Author response to reviewer comments on “A cross-site comparison of ecosystem- and plot-scale methane fluxes from wetlands and uplands” by Määttä et al.

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Please find our responses to each reviewer comment below in bold.

Response to comments by Reviewer 2
https://doi.org/10.5194/egusphere-2026-467-RC2:

This study is an exploratory in situ experiment in finding soil biomass trades that can explain CH_4 emission. Specifically, these biomass trades are linked to plant-mediated transport of CH_4 in different thawing stages in a permafrost peatland in north Sweden.

The topic of this study is relevant and needed to get a better understanding in the processes behind measured CH_4 fluxes, which is relevant for upscaling and modelling.

It is a very well written paper (with some minor suggestions for improvement below) and the gathered data seems to be analysed with precision.

We thank the reviewer for the careful and encouraging assessment of our manuscript. Below, we address each point raised by the reviewer.

However, due to the limited amount of samples and not having a reference (no biomass) in the different thawing conditions, it is very hard to draw conclusions out of the results. The authors should therefore be careful in their statements and conclusions. I will elaborate on this more below.

We agree that it is important to show a reference for root and rhizome quantity as, for example biomass and root total length. However, we did already include root and rhizome biomass per thaw stage in Fig. 2 in the main text and show root total length variation along the thaw gradient in the Appendix (Fig. B4). As per Reviewer 1 comment, we have now also added mention of root total length variation along the thaw gradient into the main text in the results. Nonetheless, we agree that the small sample size makes drawing conclusions challenging, and discuss this more in the discussion section:

L438 onwards (also see our response to Reviewer 2 comment related to environmental variables along the thaw gradient): “However, due to the low sample size we were unable to separate the effects of plant traits and soil moisture in multivariate models, and larger sample sizes are recommended to analyze the interactions between soil moisture and plant belowground traits in future studies.”

L613: “Taken together, the temporal variation in root and rhizome traits may have contributed to CH_4 fluxes but belowground trait sampling with larger sample sizes

throughout the productive season is needed to investigate these relationships further."

L429: "SRL was highest and root diameter lowest at the partly thawed stage, which could reflect increased resource acquisition particularly for shrubs, but further research with larger sample sizes are needed to look into the potential changes in shrub resource acquisition (Bergmann et al., 2020)."

Further, for persons who do not work in permafrost regions (like me) it would be very helpful to get a better explanation what kind of processes are relevant in this system and specifically what is changing when thawing occurs. Also explain what a palsa exactly is.

We have added more details about permafrost peatland ecology and biogeochemistry and explain what palsa is in the introduction:

L40 onwards: "Palsas are ca. 0.5-10 m high peat hummocks with a frozen peat and mineral soil core, which form as a result of water-saturated peat freezing in winter and the dry surface peat protecting the frozen peat in summer, raising the peat above the surrounding area (Luoto et al., 2004). In northern Fennoscandia, permafrost thaw has formed transitional gradients from frozen palsas and peat plateau to permafrost-free bogs and fens (Luoto et al., 2004; Olvmo et al., 2020). Following palsa collapse, soil moisture increases, shifting the system from an ombrotrophic bog-like system to a minerotrophic fen. Vegetation composition shifts from shrub- (palsas) to graminoid-dominated (fens), and soil redox and pH change, all of which influence methanogenic CH_4 production, methanotrophic CH_4 consumption, and CH_4 transport from the soil to the atmosphere, and thus net CH_4 fluxes (Perryman et al., 2020; Turetsky et al., 2014; Varner et al., 2022)."

Overall, I think the study is a relevant stepping stone to a wider study with or more sites, or more samples from this site. I would recommend it for publishing after revisions, where 1) statements and conclusions are nuanced, 2) other explanatory variables are explored (if possible), and 3) where authors give suggestions on what is needed to link below-ground biomass trades to plant-mediated CH_4 transport based on what they have learned from their study.

We thank the reviewer for the helpful feedback and will implement it in the revised manuscript.

Concerns

If I look at Figure 3 and Figure B6, I see mainly a trend between thaw stage and CH_4 fluxes. As the authors state in the discussion, other drivers for CH_4 fluxes are soil moisture, water table depth, substrate availability and (not mentioned) temperature. There is a clear increase in CH_4 fluxes with the increase in thawing of permafrost. How do the above-mentioned drivers change with the thawing gradient? It would be very relevant to know how the below-ground biomass characteristics are related to the drivers mentioned above. If it's possible then a multi variate regression or a mixed effect model could be done to exclude the effect of other drivers than below ground biomass characteristics. Or add these drivers to you PCA analyses. Authors state that 'we studied the permafrost thaw-driven CH_4 flux variation with a plant trait-based approach with a focus on belowground traits' (L392), I think you can only do that if you exclude the other factors.

This is an important point. Due to the low sample size and degrees of freedom, we were unable to run linear mixed models and multivariate linear regressions to separate the effects of other environmental CH_4 flux drivers, such as soil moisture, temperature and water table level. However, we did explore the potential effect of plant green area and peat temperature on CH_4 fluxes by looking at correlations between green area, peat temperature and CH_4 flux at the different CH_4 flux periods (the same CH_4 flux values that were used in the trait-CH_4 flux regressions). We then qualitatively compared these relationships to the trait-CH_4 flux regressions and Kendall correlation coefficients. We have shown these results in Fig. B10 in the Appendix and included text about these results in the Results (3.2) section.

We also agree that it is important to try to disentangle the effects of environmental variables and traits on CH_4 fluxes along the thaw gradient. In fact, as has been found in previous studies at Stordalen and other wetlands, water table level is an important CH_4 flux driver. However, water table level has not been measured in Stordalen since 2017, and we were unable to use it as a predictor of CH_4 fluxes. We did obtain soil moisture data from each CH_4 flux chamber location from 2024 and 2025, and observed a positive relationship between soil moisture and CH_4 flux along the thaw gradient. We decided to not include this data, however, due to data license issues. We will now add similar correlation analyses for soil moisture and CH_4 flux period values as for the other environmental variables (peat temperature and green area) if we are successful in publishing the soil moisture data.

Even though soil moisture and water table level are important CH_4 flux drivers also at Stordalen, as we mention in the discussion, high soil moisture also drives aerenchyma formation particularly in herbaceous plant roots (a relatively well-known phenomenon in plant ecology). Thus, we think that the CH_4 flux trends following thaw stage gradient does also reflect changes in the root traits, especially in root porosity which can be a proxy for plant-mediated CH_4 transport. Due to this, we would also expect soil moisture and root tissue density to be collinear in linear (mixed) models and we would likely be unable to include them in multivariate models if we had larger sample sizes. Nonetheless, we have now added more discussion of the importance of soil moisture driving CH_4 fluxes possibly simultaneously with increasing root porosity (i.e., decreasing root tissue density) in Stordalen.

New sentences:

L438 onwards (beginning of the first paragraph of 4.2): "The increasing soil moisture and associated changes in belowground plant traits contributed to the increasing CH_4 fluxes along the permafrost thaw gradient. Given our exploratory results (see 3.2 and Appendix Fig. B10) and earlier studies conducted at Stordalen (Holmes et al., 2022; Malhotra and Roulet, 2015), the increasing soil moisture was likely one of the primary drivers of the increasing CH_4 fluxes along the thaw gradient. However, due to the low sample size we were unable to separate the effects of plant traits and soil moisture in

multivariate models, and larger sample sizes are recommended to analyze the interactions between soil moisture and plant belowground traits in future studies. Nonetheless, the univariate relationships between plant belowground traits and CH_4 fluxes indicated 1) maintained carbon substrate provision and 2) increasing plant-mediated CH_4 transport across the permafrost thaw gradient."

L471 onwards: "Plant-mediated CH_4 transport may have been pronounced in the fully thawed stage with high soil moisture, herbaceous plant coverage, and low porewater CH_4 concentrations (Table C1 and Fig. B13, Fig. B10), indicating plant CH_4 uptake."

L472: "As low root and rhizome TD indicates higher porosity (Ye & Ryser, 2022), the negative relationships between root TD and CH_4 flux suggest increased plant-mediated CH_4 transport in response to increasing soil moisture."

We have also added peat temperature as a potential driver of CH_4 fluxes in Stordalen in the discussion (L386-390): "The increased CH_4 fluxes with permafrost thaw in Stordalen are driven by a complex network consisting of drivers such as higher water table level and increased anoxia (Holmes et al., 2022; Malhotra & Roulet, 2015), higher peat temperatures at the end of growing season (Mollenkopf et al., 2026), …"

In this context, we have now changed the highlighted sentence to: "we explored the effect of belowground plant traits on CH_4 fluxes." (L392), to avoid possible confusion and to highlight that we looked at univariate instead of multivariate relationships to study the trait-CH_4 flux connections.

Further, I think the authors could have done some more investigation in looking into relationships between GPP-CH4 and diurnal cycles in CH4 fluxes to give more evidence for plant mediated transport.

Good idea- we will now explore diurnal GPP-CH_4 flux relationships and add the resulting plot(s) in the Appendix. However, as the focus of this study was more on the daily to productive season time scale, we will limit these additional analyses to one or two sentences in the discussion similar to the other GPP analyses and discussion (L519-522).

The following sentence is due to the above mentioned uncertainty too speculative 'SRL was highest and root diameter lowest at the partly thawed stage, possibly reflecting increased resource acquisition particularly for shrubs with high SRL and low root TD' .

We have now changed this sentence to: "SRL was highest and root diameter lowest at the partly thawed stage, which could reflect increased resource acquisition particularly for shrubs, but further research with larger sample sizes are needed to look into the potential changes in shrub resource acquisition".

dC13 and ac are measured and it seems that the results are interesting (Fig. B13). Maybe it's worth adding that to the results, but also explain a bit better the mechanism behind the results and why it is relevant. It would help to make two who dC13 and ac in separate plots.

Be careful with statements about CH4 oxidation being higher or lower. It's not clear for the data isn't it. Or if it is, then please explain a bit better why it is.

We made the decision of keeping the porewater CH_4 isotope and concentration results in the Appendix to keep the focus of the main text on the trait-CH_4 flux relationships, where the pore water data provided supporting information on the depth-resolved trait-CH_4 relationships.

As suggested, we have now separated α_C and ^{13}C-CH_4 into their own separate plots in Appendix Fig. B13.

We included discussion about CH_4 oxidation because lower root tissue density can also reflect increased O_2 transport to the soil. Some studies at Stordalen have also found increased methanotrophic CH_4 consumption with permafrost thaw and partly suggested that this could be related to increased O_2 transport from aerenchymatous plant roots. It is true that drawing conclusions about CH_4 oxidation based on the isotopic data can be uncertain, and we will now add 1-2 sentences about this in the discussion (in L487-498).

Details

L110-117: This part could be in the introduction, which helps to understand the system.

As this part is very specific to Stordalen, instead of moving this text to the introduction, we have added more details of the general variation in soil biogeochemistry and vegetation composition along peatland permafrost thaw gradients in the introduction. Related to this, we now also explain what palsas are in the introduction.

L40 onwards: "Palsas are ca. 0.5-10 m high peat hummocks with a frozen peat and mineral soil core, which form as a result of water-saturated peat freezing in winter and the dry surface peat protecting the frozen peat in summer, raising the peat above the surrounding area (Luoto et al., 2004). In northern Fennoscandia, permafrost thaw has formed transitional gradients from frozen palsas and peat plateau to permafrost-free bogs and fens (Luoto et al., 2004; Olvmo et al., 2020). Following palsa collapse, soil moisture increases from bogs to fens, which further shifts vegetation composition from shrub- (palsas) to graminoid-dominated (fens) and changes soil redox conditions and pH, all of which influence methanogenic CH_4 production, methanotrophic CH_4 consumption, and CH_4 transport from the soil to the atmosphere, and thus net CH_4 fluxes (Perryman et al., 2020; Turetsky et al., 2014; Varner et al., 2022)."

L134: -2 is in superscript

This was an accident and is now fixed.

L155, 166: Peat and soil are used in a similar way (peat temperature or soil temperature?)

Good catch- we prefer "peat temperature" and have now changed this throughout the text and in Fig. B10.

L222: Filtering on R2 only could lead to removing very low fluxes. Adding the actual slope to the filter (allowing a higher R2 with lower slopes would help)

In principle, filtering based solely on R^2 can bias against low fluxes when measurements are close to the detection limit. However, in our dataset, this effect appears to be limited because the automated chamber system has high analytical precision, and particularly for the partly thawed and fully thawed plots CH_4 fluxes are well above the detection limit. In these cases, low fluxes do not necessarily correspond to low R^2 values. Instead, low R^2 values are more likely associated with measurement artefacts (e.g. chamber leakage, pressure effects, or non-linear concentration changes) rather than true low fluxes. We evaluated the effect of R^2-based filtering and found that excluding low-R^2 measurements has minimal impact on mean CH_4 fluxes across plots. Based on comparing CH_4 fluxes before and after applying a 95% threshold R^2 criterion for a subset of the data (days 101–250 in 2023), only a small proportion of CH_4 fluxes were removed in partly thawed (2%) and fully thawed (1%) plots, with negligible changes in mean fluxes (partly thawed: 35.55 to 35.90 mg m^{-2} d^{-1}; fully thawed: 85.45 to 86.05 mg m^{-2} d^{-1}). Even in the intact palsa plots, where a larger fraction of fluxes (18%) was removed, mean CH_4 fluxes remained within a similar range (7.7 to 9.3 mg m^{-2} d^{-1}).

Nevertheless, we will update the methods to provide more detail to reflect the QA/QC workflow provided with the dataset, which includes regression diagnostics, manual quality flags, and concentration-based filtering criteria. We will also rerun all analyses using the fully QA/QC'd CH_4 flux dataset and update the results where necessary.

L243-245: I don't understand what that means. And for which results is this used?

This was used for determining the CH_4 flux period values (early, middle and peak CH_4 flux within the productive season) from the daily-aggregated CH_4 flux data. For this, we fit a GAM where the date was the explanatory variable of CH_4 flux (response) so that we can get general estimates of CH_4 flux for each date and then calculate the different CH_4 flux period values for each chamber. Delwiche et al. (2021; https://doi.org/10.5194/essd-13-3607-2021) did a similar thing but with a Gaussian curve because they had full year CH_4 flux data. We had CH_4 flux data only from the growing season, so we used a GAM which was able to capture the general CH_4 flux trend during the productive season better than a Gaussian curve.

We have now improved the sentence and the sentence before it as follows: "To explore the variation in the trait-CH_4 flux relationships during the productive season, we calculated CH_4 flux period values (early, middle and peak CH_4 flux) by fitting Gaussian generalized additive models (GAM) with identity link function for daily median CH_4 flux data per chamber with function gam from package mgcv (Wood, 2011, 2017). In the models used for determining CH_4 flux period values, CH_4 flux (response variable) was transformed to approximate normality using inverse

hyperbolic sine and date was included as an explanatory variable in a thin plate regression spline."

L293: This is a very long title

We shortened the title to: "More herbaceous roots and rhizomes with decreasing tissue density".

L298: 1.5x lower

Fixed.

L301: 22.2x 22x (remove decimal to be consistent)

We have used these decimals for the other values in this section as well, and did not show the decimal for the "17x" because it was 17.006≈17. Thus, we have instead added ".0" to the sentence: "Summed root biomass and surface area (SA) were 22.2x and 17.0x lower, respectively…"

L312: Introduce the abbreviation CV, and add for between mean and intact

Fixed: "Most of the root biomass was found in the top 10 cm for shrub (coefficient of variation CV and mean for intact:..."

L323-328: Could you show all results in a graph? That would be easier to follow

These results are in fact shown in two graphs: Fig. 3 (only for root tissue density, diameter and specific root length from the middle CH_4 flux period) and for all CH_4 flux period values in Appendix Fig. B6 and B7. We chose to show only the root tissue density, diameter and specific root length in Fig. 3 from the middle CH_4 flux period because the trait-CH_4 flux relationships did not vary a lot within the productive season. However, as per Reviewer 2 comment related to replacing Fig. 5 with Fig. B6, we will now replace Fig. 5 with Fig. B6 (only for root tissue density, diameter and specific root length, and keep the rest of the traits in the Appendix to save space) but also add Fig. B7 (biomass-weighted root traits only for root tissue density, diameter and specific root length and the rest in the Appendix), or combine the PFT-grouped plots from Fig. B6 with biomass-weighted plots from Fig. B7 (only for root tissue density, diameter and specific root length) and replace Fig. 4 with Fig. B8 and B9 but only for rhizome biomass, surface area and diameter, and keep the rest in the Appendix). Thus, we will now remove the values (e.g., R^2s) shown in the figures main text (results 3.2) to make it easier to read.

L382-383: why is it relevant to know if CH4 is produced by hydrogenotropic or acetoclastic methanogenesis?

To our knowledge, a shift from hydrogenotrophic to acetoclastic methanogenesis could suggest a change to a more root exudate-driven methanogenesis (e..g, Saarnio et al., 2004 https://doi.org/10.1007/s11104-005-0140-3 and Ström et al., 2003

https://doi.org/10.1046/j.1365-2486.2003.00655.x**). We discuss this in more detail in section 4.2 (L455-460) in relation to shrub root traits.**

We have now added a clarifying sentence about this after the highlighted sentence: "Shifts from hydrogenotrophic to acetoclastic methanogenesis can indicate increased root exudate-driven CH_4 production (see 4.2) (Saarnio et al., 2004; Ström et al., 2003)."

L416: How heterogeneous is your plant cover? Can differences not be explained by that or the sample size?

It is difficult to estimate the exact cause of these differences since the referenced studies used different root sampling methods than us and they did not report all the steps taken. However, we agree with the reviewer's point, and we have now added a new sentence addressing the uncertainty caused by the low sample size and the fact that we combined different species in our root samples, which the other studies did not do: "In addition, our root samples may have consisted of a different mix of species than in Hough et al. (2022), which together with the low sample size, may have influenced these results."

L488-490: It is not clear what is the result of this study and what not. It's also not clear why this is relevant.

We think it is important to discuss the potential CH_4 oxidation along the thaw gradient, as the decreases in root tissue density (and thus increases in root porosity) could also increase O_2 transport to the soil and thus CH_4 consumption in the peat. However, we agree that mentions of methanotrophic community structures are unnecessary details in the context of this study, and have streamlined the sentence to clarify that previous studies reporting increased oxidation with thaw could be related to our observation of increased root tissue density.

We have now modified the sentences as follows: "Simultaneously to plant-mediated CH_4 transport, herbaceous roots may have enhanced rhizospheric CH_4 oxidation. Previous studies at Stordalen have reported shifts in methanotroph communities with thaw as well as an increase in CH_4 consumption, which may result from greater plant-mediated rhizospheric oxidation (i.e., more O_2 transport with lower root TD) and acetoclastic methanogenesis (Perryman et al., 2020; Singleton et al., 2018)."

L498: '…with belowground traits for the first time…', what does that mean?

We wanted to highlight the significance of our paper here, but we agree that this part can make the sentence a bit hard to understand. Thus, we have removed this from the sentence: "Thus, based on the lower α_C (i.e., maintained acetoclastic methanogenesis) at 20-44 cm depth, and the strongly negative relationships between root TD and CH_4 fluxes, it seems that the CH_4-oxidizing effect of herbaceous plants particularly in the fully thawed stage is overshadowed by increased carbon provision for methanogenesis and enhanced plant-mediated CH_4 transport."

L500-501: '…differed only slightly in strength.' What does this mean, that there is a linear trend in every season and only slightly differ? Are they significantly different? If not, don't write it.

We meant here that the linear trends only differed slightly. We have now modified this sentence as follows: "The relationships between the static belowground traits and CH_4 fluxes (early, middle, peak, and season median) did not vary strongly within the productive season."

L504: In figure 5 I mainly see a relation between the three thawing stages which can be related to many different factors. It would be better to replace Figure 5 with figure B6, that one is clearer.

We agree, and we will now replace Fig. 5 with Fig. B6 (only for root tissue density, diameter and specific root length, and keep the rest of the traits in the Appendix to save space) but also add Fig. B7 (biomass-weighted root traits only for root tissue density, diameter and specific root length and the rest in the Appendix), or combine the PFT-grouped plots from Fig. B6 with biomass-weighted plots from Fig. B7 (only for root tissue density, diameter and specific root length). Similarly, we will also replace Fig. 4 with Fig. B8 and B9 but only for rhizome biomass, surface area and diameter, and keep the rest in the Appendix to save space).

L504: 'strongly associated' what does associated mean? (same in next sentence). Be specific about that

By "associated", we mean the beta coefficients and R^2s of the linear regressions between the traits and CH_4 flux period values. To make this clearer, we now say "related" and explain the statistical basis in parentheses.

We have now clarified this as follows: "In contrast to our hypotheses, shrub root traits were more strongly related (i.e., higher linear regression β and R^2) with middle and peak CH_4 fluxes whereas herbaceous root (TD) and rhizome (SA) traits were strongly related with CH_4 fluxes throughout the season."

L505: '…root porosities not responding strongly to changes…' this statement is too big for the results you have.

Agreed- we have now removed this sentence from the paragraph.