular green surface m^{-2} forest floor) and coverage (%) of forest mosses (C_{FM}) and *Sphagnum* mosses (C_{SP}).

Chamber	Vegetation	VGA_{max}	C_{FM}	C_{SP}
1	*Pleurozium schreberi* *Dicranum polysetum* *Vaccinium myrtillus*	2.04	56	0
2	*Pleurozium schreberi* *Dicranum polysetum* *Vaccinium vitis-idaea*	0.85	60	0
3	*Maianthemum bifolium* *Pleurozium schreberi* *Dicranum polysetum*	0.01	3	0
4	*Dryopteris carthusiana* Vaccinium myrtillus *Vaccinium vitis-idaea* *Pleurozium schreberi* *Dicranum polysetum*	2.34	26	0
5	*Pleurozium schreberi* *Dicranum polysetum*	0.11	30	0
6	*Sphagnum girgensohnii*	-	0	90

Table 32: a) Seasonal (summer=JJA, autumn=SON, winter=DJF, spring=MAM) averages of CH_4 flux (μg CH_4 m^{-2} h^{-1}) calculated with linear ('linear flux') and exponential regression ('exponential flux') with 95 % confidence intervals (±). The ~~lowest row~~difference shows how much smaller the linear ~~CH_4~~ flux was on average when compared to the exponential ~~CH_4~~ flux. ~~Values~~ The data include the fluxes measured by all ~~the~~ six chambers with a 6 min closure time. ~~b) Same as in (a) but only includes fluxes with values > 3.5 μg CH_4 m^{-2} h^{-1}~~

~~a)~~

	Summer 2011	Summer 2012	Autumn 2011	Autumn 2012	Winter 11-12	Winter 12-13	Spring 2011	Spring 2012	4/11-3/13
Mean linear flux	-38.9 ±1.3	-28.7 ±0.6	-39.0 ±1.2	-31.3 ±0.4	-18.1 ±0.7	-4.5 ±0.1	-6.8 ±0.5	-9.5 ±0.4	-18.6 ±0.2
Mean exponential flux	-45.1 ±1.5	-32.2 ±0.7	-44.9 ±1.3	-34.9 ±0.4	-21.0 ±5.3	-4.8 ±5.2	-25.9 ±26.5	-12.3 ±1.2	-22.3 ±0.4
Number of closures	1558	3685	1477	10642	1597	12209	3180	10272	48182
Difference (%)	14.4 ±0.5	11.7 ±0.3	14.2 ±0.5	10.9 ±0.2	24.9 ±1.0	38.9 ±0.8	44.4 ±1.5	38.2 ±1.0	27.5 ±0.3

	~~Summer 2011~~	~~Summer 2012~~	~~Autumn 2011~~	~~Autumn 2012~~	~~Winter 11-12~~	~~Winter 12-13~~	~~Spring 2011~~	~~Spring 2012~~	~~4/11-3/13~~
~~Mean linear flux~~	~~-12.4 ±0.2~~	~~-9.5 ±0.3~~	~~-12.5 ±0.2~~	~~-9.1 ±0.2~~	~~-5.8 ±0.2~~	~~-0.9 ±0.1~~	~~-2.9 ±0.1~~	~~-3.1 ±0.2~~	~~-7.2 ±0.1~~
~~Mean exponential flux~~	~~-15.5 ±0.2~~	~~-12.2 ±0.4~~	~~-15.4 ±0.2~~	~~-11.3 ±0.2~~	~~-8.5 ±0.4~~	~~-2.6 ±0.6~~	~~-5.8 ±0.5~~	~~-5.4 ±0.5~~	~~-9.8 ±0.1~~
~~Number of closures~~	~~9114~~	~~2962~~	~~8376~~	~~8354~~	~~7228~~	~~7292~~	~~6338~~	~~4987~~	~~56579~~
~~Difference (%)~~	~~21.7 ±0.4~~	~~23.8 ±0.9~~	~~19.0 ±0.3~~	~~21.4 ±0.5~~	~~37.0 ±0.8~~	~~59.5 ±0.9~~	~~50.4 ±0.9~~	~~47.2 ±1.0~~	~~35.3 ±0.3~~

~~b)~~

	~~Summer 2011~~	~~Summer 2012~~	~~Autumn 2011~~	~~Autumn 2012~~	~~Winter 11-12~~	~~Winter 12-13~~	~~Spring 2011~~	~~Spring 2012~~	~~4/11-3/13~~
~~Mean linear flux~~	~~-13.1 ±0.2~~	~~-10.4 ±0.3~~	~~-12.7 ±0.2~~	~~-9.8 ±0.1~~	~~-8.4 ±0.2~~	~~-3.2 ±1.0~~	~~-6.0 ±0.2~~	~~-7.4 ±0.4~~	~~-10.8 ±0.1~~
~~Mean exponential flux~~	~~-16.1 ±0.2~~	~~-13.3 ±0.3~~	~~-15.6 ±0.2~~	~~-12.1 ±0.2~~	~~-11.9 ±0.4~~	~~-4.6 ±3.3~~	~~-9.1 ±0.5~~	~~-10.3 ±0.6~~	~~-13.7 ±0.1~~
~~Number of closures~~	~~8538~~	~~2592~~	~~8252~~	~~7360~~	~~4738~~	~~512~~	~~2518~~	~~1765~~	~~36195~~

~~Difference (%)~~	~~20.1 ±0.3~~	~~21.1 ±0.7~~	~~18.5 ±0.3~~	~~19.3 ±0.4~~	~~27.3 ±0.6~~	~~35.1 ±3.1~~	~~32.7 ±1.0~~	~~30.3 ±1.0~~	~~22.1 ±0.2~~

Table 43: Average cCorrelation coefficients (r) between hourly methane (CH4) flux and environmental variables averaged forfrom six chambers during different seasons. **Bolded and underlined:** r values indicate that all six chambers had with p < 0.01,; **bolded:** values indicate that five chambers had with p < 0.01, underlined: numbers indicate that 4four chambers had with p < 0.01; *and cursive numbers indicate thatitalics*: 3 three chambers had with p < 0.01. AirT=air temperature, ST=soil surface temperature, PAR=photosynthetically active radiation, WS=wind speed u*=friction velocity measured above the canopy, Tx=soil temperature at a depth of x cm, WTL=water table level. For clarity, negative r-values typically denote situations where CH_4 uptake increases when the value of explaining variable increases. The season definitions are the same as in Table 3.

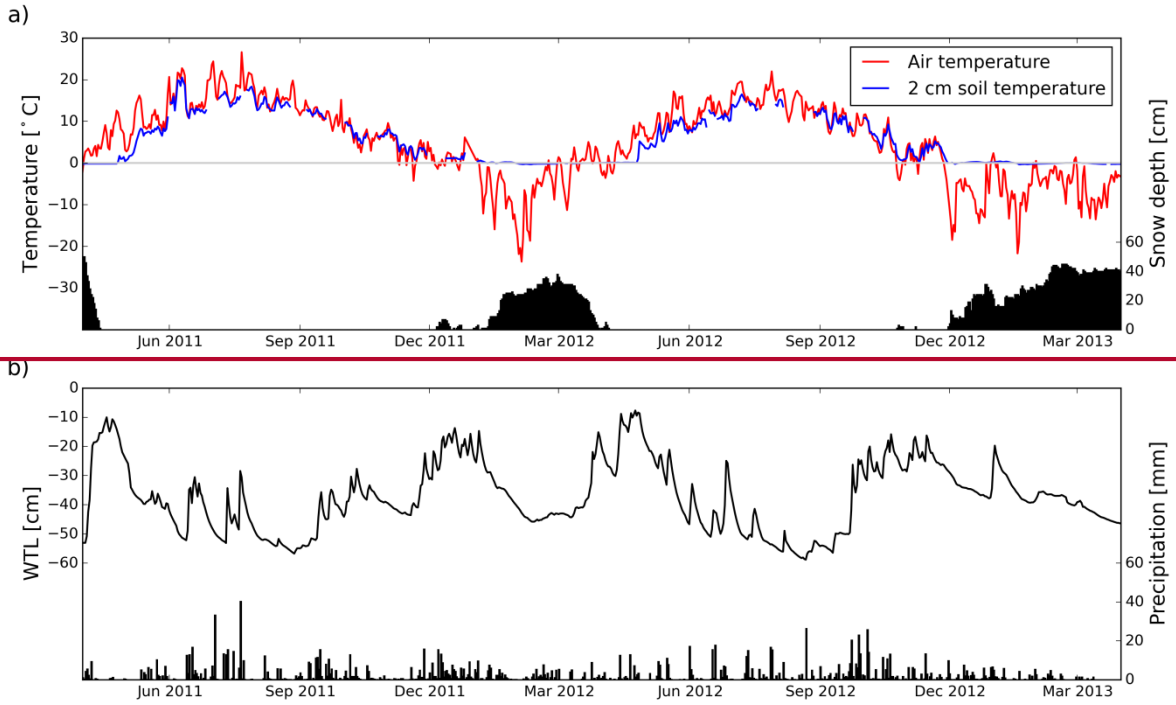
Season	AirT	ST	PAR	WS	T2	T5	T10	T20	T30	WTL*
Spring 2011	-0.03	**-0.04**	*-0.18*	-0.08	**-0.41**	**-0.52**	**-0.61**	**-0.67**	**-0.70**	**0.52**
Summer 2011	-0.05	*0.05*	**0.17**	**0.30**	0.08	**-0.26**	**-0.37**	**-0.54**	**-0.61**	**0.60**
Autumn 2011	**-0.19**	**-0.16**	0.16	**0.40**	**-0.19**	**-0.19**	**-0.2**	**-0.21**	**-0.22**	**0.39**
Winter 11-12	**-0.34**	**-0.23**	-0.17	*-0.05*	**-0.70**	**-0.75**	**-0.59**	**-0.83**	**-0.83**	**-0.83**
Spring 2012	**-0.48**	**-0.57**	0.00	**0.15**	**-0.69**	**-0.74**	nd	**-0.82**	**-0.82**	**0.47**
Summer 2012	-0.16	-0.17	0.14	**0.21**	**-0.30**	**-0.42**	nd	**-0.60**	**-0.65**	**0.59**
Autumn 2012	**-0.47**	**-0.53**	**0.11**	**0.28**	**-0.58**	**-0.61**	**-0.45**	**-0.64**	**-0.64**	**0.60**
Winter 12-13	**0.29**	**0.37**	*0.07*	0.02	**-0.37**	**-0.73**	**-0.79**	**-0.79**	**-0.79**	**-0.35**

*Negative WTL denotes water level below the soil surface, i.e. positive correlation results from increasing uptake with decreasing WTL.

nd = not determined

Season	AirT	ST	PAR	U*	T2	T5	T10	T20	T30	WTL*
Spring 2011	0.15	0.08	*-0.17*	-0.07	-0.22	**-0.33**	**-0.44**	**-0.53**	**-0.56**	**0.38**
Summer 2011	**0.04**	**0.12**	0.09	**0.25**	**0.17**	-0.16	**-0.27**	**-0.47**	**-0.55**	**0.49**
Autumn 2011	**-0.24**	**-0.17**	-0.06	**0.18**	**-0.14**	**-0.13**	-0.02	**-0.12**	**-0.14**	**0.31**
Winter 11-12	**-0.31**	**-0.20**	-0.09	-0.04	**-0.52**	**-0.56**	-0.11	**-0.63**	**-0.63**	**-0.63**
Spring 2012	**-0.43**	**-0.46**	-0.18	-0.04	**-0.46**	**-0.46**	*-0.07*	**-0.45**	**-0.46**	*0.04*
Summer 2012	**-0.50**	**-0.49**	-0.11	-0.09	**-0.52**	**-0.50**	0.04	**-0.46**	**-0.50**	**0.50**
Autumn 2012	**-0.54**	**-0.57**	0.11	0.10	**-0.58**	**-0.58**	**-0.14**	**-0.57**	**-0.56**	**0.60**
Winter 12-13	*0.05*	0.19	0.07	-0.05	-0.16	**-0.36**	**-0.42**	**-0.43**	**-0.43**	-0.11

*Negative WTL denotes water level below the soil surface, i.e. positive correlation results from increasing uptake with decreasing WTL.


a)
Temperature [˚C]
Snow depth [cm]
Air temperature
2 cm soil temperature
Jun 2011
Sep 2011
Dec 2011
Mar 2012
Jun 2012
Sep 2012
Dec 2012
Mar 2013
b)
WTL [cm]
Precipitation [mm]

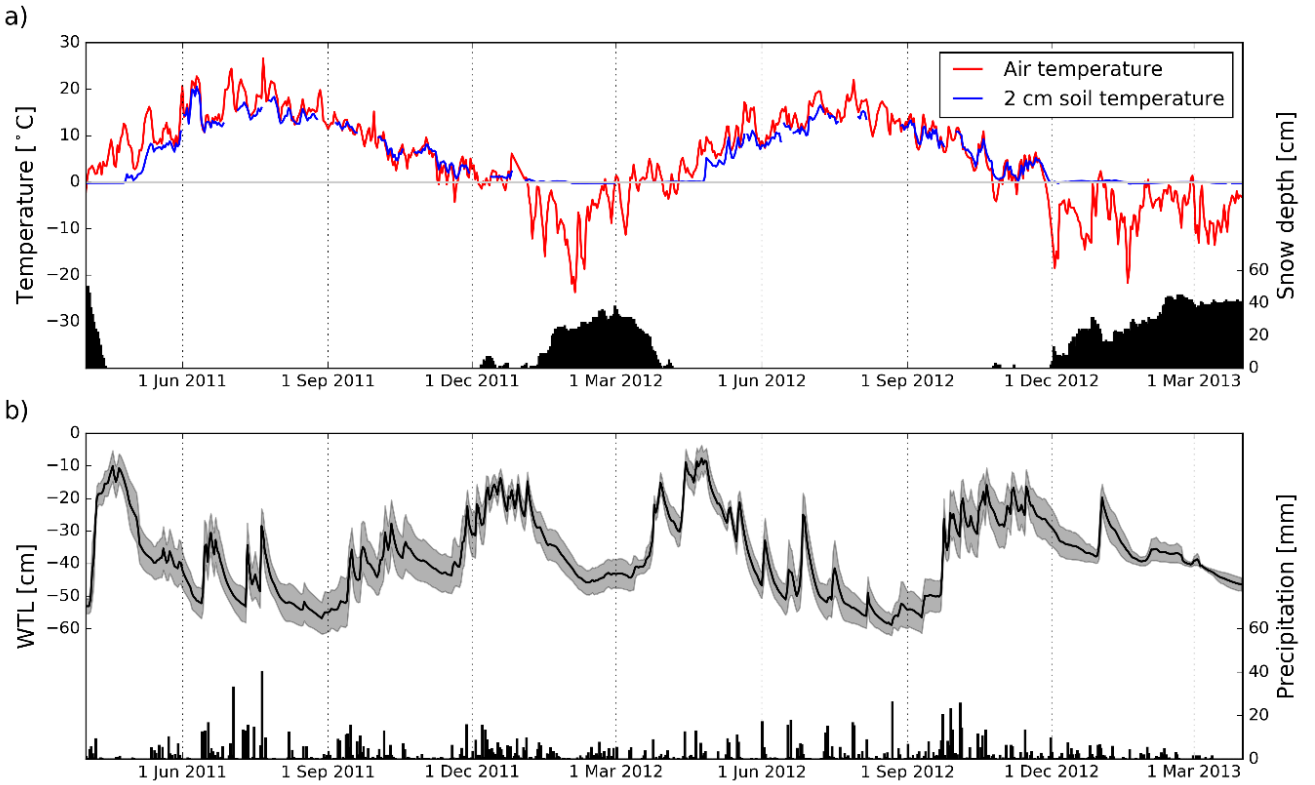
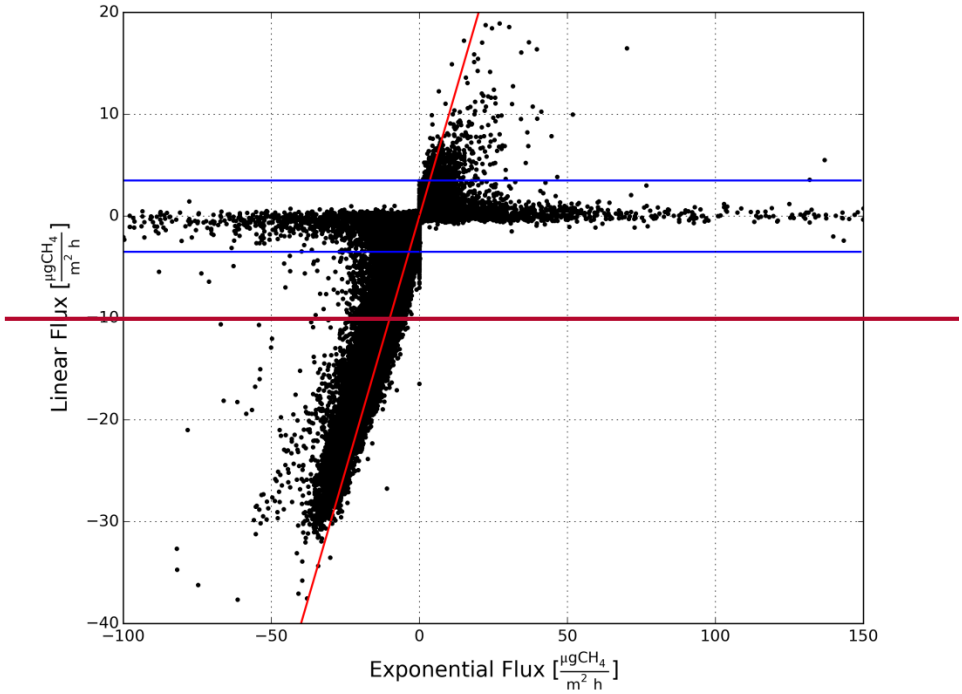
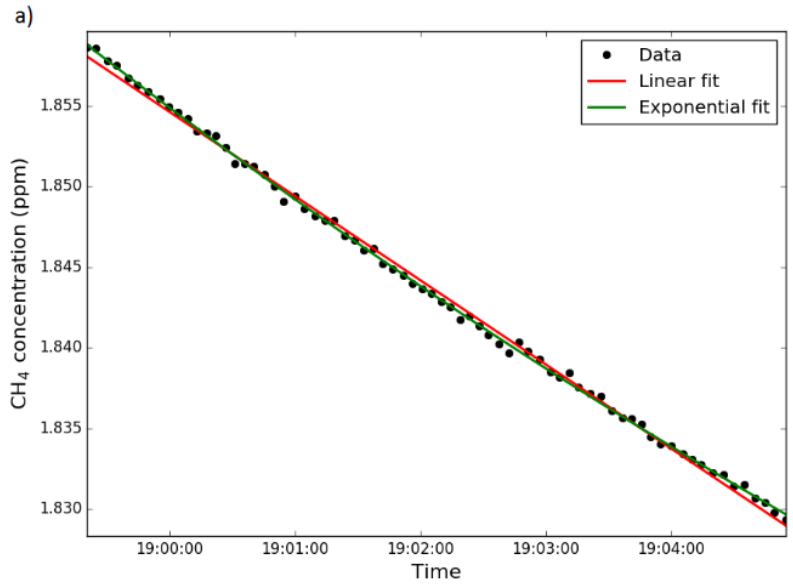


Figure 1: (a) The daily mean of air temperature (red) and soil temperature at 2 cm depth (blue) ~~measured above the canopy~~ at ~~the site~~Lettosuo during the measurement period (1 April 2011 to ~~end of~~31 March 2013), and the daily snow depth (bars) measured at the nearby Jokioinen observatory. (b) The daily mean water table (WTL) (line) and its standard deviation (shading) from four different points at ~~the site~~Lettosuo and the daily precipitation (bars) measured at ~~the~~ Jokioinen ~~observatory~~.



~~**Figure 2: Flux based on linear regression (Linear Flux) versus flux based on exponential regression (Exponential Flux) over the two year measurement period. Red line describes the 1:1 relationship and blue lines are the ±3.5 µg CH_4 m^{-2} h^{-1} limits. If the datapoint was within the blue lines, linear regression was used instead of exponential regression.**~~



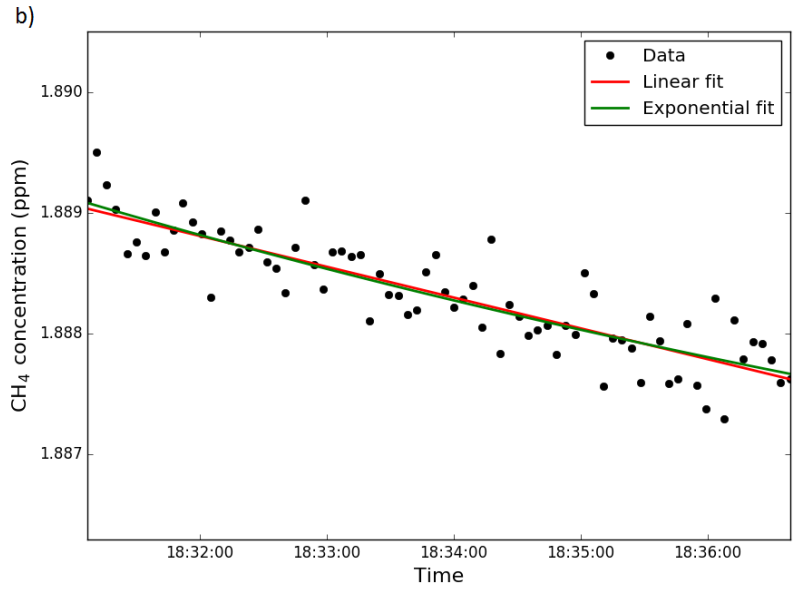


Figure 2: Concentration data during one chamber closure for a case with a higher (a: linear and exponential: -90 and 104 µg CH_4 m^{-2} h^{-1}, respectively) and lower (b: lin -3.5, exp -4.3 µg CH_4 m^{-2} h^{-1}) flux.

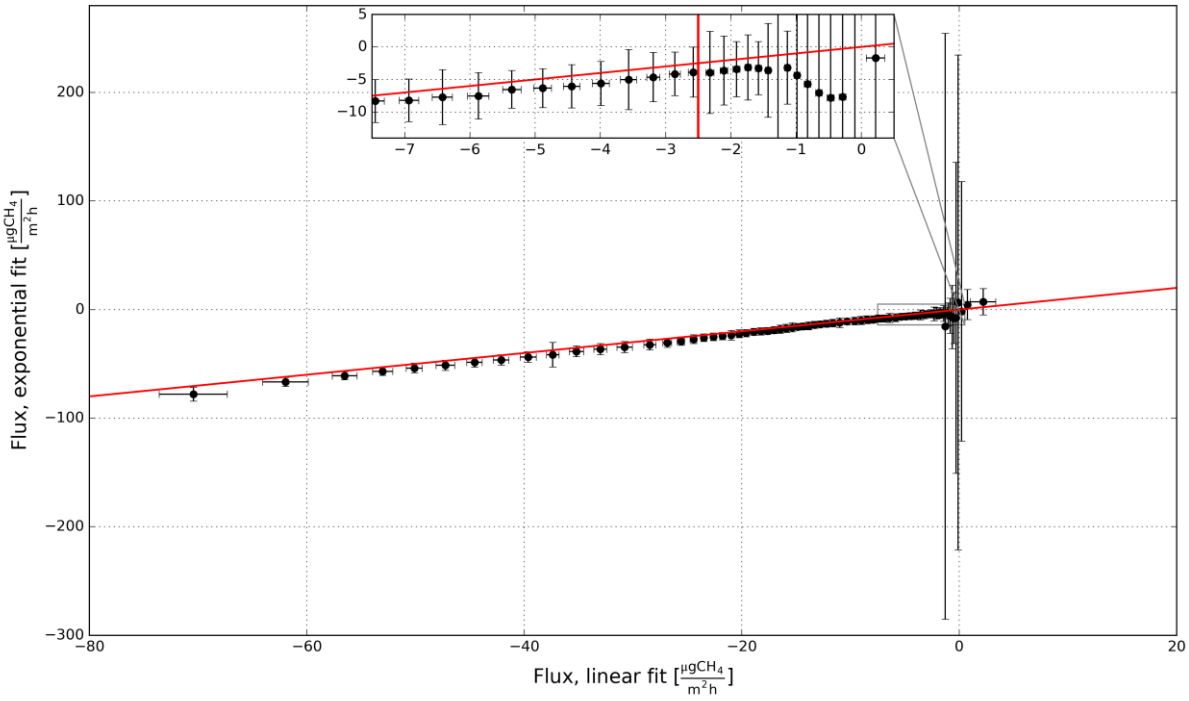
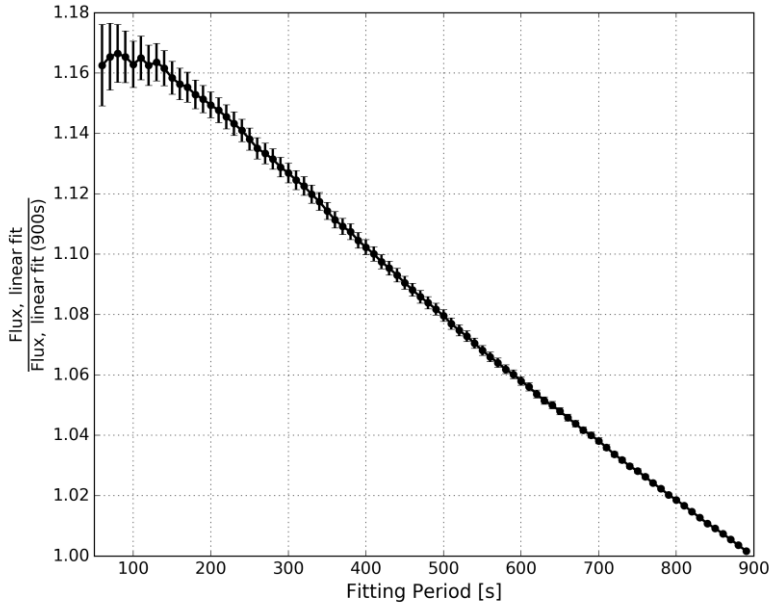


Figure 3: Bin averages (n=500) of the linear and exponential fluxes of the whole data set (6 min closures only). In the small zoom figure the red vertical line denotes the selected flux limit of 2.5 µg CH_4 m^{-2} h^{-1}. Vertical and horizontal error bars show the standard deviation of flux determined with the exponential and linear fit, respectively.

a)



b)

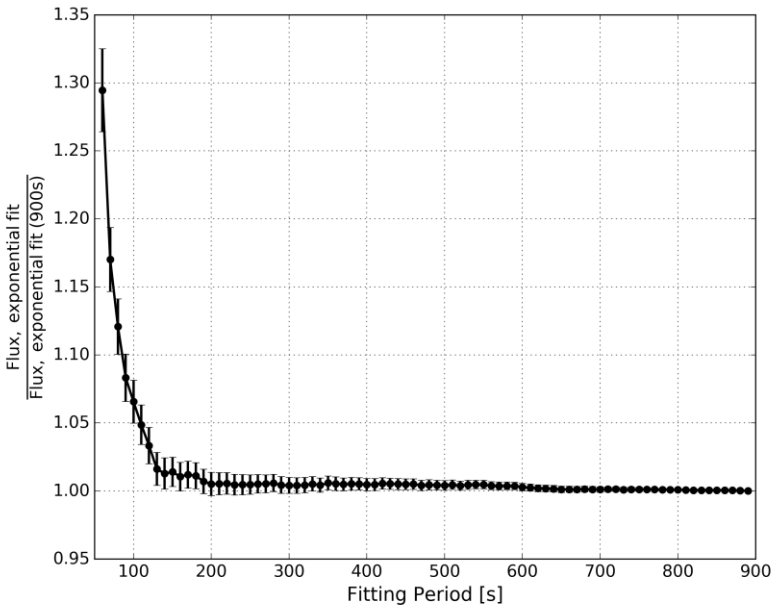


Figure 4: The linear (a) and the exponential flux (b) as a function of fitting period. The fluxes are scaled by the flux calculated with the longest fitting period (900 s). The error bars show the 95 % confidence intervals. The data are from summer 2012.

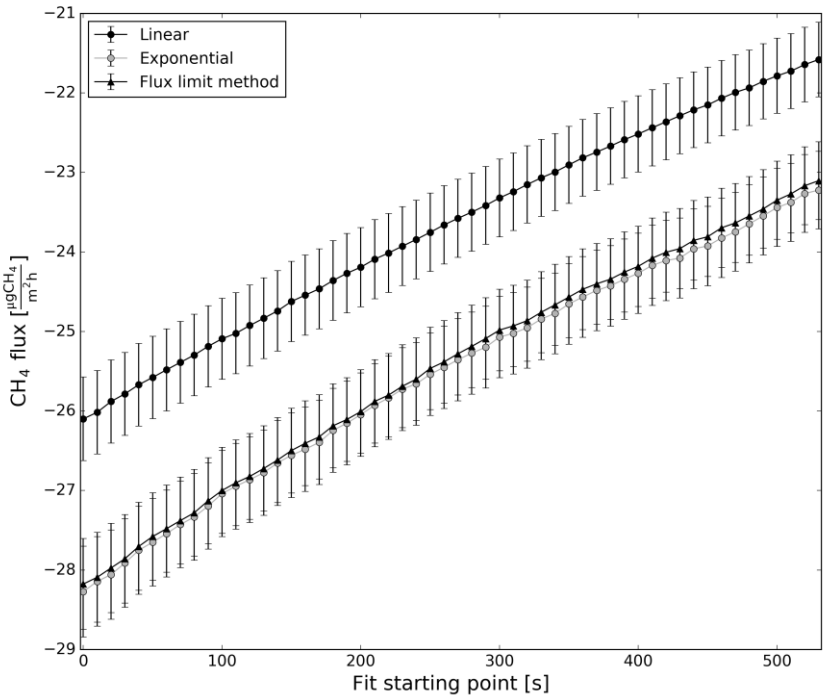
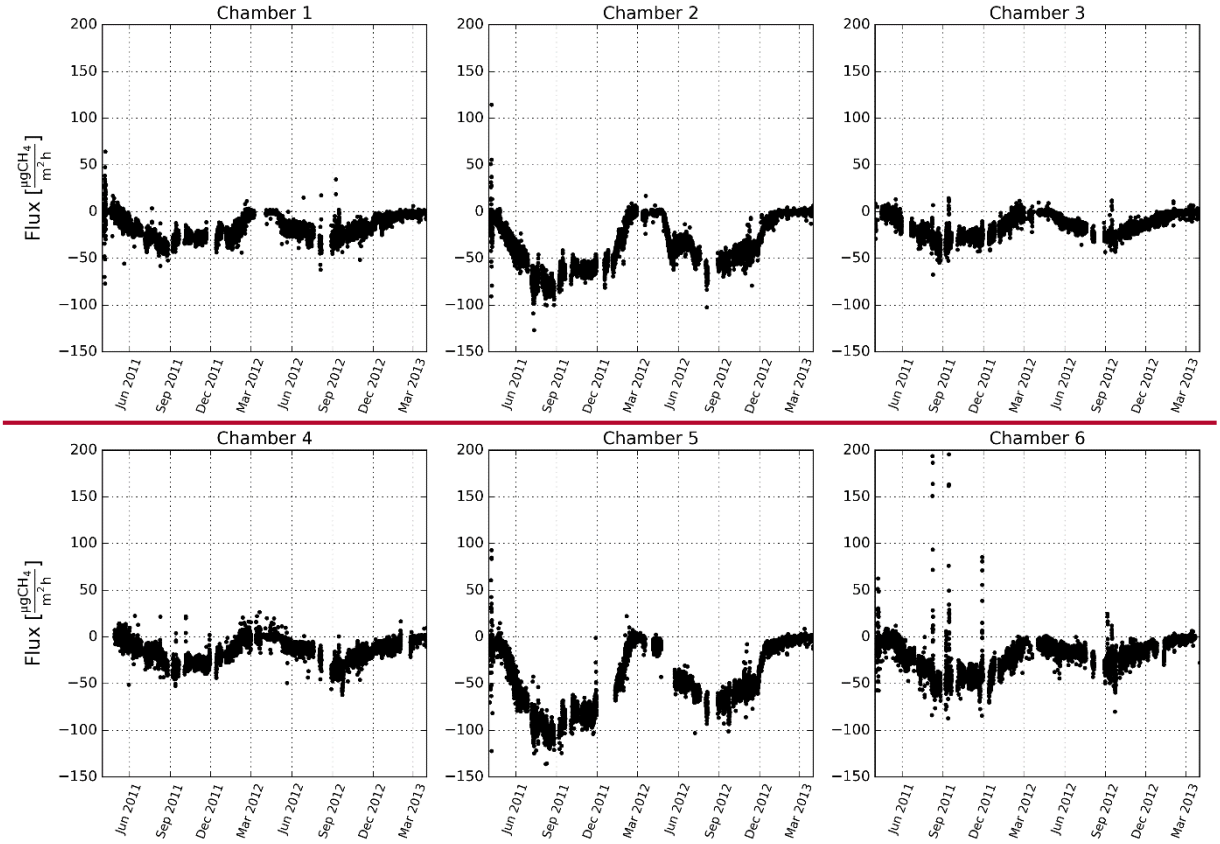


Figure 5: Fluxes calculated with the linear, exponential and 'Flux limit' methods using a 6 min fitting period with different starting points for the fits. The error bars show the 95 % confidence intervals. The data are from summer 2012.


Chamber 1
Chamber 2
Chamber 3
Chamber 4
Chamber 5
Chamber 6
Flux [μgCH4 / m²h]
200
150
100
50
0
−50
−100
−150
Jun 2011
Sep 2011
Dec 2011
Mar 2012
Jun 2012
Sep 2012
Dec 2012
Mar 2013

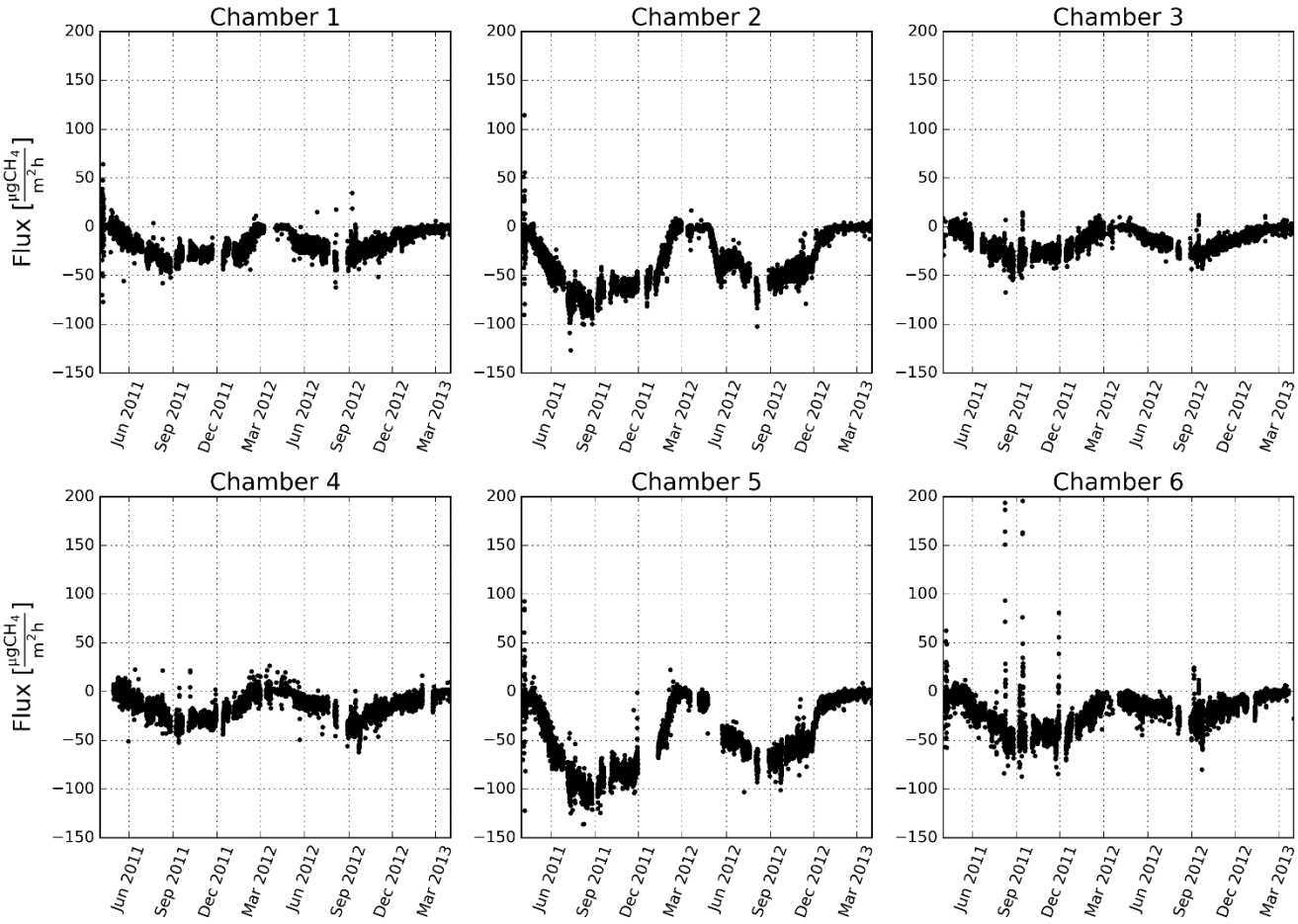
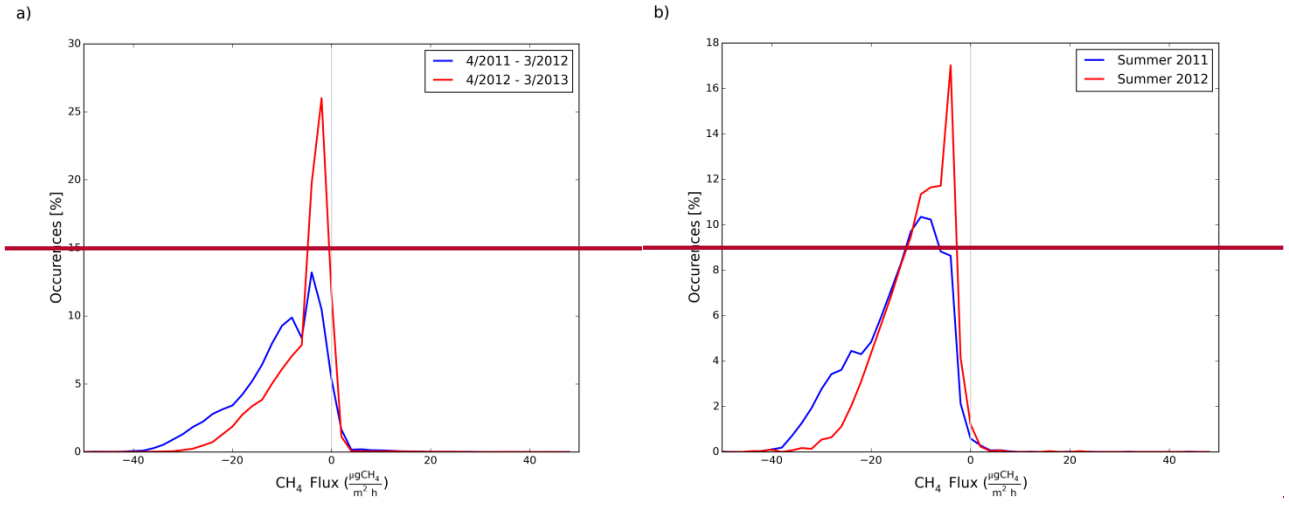
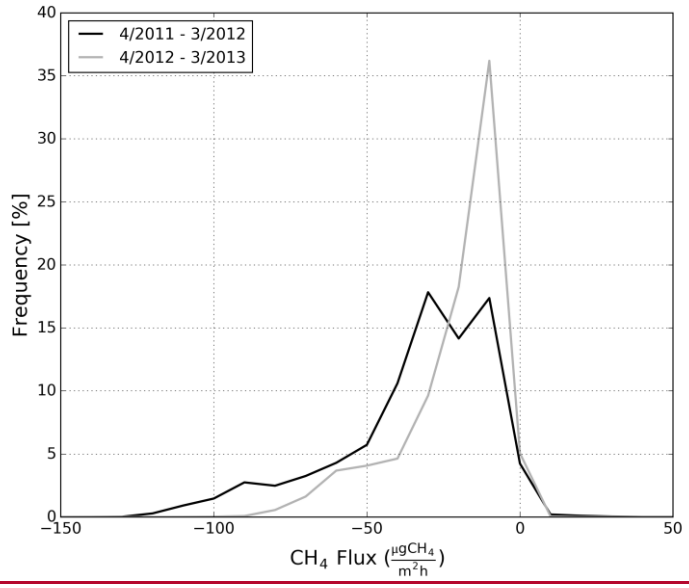


Figure ~~3~~6: Hourly ~~methane (~~CH_4~~)~~ fluxes from April 2011 to March 2013 measured in~~from~~ each chamber. Negative values indicate uptake by the soil, and positive values indicate emission to the atmosphere. Fluxes have been calculated using the exponential fit unless the value of the flux obtained from the linear fit was below ~~3~~2.5 µg CH_4 m^{-2} h^{-1}.


a)
4/2011 - 3/2012
4/2012 - 3/2013
Occurences [%]
CH4 Flux (μgCH4 / m² h)
b)
Summer 2011
Summer 2012
Occurences [%]
CH4 Flux (μgCH4 / m² h)

a)



b)

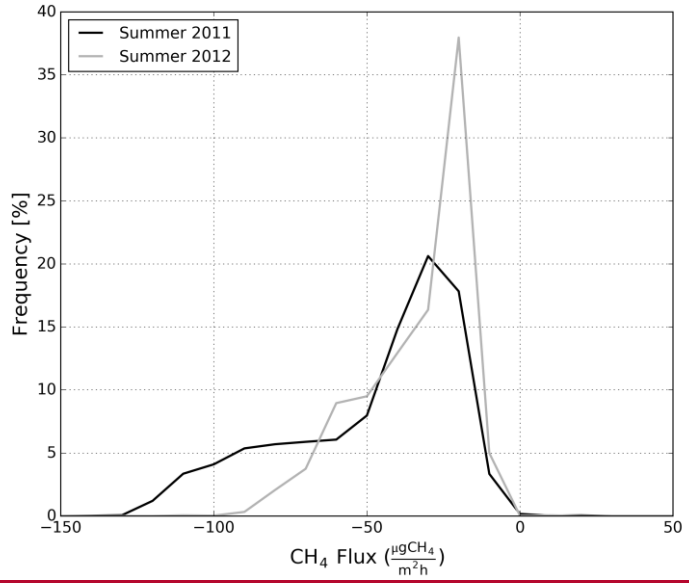
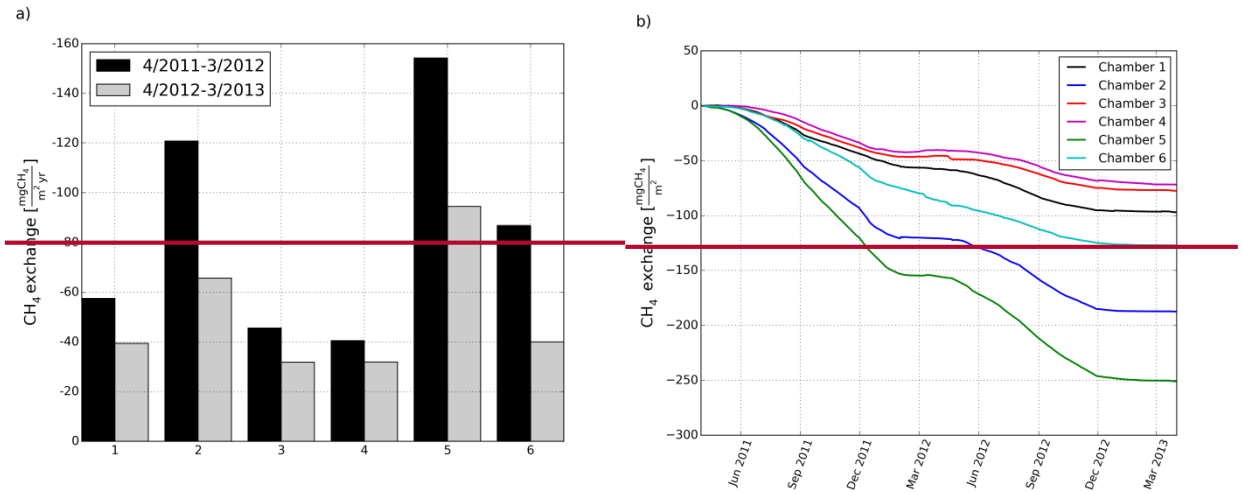


Figure ~~4~~7: The ~~flux rate~~frequency distribution of fluxes~~s~~ measured with all ~~the~~ chambers in (a) different years and (b) different summers. The flux~~ rates~~ es were grouped into classes of ~~2~~10 µg CH_4 m^{-2} h^{-1}.


a)
4/2011-3/2012
4/2012-3/2013
CH4 exchange [mgCH4 / m2 yr]
-160
-140
-120
-100
-80
-60
-40
-20
0
1
2
3
4
5
6
b)
Chamber 1
Chamber 2
Chamber 3
Chamber 4
Chamber 5
Chamber 6
CH4 exchange [mgCH4 / m2]
50
0
−50
−100
−150
−200
−250
−300
Jun 2011
Sep 2011
Dec 2011
Mar 2012
Jun 2012
Sep 2012
Dec 2012
Mar 2013

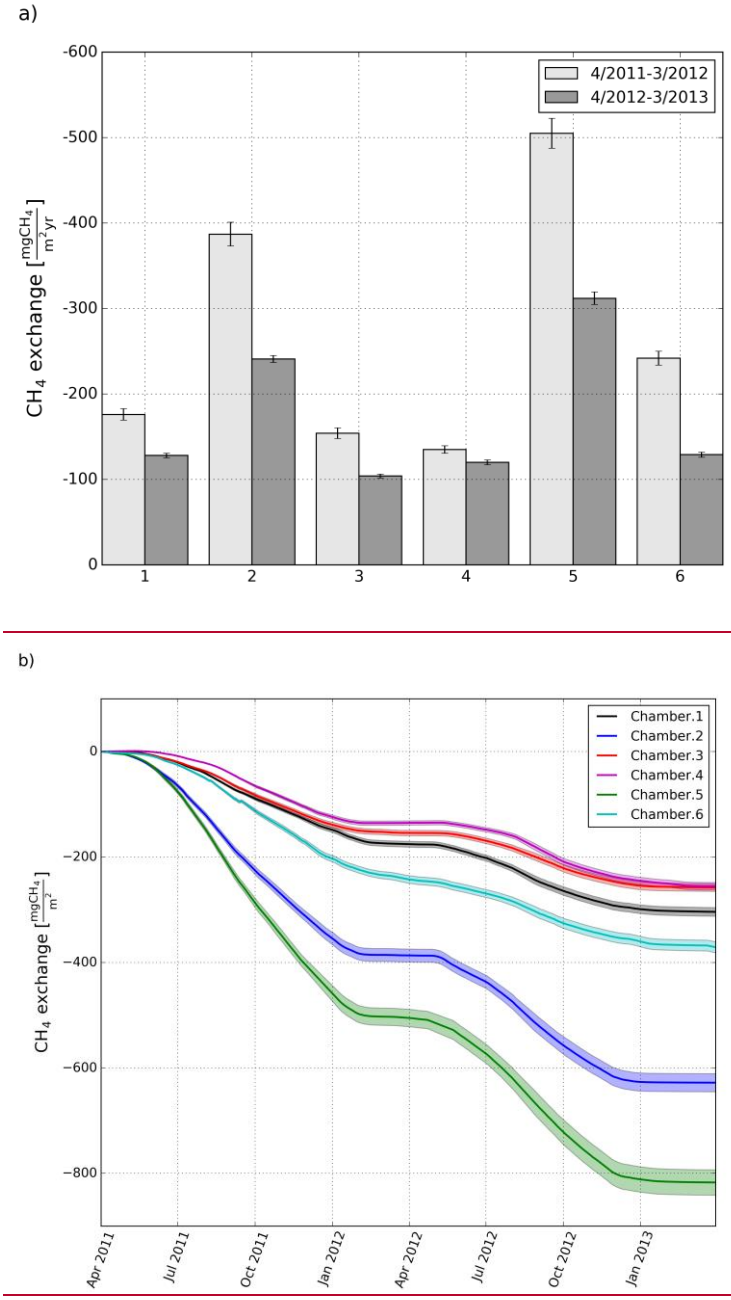
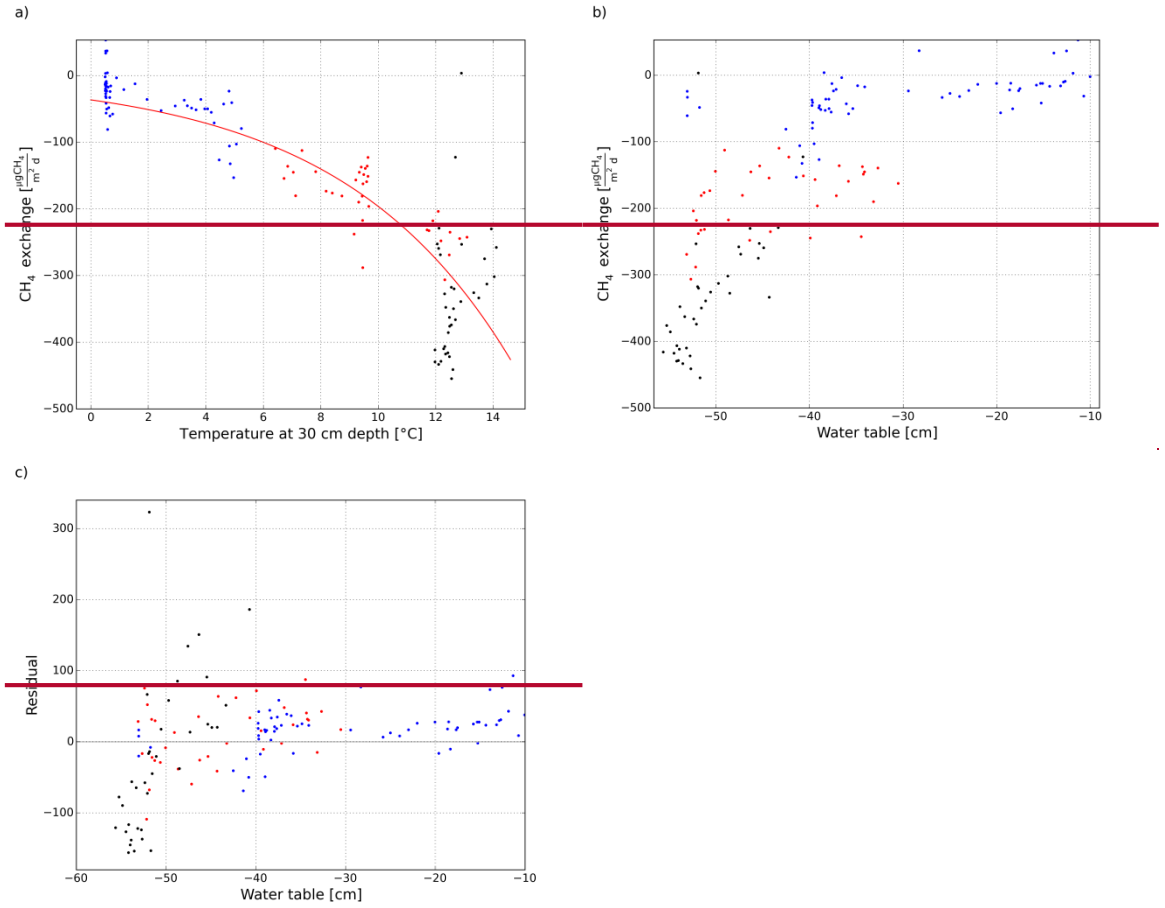


Figure ~~85~~: (a) Annual CH_4 exchange for each chamber for ~~the~~ two one-year monitoring periods, and (b) cumulative CH_4 exchange for each chamber ~~starting~~ from 1 April 2011 to 31~~until~~ March 2013. The error bars (a) and shading (b) include estimations of the random error, the error caused by gap filling and the uncertainty of the correction of the fluxes measured using the 2-min closure time (see Sect. 2.7).


a)
b)
c)
CH_4 exchange [$\frac{\mu g CH_4}{m^2 d}$]
Temperature at 30 cm depth [°C]
Water table [cm]
Residual

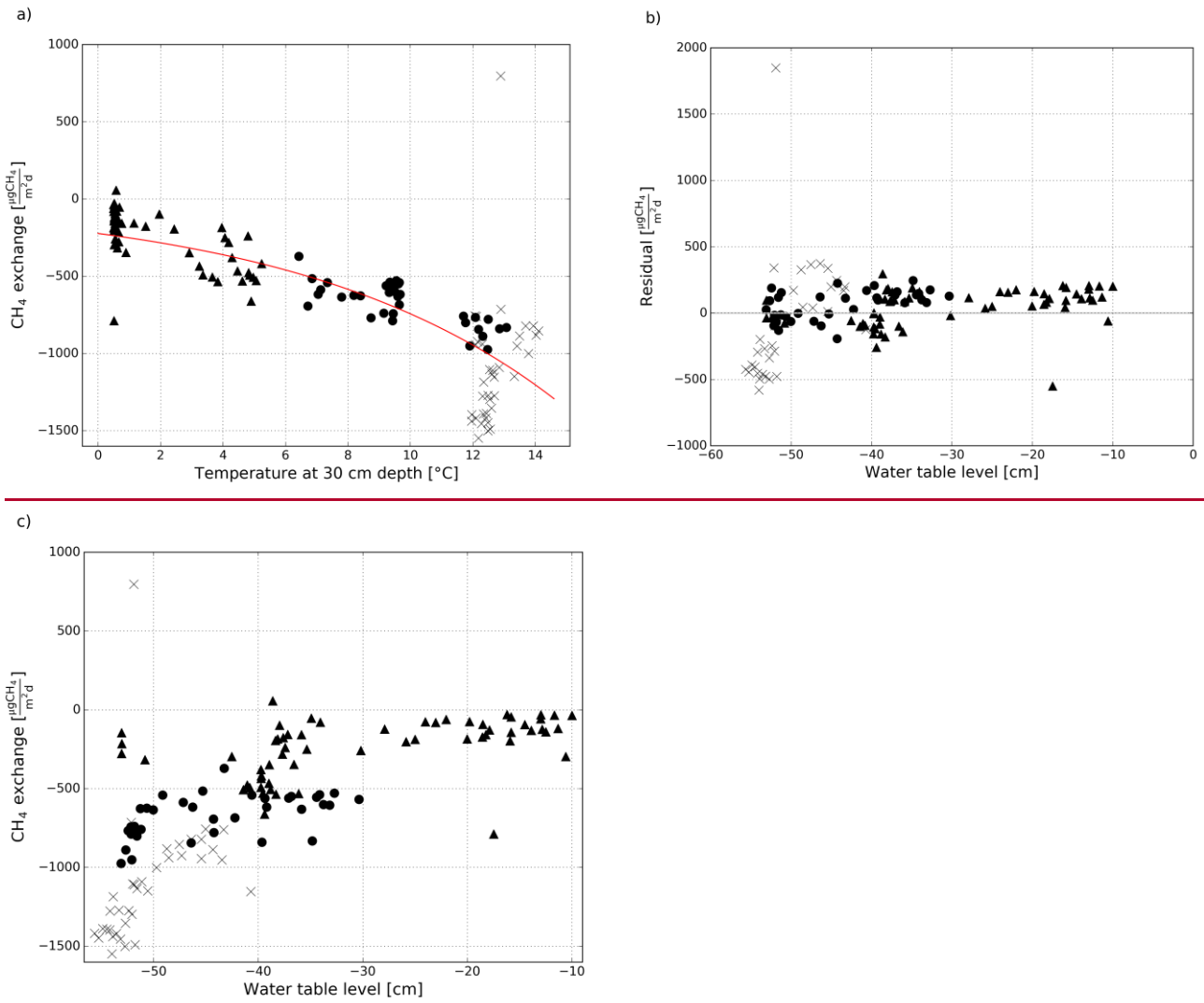


Figure ~~69~~: (a) Daily CH_4 exchange plotted against soil temperature at 30 cm in chamber #6 for spring (April and May) (~~blue~~triangles), for the first half of the summer (1 June ~~and part of~~to 15 July) (~~red~~circles) and for the second half of the summer (~~part~~16 ~~of~~ July to 31~~and~~ August) (~~black~~crosses) in 2011. Red curve in (a) denotes the exponential fitting (~~of~~ Eq. 2) to the data. (b) Residuals of the exponential fitting in panel (a) against water table level. (~~b~~c) Daily CH_4 exchange in chamber #6 ~~plotted~~ against ~~daily mean~~ water table level ~~(WTL) in chamber #6 using~~(the same flux data as in panel (a)). ~~(c) Residuals of the exponential fitting (Eq. 2) in panel (a) plotted against WTL.~~

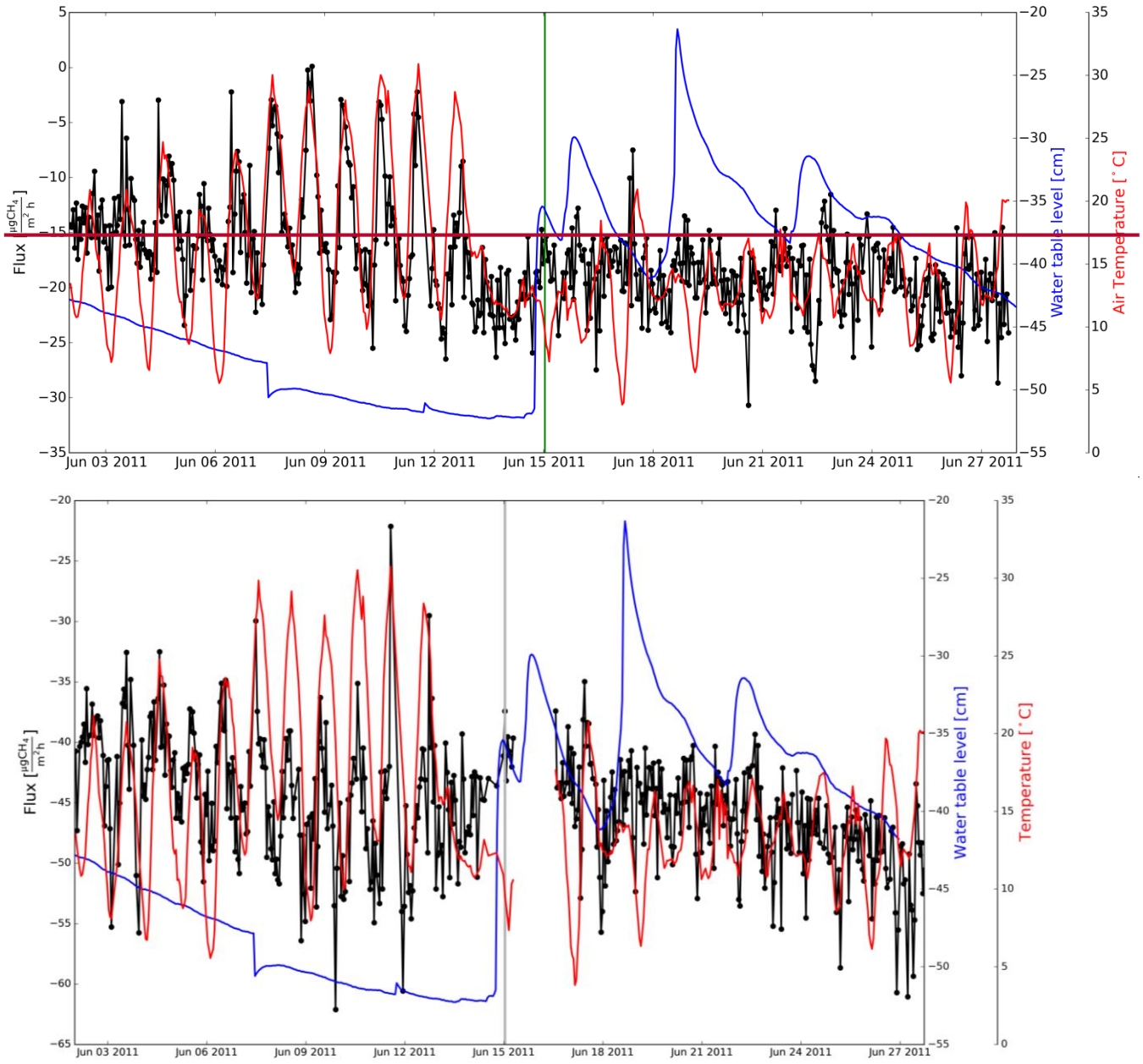
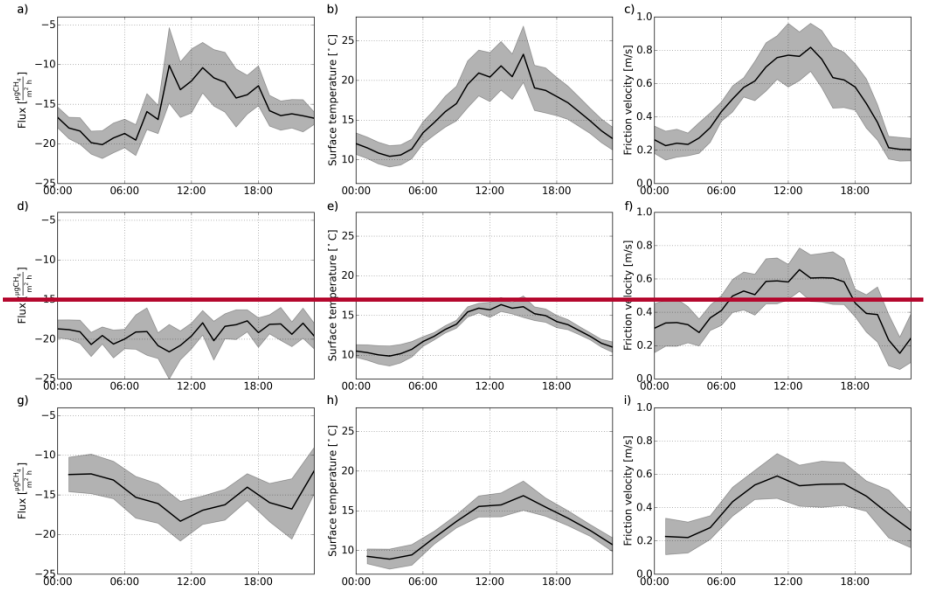


Figure ~~7~~10: Hourly ~~methane (~~CH_4~~)~~ flux~~es~~ (black circles), air temperature (red curve) and water table level (WTL) (blue curve) in June 2011 ~~measured by~~in chamber #5. The grey~~Green~~ vertical bar shows ~~where the data is~~the split ~~to panel groups of (a), (b), (c) and (d), (e), (f) in~~of the data for Fig ~~8~~11.



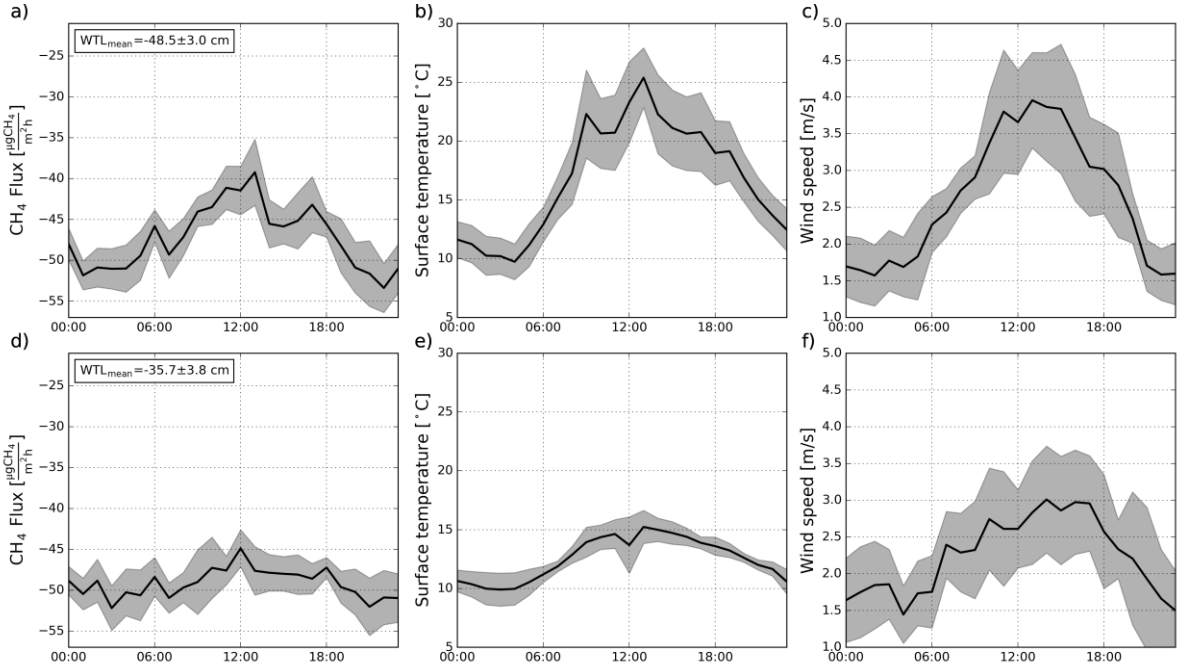
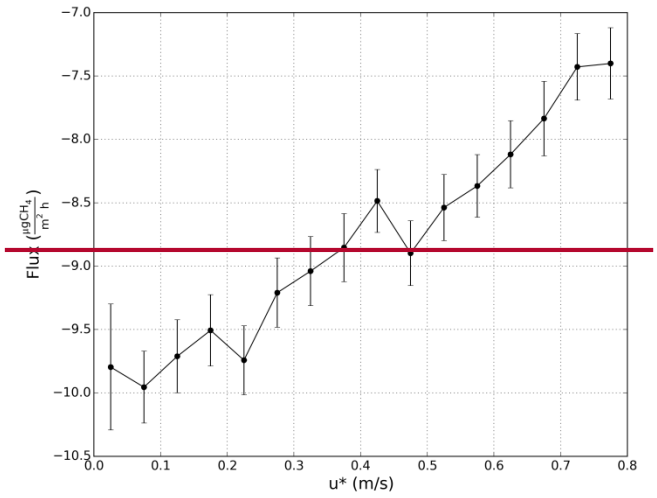
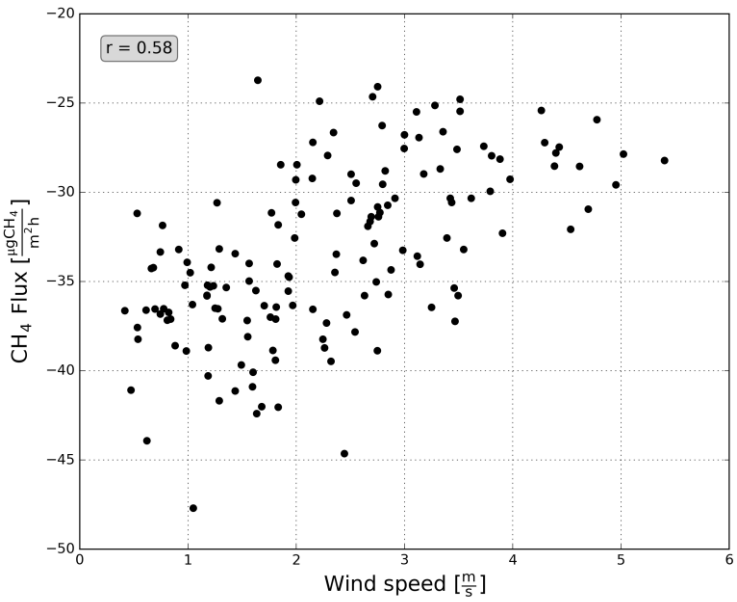


Figure 11~~8~~: Diurnal variation of mean ~~methane (~~CH$_4$~~)~~ flux ~~rate~~ (a, d~~, g~~) and soil surface temperature (°C) (b, e~~, h~~) measured in chamber #25, and the wind speed ~~friction velocity (u*)~~ (c, f~~, i~~) measured above the canopy, in 2-14 June 2011 (a, b, c) and~~,~~ 15-27 June 2011 (d, e, f)~~ and 15-30 June 2012 (g, h, i)~~. Shading shows the 95 % confidence intervals.



~~**Figure 9. Average hourly methane (CH_4) flux over the whole measurement period against friction velocity (u*) measured above the canopy. Only negative fluxes (uptake by soil) are included. Data were grouped into u* classes of 0.05 m s^{-1} (n=1030-3658). Whiskers show 95 % confidence interval.**~~

a)



b)

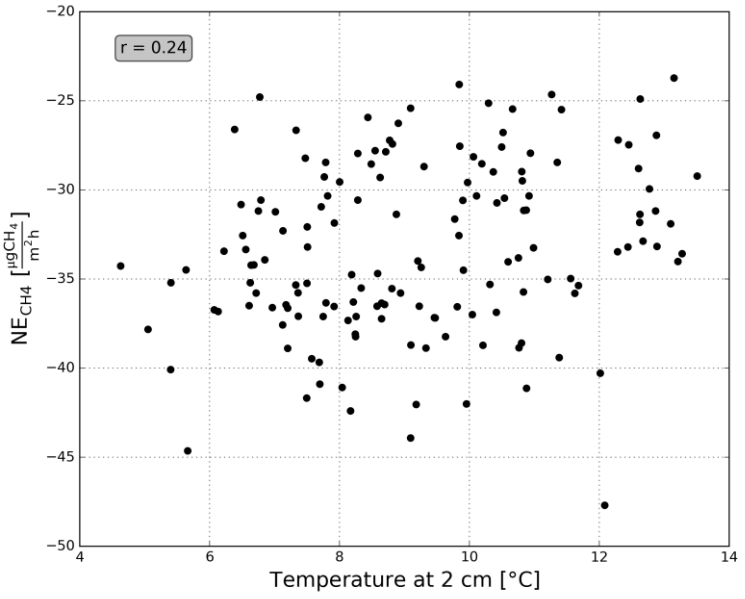


Figure 12. Average hourly CH_4 flux in 1-15 June 2012 against a) wind speed above the canopy and b) temperature at 2 cm depth in soil. r shows the Pearson correlation for the data.

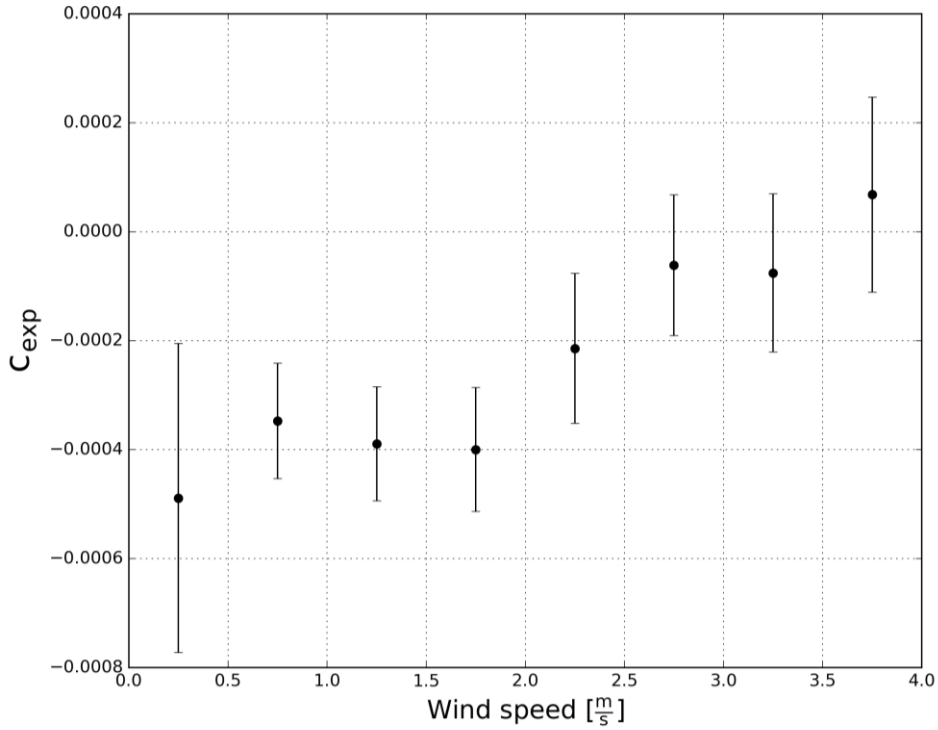


Figure 13. Bin averages of the curvature parameter (c_{exp}) against wind speed in June 2012. Only negative fluxes (uptake by soil) are included. The error bars show 95 % confidence intervals.