Reply to reviewers comments on "Growing season CH_4 and N_2O fluxes from a sub-arctic landscape in northern Finland" by Kerry J. Dinsmore et al.

Referee #1

GENERAL COMMENTS

The paper you present here is a clearly written and logically constructed report on fluxes of the two important non-CO_2 GHGs, CH_4 and N_2O, of a subarctic landscape in Northern Finland…The used field methods seem sound, replication of the chamber measurement is good, and the careful data analysis of the flux results is a particular strength of this study… this kind of regional upscaling efforts are still quite rare and very much needed to improve our ability to calculate more accurate GHG balances in a large scale.

We thank reviewer 1 for their positive comments and constructive criticism, we believe the edits described below will significantly improve the original manuscript. In particular we have significantly edited the introduction and discussion to reflect the comments regarding manuscript focus and the relevance of N_2O fluxes despite their small magnitude.

The flux measurements were carried out during two relatively short campaigns in the summer and autumn season of a single year, which is a short data collection period compared to the similar studies published during recent years.

We agree the data collection period is limited for a temporal analysis if annual or inter-annual fluxes were the focus however the aims of the study were to a) consider the drivers of CH_4 and N_2O fluxes which given the range of variables observed we believe we can achieve well with the dataset, and b) to upscale from chamber to landscape level. These aims, particularly the upscaling, have hopefully now been brought out more with the edits suggested by both reviewers. See comments below.

SPECIFIC COMMENTS

The biggest problem of this manuscript is that the relevance of this particular study is not argumented well enough. More specifically: In the introduction you base the importance of the study on large SOC pool in high-latitude soils and uncertainties of the carbon-climate feedback. Since you are not measuring CO_2 fluxes that represent the most of the C gas fluxes between ecosystems and atmosphere, you should much more emphasize the importance of the non-CO_2 GHGs instead

Agree, the introduction has now been amended to better reflect the focus on non-CO_2 GHGs

The text in the abstract on lines 9-11 is a good start, but it belongs to the introduction section, since abstract should not contain ideas not mentioned in the main text of the manuscript.

Agree, in line with the previous comment have expanded on this in the introduction.

You should also put the CH_4 and N_2O emissions into context, and mention clearly enough their secondary importance relative to CO_2.

This has now been incorporated into the introduction.

Similarly, the discussion/conclusion section does not fully convince of the importance of the study. It is very good to point out the uncertainties of the presented results, but at the present state the conclusion chapter does not fully justify, why this study should be published as an important contribution to the field.

The relevant sections have now been amended to bring out the importance of the study, linking to the additional comments added in the introduction and highlighting the strength of the upscaling rather than temporal variability.

I find that the upscaling exercise is the most interesting part of the study, and should be more emphasized in the paper, e.g., at the expense of the discussion on the impact of the water table level on CH_4 flux that does not reach very clear conclusions. A review of similar upscaling efforts is needed. Are there many previous studies like this in the subarctic region, how about in the rest of northern Scandinavia? Are the methods used here similar or very different compared to the previous studies? What do we learn here that was not previously known?

We have tried to emphasise the importance of the upscaling more throughout the paper, including more discussion on previous similar efforts, which are very few. Whilst we highlight that the correlations used here to upscale to spectral data are limited to the area from which data was collected, i.e. the formulas could not be used to upscale across the wider northern Scandinavian area, the method itself worked well and could be applied to similar small scale chamber studies to improve estimates over their specific landscapes. Whilst enhancing this scaling discussion we have chosen not to replace the water table discussion. Whilst we agree patterns were not clear, what we did find was counter to much previous literature making it in itself an important finding, even if further work is required to narrow down the control mechanisms.

The N_2O fluxes from the studied plots were mostly not statistically different from zero. However, the results of the N_2O fluxes are too much down-tuned in the manuscript text. Based on results from the last decade, there are surfaces in the subarctic and Arctic that have potential for N_2O emissions (Elberling et al. 2010 NGeo, Marushchak et al. 2011 GCB, Abbott et al. 2015 GCB), although N_2O is still rarely included in GHG ecosystems for N_2O fluxes and also produce base-case flux balances against which possible climate change induced changes in the fluxes can be observed. The "zeroresult" is not irrelevant, but it is important knowledge, which should be much stronger stated in the manuscript.

We agree with the reviewer that a zero result is still an important one however our data did not lend itself to an analysis of drivers of N_2O and sufficient correlations were not present to enable an upscaling, hence the inevitable omission from much of the discussion. We do however acknowledge that the magnitude of the flux, which as rightly pointed out is an important baseline for future studies, has become lost within the manuscript. Where possible within the discussion and especially conclusions we have tried to emphasis the result more and based on previous comments have added more on N_2O to the introduction, utilising the helpful references the referee has suggested.

ABSTRACT

The abstract seems rather long to me. Could you make it more compact, concentrating just to the main outcome of the study?

We have reduced the length of the abstract as suggested, retaining the results but reducing the interpretation, e.g. paragraph 3 is much more succinct, now reading

'We found a weak negative relationship between CH_4 emissions and water table depth in the wetland, with emissions decreasing as the water table approached and flooded the soil surface. Temperature was also an important driver of CH_4 with emissions increasing to a peak at approximately 12°C. Little could be determined about the drivers of N_2O emissions given the small magnitude of the fluxes.'

Page 1, line 2: Why should the ecosystems be described as consistent sinks or sources, if you can with high confidence state that the emissions are negligible?

We have removed the reference to N_2O sources or sinks in the abstract and now state only that N_2O results were near-zero across both ecosystems.

INTRODUCTION

Page 2, lines 5 and 9: emissions of what? Please specify!

This has been amended to read '*GHG emissions are still poorly constrained (e.g. Bridgham et al., 2013)*'

Page 2, line 11: Here, you mention permafrost thaw as one of the secondary drivers of GHG emissions, but you do not tell in the site description if your site had permafrost or not.

The site did not contain permafrost and this has now been added to the site description as suggested.

Page 2, lines 16-18: This is very general. How does this particular study answer to this need? What does it give that is not yet known?

We look at the drivers of CH_4 in significant detail, in particular the water table and temperature relationships and also the use of the soil probes to consider nutrient availability. We believe this is well discussed and highlighted throughout the results section. However in light of the referee's comments we've added to the discussion the importance of the water table result, in particular that it is different to what much of the previous literature states, and what this tells us about the underlying mechanisms.

Methods Page 4, line 17: Here, you mention that the intermediate enclosure time was 15 years, while later (page 5, line 6) you say that it was 12 years

This has been corrected to 12 years.

Page 5, lines 7 and 8: Even if you want to avoid subjective classification of the wetland plots, and rather rely to clustering analysis, it should be easy to distinguish between ridges and flarks. Please, mention how many of your collars were located in these different mire microforms, and does this represent the proportional coverage of these microforms. This is relevant knowledge for the later upscaling exercise (upscaling based on simple averaging within wetland and forest classes).

The chambers were located across the range of water levels however clear ridges and flarks were not easily distinguished at that time of year; whilst hummocks and hollows were visible as microtopographical features of the wetland these are smaller than the resolution of the satellite are therefore not a useful classification in this context. The chambers covered a range of water levels and a range of vegetation types, some becoming submerged for extended periods but all dry at some point within the 2 sampling campaigns. We have therefore chosen not to subjectively label each chamber.

Page 5, lines 13-15: … I am missing details on how the disturbance caused by the field workers was minimized. Did you construct boardwalks in the vicinity of study plots? Did you observe (CH_4) ebullition events during the measurements, and do you think they were natural or caused by people? If yes, how large proportion of the flux measurements you had to exclude for this reason?

The following text has now been added to the methods. Sampling was carried out from existing boardwalks therefore human-induced ebullition was not a problem and no fluxes were omitted due to this.

'*Wetland chambers were located so that sampling could be carried out from an existing boardwalk, this served the dual purpose of avoiding disturbance during chamber enclosure and minimised the environmental impact of footfall on the site. The ground surface within the forest plots was considered to be solid and therefore no such precautions were required.'*

Page 5, lines 29-30: If it includes respiration from ground vegetation, ecosystem respiration would be more accurate term than soil respiration. You can anyway determine what was included (not the respiration from taller vegetation due to the methodological limitations).

We have chosen to keep the definition of soil respiration as ecosystem respiration implies much more vegetation than was included, we have edited the appropriate description as below to clarify.

'Soil respiration (note whilst we refer to this as soil respiration throughout, it also includes respiration from the ground surface vegetation defined as anything with a height of less than 2 cm above ground surface), was measured using a PP-Systems SCR-1 respiration chamber'

Page 5, line 33: 'vegetation coverage' instead of just 'vegetation' would be more precise.

Agree, amendment made as suggested

Page 6, line 1: Please, add a reference on PRS and/or some specification on what they sample and by which principle? Is it just collection of soil pore water, from which nutrients are analyzed or something else? A list of the measured ions would also be good to include here.

The following text has been added as requested:

'*The PRS probes utilise ion-exchange resin membranes to provide an index of relative plant nutrient availability (Hangs et al., 2002), measured ions included total N, NO3-N, NH4-N, Ca, Mg, K, P, Fe, Mn, Zn, B, S, Pb, Al, and Cd.* '

Page 6, lines 8-12: Please, specify the criteria used to include or exclude the flux data for analysis, and mention (here, or in the results) how many percent of the fluxes had to be rejected.

No data was excluded from the analysis, we rely on the GCFlux model to accurately choose the best fit method to determine the fluxes with 4 sampling points within each chamber deemed sufficient to prevent a single point overly influencing the final calculated flux. An uncertainty is calculated for each flux during the GCFlux processing and this has been used to say whether the data gives confidence in the calculated flux, i.e. leading to the discussion about fluxes not being significantly different to zero.

Page 6, line 24-25: Did you try the correlations on the level of single plots to investigate the drivers of temporal variability? Sometimes there can be large variability even at small scale, and this is needed to reveal the factors behind the variability. What made you think that the plots with similar flux magnitude would have similar mechanistic behavior?

Yes we considered individual fluxes as suggested by the reviewer however the high variability within each chamber produced messy results which did not show clear or useful conclusions. Grouping the data produced a much clearer picture that could be analysed. We explored multiple options for grouping the data including based on vegetation alone and on soil and other environmental factors. Using flux magnitude to group the chambers ensured that those variables that were important in controlling the spatial variability were included as part of the analysis e.g. the proportion of *Sphagnum* within the chambers was captured as a by-product of this grouping approach. Therefore whilst the group is based on flux magnitude we do not assume that this itself is related to mechanistic behaviour, rather it provides a method of capturing those variables that do.

Page 7, line 3: It does not seem correct to state that the uncertainty of the N_2O fluxes was large.

What was meant was the variability 'relative' to the flux was large. This has now been amended and clarified in the text.

RESULTS

Page 7, lines 8-9: Were these 8-9 % of the N_2O fluxes that were significantly different from zero evenly distributed between study plots.

Yes these were evenly distributed, no patterns could be seen with particular groups showing significant sources or sinks. The following text has been added to clarify:

"*The proportion of chambers displaying significant N_2O fluxes could not be linked to any measured environmental factors and were distributed randomly across the dataset*".

Page 8, line 3: What do you mean by soil concentration data…

This has been amended to read "*to summarise the available soil nutrient availability data from the PRS probes*"

Page 8, line 16: Do I understand this correctly, that you had higher fluxes from ridges with deep water tables than from flarks with high water tables? This is interesting. Is this a common observation from aapa mires?

We found highest emissions in groups containing low proportions of open water (open water being a feature of flarks) and high proportions of *Sphagnum*. This finding is discussed in detail within the discussion, pg 11, with references such as Pelletier et al. (2007) describing similar water table dynamics. Much of the literature shows higher CH_4 emissions from flarks than ridges. However in our case we are not measuring from true flarks where the water level is above the soil surface almost permanently and vegetation is no longer present. Here we experienced fluctuating water levels with vegetated chambers becoming submerged therefore the production and consumption mechanisms, and importantly the soil redox potentials are likely to be different to those the reviewer is referring to. We have added to the text, particularly the field description, to clarify.

Page 8, line 24: Since this classification is very abstract, it would make sense to somehow relate it to wetland microforms, vegetation or similar. How were the flark and ridge collars distributed in these classes?

Whilst initial chamber placement used prior expertise of the likely variability due to vegetation and microtopography, we have purposely kept the cluster analysis quantitative. We have now added more detail on the microtopography within the discussion to hopefully address the reviewer's comments.

DISCUSSION

Page 10, line 17 onwards: The CH_4 fluxes were not very well correlated with environmental factors. One explanation could be that the differences in vegetation cover were overruling the effect of other factors… Please add adequate discussion on this topic in the discussion section.

We acknowledge the importance of vegetation cover and in fact found vegetation to be the primary correlate with CH_4 emissions. Vegetation data comprised % coverage values which themselves were not normally distributed and could not therefore be individually tested against chamber emissions using standard statistical methods. We therefore chose to summarise the variability in chamber specific vegetation cover using a principal components approach, the resulting PCA scores were then used in further statistical analysis. From this we found a positive significant relationship between the PC2 value and CH_4 emissions and go on to explain that PC2 relates primarily to *Sphagnum* cover (4.1 Drivers of CH_4 emissions). We have highlighted the importance of vegetation cover in predicting long term antecedent water table conditions but did not discuss the further mechanistic reasons linking CH_4 and vegetation functional group. We thank the reviewer for highlighting this, the section has now been amended with further discussion added as requested.

Page 11, line 29-33: These citations (Tupek, Turetsky) would need some mechanistical explanation, is this water table optimum of around 20 cm related to differences in plant productivity, i.e., a side product?

Agree, this was not well addressed in the submitted manuscript. We have since added the following paragraph.

"*Potential explanations for the inhibition of CH_4 emissions at high water levels given by Turetsky et al. (2014) include limited diffusion of CH_4 through standing water as discussed above, reduced CH_4 production due to lower plant biomass and associated labile C inputs, or unfavourable redox conditions resulting from inputs of oxygen rich water potentially containing alternative electron acceptors. Whilst we saw no clear correlations between the percentage of bare soil and that of open water in our chambers, a reduction in plant activity may have occurred during submersion so reduction in C inputs for methanogenesis cannot be ruled out. Neither do we have the data to rule out a change in redox potential due to water flow. A more detailed analysis under controlled conditions would be required to accurately explain the mechanism for high water CH_4 limitation at this site."*

Page 12, line 5: The spatial variability in temperatures is rather small. Do you think that this is a true temperature dependence, or is it more a result of another factor that is more important for CH_4 flux, such as water table level?

We believe this comment is already addressed as stated below (Pg 12 ln 8)

"The spatial variability in soil temperature is likely to be linked to a combination of soil water content and the surface reflectance of the vegetation cover"

Page 12, lines 28-32: To make this discussion meaningful, you should mention, what where the proportions of wetlands and forests in the study by Hartley et al. vs. this study. Please, add this information!

Agree, this information has now been included alongside the relevant discussion.

"*Whereas we carried out our upscaling over an area characterised by 61% wetlands and 32% forest, the landscape unit measured by Hartley et al. (2015) contained only ~22% wetland (classified as both mire and mire edge) and 60% forest."*

FIGURES

Figure 4. Please, indicate the sampling period used for this representation – are the averages for both summer and autumn campaigns used?

Data was used from full sampling period. This information has been added to the figure legend to clarify

Figure 6. The water table of the forest plots seems too high – was it really at 5 cm below the surface and not different from wetland plots? How do you explain this?

As stated on page 8, ln 22, "*the cluster identified with the lowest emissions contained all the forest chambers and an additional two low emitting wetland chambers"*. It is these wetland chambers which have skewed the water table data in the figure. Water table was not measured in the forest plots as soil moisture was deemed a more appropriate measure of soil water conditions. This clearly leads to a false impression in the figure, we have therefore included a note in the legend to explain this detail.

TECHNICAL CORRECTIONS

Figure 3. In the figure caption, you mention PC 1 and 2, while PC 2 and 3 are shown in the figure. Please, check this.

This has now been corrected.

Referee #2

The paper "Growing season CH_4 and N_2O fluxes from a sub-arctic landscape in northern Finland" is very well structured and is written with very good, fluent language. The study based on the state of the art methods of chamber measurements (at least for CH_4 andN_2O). The topic fits well within the scope of 'Biogeosciences'. Although the CH_4 and N_2O measurements do not provide new insights, the subject of the study is very important, since reliable but simple upscaling approaches for GHG are still rare in literature, but are urgently needed.

We thank the referee for their positive comments and as with referee 1, we feel the edits made in response to their constructive criticism has significantly improved the manuscript.

MAJOR COMMENTS:

1) I would suggest to change the title since the actual one describe insufficient the intention of the study concerning the applied modelling approach to extrapolate measured CH_4/N_2O fluxes to landscape scale.

Agree, the tile has now been changed to '*Growing season CH_4 and N_2O fluxes from a sub-arctic landscape in northern Finland; from chamber to landscape scale'.*

2) **In order to receive reliable mean GHG flux rates, the amount of measurements seems rather short for me… For upscaling to landscape scale calculated mean flux rates or emission factors should at least represent annual values…. also inter annual variability can be very high which necessitate the need for long-term studies to receive reliable mean GHG flux rates. …measurements during springtime would have been quite useful in regard to thawing soil conditions, which perhaps resulting in a markedly different behaviour of CH_4 emissions…. a rough estimation of winter time fluxes or literature values should be given. Generally, I strongly recommend that this issue should be taken up in more detail in the introduction, discussion and the conclusion of the manuscript. Please further include a sentence in the abstract that the study based just on a few single measurements during a single year.**

We acknowledge the limitations pointed out by the referee and have, as advised, addressed these issues within the relevant sections of the introduction, discussion and conclusions. In particular we have used longer term studies such as Jackowicz-Korczyński *et al.* (2010) who found 65% of CH_4 emissions occurred during the summer, 25% during shoulder seasons and only 10% during winter, to put our results in context. We have also edited the abstract as advised to now read: *'Hence this study aims to increase our understanding of what drives fluxes of CH_4 and N_2O in a subarctic forest/wetland landscape during peak summer conditions and into the shoulder season,…'*

Additional references considering seasonality in fluxes include:

Jackowicz-Korczyński, M., T. R. Christensen, K. Bäckstrand, P. Crill, T. Friborg, M. Mastepanov, and L. Ström (2010), Annual cycle of methane emission from a subarctic peatland, J. Geophys. Res., 115, G02009, doi:10.1029/2008JG000913.

Panikov, N. S., and Dedysh, S. N.: Cold season CH4 and CO2 emission from boreal peat bogs (West Siberia): Winter fluxes and thaw activation dynamics, Global Biogeochemical Cycles, 14, 1071-1080, 10.1029/1999gb900097, 2000.

Dise, N. B.: Winter fluxes of methane from Minnesota peatlands, Biogeochemistry, 17, 71-83, 10.1007/bf00002641, 1992.

3) Your data analysis includes an interesting approach to consider the skewness of observed CH_4 fluxes in the calculation of means and variations. In general the issue of skewed data and the resulting error in the calculation of means and variances of those data sets is mostly disregarded in almost all studies…

a) The geometric mean is limited by the fact that variables have to be > 0. In the presented study, CH_4 and N_2O exchange include the release and uptake of both gases. To take this into account you calculate the geometric mean of all positive and all negative flux rates independently and from this a frequency-weighted mean? Maybe it would be helpful to include the formula of the calculation approach.

The formula for the calculation of the geomean from temporal fluxes is set out below, where $\bar{F}_{geom}$ is the geometric mean flux across the time period, P_E and P_U are the proportion of individual fluxes which represent emissions and uptake, respectively, n is the number of fluxes in the appropriate category, and E and U represent individual emission and uptake vales, respectively.

$$\bar{F}_{geom} = P_E \sqrt[n]{E_1 . E_2 \dots E_n} - P_U \sqrt[n]{U_1 . U_2 \dots U_n}$$

However, as the geometric mean itself is a well-defined parameter, we feel the description already included in the methods (see below), more simply represents the calculation. For now we have left the manuscript as is however if advised we are happy to edit to include the above formula.

'Where periods of uptake and emission were both present within a time series, geometric means were calculated for each flux direction independently. The presented geometric means are the frequency-weighted sum of emissions and uptake'.

b) In contrast to the arithmetic mean, the use of ± standard deviation or standard error is not meaningful for the geometric mean. Instead, the standard deviation should be given as multiplication or division factor (Lozán and Kausch, 2007). This has to be considered in the manuscript.

As geometric means are used as a first step to summarise temporal data and are not presented in their own right, standard deviations are only given when arithmetic means are calculated. We have edited the text where appropriate to ensure the reader is not confused as to which mean is being presented.

c) Why do you choose the geometric mean for the estimation of mean CH_4/N_2O fluxes instead of trying to apply e.g. method of moments estimators or uniformly minimum variance unbiased estimators (for this see: Parkin et al., 1988: Evaluation of statistical estimation methods for lognormally distributed variables; Parkin et al., 1990: Calculating Confidence Intervals for the Mean of a Lognormally Distributed Variable)? Can you cite any other study who calculates a geometric mean for GHG fluxes? I suggest to recalculate the mean flux rates with both methods, presented by Parkin et al., (1988) and to compare the corresponding results with the calculated geometric mean. I think this procedure will significantly contribute to reduce the uncertainty in future investigations.

The geometric mean is a standard mathematical descriptor that avoids bias due to extreme measurements in skewed datasets. When summarising the temporal dataset, if a straight arithmetic mean was used, as is often the case, the assumption is that essentially a straight line can be applied between time points, however, as we know from previous literature that the recorded 'spikes' in the dataset are likely to last a lot shorter time period than that between our measurements, this gives an unrealistically high estimate to be used in further calculations. In this instance when prior knowledge of normal temporal variability exists the geometric mean is a more logical approach. The primary issue which prevents its common use is its inability to deal with negative vales. As we can separate our datasets into emissions and uptakes this problem is easily overcome. Other published studies have also presented geometric means to summarise GHG data e.g. Cowan et al Biogeosciences 12, 1585-1596, Dinsmore et al Soil Biology and Biochemistry, 41 (6). 1315-1323. 10.1016/j.soilbio.2009.03.022.

We acknowledge that this is an area that would benefit from a full statistical analysis and comparison of methods as pointed out by the referee. However without more measurements, e.g. a high frequency time series, where actual population means and variances are known to a high degree of certainty, we cannot carry out a proper comparison of the methods listed above, we would simply obtain a variety of estimated means without knowing which was most appropriate. This is something that would, and we believe should, be the focus of another study. In this instance we have chosen to keep our method as is, as it is the simplest of the options presented with no clear disadvantages and an amendment would require all the analysis, figures and tables to be redone. We are however happy to reconsider at the request of the editor.

MINOR COMMENTS AND SUGGESTIONS:

1) Page 2, line 30: Vegetation also exerts a direct and indirect control on N_2O emission!

A reference to plant-mediated transport has now been added to the following paragraph which discusses N_2O emissions.

2) Page 3, line 7: N_2O can also be produced through abiotic processes (chemodenitrification, chemical decomposition of NH2OH, surface decomposition of NH4NO3; e.g. Butterbach-Bahl, 2013: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?). Change the formulation of the sentence accordingly.

The sentence has been deleted. We focus on measuring the drivers, and not the processes involved in the N2O production/emission. In hind side it would be better to just refer to nitrification processes and denitrification processes, which was done in the preceding sentence.

3) Page 5, line 12: Please ad short information's about chamber configuration: chamber height or volume, air mixing yes or no, chamber inside thermometer yes or no, rubber lip or similar to ensure air tightness during chamber placement on in situ bases, etc…

These details have been added as requested

4) Page 5, line 17: How was the chamber air collected? Did you evacuated the vials previously? How do you protect the vials for air pressure differences during air transport (e.g. Glatzel and Well, 2008: Evaluation of septum-capped vials for storage of gas samples during air transport)?

To avoid any of these problems we did not evacuate vials, instead a 100 ml air sample was withdrawn from the chamber and flushed through a 20 ml glass vial using a double needle system. This information is already in the text, page 5 line 18 but has been amended further for clarity to read:

'Chamber air (100 ml) was sampled 4 times throughout the approximately 45 minute sampling period and flushed through 20 mL glass vials sealed with butyl rubber plugs using a double needle system; vials were therefore at atmospheric pressure reducing problems associated with pressure changes during transportation'

5) Page 5, line 24: In the latter manuscript, you also refer to air temperature. Please describe shortly sensor type and placement, record interval, etc. Do you measure chamber inside air temperature?

Air temperature was obtained from a met station on site, details have now been added.

6) Page 5, line 29: I recommend the term ecosystem respiration rather than soil respiration.

See comment above to reviewer #1

7) Page 5, line 30: In my point of view, the PP-Systems SCR-1 respiration chamber (150 mm height, 100 mm diameter) seems very inappropriate for measuring ecosystem respiration (or soil respiration including ground vegetation). The dimension of the chamber is by far too small to cover the predominant vegetation at your sites investigated. Therefore, it can be assumed that this approach significantly disturbed the plants and thus markedly change the CO_2 fluxes. I strongly recommend to remove all related parts in the manuscript.

The PP-Systems SCR-1 respiration chamber is a well-used method with data from it published many times. We accept this is not a measure of ecosystem respiration which is why we have chosen to use the term soil respiration. Neither do we propose it covers all ground vegetation, this has been amended following reviewer #1's comments. We do not suggest that these represent true ecosystem CO_2 fluxes however they are a useful indicator of soil respiration, and therefore general conditions within the soil, so we have kept the measurements as part of the analysis. Vegetation removal to get a true soil respiration value would have caused significant disturbance so

chambers were placed in an appropriate area with no or as little as possible natural vegetation coverage, text has been amended within the method section to clarify this.

8) Page 6, line 18: Did you apply any transformations (or did you remove outliers) to achieve a normal distribution in the data set (e.g. for CH_4 fluxes) prior to the PCA? I think that this might be necessary since PCA based on parametric Pearson correlations!

The skewness was primarily in the temporal dataset, as this analysis was carried out on the geometric means summarising this temporal data, the data were sufficiently much less skewed. Where non normal distributions were still a problem, log transformations were carried out. More details on this have been added in the data analysis section.

9) Page 7, line 14 and following manuscript: Did you always mean geometric mean if you write mean?

No, geometric means are only used to summarise the highly skewed temporal datasets, arithmetic means were appropriate when considering spatial variability. This has now been clarified in the data analysis section.

10) Page 7, line 17: Did you mean 1.06 ± 0.44 µg N m−2 hr−1 instead of s−1? (This also relates vice versa to Table 1).

This has now been corrected, the correct unit is hr-1.

11) Page 8, line, 25: Have you tested the assumptions for linear models (e.g. normal distribution of residuals, homogeneity of variances, autocorrelation etc.)? I guess that the strong skewed dataset will partly violate the assumptions of an ANOVA? Please describe your statistical procedure in the section Data analysis. Please also describe which factors (e.g. single CH_4 fluxes or mean group CH_4 fluxes, temperatures, PCA_veg, etc.) were included as fixed effects in the ANOVA. Have you tested just one factorial or also multifactorial approaches? Did you consider temporal pseudoreplication in case of chamber specific GHG fluxes?

More information has now been supplied within the data analysis section including the additions below. Pseudoreplication due to temporal datasets was not an issue as only the spatial datasets were used i.e. PCA results and means.

'In all further analysis, log transformations were applied where data-sets displayed non-normal distributions; given the time between measurements, autocorrelation within datasets was never significant'

'ANOVA and Tukey's pairwise comparisons were used to explore the differences in environmental variables between clusters, tested variables included means of soil temperature, water table depth and soil respiration alongside vegetation principal component and soil principal component.'

12) Page 9, line 13: Have you tested for non-linear relationships? In case of non-normal distribution of data, Pearson correlation coefficient (r) is perhaps not the right choice as a measure for the intensity and direction of a relationship. Maybe Spearman rank correlation coefficient is more appropriate?

This discussion refers to the temporal dataset, relationships were non-linear but could not be modelled with simple non-linear approaches. It was not deemed necessary within the context of the manuscript to delve further into complex non-linear modelling approaches. These relationships are not described using statistics due to the complex patterns that would be oversimplified and liable to misinterpretation with summary descriptors of intensity and direction.

13) Page 9, line 27: Please mention that the mean CH_4 flux which you use for upscaling did not represent an annual mean CH_4 flux rate (e.g. average CH_4 flux over the growing season Page 12, Line 27). Have you tried to separate between summer and autumn CH_4 fluxes for model building and upscaling?

We have now added text both here and throughout the manuscript to highlight our upscaling is only valid over our sampling period between 12th July and 14th October. Whilst we set up the field campaigns with the intention to cover mid-summer and shoulder seasons, for the upscaling we do not have a long enough time series to clearly define these seasons based on fluxes or meteorological data in a way that is scientifically useful. We have therefore chosen to combine the campaigns to give us the best estimate of growing season fluxes.

14) Page 10, line 1: Is the area weighting factor 61% wetland and 32% forest?

This is correct, this information is already in the site description but has now been added to Pg 10 ln 1 as well.

15) Page 10, line 11 to 15: Don't be too critical with the observed close to zero net N_2O fluxes and the fact that no drivers for upscaling are found. Maybe gross production of N_2O occurs at your sites investigated, but in the end it is an important result that both ecosystems actual did not significantly contribute to global warming through the release of N_2O emissions. However, this fragile balance can change very quickly in the course of e.g. climate warming, drainage, etc. and should therefore shortly be mentioned in the discussion and conclusion. Further, it would be fine to include also N_2O fluxes as an additional Figure.

This has been primarily dealt with in response to reviewer 1's comments as described above and should now satisfy referee 2 also. The N_2O figure was removed after significant discussion among co-authors as it was felt that it did not give the reader any useful information and the manuscript already contain a significant number of plots. We are happy to reconsider if it is felt by the editor it would be a useful addition.

Technical corrections:

1) Page 2, line 9: are essential -> is essential

Corrected

2) Page 3, line line 6: aerobic condition -> aerobic conditions

Corrected

3) Page 4, line 14: in the area our -> in the area where our ..

Corrected

4) Page 5, line 2 and 3: Formatting of the date: 12th July – 2nd August……

Please advise further?

5) Page 5, line 14: occasions, the short -> occasions. The short …

Corrected

6) Page 5, line 15: fluxes, and -> fluxes, which

Corrected

7) Page 5, line 26: 5 mm instead of 5mm (maybe you mean 5 cm for dip well instead of 5 mm?)

Changed to 5 cm

8) 5 line 28: located equidistance -> located at equidistance …

Kept as original wording

9) Page 6, line 2 and 3: Formatting of the date…

Please advise further?

10) Page 6, line 30: Formatting of the date…

Please advise further?

11) Page 7, line 9: 8 and 9% instead of 9 %

Kept as original, please advise if this is incorrect

12) Page 7, line 14: both units mg C m-2- hr-1 -> mg C m-2 hr-1

Corrected

13) Page 7, line 24 and 25: P < 0.01 instead of P <0.01

Corrected here and additional 3 instances throughout

14) Page 7, line 29: emissions thus -> emissions, but …

Changed to emissions, thus…

15) Page 8, line 13: emissions wert -> emissions was …

Kept as emissions were

16) Page 8, line 19: correlated CH_4 -> correlated to CH_4 …

Corrected

17) Page 8, line 33: Between-group differences or Between group differences; please be consistent (relates to the entire manuscript).

Changed to 'Between-group' throughout

18) Page 9, line 23: 45%

Kept as original, please advise if this is incorrect

19) Page 9, line 27: Methane can be abbreviated. This also relates to the following manuscript.

Edited as suggested throughout

20) Page 10, line 4: -0.06 + <0.01 -> -0.06 ± <0.01

Corrected

21) Page 10, line 15: Or instead of over?

Word 'over' removed, now reads 'N_2O emissions within our landscape'

22) Page 10, line 24: Turetsky et al., 2014. -> Turetsky et al., 2014).

Corrected

23) Page 11, line 32: water level was -> water level were …

Kept as original

24) Page 12, line 3: show are -> show is …

Corrected

25) Page 12, line 31: landscape scales fluxes -> landscape scale fluxes ..

Corrected

26) Page 13, line 6: Hartly et al. (2015) who's study -> Hartly et al. (2015) whose study…

Corrected

27) Page 13, line 22: temperature -> soil temperature

Corrected

28) Page 18, Table 1: Please note that mean represent the geometric mean.

These represent arithmetic means, geometric means are only used to summarise the temporal datasets

29) Page 18, Table 3: I strongly recommend the use of an adjusted r^2 instead of r^2 since r^2adj. considered the number of predictors in the model.

Adjusted r2 are used, this has been amended in table

30) Page 19, Figure 1: Minus sign is missing in the unit of the X-axis

Unsure what this refers to, minus sign is already visible, figure left as is.

31) Page 21, Figure 3 a) and b): X and Y-axis show principle components 2 and 3 instead of 1 and 2!

This has been edited in the legend.

32) Page 22; Figure 4: Unit of soil moisture is missing!

Corrected

33) Page 24, Figure 6: The Unit of soil respiration differs from Figure 4 and Figure 9 (g m-2 hr-1, instead of mg m-2 hr-1)! Did soil respiration represent CO_2 or CO_2-C? See also Minor comments and suggestions Nr. 7

Corrected

34) Page 25, Figure 7: Units are missing!

Corrected

Growing season CH_4 and N_2O fluxes from a sub-arctic landscape in northern Finland; from chamber to landscape scale

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Abstract. Subarctic and boreal emissions of CH_4 are important contributors to the atmospheric greenhouse gas (GHG) balance and subsequently the global radiative forcing. Whilst N_2O emissions may be lower, the much greater radiative forcing they produce justifies their inclusion in GHG studies. In addition to the quantification of flux magnitude, it is essential that we understand the drivers of emissions to be able to accurately predict climate-driven changes and potential feedback mechanisms. Hence this study aims to increase our understanding of what drives fluxes of CH_4 and N_2O in a subarctic forest/wetland landscape during peak summer conditions and into the shoulder season, exploring both spatial and temporal variability, and uses satellite derived spectral data to extrapolate from chamber scale fluxes to a 2 x 2 km landscape area.

From static chamber measurements made during summer and autumn campaigns in 2012 in the Sodankylä region of Northern Finland, we concluded that wetlands represent a significant source of CH_4 (3.35 ± 0.44 mg C m^{-2} hr^{-1} during summer campaign and 0.62 ± 0.09 mg C m^{-2} hr^{-1} during autumn campaign), whilst the surrounding forests represent a small sink (-0.06 ± <0.01 mg C m^{-2} hr^{-1} during the summer campaign and -0.03 ± <0.01 mg C m^{-2} hr^{-1} during the autumn campaign). N_2O fluxes were near-zero across both ecosystems ~~and as such could not be accurately described as either consistent sinks or sources.~~.

We found a weak negative relationship between CH_4 emissions and water table depth in the wetland, with emissions decreasing as the water table approached and flooded the soil surface~~. We attribute this relationship, which initially seems counter to much of the current literature, to water tables being consistently above the level where~~ and a positive relationship ~~would be expected. Whilst conditions may appear optimal for~~between CH_4 ~~production at higher water tables, reduced diffusivity may reduce the net~~ emissions~~, indicating a complex interaction of processes which combine to produce the net emission rate measured.~~ and the presence of *Sphagnum* mosses. Temperature was also an important driver of CH_4 with emissions increasing to a peak at approximately 12°C. ~~Increases in temperature beyond 12°C led to a subsequent reduction in~~Little could be determined about the drivers of N_2O emissions~~, indicating~~ given the ~~presence~~small magnitude of ~~multiple interacting processes~~the fluxes.

A multiple regression modelling approach was used to describe CH_4 emissions based on spectral data from PLEIADES PA1 satellite imagery across a 2 x 2 km landscape. ~~Our best model described 45% of spatial variability using blue and near infra-red bands with the inclusion of the commonly described simple ratio (SR) and normalised difference vegetation index (NDVI).~~ When applied across the whole image domain we calculated a CH_4 source of 2.05 ± 0.61 mg C m^{-2} hr^{-1}. This was significantly

higher than landscape estimates based on either a simple mean or weighted by forest/wetland proportion (0.99 ± 0.16 mg C m^{-2} hr^{-1}, 0.93 ± 0.12 mg C m^{-2} hr^{-1}, respectively). Hence we conclude that ignoring the detailed spatial variability in CH_4 emissions within a landscape leads to a potentially significant underestimation of landscape scale fluxes. Given the small magnitude of measured N_2O fluxes a similar level of detailed upscaling was not needed; we conclude N_2O fluxes do not currently comprise an important component of the landscape scale GHG budget at this site.

1 Introduction

Almost a third of the world's soil carbon is estimated to be stored in boreal and sub-arctic wetlands (Gorham, 1991) yet greenhouse gas (GHG) emissions are still poorly constrained (e.g. Bridgham et al., 2013). Furthermore, the potential feedbacks between high latitude carbon and the global atmospheric radiative balance is not fully understood or accurately accounted for in coupled carbon cycle-climate models (Koven et al., 2011). Boreal nitrogen (N) stocks are significantly understudied compared to C. However boreal forests are known to significant stocks of organic N, peatlands are estimated to contain approximately 10-15% of the global N pool, and permafrost regions are thought to contain between 40–60 Pg of N (Abbott and Jones, 2015;Loisel et al., 2014;Valentine et al., 2006).

It is now accepted that global surface air temperatures are rising and the rate of increase is greatest in these high latitude areas (Pachauri and Reisinger, 2007). Hence understanding both the current magnitude of GHG emissions and the drivers ~~are~~is essential to monitor and predict climate-driven changes and climate feedback mechanisms.

Whilst it is important to understand the direct implications of increased temperature on net ~~greenhouse gas (~~GHG~~)~~ emissions~~,~~ (CO_2, CH_4 and N_2O), it is also critical to consider the indirect impact through secondary drivers such as permafrost thaw, changes in vegetation community structure, substrate availability, soil hydrological regimes and flow path dynamics. These factors, both individually and via interactions, are likely to alter both net GHG emissions and GHG speciation; e.g. a recent meta-analysis showed the temperature sensitivity of CH_4 was greater than that of CO_2 suggesting increased temperature may lead to changes in the CH_4:CO_2 emission ratio (Yvon-Durocher et al., 2014). The sensitivity of CH_4 fluxes to these environmental controls is not currently well understood, ~~limiting~~for example previous studies show differing responses to water table dynamics (e.g. Aerts and Ludwig, 1997; Olefeldt et al., 2013; Turetsky et al., 2014; Waddington et al., 1996). This limits the ability of mechanistic models to accurately simulate actual net fluxes. ~~Hence a~~A significant research focus is required to fully explain the drivers of GHG emissions ~~and therefore~~to provide a solid basis for future prediction.

Much of the previous research effort in this field has been focussed on CO_2, the most abundant atmospheric GHG, often followed by CH_4 and to a much lesser extent N_2O. Knowledge of the distribution of N_2O fluxes across high-latitude ecosystems is in fact almost entirely lacking. Examples of mean growing season net ecosystem exchange values across subarctic/boreal regions include an uptake of 1.7 g CO_2 m^{-2} d^{-1} (Lafleur, 1999) and 5.47 g CO_2 m^{-2} d^{-1} (Fan et al., 1995), both from Canadian forest sites and an uptake of 3.86 g CO_2 m^{-2} d^{-1} (Aurela et al., 2002) from a Finnish mesotrophic flark fen. Whilst CH_4 and N_2O emissions are generally lower than net CO_2 emissions, the greater radiative forcing they produce, as described by the global

warming potential (GWP), justifies their inclusion in GHG studies. The 100 year GWPs with and without climate-carbon feedbacks, respectively, are currently estimated as 28 and 34 for CH_4 and 265 and 298 for N_2O (Myhre et al., 2013). Overall, boreal forests appear to be a small sink for CH_4 and a small source of N_2O (Moosavi and Crill, 1997; Pihlatie et al., 2007) whilst wetlands typically represent sources of CH_4, and a small sink for N_2O (e.g. Bubier et al., 1993; Drewer et al., 2010b; Huttunen et al., 2003). Growing season emissions of CH_4 from subarctic and boreal ecosystems are estimated as 112.2 ± 6.2 and 72.7 ± 1.3 mg m^{-2} d^{-1}, respectively (Turesky et al. 2014), compared to modelled estimates of N_2O emissions from tundra, forest tundra and boreal forest of 0.02, 0.09 and 0.15 mg m^{-2} d^{-1}, respectively (Potter et al. 1996). Most studies focus primarily on growing season fluxes. Whilst the logistics of making winter measurements in these ecosystems certainly plays an important role, the growing season has also been shown to represent the period of greatest emissions and therefore the most suitable time to study drivers. Jackowicz-Korczyński et al. (2010) found that summer season CH_4 emissions represented 65% of the annual flux (with the shoulder seasons representing 25% and the winter season only 10% of annual flux) in a subarctic peatland. Similarly Panikov and Dedysh (2000) found that winter CH_4 emissions contributed only 3.5 to 11% of total annual flux in Western Siberian boreal peat bogs and Dise (1992) reported winter CH_4 fluxes representing between 4 and 21% of total annual flux in peatlands across Northern Minnesota.

Net CH_4 emissions are controlled by the balance of activity between anaerobic methanogenic and oxidizing aerobic methanotrophic bacteria. Hence the degree of soil saturation, which controls the position of the oxic-anoxic boundary and the associated soil redox potential, has been identified as an important driver of net CH_4 emission (Bubier et al., 1995; Kettunen et al., 1999; Nykanen et al., 1998). Other factors such as temperature, substrate availability, soil porosity and pH are also commonly reported drivers of CH_4 emissions (Baird et al., 2009; Dinsmore et al., 2009b; Levy et al., 2012; Strack et al., 2004; Yvon-Durocher et al., 2014). Whilst the rate of methanogenesis and methanotrophy are both influenced by temperature, methanogenesis is generally considered to be more temperature-sensitive resulting in a positive relationship between temperature and net CH_4 emission (Dunfield et al., 1993; van Hulzen et al., 1999). CH_4 produced within the soil environment is then transported to the atmosphere via diffusion, ebullition or plant-mediated transport.

Vegetation can exert either a direct control on CH_4 emission via plant-mediated transport, or indirect control via its contribution to soil structure, moisture, anaerobic microsites and substrate availability. The development of aerenchyma is an adaptation to waterlogged conditions found in many vascular wetland species. Where such species are present they can act as gas conduits, allowing GHGs produced in the anoxic layer to be transported to the atmosphere with minimal oxidation, subsequently increasing emissions by up to an order of magnitude (Dinsmore et al., 2009a; MacDonald et al., 1998; Minkkinen and Laine, 2006). Vegetation community structure also provides a useful proxy for environmental variables that are themselves difficult to measure, such as long-term water table dynamics (Gray et al., 2013; Levy et al., 2012).

The primary processes controlling N_2O emissions from soils, including boreal soils, are nitrification processes, where ammonium is oxidised to nitrate under aerobic ~~condition~~conditions and denitrification processes, where oxidised nitrogen species are reduced to N_2O or N_2 under anaerobic conditions (Firestone and Davidson, 1989). As N_2O production is again a microbial process and one that is strongly dependent on the ratio of aerobic to anaerobic soil microsites, factors such soil

moisture status, temperature, pH, and substrate availability, in particular nitrate and ammonium, are also commonly reported drivers of N_2O emissions (Kettunen et al., ~~1999). Whereas nitrification is likely to be the dominant process in forests, denitrification is considered the most important source of N_2O in wetlands; further work is still needed before the importance of more recently recognised processes such as anaerobic ammonium oxidation (anammox) can be quantified (Sutton and et al., 2011).~~1999), with transport through aerenchymam, as discussed above, a potenital transport mechanism.

A number of different in-situ methods are available for the measurement of GHG emissions. Eddy covariance methods can produce high temporal resolution measurements integrated at the field and ecosystem ~~scale~~ (Baldocchi et al., 2001; Hargreaves and Fowler, 1998); whilst useful for field scale quantification, the method does not allow separation of individual landscape components. Traditional chamber based studies allow a more targeted experimental design where individual microtopographical features or vegetation communities can be selected and compared (Dinsmore et al., 2009b; Drewer et al., 2010a). By explaining small-scale spatial variability we can gain a greater understanding of GHG drivers and begin to predict how climate or land-use management changes will alter the GHG balance over the full landscape. Furthermore both CH_4 and N_2O can be measured simulataneously within the same chamber allowing greater confidence in comparisons bewteen the flux estimates.

There exists a fundamental mismatch between the scale of measurement required to increase process level understanding of ~~GHG~~CH_4 and N_2O emissions, and the scale required to make useful assertions about the magnitude of emission sources that are relevant to the global GHG budget. Whilst land-surface models provide one way to bridge this mismatch of scale, they are often limited by the availability of specific input variables e.g. water table depth, which cannot be measured at the spatial resolution required to provide an accurate output. As a result, modelled estimates of northern high-latitude wetland CH_4 sources are highly variable between studies ranging from approximately 20 - 157 Tg CH_4 yr^{-1} (Zhu et al., 2013 and references therein). An alternative method of upscaling is empirically mapping emission factors onto spectral data provided by high resolution satellite imagery. This method utilises the spectral signatures of different vegetation types and vegetation specific differences in GHG emissions to create a landscape scale emission map.

In this study we use static-chambers and satellite imagery to assess the primary spatio-temporal drivers of ~~GHG~~CH_4 and N_2O emissions in sub-arctic/boreal Finland and upscale this to a 4 km^2 landscape containing both forest and wetland ecosystems.

2 Methods

2.1 Site Description

The Arctic Research Centre of Sodankylä (67°22'N 26°39'E, 179 m a.s.l.) is located in central Lapland, Northern Finland, approximately 100 km north of the Arctic Circle. The centre is run by the Finnish Meteorological Institute, is part of the Pallas-Sodankylä GAW station and includes a level 1 ICOS ecosystem station. Whilst referenced as an Arctic site in respect to stratospheric meteorology and geographical location, it is considered to be within the sub-arctic/boreal vegetation zone~~.~~ and is not underlain by permafrost. Mean annual temperature and precipitation on site from 1981-2010 was -0.4°C and 527 mm,

respectively. Records of mean annual air temperature on site have shown an increase of 0.02°C yr^{-1} over the period 1961-2000; the rate of increase specifically during March to May was 0.04°C yr^{-1} (Aurela et al., 2004; Tuomenvirta et al., 2001).The mean snow depth (mid-March) is 75 cm with median ~~snow cover~~snowfall start and end dates of 26th September and 14th May (Finnish Meteorological Institute). Permanent snow cover starts approximately end of October, beginning of November. Scots pine forests and wetlands are the two dominant ecosystems in this region. Both ecosystems were covered by the greenhouse gas flux measurements in order to enable the landscape scale upscaling of the results.

The forest (N67°21.708' E26°38.290', 179 m.a.s.l.) is classified as an Uliginosum-Vaccinium-Empetrum (UVET) type Scots pine (*Pinus sylvestris*) forest on a sandy podzol. The mean vegetation height within the forest is 12 m in the area where our measurements were made with an average stand age of 60-100 years and tree density of 2100 ha^{-1}. The forest floor contains a varying degree of lichen (*Cladonia* spp.) which is heavily dependent on the presence/absence of reindeer. We located static chambers evenly between 3 forest sites (unfenced, ~~15~~12 year enclosure, 50 year enclosure) to ensure variability in GHG emissions due to lichen cover was included in our results. The nearby Halssiaapa wetland (N67°22.111' E26°39.269', 180 m.a.s.l.) is described as a eutrophic ~~flark~~ fen dominated by large, treeless flarks with abundant sedge vegetation and intermittent brown moss and *Sphagnum* cover. Intermediate, low ridges consist of birch fen vegetation interspersed with pubescent birch trees (*Betula pubescens*), with a dominant height of approximately 5-7 m. The most common shrubs are *Betula nana*, *Andromeda polifolia* and *Vaccinium oxycoccos*, herbaceous plants are primarily *Potentilla palustris* and *Menyanthes trifoliata*, and grasses are predominantly *Care*x species (several different species observed) or *Scheuchzeria palustris*. Across the duration of the study water table levels varied substantially and no consistently submerged areas which could be easily distinguished as flarks existed, we have therefore avoided subjective classification of ridges and flarks within our plots and refer only to measurable environmental variables such as water table depth and temperature.

When set within a wider 2 x 2 km landscape unit (to which we will upscale measurements), the proportion of wetland to forest was almost 2:1 with wetlands making up 61% of the area, and forests 32%. The remaining 7% included open water and grass, bare soil and buildings primarily associated with the Sodankylä Arctic Research Centre. Within the larger regional area described in an associated study by O'Shea et al. (2014) (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster) forests made up a much greater proportion of the landscape with coniferous and mixed forests representing 33% and 16% of the land area, respectively, and wetlands 23%.

2.2 Field Methodology

Measurements were carried out during growing season 2012 in two measurement campaigns (Summer: 12th July – 2nd August; Autumn: 22nd September – 14th October), with the intention of capturing peak summer CH_4 emissions and the subsequent shoulder season.

A total of 60 static chambers were measured, 21 within the forest and 39 within the wetland. Within the forest, 7 chambers were located in each of three subplots representing no enclosure, 12 year enclosure (built in summer 2000) and an approximately 50 year enclosure. Within the wetland, chambers were strategically located to cover the perceived range of

both vegetation communities and water table depths~~.~~ covering both hummock and hollow microtopographic types (chamber numbers per microtopographic type: hummocks = 16, hollows = 11, neither hummock nor hollow = 12). Fluxes were measured on approximately 2 day intervals resulting in a total of 10 measurements for all chambers during the summer campaign, and 7 for the forest and 8 for the wetland chambers during the autumn campaign.

Static chambers were constructed from 40 cm diameter opaque polypropylene pipe following the guidelines discussed in Clough et al. (2015). Wetland chambers were located so that sampling could be carried out from an existing boardwalk, this served the dual purpose of avoiding disturbance during chamber enclosure and minimised the environmental impact of footfall on the site. The ground surface within the forest plots was considered to be solid and therefore no such precautions were required. Shallow bases (10 cm depth) were inserted into the ground the day before the first sampling; bases were left in-situ for the remainder of the study period. Fluxes calculated from the first sampling day were not significantly different from subsequent sampling occasions~~, the~~. The short settling period after base installation is therefore considered to have had no significant effect on subsequent fluxes, ~~and~~which therefore were included in the data analysis. ~~-~~Chamber lids, consisting of a 25 cm section of polypropylene pipe with a closed metal top ~~and,~~ pressure compensation plug and draft excluder tape for sealing, were attached and sealed to the in-situ bases during the 45 min flux measurement period. Chamber air (100 ml) was sampled 4 times throughout the approximately 45 minute sampling period and flushed through 20 mL glass vials sealed with butyl rubber plugs~~.~~ using a double needle system; vials were kept at atmospheric pressure reducing problems associated with pressure changes during transportation. Vials were returned to the laboratory at the Centre for Ecology and Hydrology, Edinburgh, for analysis within approximately one month. Samples were analysed on an HP5890 Series II gas chromatograph (Hewlett Packard (Agilent Technologies) UK Ltd, Stockport, UK) with electron capture detector (ECD) and flame ionisation detector (FID) for N_2O (detection limit<7 µg l−1) and CH_4 analysis (detection limit<70 µg l−1), respectively. Soil temperature was recorded at a depth of 10 cm from four replicate points immediately outside the chamber bases on each sampling occasion using the Omega HH370 temperature probe (Omega Engineering UK Ltd.,Manchester, UK). Within the forest plots, 4 replicate volumetric soil moisture content (VMC) measurements were made, adjacent to each chamber base, using a Theta probe HH 2 moisture meter (Delta T-Devices, Cambridge, UK). Within the wetland, a total of 21 dip wells constructed from ~~5mm~~5 cm internal diameter pipe, were installed either adjacent to, or where chambers were located close together, between chamber bases. All wetland chambers had at least 1 dip well located within a 50 cm radius, where more than one dip well was located equidistance from the chamber, the mean water table depth from the adjacent dip wells was calculated. Soil respiration (~~including~~note whilst we refer to this as soil respiration throughout, it also includes respiration from the ground surface vegetation defined as anything with a height of less than 2 cm above ground surface), was measured using a PP-Systems SCR-1 respiration chamber (10 cm diameter) attached to an EGM-4 infrared gas analyser (IRGA,PP Systems; Hitchin, Hertfordshire, England) on each sampling occasion. Soil respiration was measured adjacent to each forest chamber and adjacent to 14 chambers within the wetland, chosen to cover the perceived range of spatial variability. Vegetation within each chamber was recorded upon visual inspection.

A pair of cation and anion Plant Root Simulator (PRS)™ probes were deployed adjacent to each of the 60 chamber bases during both sampling campaigns. The PRS probes utilise ion-exchange resin membranes to provide an index of relative plant nutrient availability (Hangs et al., 2002), measured ions included total N, NO_3-N, NH_4-N, Ca, Mg, K, P, Fe, Mn, Zn, B, S, Pb, Al, and Cd. During the summer campaign probes were deployed on the 11th and 12th July, and recovered on the 1st August. During the autumn campaign forest probes were deployed on the 22nd and 23rd September and recovered between the 13th and 15th October. As part of the standard analytical processing, concentrations from each probe are corrected for length of deployment. After recovery, probes were processed and cleaned with deionised water following the standard procedure supplied by the manufacturers and returned to Western Ag Innovations Inc., Canada for analysis.

2.3 Data Analysis

Fluxes and confidence intervals from static chambers were calculated using GCFlux, version 2, which calculates fluxes based on 5 methods before choosing the most appropriate fit for individual chamber sets (Levy et al., 2011). Reported CH_4 fluxes correlate to the best-fit model for individual chambers (either linear or asymptotic). Due to the larger uncertainty in calculated N_2O concentrations which are often close to the GC detection limits, reported N_2O fluxes were calculated from the linear model approach only. Instantaneous fluxes are presented in units of nmol m^{-2} s^{-1}. Confidence intervals include errors introduced by a combination of natural variability in the flux over the measurement period, methodological and analytical limitations and uncertainty in model fitting. When these range from negative to positive, no sign can be accurately attributed to the flux and therefore it is treated as indistinguishable from zero.

The data distribution of fluxes, from all chambers, and over the full study period, had a strong positive skew (Figure 1). To summarise the data and account for the skewed distributions, geometric means were calculated across time points for all chambers. Where periods of uptake and emission were both present within a time series, geometric means were calculated for each flux direction independently. The presented geometric means are the frequency-weighted sum of emissions and uptake. The resulting spatial dataset had a distribution much closer to normal and is therefore summarised throughout using arithmetic means. Upscaled emission estimates are presented in units of either g C m^{-2} hr^{-1} or g N m^{-2} hr^{-1} for CH_4 and N_2O, respectively. In all further analysis, log transformations were applied where data-sets displayed non-normal distributions; given the time between measurements, autocorrelation within datasets was never significant. To summarise the complex vegetation and soil data, principal component analyses (PCA) were performed using the princomp function within the R stats package (R version 3.1.1), this uses a spectral decomposition approach which examines the covariances and correlations between variables. Correlation analyses were carried out with principal components one, two and three (PC1, PC2, PC3) against spatial CH_4 fluxes and the most appropriate component taken forward into subsequent explanatory models. No attempt to correlate vegetation or soil components was made with N_2O fluxes given the ~~high uncertainty in the~~large proportion of near-zero fluxes. Spatial variability between chambers on all sampling occasions was large. To allow temporal variability to be considered it was necessary to group chambers. Rather than subjectively assign chambers to groups based on observed landscape features we carried out a cluster analysis (R, version 3.1.1) based on emission rates. This method produced independent groups which

could also be used in further analyses to consider the environmental controls of emissions. The total number of clusters was chosen to be 5, after multiple cluster analysis runs this was considered the most appropriate number taking into consideration the complexity for further analyses and clear distinctions between groups. ANOVA and Tukey's pairwise comparisons were used to explore the differences in environmental variables between clusters, tested variables included means of soil temperature, water table depth and soil respiration alongside vegetation principal component and soil principal component.

Optical remote sensing imagery was acquired by the Pleiades satellite on 28th August 2012. This provided data in the blue, green, red, and near-infrared (NIR) part of the spectrum for the 2 x 2 km region around the chamber sites, with 2 m resolution on the ground. From these data both the simple ratio (SR = NIR / Red) and normalised difference vegetation index (NDVI = [NIR - Red] / [NIR + Red]) were calculated. The optical data for each chamber location were extracted and related to the geometric mean of the CH_4 flux at that location. Multiple regression modelling was then carried out using R (version 3.1.1) to describe the CH_4 fluxes of individual chambers initially utilising all four wavebands and the two calculated ratios. The best fit model was used to upscale CH_4 fluxes to the full image domain (4 km^2). Due again to large uncertainties in the flux estimates, large proportion of fluxes indistinguishable from zero, and subsequent inability to accurately model the data, upscaling of N_2O emissions was not carried out using satellite imagery.

3 Results

Confidence intervals calculated from each chamber measurement, which include errors introduced by a combination of natural variability in the flux over the measurement period, methodological and analytical limitations and uncertainty in model fitting, show a high proportion of calculated fluxes which are indistinguishable from zero. Given the high relative variability in individual chambers and low fluxes in N_2O, only 8 and 9 % of fluxes were significant in the wetland and forest, respectively. The proportion of chambers displaying significant N_2O fluxes could not be linked to any measured environmental factors and were distributed randomly across the dataset. For CH_4, whilst only 56% of fluxes were significantly different from zero in the forest, the wetland was much clearer with zero excluded from the confidence range in 94% of cases.

When separated by site (forest, wetland) and by campaign period (summer, autumn) the highest instantaneous CH_4 fluxes, greatest skew and largest range were all observed in the wetland chambers during the summer period (Figure 1). These equated to a mean flux of 3.35 ± 0.44 mg C m^{-2} hr^{-1}, compared to only 0.62 ± 0.09 mg C m^{-2} hr^{-1} in the wetland during the autumn period. The mean CH_4 flux across the whole measurement period represented an emission of 1.56 ± 0.20 mg C m^{-2} hr^{-1} from the wetland chambers, compared to a mean uptake of 0.04 ± <0.1 mg C m^{-2} hr^{-1} from the forest chambers (Table 1).

N_2O fluxes had a mean emission across the full sampling period of 1.06 ± 0.44 µg N m^{-2} ~~s~~hr^{-1} and 0.73 ± 0.40 µg N m^{-2} ~~s~~hr^{-1} from forest and wetland chambers, respectively (Table 1).

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3.1 Spatial Variability

Surface cover data (vegetation and presence of standing water) was summarised using a PCA analysis; combined the top three principal components explained 51% of the total variation between chamber vegetation communities, with principal components 1, 2 and 3 (PC1, PC2, PC3) explaining 24%, 15% and 11%, respectively. PC1, PC2 and PC3 were subsequently tested for correlations with CH_4 fluxes. Spatial variability in CH_4 emissions among wetland chambers was best captured using PC2 ($r = 0.40$, $P < 0.01$). PC2 also correlated strongest with CH_4 emissions when all chambers (both wetland and forest) were included ($r = 0.31$, $P < 0.01$), however PC1 showed the best correlation with forest chambers alone ($r = 0.25$, $P < 0.01$). PC2 was therefore used throughout future analysis to describe the spatial variability in CH_4 emissions.

PC2 (which best described CH_4 fluxes) showed a strong dependence on the proportion of green *Sphagnum* species within the chamber with positive PC2 values indicating a high prevalence (Figure 2). Due to the strongly non-normal distribution of the data, *Sphagnum* sp. alone could not be correlated with emissions, thus the principal component method provides an indirect measure of the relationship. Low PC2 scores indicate a higher abundance of non-*Sphagnum* moss species and high proportion of open water within the chambers. Of the measured environmental variables relating to spatial variability (soil temperature, soil moisture, water table depth and soil respiration), PC2 only correlated significantly with water table depth ($r = 0.17$, $P < 0.01$) with PC2 scores increasing with water table depth.

A similar PCA analysis was carried out to summarise the available soil ~~concentration data.~~nutrient availability data from the PRS probes. The first three principal components combined explained 56% of total variation with PC1, PC2 and PC3 individually accounting for 31%, 15% and 10% of variability, respectively. PC1 gave the best correlation with CH_4 emissions when all data was combined and for forest chambers alone. PC2 gave a better correlation with wetland chambers alone (PC2: $r = 0.40$, $P < 0.01$). PC2 was therefore utilised throughout the remainder of the analysis due to the greater magnitude of wetland versus forest CH_4 emissions, and their subsequent importance to landscape scale emissions.

PC2 was influenced strongly by total N and NH_4^+ concentrations with high concentrations resulting in a low PC2 score (Figure 3). The only environmental variable significantly correlated with PC2 was water table depth ($r = 0.19$, $P < 0.01$) with high PC2 scores indicating a deep water table. However, when wetland chambers were considered alone soil respiration also showed a significant positive correlation with PC2 ($r = 0.31$, $P < 0.01$).

Spatial variability in GHG emissions were tested against the measured environmental variables as well as the most appropriate PCA score for both vegetation and soil, as described above. CH_4 flux was not statistically correlated to water table depth in the wetland chambers (Figure 4). However a relatively strong positive correlation was seen between CH_4 flux and the PCA score from the vegetation analysis; a high score from the vegetation principal component represented a deep mean water table depth. Positive correlations were also found between CH_4 flux, mean soil temperature and the principal component from the soil analysis when the wetland chambers were considered alone. Within the forest chambers, only the soil principal component was statistically correlated to CH_4 flux.

To further summarise the CH_4 data and provide a method for both upscaling and consideration of temporal variability, chambers were grouped independently based on net emissions. Data distributions within each cluster group are shown in Fig. 5. The cluster identified with the lowest emissions contained all the forest chambers and an additional two low emitting wetland chambers; for explanatory purposes this cluster is subsequently referred to as the 'forest' cluster. The remaining clusters, with sequentially increasing emissions, are labelled wetland_a, wetland_b, wetland_c and wetland_d, respectively.

ANOVA showed significant between cluster variability in all tested environmental variables (soil temperature, water table depth, soil respiration, vegetation principal component and soil principal component) with the exception of water table depth (Figure 6). The patterns in soil temperature, PCA_veg and PCA_soil are in line with the previously discussed correlation analysis. When the components of PCA_veg are considered independently the results highlight the importance of *Sphagnum* cover and open water in controlling the CH_4 emissions within the wetland clusters, however this relationship is complicated by the high variability shown by large standard deviations from the mean cluster values (Table 2). Wetland clusters 'a' and 'b', which represent the two lowest emitting wetland groups, had the lowest proportions of *Sphagnum* moss species and the greatest proportion of chambers containing open water.

Between-group differences in soil nutrient concentrations were also considered using ANOVA; only nutrients which displayed significant between-group differences are displayed in Fig. 7. The strongest between-group difference was evident in the soil Fe concentrations, with high Fe linked to high CH_4 emitting chambers ($F = 62.0$, $P < 0.01$); positive correlations with mean group CH_4 emissions were also seen for B ($F = 49.2$, $P < 0.01$), Zn ($F = 39.0$, $P < 0.01$) and Mg ($F = 49.2$, $P < 0.01$). Negative correlations were seen between mean group CH_4 emission and K ($F = 10.6$, $P < 0.01$), NO_3-N ($F = 6.38$, $P < 0.01$), and NH_4-N ($F = 6.36$, $P < 0.01$). Within the wetland, total-N was lowest in groups with the highest CH_4 emission; however the pattern is less clear when forest chambers are included as these displayed a wide range of total-N but a low CH_4. Only the forest had distinct soil Ca concentrations.

3.2 Temporal Variability

Temporal variability, summarised by cluster, is displayed in Fig. 8 for both the summer and autumn campaign periods. CH_4 emissions remain relatively constant throughout both campaign periods despite a significant drop in emissions between them. Despite the low temporal variability, emissions appear to peak around mid-July in the higher emitting chamber clusters (e.g. wetland_c and wetland_d).

CH_4 emissions did not follow linear relationships with the measured environmental variables (soil temperature, air temperature, water table depth and soil respiration) (Figure 9). CH_4 emissions peaked at a soil temperature of approximately 12°C and an air temperature of approximately 15°C, after which they began to fall. The time series suggests a general decrease in CH_4 emissions with rising water table, however the relationship appears to be chamber specific and non-linear suggesting a greater complexity than is usually accounted for. In the high emitting chambers, there is a peak in CH_4 emissions as the water level reaches the surface, the emissions drop until water tables of approximately 5 cm depth and then rise again as the water level deepens further. Chamber clusters associated with lower total CH_4 emissions did not show this peak associated with surface

water tables but instead followed a smoother, but still non-linear, increase in emissions with increasing water table depth. No relationship was observed between soil temperature and water table depth ruling out a potential interaction as the cause of the peaks associated with particular water table depths or soil temperatures.

3.3 Spectral analysis and upscaling

A multiple regression model including blue, green, red, NIR, SR and NDVI explained 45 % of the variance in the spatial ~~methane~~CH_4 flux. Transformations of the data and more complex models were explored, but did not substantially improve the model fit. A simpler model containing only SR, NDVI and the blue and NIR wavebands performed equally as well as the full model also explaining 45% of the spatial variation (Table 3), this simpler model was therefore used in subsequent analysis. To predict mean ~~methane~~CH_4 flux over our sampling period at landscape scale, we applied the regression model to the optical data over the whole 2 x 2 km domain. This predicted high ~~methane~~CH_4 fluxes in the wetland areas in the north-east and at forest edges (Figure 10). Using the optical data to scale up the chamber measurements, the mean ~~methane~~CH_4 flux over the whole domain between 12th July and 14th October is estimated to be 47.4 ± 14.1 nmol CH_4 m^{-2} s^{-1} or 2.05 ± 0.61 mg C m^{-2} hr^{-1}. By comparison, if the flux over the whole spatial domain were estimated simply as the arithmetic mean of the individual chamber measurements (geometric mean to summarise temporal variability) the value would be significantly lower (23.0 ± 3.78 nmol CH_4 m^{-2} s^{-1}). If we account for the differences between wetland and forest alone using an appropriate area weighting factor~~,~~ (61% wetland; 32% forest), ignoring variability within these landscape units, estimated emissions are 21.6 ± 2.85 nmol CH_4 m^{-2} s^{-1}, also substantially lower than our modelled approach.

4 Discussion

Fluxes of CH_4 from the forest and wetland areas within the landscape were significantly different at -0.06 ~~+~~± <0.01 and 3.35 ± 0.44 mg C m^{-2} hr^{-1}, respectively. Whilst the error displayed here suggests confidence in the forest as a net sink for CH_4, when individual chamber measurements are considered, only 56.3% of the measured fluxes had an error bar that did not cross the zero line. Hence we can only be confident that the sign of the flux is correct in just over half of our forest data. On removal of all fluxes with an uncertain sign, the mean remains negative in the forest chambers. This gives confidence that whilst the calculated flux is very small, it is a small sink rather than a source. In the wetland however, 94.4% of the measured fluxes differed significantly from zero, so we can be confident that the wetland represented a strong source of CH_4.

A similar analysis was carried out on the N_2O flux data and here due to very high uncertainties in the sign of individual flux measurements (only 8.68% and 7.79% of measurements in the forest and wetland, respectively, did not have error bars crossing the zero line) we cannot differentiate either the forest or wetland as being a net sink or source over the campaign period. We can simply state that N_2O fluxes in both landscape units were near-zero. ~~Due~~N_2O fluxes were therefore not an important component of this study area. Whilst minimal, the near-zero result is still an important finding given the lack of N_2O emissions reported in the current literature. Assuming these near-zero fluxes are similar across the region we have an important baseline

from which to monitor change related to future climate or land-use practices. However, due to consistently near-zero fluxes, little could be concluded about the drivers of N_2O emissions over within our landscape area.

4.1 Drivers of CH_4 emissions

The relationship between CH_4 emissions and water table position was not straightforward. Considering the mean CH_4 flux for each chamber and testing this against the mean water level position of that chamber showed no significant relationship (Figure 4), suggesting water table was not an important factor in controlling spatial variability in emissions across the site. Furthermore, when chambers were clustered based on their CH_4 emissions, there was high within-group variability in water table and subsequently no significant differences in water table between groups (Figure 6). Whilst much of the previous literature suggests water level as the primary driver of CH_4 (Aerts and Ludwig, 1997; Hargreaves and Fowler, 1998; Waddington et al., 1996) due to its role in controlling the oxic/anoxic boundary, there is a growing body of evidence which suggests this is true only in drier ecosystems (Hartley et al., 2015; Olefeldt et al., 2013; Turetsky et al., 2014.). The water levels used in this analysis only represented the water level during the campaign periods, with no consideration of longer term means. Due to the presence of alternative electron acceptors and the delay in returning to favourable redox conditions, fluctuations in the water level can result in a reduced population and a subsequent reduction in CH_4 production, even after water levels and anoxic conditions recover (Freeman et al., 1994; Kettunen et al., 1999). Hence whilst soil conditions may appear suitable for CH_4 production at the time of measurement, an unfavourable water table in the days to weeks prior to the measurement can limit methanogenesis and mask the expected relationship.

CH_4 in the wetland correlated positively and significantly with a component from the vegetation PCA analysis. The vegetation component that best described CH_4 emissions (PC2) related primarily to *Sphagnum* cover within the chambers and also linked low scores to a high proportion of open water. *Sphagnum* is an indicator of long term near-surface water table position, hence whilst the directly measured water table did not correlate significantly with CH_4 emissions, the vegetation analysis suggests that longer term water level conditions do correlate with spatial variability in CH_4. Several other studies have also highlighted the importance of vegetation as an indirect indicator of CH_4 flux as it integrates across multiple ecological variables (e.g. Bubier et al., 1995; Davidson et al., 2016;Gray et al., 2013;Oquist and Svensson, 2002). It is also this link to vegetation that makes upscaling such as that described below possible as the spectral data is primarily picking up spatial variability in above-ground plant community cover. Vegetation can also play an important direct role in GHG emissions via plant-mediated transport and the supply of labile substrate, thought to be particularly important for methanogenesis (e.g. McEwing et al., 2015;Ström et al., 2005). *Sphagnum* mosses can be additionally important in controlling CH_4 emissions through their association with methanotrophic bacteria, an association that has been shown to exist across the globe and across a range microtopographic features (Kip et al., 2010). Here we find no correlation between CH_4 emissions and soil respiration and a positive influence of *Sphagnum* cover. This suggests that the role of vegetation as an indirect indicator of other environmental factors is more important to CH_4 emissions in this landscape than methanotrophic associations or substrate availability.

The water table relationship is further complicated by the presence of standing water which related to low emitting chambers. This may be a consequence of reduced diffusion from the soil to the atmosphere rather than a result of reduced production. If standing water remains for long periods of time, the sustained anoxic conditions can alter the vegetation and soil chemistry. For example reduced nitrification, an oxic process, can lead to a build-up of NH_4^+ in water logged conditions. Soil PCA component 2 which correlated positively with CH_4 emissions showed a strong link to the concentration of NH_4^+; high concentrations were linked to low PCA scores and low CH_4 emissions. NH_4^+ in this case may be acting as an indicator of the chambers which were inundated with surface water for sustained time periods.

Our chambers were not specifically designed to measure emissions from water surfaces and as a result cut out all wind driven turbulence which is likely to be an important driver of the evasion flux (MacIntyre et al., 1995). It is therefore difficult to identify whether standing water produced a decrease in CH_4 production, a real decrease in flux due to low diffusivity through the water column, or if our results were a consequence of our methodology artificially reducing gas transfer across the water-air boundary. A previous study showed an increase in CH_4 emissions along a water table gradient from 35 cm depth to 5 cm above the soil surface. Above 5 cm the relationship with increasing water level was negative (Pelletier et al., 2007). Whilst our results are not as clear as those presented by Pelletier *et al.* (2007) a similar mechanism of reduced CH_4 diffusion through standing water may be responsible in both cases.

Figure 7 shows a clear positive relationship between Fe, Zn and CH_4 emissions, with high emitting clusters also displaying the highest concentrations. These cations reflect the redox potential of the soil with increasing concentrations indicating a lowering of the redox potential. The CH_4 water table relationship is indirect with water table used as a proxy for soil oxygen content and redox potential. Here we find cation concentrations have a greater explanatory power than water table hence they may represent a more appropriate indicator of soil redox status and methanogenic potential.

When we consider the temporal patterns in CH_4 emissions across the 2 campaign periods we see a similar response as in the spatial analysis, with emissions falling as the water level rises between approximately 15 and 5 cm depth. No relationship was found between water table and soil temperature ruling out an interaction as the primary cause of the water table relationship. Tupek *et al.* (2014) measured increasing CH_4 emissions in response to a rising water table until a peak at approximately 20 cm depth in a central Finnish mire, after which the relationship changed with emissions decreasing as the water table approached the surface. Water table depths measured in this study covered a smaller range and therefore we can assume similar dynamics may be apparent if the water level was to drop below 20 cm. Similarly a recent synthesis (Turetsky et al., 2014) involving 71 wetlands found the optimum water table depth for CH_4 emissions to be 23.6 ± 2.4 cm for bog ecosystems. Again suggesting the negative water table relationship observed here is due to water table depth being consistently above the optimum. Potential explanations for the inhibition of CH_4 emissions at high water levels given by Turetsky et al. (2014) include limited diffusion of CH_4 through standing water as discussed above, reduced CH_4 production due to lower plant biomass and associated labile C inputs, or unfavourable redox conditions resulting from inputs of oxygen rich water potentially containing alternative electron acceptors. Whilst we saw no clear correlations between the percentage of bare soil and that of open water in our chambers, a reduction in plant activity may have occurred during submersion so reduction in C inputs for methanogenesis

cannot be ruled out to explain the temporal changes in CH_4 emissions across the growing season. Neither do we have the data to rule out a change in redox potential due to water flow. A more detailed analysis under controlled conditions would be required to accurately explain the mechanism for high water CH_4 limitation at this site.

As the water table rose between 5 cm depth and the soil surface, emissions appear to increase again peaking at approximately the soil surface and then decreasing with increasing water depth above the soil surface. This could be due to physical forcing of CH_4 out of the soil pore space as it reaches the soil surface. Importantly, what our results clearly show ~~are~~is that there are a number of driver mechanisms interacting to produce the observed CH_4-water table relationship.

A significant positive spatial relationship was seen between soil temperature and CH_4 (Figure 4 and Figure 6). The relationship between CH_4 emission and temperature is a well-established one often observed in the literature (Segers, 1998) as a result of the greater sensitivity of methanogenesis than methanotrophy; however most studies focus on the implications of temporal variation rather than the spatial pattern. The spatial variability in soil temperature is likely to be linked to a combination of soil water content and the surface reflectance of the vegetation cover. Changing soil temperature therefore represents an important by-product of other environmental changes that needs to be accounted for in predictive mechanistic models.

The temporal relationship between CH_4 emissions and temperature showed a Gaussian response curve typical of microbial control. Peak CH_4 emission occurred at a soil temperature of ~12°C. A similar pattern was observed in a central Finland mire by Tupek *et al*. (2014) who recorded a peak in emissions corresponding to 14°C.

4.2 Upscaling

The wetland CH_4 fluxes calculated here (3.35 mg C m^{-2} hr^{-1} during the summer season and 1.56 mg C m^{-2} hr^{-1} when the autumn period is included) are similar in magnitude to those described in a multisite analysis by Turesky et al. *(2014)* for subarctic (3.51 ± 0.19 mg C m^{-2} hr^{-1}) and boreal wetlands (2.27 ± 0.04 mg C m^{-2} hr^{-1}). However given the large differences between fluxes calculated within the forest and wetland, and the heterogeneous mix of these two primary ecosystem types across the subarctic/boreal system, landscape scale emissions are of greater importance in understanding global CH_4 source estimates than wetland emissions alone. By extending our sampling site to a 2 x 2 km landscape we can calculate emissions which are more relevant to the region as a whole. Based on a weighted average of fluxes from the forest and wetland within the landscape, and assuming CH_4 emissions from the other landscape units are zero, we can calculate average landscape scale emissions of 0.93 ± 0.12 mg CH_4-C m^{-2} hr^{-1}.

~~However, whilst~~ Whilst calculations at this level of detail have previously been shown to give good agreement with more top down methodologies (O'Shea et al., 2014), significant information is lost regarding spatial variability which we have already shown to be large, especially within the wetland. Utilising spectral data across the 2 x 2 km landscape and a multiple regression model, we calculated average CH_4 flux over the growing season as 47.4 ± 14.1 nmol CH_4 m^{-2} s^{-1} or 2.05 ± 0.61 mg C m^{-2} hr^{-1}. This is significantly higher than the landscape scale CH_4 flux of 1.1 to 1.4 g CH_4 m^{-2} during the May to October growing season (0.19 to 0.23 mg C m^{-2} hr^{-1}) calculated by Hartley et. al. ~~(2015) from~~(2015). The Hartley et. al. (2015) study was based on field measurements collected approximately 240 km north of our study site, up-scaled using aerial imagery and

satellite data. Even when utilising data presented from only July-September, Hartley et al. (2015) still recorded much lower landscape ~~scales~~scale fluxes (~~approx..~~approximately 0.24 mg C m^{-2} hr^{-1}) than this study due to the different landscape units and proportions of vegetation communities. Whereas we carried out our upscaling over an area characterised by 61% wetlands and 32% forest, the landscape unit measured by Hartley et al. (2015) contained only ~22% wetland (classified as both mire and mire edge) and 60% forest. Heikkinen et al. (2004) also upscaled chamber based CH_4 emissions to landscape, in this instance a 114 km^2 catchment in the eastern European Russian tundra, concluding a mean summer CH_4 emission rate of 0.43 mg C m^{-2} hr^{-1}. CH_4 emissions from areas classified as peaty tundra (including intermediate flarks, *Carex + Sphagnum* and hummocks), which ranged from 0.15 to 4.25 mg C m^{-2} hr^{-1}, were similar to those presented here. However, again it is the proportion of wetland within the landscape (16.1 %) and to a lesser extent the distribution of emissions within the wetland that appears to be most important in defining the landscape scale flux.

Open water has not been included in this study as it was not an important feature in the 2 x 2 km study area. However given the large proportion of lakes and ponds across sub-arctic and boreal ecosystems, and the potential increase in surface water as the changing climate alters subsurface hydrology, this is something that will become more important both in the future and as we scale to larger or regional landscapes. CH_4 emissions from Arctic lakes are estimated to total 11.86 Tg yr^{-1}, varying spatially over high latitudes from 3.46 mg C m^{-2} hr^{-1} in Alaska to 0.40 mg C m^{-2} hr^{-1} in northern Europe (Zeli and Qianlai, 2015); this puts lake fluxes in the same order of CH_4 emissions as northern high-latitude wetlands and comparable to the values measured in this study.

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There is still considerable uncertainty in extrapolating to our 2 x 2 km landscape despite optical remote sensing data having complete coverage and a reasonably well-defined relationship with CH_4 flux. Greatest emissions and subsequently the greatest uncertainty are observed in an area to the north east of our landscape which represents an area of yellow/green *Sphagnum*. Further flux measurements are required to reduce the uncertainty in this area. Therefore, in addition to providing upscaled emission estimates, this spectral approach could also potentially be applied to define specific areas for future research focus, maximising the potential explanatory power of future campaigns. .

~~Whilst useful as an upscaling tool over this small landscape area, this method relies on local chamber measurements and is therefore not appropriate for extrapolation to larger spectral datasets. Equally, as demonstrated in the comparison with Hartley et al. (2015), who's study landscape is in relatively close proximity to that considered here, the variability in ecosystem features across the region is extremely important, therefore larger regional scale estimates cannot be achieved by extrapolating from the land-scape mean presented here without significant further research effort.~~We were unable to carry out a similar upscaling exercise for N_2O, however given the near-zero fluxes across the majority of study chambers, a detailed spatial method is not required to say with a large degree of certainty that N_2O emissions are not currently a major component of the growing season GHG balance of our landscape. Whilst potentially subject to changes in temperature and hydrology as a result of climate, our site was not underlain by permafrost and therefore is not going to be affected by thaw-related processes. Recent studies have shown potentially large increases in N_2O emissions related to permafrost thaw (Elberling et al., 2010;Abbott and Jones, 2015;Marushchak et al., 2011) so whilst negligible here, N_2O emissions across the wider northern boreal and sub-arctic zone

may become increasingly important to the total GHG balance of the landscape and should therefore continue to be monitored in future research.

4.3 Conclusions

Our results showed a significant proportion of measured N_2O fluxes, across both wetland and forest, and CH_4 fluxes within the forest, were not distinguishable from zero. Considering only those fluxes that did differ significantly from zero we can be confident that the wetland represented a strong source of CH_4, especially during the summer peak growing season (3.35 ± 0.44 mg C m^{-2} hr^{-1}), and the forest a small CH_4 sink (summer: -0.06 ± <0.01 mg C m^{-2} hr^{-1}). We ~~can only~~ conclude that N_2O fluxes were near-zero across the landscape~~.~~ in both forest and wetland. Despite the small magnitude of N_2O fluxes this is still an important result given the current lack of data available for N_2O across northern boreal, sub-arctic regions, and the potential for future increases in relation to climate and land-use.

We did not observe a direct water table control on spatial variability in CH_4 emissions but instead found a relationship with vegetation communities, in particular the presence of *Sphagnum* mosses, and with soil chemistry which we attribute to redox potential. Both these parameters suggest that water table level and water table variability over a longer time scale prior to flux measurements is required to accurately predict CH_4 emissions. When temporal variability across the campaigns was considered we found a decrease in CH_4 emissions as water table approached the soil surface and the soil became fully saturated. We attribute this apparent reversal of the literature described relationship between CH_4 and water table to the water table depth being consistently above the optimum. As water levels continue to rise beyond this point diffusion becomes restricted and the flux diminished. We also found a temporal relationship between CH_4 emissions and soil temperature with peak emissions at approximately 12°C.

To upscale the chamber measurements of CH_4 to a 2 x 2 km landscape area we utilised PLEIADES PA1 satellite imagery and could account for 45% of spatial variability in CH_4 flux using SR, NDVI, Blue and NIR spectral data. Applying this model to the full area gave us an estimated CH_4 emission of 2.05 ± 0.61 mg C m^{-2} hr^{-1}. This was higher than landscape estimates based on either a simple mean or weighted by forest/wetland proportion alone (0.99 ± 0.16 mg C m^{-2} hr^{-1}, 0.93 ± 0.12 mg C m^{-2} hr^{-1}, respectively). Hence whilst there are clearly uncertainties associated with the modelled approach, excluding spatial variability as with the latter two methods is likely to lead to underestimations in total emissions. ~~Whilst the modelled extrapolation method described here is unlikely to be accurate over a large regional area, we conclude that over an area similar in size to our 2 x 2 km landscape, it is a useful upscaling tool~~This approach therefore has considerable potential for increasing the accuracy of future landscape scale emission estimates and making better use of the wide variety of chamber measurements currently presented in the literature. When compared to similar upscaling studies our landscape estimate showed significantly higher CH_4 emissions, even when individual chamber scale fluxes were similar. Whilst spatial variability within the wetland area was important, the primary difference was the proportion of ecosystem units within the measurement landscape e.g. the proportion of wetland vs forest or tundra. It is therefore not applicable to take the results presented here and simply apply the landscape

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mean to larger area given the proportion of wetland will change substantially with scale, however with the addition of further ground-truthing and a larger spectral image, larger areas could be similarly modelled.

Data availability

Data will be made available through the Environmental Information Data Centre (EIDC), a Natural Environment Research Council data centre hosted by the Centre for Ecology & Hydrology (CEH), UK.

Author contribution

J. Drewer, U.M. Skiba and K.J. Dinsmore designed and carried out the field experiments and subsequent laboratory analysis. A. Lohila and M. Aurela provided help with the experimental set-up, selection of the field site and local knowledge. P.E. Levy and C. George analyzed the spectral data and developed the model for upscaling chamber emissions to landscape. K.J. Dinsmore carried out the remainder of the analysis and prepared the manuscript with contributions from all co-authors.

Acknowledgements

This work was funded through the MAMM project (Methane and other greenhouse gases in the Arctic: Measurements, process studies and Modelling, http://arp.arctic.ac.uk/projects/) by the UK Natural Environment Research Council (grant NE/I029293/1).

We wish to thank staff from the Finnish Meteorology Institute at Sodankylä and Helsinki, in particular Annalea Lohila, Tuula Aalto and Tuomas Laurila for their kind hospitality, invitation and collaboration and the EU project InGOS for supporting the two field campaigns in Sodankylä through the TNA2 travel budget (*www.**ingos**-infrastructure.eu/access/**tna2**-access-to-stations)*.

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Tables

Table 1. Mean ± SE CH_4 and N_2O fluxes split by both campaign period (summer, autumn) and site (forest, wetland).

	Summer	Autumn	Full Period
CH_4 (mg C m^{-2} hr^{-1})			
Forest	-0.06 ± <0.01	-0.03 ± <0.01	-0.04 ± <0.01
Wetland	3.35 ± 0.44	0.62 ± 0.09	1.56 ± 0.20
N_2O (µg N m^{-2} hr^{-1})			
Forest	0.75 ± 0.33	1.29 ± 1.39	1.06 ± 0.44
Wetland	1.63 ± 0.64	-1.60 ± 1.18	0.73 ± 0.40

Table 2. Mean ± stdev ground cover data for wetland clusters. Only variables which showed significant between cluster variability are included. Test statistic refers to the F-value with * and ** indicating P-vales of <0.05 and <0.01, respectively.

	Sphagnum sp.	Openwater
Wetland_a	39.3 ± 46.0	59.5 ± 62.0
Wetland_b	68.6 ± 47.4	11.4 ± 18.6
Wetland_c	95.7 ± 11.3	5.71 ± 9.32
Wetland_d	50.0 ± 70.7	20.0 ± 28.2
ANOVA test statistic	4.62**	3.59*

Table 3. Model summary utilising spectral data to estimate CH_4 emissions

	Estimate	t-value	p-value
Intercept	-233	0.00002	<0.01
SR	354	0.00002	<0.01
NDVI	-283	0.03883	<0.05
Blue	0.99	0.00365	<0.01
NIR	-0.91	0.00022	<0.01
model adjusted r^2	0.45		
model p-value	<0.01		

Formatted Table

Figure Captions

Figure 1. Frequency plot showing distribution of all fluxes across both campaign periods

Figure 2. Loading values for principal components 1 and 2 of the chamber vegetation analysis

Figure 3. Loading values for principal components ~~1~~2 and ~~2~~3 of the chamber soil concentration analysis

Figure 4. Relationships between geometric mean CH_4 flux (nmol m^{-2} s^{-1}) against measured environmental variables. across full sampling period. Text refers to the results from statistical correlations were 'ns' refers to a non-significant results, * and ** represent $P < 0.05$ and $P < 0.01$, respectively.

Figure 5. Chambers clustered based on emissions with n indicating the number of chambers within each group.

Figure 6. Boxplots showing range of measured environmental variables within each of the CH_4 clusters. Letters represent results from Tukeys family test statistic where clusters with similar letters are not significantly different from one another at 95% confidence level. Clusters Wetland_a to Wetland_d represent groups with sequentially increasing CH_4 emissions. Note water table was not measured within the forest plots therefore the water table values given in the 'forest' cluster actually represent only the 2 wetland chambers which have quantitatively been assigned to this cluster and have therefore been excluded.

Figure 7. Boxplots showing range of soil variables within each of the CH_4 clusters. Units represent probe supply rate (µg per $10cm^2$ across burial period). Letters represent results from Tukeys family test statistic where clusters with similar letters are not significantly different from one another at 95% confidence level. Clusters Wetland_a to Wetland_d represent groups with sequentially increasing CH_4 emissions.

Figure 8. Temporal variability across the 2 field campaigns in CH_4 emissions, separated by clusters, with shaded area representing loess smoothing. Clusters Wetland_a to Wetland_d represent groups with sequentially increasing CH_4 emissions.

Figure 9. Drivers of temporal variability in CH_4 fluxes, separated by clusters, with shaded area representing loess smoothing. Clusters Wetland_a to Wetland_d represent groups with sequentially increasing CH_4 emissions.

Figure 10. Mean (a) and SE (b) of CH_4 fluxes extrapolated over a 2 x 2 km area predicted from chamber flux measurements (black circles), and satellite spectral data. Coordinates are in WGS84.