2nd round of reviews

Author responses to reviewer comments, and edits to the manuscript *"Accelerated lowland thermokarst development revealed by UAS photogrammetric surveys in the Stordalen mire, Abisko, Sweden"*

(Paper submitted to 'The Cryosphere' | egusphere-2025-3788-R1)

We would like to thank the reviewers for the comments on our manuscript # egusphere-2025-3788-R1. We have paid close attention to the suggested edits and made the requested changes as detailed below, with reviewer's comments in regular font, directly followed by our responses in italic (*blue font*).

Editor decision: Publish subject to minor revisions (review by editor)

Report #1 | Submitted on 14 May 2026
Anonymous referee #1

The detailed response by the authors to the review comments is much appreciated. Revisions have been made to the manuscript to address the comments, such as restructuring the Methods section and providing additional figures in both the main text and the Appendices. I recommend minor revisions to the text, as outlined below:

We would like to thank the reviewer for their positive evaluation and valuable comments.

P2 L41, Consider changing to "…three to four times faster than the rest of the globe…" to reduce the repetition of "increasing/increase" in the same sentence.

We have changed the text accordingly.

P3 L67, Can a reference be added here to support this statement, where permafrost degradation and wetland development should lead to an increase in soil EC?

We have added a new reference. The new sentence now reads: "[…] and is therefore expected to increase as permafrost degrades and wetlands form (e.g., Mollaret et al., 2019 and references therein)."

P3 L81, Add "can" so that it reads as "…landscape deformations can occur on very subtle spatial scales…". Landscape changes in peatlands can be more noticeable if the time scale/interval is larger.

We have changed the text accordingly.

P3 L83, "constraints" instead of "constrains"?

Thank you for spotting the spelling mistake. We have changed the text accordingly.

P4 L104-105, These phrases seem contradictory, where at least ten years of survey data are required to enable quantification of palsa loss rates, but this study covers only 2019 to 2021. Please revise as needed.

Thank you for your comment. The text now reads "A few studies suggest an accelerated rate of degradation in more recent years (i.e., from the 1950s to the last decade; de la Barreda-Bautista et al., 2022; Borge et al., 2017; Olvmo et al., 2020), but still require at least ten years of survey data to enable quantification of palsa loss rates. In this study, we provide a quantification of the rate of palsa degradation over a shorter timescale, namely between the summers of 2019 and 2021 in the Stordalen mire (Abisko, Sweden) using UAS-based photogrammetric surveys"

P4 L123, Which are the 20 probes that are being referred to?

Before 2022, the soil temperature were measured at all locations with Campbell 105E thermocouple ground probes. Some probes were updated/renewed in the fall of 2021, so that recent soil temperatures are measured with Campbell Scientific SoilVUE10, TEMP-MicroStep temperature profile probes and MicroStep PT100 (all thermistor probes/sensors). We propose not to burden the text with detailed information on all these sensors, as there is a cited reference for the dataset.

P4 L135, Replace “during” with “from”.

We have changed the sentence to: “The area also includes open water ponds formed by the thawing of permafrost […]”.

P6 L168, What do the authors mean here by “RGB imagery”? Was this imagery processed into an orthomosaic as with the 2019 survey described in L160?

We agree that ‘RGB imagery’ was potentially misleading here due to a lack of consistency with the text above. We have now changed it to ‘RGB orthomosaics’.

P8 L207, Remove “of”.

We have changed the sentence accordingly.

P8 L214, How many training points were sampled?

*There were ~10,500 points in total. We provide details by referring to **Tab. A. 2** in the next sentence.*

P13 L317, Change “palsas” to “palsa”.

Thank you for spotting the spelling mistake. We have changed the text accordingly.

P14 Figure 4, Consider changing the label for “degraded areas” to “areas without permafrost” or something similar. Otherwise, it may suggest that all of the area shown in blue has degraded, when in reality it may not have been previously underlain by permafrost.

*We appreciate the reviewer’s point and have carefully included it in the text (L192-193) when defining the various classes. We have also changed “degraded areas” to “degraded areas/ areas without permafrost” in **Fig. 4**.*

P15 L375, Please provide citations when referring to “published literature”.

*The citations are provided at the end of the sentence: “According to the published literature and from this study, however, a permafrost peatlands degradation rate of 0.5%·a^{-1} appears to be a fairly conservative estimate in comparison with other studies across the Arctic, which show extremely variable estimates (0.1 – 9%·a^{-1}), although most are above 0.5%·a^{-1} (**Fig. 5**; Borge et al., 2017; Mamet et al., 2017; Olvmo et al., 2020; Payette et al., 2004; Thie, 1974; Verdonen et al., 2023; Wang et al., 2023; Zuidhoff and Kolstrup, 2000). ”*

P15 L375, Add an apostrophe to “peatlands”, so that it reads as “peatland’s”.

Thank you for spotting the spelling mistake. We have changed the text accordingly.

P16 L379, Should “decline” be changed to “increase”? I understand that the authors are saying that palsa coverage will decline, but the way that this sentence is written, it is saying that the palsa degradation would decline.

*The new sentence now reads: “This meta-analysis (**Fig. 5**) suggest that palsa degradation is likely to continue, following a non-linear course, probably at a higher rate than today”.*

P16 L386, I fear that this statement about the ability to trace the evolution of palsa degradation from biennial surveys dismisses the critical context that previous studies (Christensen et al., 2004 and Varner et al., 2022) provide to this study. Without those previous estimates, it would be impossible for the authors to find accelerated degradation in Stordalen. Please revise.

The new sentence now reads: “From this study, we have shown that biennial data from photogrammetric surveys make it possible to monitor the progression of palsa degradation, although historical data (Christensen et al., 2004; Varner et al., 2022) are essential for assessing the increase in the rate of degradation”

P16 Figure 5, This meta-analysis will be helpful for readers.

We thank the reviewer for their encouraging comment.

P21 L454, Remove “surfaces”.

We have changed the sentence accordingly.

P21 L459, Change “turns” to “becomes”.

We have changed the sentence accordingly.

P21 L471, Capitalize “arctic”.

Thank you for spotting the spelling mistake. We have changed the text accordingly.

P22 L488-490, This phrase is almost word for word the same as a similar phrase in the Abstract. Please revise so that it is not as repetitive.

We have changed the sentence to “We examined a gradient of lowland thermokarst development at Stordalen mire, Abisko, Sweden, extending from well-drained stable palsas to inundated fens affected by ground subsidence. Palsa degradation was quantified using RGB imagery and topographic data from UAS surveys between 2019 and 2021, together with a coarser assessment based solely on RGB imagery spanning 2014 – 2022.”

P22 L496, Include references to Christensen et al. 2004 and Varner et al. 2022 here.

We have added the citations.

P22 L502, Change “calculated” to “estimated”, and change “might” to “may”?

We have changed the sentence accordingly.

P22 L504-505, This sentence is almost exactly word for word the same as the last sentence of Section 3.4. Please revise so that it is not as repetitive.

The new sentence now reads: “[…] we estimated that palsa degradation at Stordalen may expose approximately 12 × 10^3 kg of organic carbon annually within the top 23 cm of soil, of which roughly 25% is mineral-interacting organic carbon.”

P23, L506-509, This last point is not technically a conclusion from the study and would be better if it were not included in the numbered points, but rather if it were simply included as regular text (paragraph form).

We have taken this comment into account by removing this point from the list, as it is indeed more of a perspective than an actual outcome of our work.

Figure A.3, Why is the trend in 2021 so much larger than in 2019?

The 2019 model used ground control points for the photogrammetry campaign, which probably limited the bowl-shape effect.

Report #2 | Submitted on 29 May 2026
Anonymous referee #2

The manuscript has improved substantially after revision. The authors addressed the previous comments carefully, and the overall understanding of the methods and results is now much clearer. In particular, the additional figures and methodological clarifications strengthen the presentation and support the interpretation of the results.

We would like to thank the reviewer for their positive evaluation and valuable comments.

However, the abstract remains too long and could be further condensed. I recommend focusing more clearly on the 2–3 main findings of the study and reducing some of the background/detail. In addition, the final sentence currently remains somewhat vague. It would be helpful to state more explicitly the main contribution and broader outlook of the study. The latter also applies to the final point of the conclusion, where you could go into more detail.

We have reduced the length of the abstract by a further 15% by simplifying part of the background and streamlining a few sentences. We have also clarified the final sentence, i.e., "These results demonstrate that UAS monitoring can robustly quantify rapid thermokarst development that coarser methods miss, and provide a transferable framework for tracking permafrost degradation rates at other lowland sites." (LL34–36)

The introduction is also quite long, which is understandable given that the authors aim to introduce several research gaps and methodological approaches. However, the structure could be improved considerably. For example, the introduction currently starts with Arctic warming and GHG emissions in peatlands, but then returns to thermokarst development and GHG emissions in the Arctic permafrost region in the second paragraph. In addition, the frequent shifts between presenting research gaps and proposing methodological approaches make it difficult to follow the main focus of the study. I suggest keeping the introduction simpler and more concise, ideally structured into no more than five paragraphs: problem statement (from the permafrost region to peatlands), context/background, research gap, and finally the study objectives. More detailed methodological information could be moved to the methods section. For clarity and readability, the same order of objectives should then be maintained consistently throughout the introduction, objectives, methods, and results/discussion sections.

We have revised our introduction, the structure of which is as follows:

- *(i) A short opening paragraph providing some high-level figures on the rate of degradation and GHG emissions from permafrost in general, and then specifically from peatlands;*
- *(ii) The second paragraph provides a detailed introduction to the physical degradation of permafrost, then defines thermokarst development and outlines some of the implications for potential GHG emissions from these landscapes;*
- *(iii) The third paragraph highlights the methods & the challenges regarding the estimation of GHG emissions from thermokarst landscapes in general, first from a biogeochemical perspective, and then at the spatial level;*
- *(iv) The fourth paragraph details the morphology and natural dynamics of palsa mires and provides the available orders of magnitude for their degradation rates. This reveals the main knowledge gap, which is that the available estimates are highly variable and derive from studies spanning long periods.*
- *(v) The final paragraph sets out the objectives of the study*

We have retained a few references to methodology (notably EMI) as this was explicitly requested by other reviewers.

Most concerns raised during the first review round were addressed satisfactorily. However, in several cases, clarifications were provided only in the "Response to Referees" document and not incorporated into the manuscript itself. Readers may encounter the same questions when reading the paper. I therefore annotated a few instances where I believe additional clarification should be included directly in the manuscript.

We have added the requested information (see comments and responses below).

The English has improved overall, but I still recommend another round of proofreading. There are still some typos (a/an, analysis/ analyses) and instances of unnecessarily wordy phrasing (e.g., "evolution of the …" where simply "palsa degradation" would be clearer and more concise; see, for example, lines 196, 199, and 233).

We have carefully re-read the text and simplified the wording as requested (L193, L196, L232).

Annotations

L. 73: "The methodology we use ... " - using the active voice (here an example) for the analyses you conducted, makes it easier for the reader to distinguish between your work vs. the work of others

This sentence has been amended in the new version of the introduction. It now reads "Estimation of GHG emissions from thermokarst landscapes can be achieved by calculating cumulative net ecosystem carbon balance (NECB) trajectories from different models of thermokarst landscape succession […]".

L 119: "ICOS" Please explain the abbreviation.

Thank you for pointing this out; we have added the definition of the acronym, which stands for Integrated Carbon Observation System.

L 124: "2" -> two

We have changed the sentence accordingly.

L 204: "(i) We calculated the mean of pixel values in 3 × 3, 5 × 5 and 7 × 7 moving windows (larger moving windows did not improve the accuracy of the classifications); (ii) We calculated of the standard deviation of pixel values in 3 × 3, 5 × 5 and 7 × 7 moving windows (larger moving windows did not improve the accuracy of the classifications);" I would state that this is done to reduce sensitivity of the model to artifacts.
L 210: "The calculated texture attributes include entropy, angular second momentum, contrast, homogeneity and the standard deviation of the GLCM, all applied within a 21 × 21 moving window." I would state that this is quite commonly applied in land cover classifications to provide additional morphological information and spatial patterns.

*The new paragraph now stands as: "We then generated spatial filters from the original bands using pixel windows of varying sizes (**Tab. 1**): (i) We calculated the mean pixel values in 3 × 3, 5 × 5 and 7 × 7 moving windows (larger moving windows did not improve the accuracy of the classifications) to reduce the sensitivity of the model to artifacts; (ii) We calculated of the standard deviation of pixel values in 3 × 3, 5 × 5 and 7 × 7 moving windows (larger moving windows did not improve the accuracy of the classifications) to distinguish between more homogeneous patches from more heterogeneous patches; (iii) We applied digital image processing techniques to produce texture attributes based on the gray-level co-occurrence matrix (GLCM; e.g., Hall-Beyer, 2017; Haralick, 1979; Haralick et al., 1973) to provide additional morphological information and spatial patterns. The calculated texture attributes include entropy, angular second momentum […]"*

L 218: "refined the initial predictions" See first round of reviews: For how many pixels (%) was this the case?

*We have added the information in the results section (L330): "Then, initial predictions were refined using elevation differences and model scores to ensure alignment with domain knowledge (see **section 2.4**). This procedure affected 0.14% of the pixels & the overall accuracy improved to 81.3% (run 7)."*

L 299: "The results consist of a TOC or MAOC stock that is made vulnerable annually as a result of palsa degradation." I recommend clarifying that you are suggesting this. This still reads like a result you are pointing to.

We have changed the text to now read: "These calculations were carried out for TOC and MAOC. We suggest that this corresponds to a stock of TOC or MAOC that is made vulnerable annually as a result of palsa degradation. The actual timing of OC loss remains unknown." (LL297-299)

L 400: “doubled in size between 2014 and 2022” What about the value in 2018? Was that supposed decrease in open water area due to seasonal water level fluctuations?

We certainly believe so, as also mentioned in the footnote (page 7; LL193–195). Although fluctuations in the water table depth are to be expected in the area, we thought it would be worth briefly mentioning the general trend we observed.

L 502: “metric tons” Above you use 10^3 kg. I recommend staying consistent.

We have changed the text accordingly, as well as in the abstract.

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