Author response to reviewer comments on “Plant belowground traits indicate increased plant-mediated methane transport along a peatland permafrost thaw gradient” by Määttä et al.

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

Response to comments by Reviewer 1 https://doi.org/10.5194/egusphere-2026-467-RC1:

Controls (or drivers) of the exchange of methane between the atmosphere and the surface of various wetlands have always been complicated, because of the nature of the processes and pathways and the large spatial variability across short distances, combined with temporal variability. Initially, simple variables such as temperature, water table and plant functional type were useful in ‘explaining’ patterns of methane exchange across landscapes. Since then, attention has been given to a variety of properties and processes which have led to a better ‘explanation’ and perhaps ‘prediction’ of the methane exchange. For belowground activities, important processes are provision of carbon for methanogenesis and the ability of plants to transport methane directly (avoiding methanotrophy in the profile) as well allowing oxygen to create a potential zone of methanotrophy in the rhizosphere. Thus, linking belowground root/rhizome traits and methane emission can be ‘complicated’ but a necessary advance.

This manuscript is an example of the latter, focusing on the role of root and rhizome traits in the exchange (emission) of methane, based along a gradient created by the thawing of permafrost palsa in northern Sweden. Three ‘thaw stages’ have been recognized at this site, with changes in thermal regime, hydrology and vegetation characteristics creating a very large variation in methane emission rates. The research focuses on determining root and rhizome traits across triplicates of each thaw phase, though this is not done in the automatic flux chambers, but from sites located nearby with similar properties. As noted by the authors, there is not complete species similarity in mean coverage between the triplicate chamber and core data but when combined into herbaceous and shrub categories there is general agreement (Table 1). Daily median flux of methane was calculated, to avoid the usual ‘burp’ of methane occurring occasionally which would be unlikely to be derived from root processes, and chamber carbon dioxide flux was used to define seasonal patterns. Root and rhizome data were collected carefully from depth increments and biogeochemical data were used to provide evidence for some of the processes leading to methane production, and how they might be related to root activity.

The manuscript is well structured and written and provides valuable evidence for the role of belowground plant activities in controlling methane emissions. It is ‘digestible’ in that the information in the manuscript is restricted to two Tables and five Figures, with voluminous supporting data in Appendices. The strong Introduction ends with several expectations/hypotheses based on previous studies, but in this case applied to the specific Stordalen site, in which palsa are thawing and thus perhaps similar to features elsewhere in the Arctic. Based on methane fluxes from the nine chambers and root characteristics from the 'similar' sites, the study presents strong evidence for correlations between methane emission rate and the herbaceous and shrub root and rhizome properties, and whether patterns changed with the season, based on carbon dioxide exchange. In general, it appears that correlations were stronger for root properties compared to rhizomes, though there are mixed relationships shown in Figures 3 and 4. The reasons for positive, negative or no correlations were examined in the Discussion and the relevance of these relationships may vary with the specific features of Stordalen, which are somewhat unusual. The relationships between the traits and methane emission were examined in terms of processes related to changes from shrubs to herbaceous plants and the root trait structure (e.g. density, specific length and diameter), and drew upon results presented elsewhere which could be applicable at Stordalen. The overall conclusion was that belowground root/rhizome activities were an important component of methane emission, that change from shrubs to herbaceous would lead to increased emissions, but there is a bit of 'ying-yang': shrubs may supply more carbon substrates, whereas herbaceous plants may be important conduits of methane to the atmosphere. Such is life in the real world of Nature and 'teams' like these authors are needed to see at least part of the whole.

Thank you, Dr. Moore, for your comprehensive analysis and positive evaluation of our manuscript.

The study is 'well referenced', with 145 in the References, perhaps too many?

We agree, and have now removed 19 references from the manuscript. However, the number of references remains rather high because we think it is valuable to cite the many studies looking at CH_4 cycling at Stordalen, and to also comprehensively discuss the root and rhizome traits with references to root (and rhizome) ecological literature.

Specific comments:

In Table 1, it seems that mosses formed a significant plant cover in the chambers (e.g. Sphagnum balticum, capillifolium and riparium in the three thaw stages). Would methane emission rates be affected by this coverage and some differences between chambers and cores and different wetness? This is addressed in 4.2 line 486 onwards …..

This is true, and we have added these points to the sentence as follows (and removed one reference as per previous comment): "In addition, *Sphagnum* spp. can host methanotrophic CH_4-consuming bacteria (e.g., Larmola et al., 2010; Putkinen et al., 2014), which may have increased CH_4 consumption in the more O_2-rich intact and partly thawed stages dominated by *S. balticum* and *S. capillifolium*, with intact stage chambers possibly having higher CH_4 consumption rates than peat cores with no *S. balticum* (Table 1). However, the average $\delta^{13}CH_4$ emitted from the partly thawed chamber plots was -79.6 ± 0.9 ‰ in 2011, similar to or ^{13}C-depleted relative to the porewater CH_4 at the same sites, indicating little CH_4 oxidation (McCalley et al., 2014)."

A tremendous amount of work went into this study, particularly in the measurements of root and rhizome properties collected from the cores. If I understand correctly, a 12 cm diameter peat core was dived into 10 cm depth increments and these were then divided into four vertical quarters, which was used for trait measurements, resulting in subsampling of the core sections (and subsampling of that in some cases). This are measurements based on an initial volume of 1130 cm3, and it must take considerable time and patience to extract roots and rhizomes, weighing in some cases to 0.00001 g. pH in 0.01M Cacl2 is much easier and quicker …….

This is correct. Picking roots (especially shrub roots) from peat is very time-consuming, and we appreciate the Reviewer's acknowledgement of this hard work.

While I accept that the belowground contribution is important to processes such as methane emission, are there any ways of making it 'easier' to define and measure these properties over a wider range of sites? If so the properties could be included and tested within models which are grappling with the high spatial and temporal variability of methane emission rates.

There are some methods that might make measuring some root (and maybe rhizome) traits a bit easier for a wider range of sites. These include for example minirhizotrons which can help with calculating root length and its changes with time. We mention minirhizotrons in the discussion (4.3) as a possible method for looking into the temporal dynamics of root-mediated CH_4 cycling in Stordalen in the future. However, minirhizotrons also come with considerable image analysis burden that has not fully been automated yet. Furthermore, root tissue density, porosity and specific root length can only be measured manually by first conducting the time-consuming root picking from samples and then measuring the volume, length and dry mass. X-ray computed tomography may be another way to do higher throughput measurements of roots from intact soil cores. However, we are hard pressed to find literature that has conducted and validated these methods for roots. Perhaps the most promising approach has been developed by Strakova et al. (2020) (https://doi.org/10.3389/fpls.2020.00597) using FTIR spectroscopy to quantify roots in peatlands. As the focus of this manuscript is not necessarily to test different root trait measurement methods, and we already have too many references, we think additional review and discussion of the different root trait measurement methods might not be needed here.

Technical issues:

I found few. I thought that the first two sentences of 2.6 (lines 214-215) could be combined into one: they are repetitive. Minor typos in places.

We have now removed the repeated sentence ("Briefly, CH_4 flux was measured at each permafrost thaw stage with automated chambers.")

Fig. B13. I was confused the right hand diagram. I think the dashed lines have circles whereas the solid lines have triangles …… not what is written in the legend?

Good catch- this was an accident. As Reviewer 2 also suggested, we have improved this figure by separating the $^{13}C-CH_4$ and α_C data into their own plots. In the new plots, we do not use the dashed lines and avoid this confusion.

I did find that the total root length of shrubs in the intact sites was about 180 km per square meter (to 30 cm depth). Jeez, as it is 10 km from Stordalen to Abisko, it means that one square meter of intact permafrost has enough shrub root to go back and forth 18 times or perhaps all the way to Norway or the Norwegian Sea? Might get the attention of readers that permafrost is not 'dead' but rich in roots and though root length decreases in thawed sites, the impact of roots and rhizomes and change from shrub to herbaceous plants allows for larger methane emission rates.

Exactly- this is a remarkable finding and highlights the importance of measuring roots also in permafrost peatlands. We have now added an additional sentence highlighting this in the results section (3.1):

"To note, total shrub root length reached a very high mean of 178.62 km m^{-2} and a maximum of 199.7 km m^{-2} in the intact stage, substantially higher values than for herbaceous roots (mean: 19.79 km m^{-2} and max 33.33 km m^{-2} in the partly thawed stage) (Fig. B4)."

And in the discussion (4.1):
"Following vegetation community shifts, most belowground shrub biomass and total length were found in the intact stage…" and
"In general, these findings, and particularly the remarkably high total shrub root length values, showed that permafrost-affected peat soils are rich in plant roots and likely contribute to the carbon cycling of these ecosystems (Bardgett et al., 2014; Iversen et al., 2015)."

Added new reference:

Bardgett, R. D., Mommer, L., and De Vries, F. T.: Going underground: root traits as drivers of ecosystem processes, Trends in Ecology & Evolution, 29, 692–699, https://doi.org/10.1016/j.tree.2014.10.006, 2014.