Growing-season variability and environmental controls of CH 4 and N 2 O fluxes across high-latitude terrestrial ecosystems (Niemi et al.)

Referee comments #1

General comments

This manuscript presents a substantial and potentially valuable dataset on the variability of CH 4 and N2O fluxes during the growing season of two consecutive years across contrasting eight high-latitude land cover classes of subarctic and boreal Northern Finland. The combination of flux measurements at wetland and non-wetland sites for the two greenhouse gases (GHGs), along with the fitting of linear mixed-effects models to examine the relationships between GHG fluxes and environmental variables, reflects interesting field work and has identified important variables for improving our understanding and modelling of both GHGs. The key findings, the seasonal trend, the relationship with land cover classes, and the correlation factors (through not decisive) provide valuable insights. The topic is timely and clearly relevant to high-latitude terrestrial ecosystems, and the study has the potential to make a useful contribution once presentation is revised. The manuscript can be improved, in particular, by 1) enhancing its presentation: in the result section, an analysis of statistical significance should be used to demonstrate how and whether the research questions posed can be answered using statistical methods; and by providing a more detailed description and presentation of the results, including additional information. It could be further strengthened 2) by highlighting the research gaps, connecting key findings to scientific context, and clarifying the implications of the research.

Answer: *Thank you for the thorough and constructive review of the manuscript. We appreciate the time and effort invested in providing these detailed comments. We will revise and improve the manuscript accordingly.*

Abstract

Line 32-36: Give clear terminology of land cover classes and use always the same terms. E.g. use “dry land cover classes” (dry tundra: bare, shrub tundra), forest sites and “wetland land cover classes”: tundra wetland, bog, fen, permafrost bog) throughout the manuscript. In **line** 34-35 it is not clear that wetlands include fens and permafrost bogs.

Answer: *We will change the terminology to be more concise throughout the manuscript. In our current descriptions, wetlands include fens, bogs, permafrost bogs and tundra wetlands, while dry soils (i.e. "non-wetland soils") are evergreen forests, deciduous forests, shrub tundra and bare tundra.*

Line 35: Are this means or medians? In the result section (**line** 309…), means are given, but in Figure 2 only medians are shown. Please use the option that is more appropriate for the data records and is consistent throughout.

Answer**:** *We will make sure to specify whether we are referring to means or medians throughout the manuscript. On line 35 we refer to means.*

Introduction

Line 55: Add literature: Climate effect on CH4 and N2O

Answer: *We will add references to this section.*

Line 65-70: Introduce definitions: peatland: fen, bog, permafrost bog in connection with wetland and dry tundra in comparison to wet tundra and forest ecosystems.

Add numbers: what is less carbon, vast extend?

Answer: *Detailed definitions are in the Materials and Methods (section 2), we will also add short descriptions to the Introduction (section 1).*

We will add further information and references to carbon storage and ecosystem distributions and remove generic descriptions that had no references.

Line 74: When giving global warming of N2O also add it for CH4

Answer: *We will edit as suggested.*

Line 76: What is the definition of wetlands here? Clarify here. What is the difference to **line** 65 where peatlands are described as methane source? Is there a general difference in carbon content (< Corg. threshold?)

Answer: *We will add a clear definition of wetlands and remove a sentence to avoid repetition.*

Line 79: Give definition of tundra and dry tundra.

Answer: *We will add definitions of tundra and dry tundra.*

Line 93-94: Give clear terminology of land cover classes (see Abstract).

Answer: *We will add more detailed descriptions to the Introduction (section 1). The terminology is also fully explained in Materials and Methods (section 2).*

Line 99: More precise. 8 land cover classes at two research sites in Northern Finland?

Answer: *We will add further details about the research sites.*

Material and Methods

Fig. 1: Please show different land cover classes e.g. with different colors or symbols on map.

Answer: *We will add colors based on land cover classes and improve the map layout.*

Line 110-125: Please describe in which areas were which land cover types found or all 8 types in both areas?

Answer: *We will add further details about research sites and locations.*

Line 125: Those are not soil conditions, but rather the source material for soil formation. Can you tell us more about the soils? Was there an organic layer, and how thick was it? The organic layer thickness (OLT) might had an influence on GHG.

Answer: *We will add a separate paragraph describing soil conditions, distinct from the paragraph on soil formation. We agree that organic soil layer thickness (OLT) can be an important factor influencing soil conditions. However, OLT is strongly associated with land-cover class and soil moisture in our study sites and is therefore partly redundant with these variables already included in the models. Including OLT alongside these variables would result in substantial collinearity and increase model complexity without providing independent explanatory information. We therefore did not include OLT in the final models. If the model structure were different, for example, without the categorical land-cover variable, OLT could be considered as an explanatory parameter. We will also provide approximate OLT values in the site descriptions to give readers a better understanding of the soil conditions represented by our sites. Finally, we will add a paragraph explaining the rationale for selecting the model parameters.*

Line 141: Please give information how many measurements at each land cover site and the growing season temperature and precipitation. Were these years comparable to one another, or were they particularly dry or wet compared to the long-term average? This might be important for the differences in N2O fluxes between 2024 and 2025.

Answer: *We will add information on the number of measurements in each land-cover class and an additional paragraph describing the climatic conditions during the 2024–2025 growing seasons, including their differences from long-term averages, based on data available from nearby weather stations.*

Line 146: Use always the same terminology “shrub” tundra instead of “shrubby”, only permafrost bog instead of palsa.

Answer: *We will change the terminology as suggested.*

Line 148: Please explain, “with some minor changes to more accurately describe our research sites”, which parameters? Vegetation, soil, moisture?

Answer: *The changes are explained in the next sentence, we will add further clarification.*

Line 151-152: What are you expecting for the organic layer?

Answer: *We will add further details on organic layer thickness to this section to clarify the differences in soil conditions between the two plot types. The bare tundra plots were characterized by the absence of vascular plants and a very thin organic layer. In contrast, the shrub tundra plots supported more extensive vegetation and had thicker, although still relatively thin, organic layers. These pronounced differences in vegetation and soil organic matter suggested substantially lower biological and biogeochemical activity in the bare tundra plots. We therefore expected gas fluxes to differ between bare and shrub tundra.*

Line 153: Introduce the main groups: dry tundra, forest and wetland and then further differentiate.

Answer: *We will add a paragraph introducing tundra, forests and wetland groups.*

Line 153: Add literature for the statement.

Answer: *We will specify that these are descriptions of our sites based on our observations.*

Line 154: Have you described the vegetation or is this specified in the land cover classification used by the others?

Answer: *We will specify that we are describing the vegetation we have observed. We will also add appropriate references to support claims that are not directly based on our observations. …W…*

Line 167: Did you measure permafrost to differentiate the permafrost bog from bog?

Answer: *Yes, we will add a sentence about measuring permafrost extent with soil cores.*

Line 178: How shallow and does “no peat” mean no H horizon, but instead an O horizon? Give more information and be more precise?

Answer: *We will provide additional information to clarify what we mean by “shallow organic layers” and “no peat”.*

Line 180: What is the meaning of very dry? In Fig. 3, tundra wetlands had the highest soil moisture.

Answer: *We will rephrase this section and add a more detailed description of the environmental conditions and clarify our terminology to specify that tundra wetlands had highly variable water-table levels, based on in-situ field observations. During spring and autumn, the water table was often above the soil surface, whereas during the peak growing season it was generally below the soil surface. Despite this seasonal variation, soil moisture remained high throughout the measurement period, as shown in Figure 3, indicating that the lower water table during the peak growing season did not result in substantially drier soil conditions.*

Line 211: The calibration function can only be used for mineral soil and normally the VWC of organic soils or high OLT will be underestimated using this technique. Please verify or discuss.

Answer: *This is a valid point, and we acknowledge that using the “unknown soils” calibration function is not an ideal solution. However, there is currently no calibration function specifically developed for boreal or subarctic peat soils. Moreover, the “unknown soils” calibration function has previously been applied to similar and identical wetland environments and has produced better results than the other available calibration options (Kemppinen et al., 2023; Zignol et al., 2025). This rationale is described in Environmental variables section (Section 2.4, lines 203–215).*

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https://doi.org/10.5194/hess-29-5493-2025

Line 227: More precise. Did you measure pH values in H2O or CaCl2?

Answer*: pH values are measured in H2O. We will specify this in the section on pH analysis.*

Line 266: How many measurements were removed in %? Please indicate the number of measurements in which the detectable average flow rates for both gases were exceeded.

Answer: *We will add a paragraph reporting the amount of removed flux measurements (N2O = 15 measurements were removed, 0.12% of all measurements. CH4=9 measurements, 0.01% of all measurements). We will also add a paragraph discussing the minimum detection limits for LI-COR instruments and report the number of measurements that exceed them.*

Line 274: Which p values were considered statistically significant?

Answer: *added definition of significance (<0.05)*

Results

Line 309-320 and **line** 335-343: Here means are given, but in Figure 2 only medians are shown. Use clear terminology for land cover classes. Statistical analyses about significant differences within land cover classes and between land cover classes are missing. Please indicate, if significant different or not with p values and indicate in Figure 2. Only by indicating the statistical significance can we determine whether the first (section 3.10) and second (section 3.11) research questions can be answered***.***

Answer: *We will specify that means are reported and change the in-text reference from the figure showing medians to the table reporting means. The structure of the Results (section 3) starts with reporting the measured data (3.1 and 3.2) and the statistical analysis is reported later in the Results (section 3.5). We will add more detailed reporting on this and rename section 3.5 to reflect the content of the added statistical analysis.*

Land cover class is included in both CH4 and N2O models as seen from Figure 4. and 6. Satterthwaite approximated P-values for model results can be found in the full model summary tables (Table A3 and Table A4). We will also conduct additional pairwise testing for statistical differences between land cover types and add appropriate descriptions of it to the Materials and Methods (section 2) and Results (section 3).

Line 322-330: Here, too, there is a lack of statistical support for the statements. Is there significant differences within the land cover class between months? Please also indicate whether the CH4 measurements differed between the two years, even if this is not crucial to answering the research question. However, this information will be provided later for N2O.

Answer: *We will add an additional mention of the (lack of) yearly differences for CH4 in the Results (section 3) and clearer references to the tables in appendix. Statistical differences between months can be found in the appendix (table A5 and A6) which is referenced on line 324.*

Line 344-345: It would be interesting to include a figure in the appendix to illustrate this point (e.g. with different colors for land cover classes)

Answer**:** *We acknowledge this as an interesting result and will add discussion of the potential mechanisms as an important direction for future research. A comprehensive assessment of these mechanisms would, however, require additional information, such as stable isotope measurements or data on the microbial communities and processes involved in methanogenesis and denitrification, which are beyond the scope of the present study.*

Line 347: Please give more information. Especially for the wetland land cover classes; there might be

lower N2O uptake in June and increasing during the season. Please describe, if this probable statement is right and test, if statistical relevant. Please show measured differences between years.

Does Figure 7c show only predicted N_2O values, or does it also include measured values?

Answer: *We will add additional information on yearly differences of N2O in the Results (section 2) and specify that model result graphs (Figure 5. and 7.) only include predicted values. Monthly measurements can be found in Figure 2. and statistical testing for monthly differences in table A5 and A6. Full model results (including Satterthwaite approximated P-values) can be found in table A4.*

Line 353-370: Statistical proofs of the given statements are missing. Please give p values for all comparison statements, also in Figure 3. Are the values given in the text means or medians?

Answer**:** *We will revise the Environmental variables section (section 2.4) to focus only on observations and remove comparisons that would require additional statistical analyses. The reported environmental variables are intended to provide general descriptions of our research sites and are not directly related to our research questions. We will also specify whether the reported values are means or medians.*

Line 367-370: Be more precise. Please consider pH classification, normally very acidic means pH in CaCl2 between 4.0-4.6 depending on the classification system, therefore the pH value of tundra wetlands is only slightly acidic.

Answer**:** *We will remove unreferenced soil pH classifications.*

Line 398: Contrary to this statement, I can see a high effect of temperature and only a low effect of pH in Figure 7b & 7d. Please explain.

Answer**:** *As shown in Figure 6. (final model), which is the figure referenced on line 398, the effect size of temperature is only 0.01, compared with 0.16 for the pH × land-cover interaction. Thus, the pH × land-cover interaction is a substantially stronger predictor than soil temperature in the final model. We will add a note to use partial eta-squared for effect size comparison to avoid any misinterpretations.*

Figure 7b. and 7d. are useful for comparing the land covers to each other and to evaluate the direction of the effect. In case of pH, the large effect in permafrost bogs (grey line) stretches the axes, thus somewhat masking the steepness of the slopes of the other groups (which is also a good example of why slope angles can be hard to interpret). On the other hand, the y-axis range in the temperature graph is narrower (-0.75 to 0.50) which changes the apparent steepness of the slope. The differences in y-axis ranges are specifically mentioned in the figure caption (Figure 7.) to avoid misinterpreting the figures. Partial eta-squared values in Figures 4. and 6. should be used for comparing effect sizes, not slope angles.

Line 400: Please discuss later the influence of temperature and moisture on N2O fluxes between the years. Was the year 2025 wetter?

Answer**:** *We will add more detailed discussion of these in the Discussion (section 4). As seen in Figure 6. Soil moisture had negligible effect on N2O fluxes, to the point where it was not even included in the final model. Temperature also had a very weak effect on N2O (partial eta-squared of 0.01), so the yearly differences are unlikely to be explained by them through any direct effects. However, it is possible that annual differences in precipitation/moisture and temperature could affect N2O dynamics indirectly (i.e. precipitations and temperatures effects on vegetation).*

Discussion

Throughout this chapter, please explain how you answered the question and whether your findings were supported by statistical tests. Structure your text so that you answer one question with another. Draw comparison to literature, try explaining reasons behind them and highlighting possible future implications (e.g. warming, change of land cover area size).

Line 407-410: Please indicate at the beginning whether you were generally able to answer the three research questions. In this paragraph, you only gave a statement to the third question.

Answer**:** *We will add further discussion about the research questions in the Discussion (section 4) and more direct answers to each of them.*

Line 412: Clear terminology, so you can begin with “Dry land cover classes”. Was there a statistical difference between the land cover classes and can the classes be used to predict fluxes for CH4 and N2O?.

Answer**:** *We will clarify the terminology used and include additional analysis and discussion about land cover class a predictor.*

Line 417: Please indicate whether and how you answered your second question?

Answer: *We will add a part in the Discussion (section 4) going over how we answered our research questions.*

Line 433: References are missing

Answer**:** *We will add references.*

Line 447: Please provide more detailed data on the gas fluxes reported in the literature, as opposed to your own gas fluxes

Answer**:** *We will make more direct numerical comparisons with previous studies, including reporting on some of the key values from the literature referenced.*

Line 461: Is this threshold value specified in the literature?

Answer**:** *We will specify that this threshold is hypothetical and based on our results (and the references mentioned in the previous sentence) and not something that is explicitly stated or tested in existing literature.*

Line474: How about discussing the temperature sensitivity of both processes here, specifying the Q10 value?

Answer**:** *We acknowledge this limitation and note that these mechanisms could be investigated in future studies incorporating microbiological data. Further discussion of the specific microbiological and enzymatic processes underlying this pattern is beyond the scope of the present study.*

Line 484-485: To better understand this, it would be helpful to see in Figure 5c which values are measured (e.g., represented by points) and which are simulated.

Answer**:** *The model results shown in the figure represent predicted values only. Overlaying measured values on top of the graphs makes them challenging to read. In addition, the data is normalized which makes the absolute values difficult to interpret. Model figures are intended to be used for comparisons between the land cover interactions and to see the direction of the effects.*

Line 490: See comment to **line** 367-370: Please provide a more detailed classification.

Answer: *We will edit as suggested.*

Line 510: References are missing

Answer: *We will add references.*

Line 506-517: Please discuss also detection limit of N2O with Licor.
Answer: *We will add discussion on LI-COR detection ranges to the Results and Uncertainties (sections 3 and 5) and add the % of measurements that are above the limit.*

Line 581-529: Please provide more detailed data on the positive and negative N2O gas fluxes reported in the literature, comparing them to your N2O emission data. Please discuss reasons, why there is production of N2O at the dry sites. Was there a statistical difference between land cover classes and can you therefore confirm your first hypothesis?

Answer: *The theory underlying N2O dynamics (including production) is discussed in the first paragraph of chapter 4.3 (lines 506-515). More detailed discussion of nitrogen cycling and the biogeochemistry of it are*

outside of the scope of this study as it requires extensive descriptions of microbiological processes, which is not the main topic of this paper. We will make sure that appropriate references will be included for those looking for more information.

We will also add a separate pairwise comparison for differences between land cover classes.

Line 523: uniform terminology for “non-wetland” write e.g. “dry land cover classes”

Answer: *We will fix the terminology throughout the manuscript.*

Line 554: Is there also a correlation between CH4 uptake and N2O emission (results **line** 344-346)?

Please discuss reasons?

Answer*: We will add a scatterplot between CH4 and N2O means (with R and p-values) to the appendix and further information on the matter to the Results (section 3).*

Appendices

Please indicate the number of measurements for each **line** in the tables.

Answer**:** *We will add the number of measurements for each land cover class per month.*

Table A2: Given the differences in N2O values between the two measurement years, it would be interesting to see the results of each year

Answer**:** *We will add a comparison between years 2024 and 2025.*

Technical corrections

Line 58: Citation: Name is wrong “Biskabjorn”. Please check the references throughout the manuscript for accuracy.

E.g., **Line** 67 & **line** 501: Citation: Kübert et al., and Weslien et al., are missing in reference list. Please check the references throughout the manuscript for accuracy.

Answer**:** *We will double check and fix errors in references throughout the manuscript.*

Line 70: GPP: Write out the full term before using the abbreviation

Answer**:** *We will edit as suggested.*

Line 162: Before using abbreviation, introduce first in **line** 155 with “()”.

Answer**:** *We will edit as suggested.*

Line 200: Is that a value without a unit?

Answer**:** *The unit is on the next line, we will double check that all units are included in the revised manuscript.*

Line 254: “c” is given in ppm but final unit is mg or µg. So please write that you also converted this.

Answer**:** *We will add a description of the conversion calculation to the Materials and Methods (section 2) as suggested***.**

Line 348: Move the point “.” out of the bracket “)”

Answer**:** *We will edit as suggested.*

Fig. 5, 7: Units are missing for fluxes.

Answer**:** *Fluxes are normalized and thus unitless. We will make a note of this in the figure descriptions.*

Fig. 7a: Please give points and no **line** between points.

Answer**:** *We will remove the line from between points.*

Line 397: Please write in capital letters for Figure abbreviations in the whole manuscript (“Fig. 1”)

Answer**:** *We will edit as suggested.*