

Response to Reviewer 1

In black: Reviewer comments.

In blue: Response to reviewer.

General comments

The study investigates long-term environmental changes in a palsa mire zone of Northern Finland using a 40-year Landsat time series (1985–2024) combined with environmental predictors and a range of statistical approaches, including mixed-effects models, PCA and RDA. The topic is timely and relevant given the rapid changes occurring in sub-Arctic permafrost regions and the increasing need for long-term monitoring approaches. The study benefits from a relatively long observation period, and an attempt to integrate multiple remote-sensing indicators describing vegetation, moisture, water conditions and surface temperature.

Overall, the study provides potentially valuable insights into environmental dynamics in a palsa mire region and demonstrates the usefulness of Landsat data for long-term environmental monitoring. However, I found that the central scientific message is currently obscured by the large number of analyses and the somewhat unclear connection between research objectives, methods, results and interpretation. Addressing the comments below would, in my opinion, substantially improve the clarity and impact of the manuscript.

We sincerely thank the Reviewer for the constructive assessment of our manuscript. We agree that, in its current form, the manuscript is overloaded with statistical analyses, which makes the main message of the study unclear, and that some statements are unnecessarily elaborate. To improve the readability, clarity, and overall presentation of the paper, we will reorganize the material and remove unnecessary information in the revised manuscript. We believe that these changes will substantially improve and clarify the manuscript. We are committed to implementing the proposed revisions and provide below a detailed point-by-point response to the Reviewer comments.

Major comments

1. Research questions, study rationale and analytical framework need to be clarified

The scientific rationale of the study remains somewhat difficult to follow. While the Introduction outlines the general objective of analysing environmental change in a palsa mire zone using Landsat data, the specific research questions are not explicitly presented until the Figure 3. As currently written, the manuscript gives the impression that a broad set of indices and statistical analyses were first applied to the dataset and that the specific questions were formulated afterwards. I encourage the authors to explicitly formulate the main research questions (and ideally hypotheses or expectations) at the end of the Introduction and then structure the Results, Discussion and Conclusions around answering those questions.

We agree with the Reviewer that the research questions should be clearly introduced at the end of the Introduction and should guide the structure of the entire manuscript. In the revised version, we will explicitly formulate the research hypotheses, which will then provide a clear reference framework for

the Results and Discussion sections. Our research was designed to answer the following research questions:

- 1/ Does the spectral signal of palsa mires differ from that of other surface types?
- 2/ Which environmental factors predict the variability of remote sensing indices across different surface types, including palsa mires?
- 3/ Are the multi-decadal trends in vegetation and moisture indices (1985-2024) in the zone of marginal extend of permafrost similar or differ to those in other Arctic regions?

2. Results section is difficult to follow and would benefit from a clearer hierarchy

The study contains many different analyses (correlations, PCA, LMM, post-hoc tests, period comparisons, regression models and RDA), which in turn leads to a large number of different results. This makes the Results section “heavy”, and it is difficult for the reader to identify the main findings of the study and link them to the research objectives and questions.

Several analyses appear to demonstrate similar patterns, particularly the separation between soil categories and the importance of soil type as a predictor. While all analyses may be statistically valid, the manuscript would benefit from a clearer hierarchy of findings and a stronger focus on the key messages emerging from the dataset. The results should be organised in the order of the research questions (RQs 1–4) and remove results that are not clearly contributing to them.

In addition, parts of the Results section contain already some ecological interpretation and speculation regarding permafrost degradation, hydrological transitions and ecosystem change. These interpretations of the results would fit better within the Discussion section. Keep the Results section as concise as possible, just report the relevant findings.

Moreover, the manuscript would benefit from a more selective use of supplementary material. The extensive number of supplementary figures and tables contributes to the overall complexity of the study and reinforces the impression that numerous analyses were conducted to describe broadly similar patterns. While supplementary material is important for transparency, the current structure requires frequent movement between the main text and the Supplement, making the manuscript difficult to follow. The authors may wish to reconsider which analyses are essential for the main narrative and whether some supplementary content could be consolidated, reduced, or integrated into the main manuscript.

We agree with the Reviewer comments. In the revised version of the manuscript, we will introduce a clear hierarchy of results and adjust their layout directly to the previously formulated research questions. We will also remove statistical analysis and elements that do not make a direct contribution to answering the research questions. Furthermore, we will clear the results section of interpretive elements, leaving solely pure facts and hard statistical data, and move those contents entirely to the discussion section. We also critically review and streamline the Supplementary Material and remove unnecessary analyses and information. As a result, the results section will become as concise as possible and focused exclusively on the reporting of key facts derived from the data and addressed to the previously formulated research questions.

3. The role of PCA, RDA and LST within the analytical framework should be clarified

The conceptual role of PCA, RDA and LST within the overall analytical framework could be explained more clearly. PCA based on multi-year means and RDA performed for three temporal periods appear to identify broadly similar gradients and highlight the same dominant explanatory factors, particularly soil category and topographic controls.

Similarly, the added value of LST remains somewhat unclear. A substantial part of the manuscript is devoted to discussing the limitations and interpretational challenges of Landsat-derived LST, yet the ecological conclusions derived from LST are relatively modest. The authors should more clearly explain what additional insight these analyses provide beyond the vegetation and moisture indices and beyond the mixed-effects modelling framework already applied.

We thank the reviewer for this valuable comments. The applied methods serve complementary roles, as each addresses a different aspect of the data structure. Principal Component Analysis (PCA) was used for initial data exploration and identifying natural environmental gradients without imposing an a priori explanatory structure. In contrast, Redundancy Analysis (RDA), performed across three distinct temporal periods, was employed to quantitatively assess how the influence of explanatory variables changed over time. Meanwhile, LST, which by definition reflects the instantaneous thermal state of the land surface, was used in this study primarily to illustrate differences in short-term surface thermal conditions among the distinguished soil categories, with particular emphasis on their spatial variability. LST therefore serves as a supplementary indicator used to verify thermal differences among points representing the individual substrate categories. In the revised manuscript, we will clarify this aspect more explicitly. We will also more clearly define the division of roles of differ statistic approaches, emphasizing that the consistency of results across these different analytical approaches confirms the robustness of the identified environmental gradients.

4. Interpretation of permafrost degradation should be more cautious

The manuscript frequently links observed changes in RS indices to permafrost degradation and palsa deterioration. While these interpretations are plausible and consistent with current understanding of palsa dynamics, the study does not include direct measurements of permafrost conditions, active-layer thickness, palsa extent, or geomorphological change. The results therefore provide indirect evidence consistent with permafrost degradation rather than demonstrating it directly. The distinction between observation and interpretation should be communicated more clearly throughout the manuscript.

Thank you for that comment. We would like to point out that the study area was specifically selected because the extent of palsa mires there had been mapped by Finnish researchers (Tammilehto et al., 2024), who also documented the progressive degradation of these landforms from the second half of the 20th century through the first decade of the 21st (Leppiniemi et al., 2025). Our research, in turn, focuses not on identifying these forms (we adopted the location of these forms from Leppiniemi et al., (2025); Tammilehto et al. (2024), but on examining how they differ from other types of areas under changing climate conditions. In the revised manuscript, we will clearly emphasize the distinction between direct observations and the interpretations derived from them, noting that the analyzed remote sensing indices serve as indirect evidence of permafrost changes and palsa degradation rather than their direct measurement.

5. Discussion is sometimes weakly linked to the study results.

Several parts of the Discussion read more like a literature review than an interpretation of the results presented in this study. Extensive sections discuss Arctic warming, permafrost degradation, and climate feedback, but the links between these topics and the actual findings of the study are not always sufficiently discussed. Therefore, I strongly recommend restructuring the Discussion around the main findings of the study and explicitly discussing how each result supports, challenges or complements previous studies and how they answer to the set research questions.

We agree that the current version of the Discussion contains too much general information on Arctic permafrost. In the revised manuscript, we will substantially reorganize and streamline the Discussion by removing general and widely established information on permafrost transformation and by giving the section a more focused structure centered exclusively on the direct interpretation of our results. Furthermore the Discussion will be divided into three dedicated subsections corresponding to our research questions provided above.

- Does the spectral signal of palsa mires differ from that of other surface types?
- Which environmental factors predict the variability of remote sensing indices across different surface types, including palsa mires?
- Are the multi-decadal trends in vegetation and moisture indices (1985-2024) in the zone of marginal extend of permafrost similar to those in other Arctic regions?

Minor comments

Thank you for the valuable Reviewer comments. Detailed answers can be found below.

1. Because most palsa features are considerably smaller than Landsat pixels, greater attention should be given to the implications of mixed-pixel effects and the extent to which the observed signal represents the palsa itself versus the surrounding mire environment. In addition, the areal change of palsas during the 40-year study period should be discussed more and the trends observed in the study should be reflected on it.

The locations of the points representing palsa mires were determined on the basis of the raster dataset made openly available by Leppiniemi et al. (2025), which presents the degree of palsa mire degradation over approximately the last 50-60 years, beginning in the 1960s. In that study, the boundaries of the palsa mires were, in turn, adopted from Tammilehto et al. (2024). Each point representing a palsa mire in our study was located at least 70 m from the mapped palsa boundary. This ensured that the remote sensing index calculated within a 60 m buffer represented the palsa area entirely, while also allowing us to minimize potential uncertainty associated with a one-pixel positional error at the boundary. In the revised manuscript, we will describe this point-selection procedure more clearly. We would also like to emphasize that the primary focus of our study is not the direct analysis of changes in palsa extent or morphology, but rather the identification of the distinct environmental and spectral characteristics of palsa areas within the marginal permafrost zone. Nevertheless, we will expand the relevant part of the Discussion to provide a clearer temporal context for palsa mire changes, particularly in relation to the multi-decadal changes documented by Leppiniemi et al. (2025).

2. I was left wondering about the rationale for the selection of the 245 sampling points. A brief explanation of how the points were chosen (e.g. random, stratified, or systematic sampling) would help readers better understand the representativeness of the dataset.

The selection of the 245 sampling points was based on purposive, expert-based sampling, targeting specific locations representing palsas, non-palsa organic soils and mineral soils. This information will be clearly described in the Methods section of the revised manuscript, helping readers to better understand the spatial representativeness of our dataset.

3. The description of data availability and year exclusions appears inconsistent across the manuscript and Supplement. Different sections refer to different years as lacking suitable imagery or being omitted from the analyses (e.g. 1999 and 2012 in Section 2.2, 2010 and 2015 in Section 2.3, and 1992, 1999 and 2008 in the Supplement). I recommend clarifying the image selection workflow and explicitly listing which years were excluded from the final analyses and why.

In the revised manuscript, we will standardize information of the years excluded from the analyses by providing a clear and consistent description of the satellite image selection procedure and by including a single, comprehensive list of all excluded years in both the main text and the Supplementary Material.

4. The environmental predictors play a central role in the statistical analyses and interpretation of the results. While their derivation is described in the Supplement, the manuscript would benefit from a slightly more detailed introduction to the selected predictors and the rationale for their inclusion in the main text. Now they are only shortly mentioned at the end of the Statistical methods -section while climate and RS data have their own sections.

We agree with the reviewer comment that the selected environmental predictors play a key role in the analyses, and their previous, sparse discussion at the end of the statistical methods section was insufficient compared to the climate and remote sensing data. In the revised manuscript, we will expand the information on these predictors, presenting them in detail.

5. Consider reorganising Figure 3 so that the workflow progresses from research questions to data sources and finally to analytical methods. This would make the structure of the study easier to follow.

In the revised version of the manuscript, we will reorganize the structure of Figure 3 so that the flowchart logically proceeds from the formulated research questions, through the data sources, to the applied analytical methods.

6. The manuscript would benefit from more consistent use of terminology throughout.

- The text alternates between “RS”, “remote sensing”, and “remote-sensing indices”. After introducing the abbreviation, the authors may consider using it consistently throughout the manuscript.

We will introduce the abbreviation “RS” at its first occurrence and use it consistently throughout the manuscript, avoiding the interchangeable use of the full term and different forms of notation.

- Soil classes are named as “mineral soils”, “non-palsa organic soils”, and “palsa mires”. However, in the text the terminology varies and for example terms such as “other peatlands”, “other organic soils”, and “non-peatland areas” are sometimes used. Personally, I would prefer term

“permafrost-free peatlands” or “permafrost-free organic soils”. The used “non-palsa organic soils” -term is a bit clumsy and unnatural.

We will standardize the terminology used for the soil. We will also replace the awkward term “non-palsa organic soils” with the Reviewer suggested term “permafrost-free organic soils” (or “permafrost-free peatlands”), thereby ensuring greater clarity and terminological consistency throughout the manuscript.

- The use of terms “predictor”, “parameter”, and “variable” should be more consistent if they are referring to same thing.

We will standardize the use of the terms “predictor,” “parameter,” and “variable” throughout the manuscript, applying them consistently and distinguishing between them only when they refer to different statistical or methodological concepts.

7. The description of the study area could be streamlined. In particular, the detailed presentation of bedrock geology appears only weakly connected to the subsequent analyses and interpretation. Consider reducing this section and focusing more on environmental characteristics directly relevant to the research questions.

We agree that the description of the study area included overly detailed lithological information that was not directly related to our analyses. To address this issue, in the revised manuscript we will shorten the sections describing the geological setting and remove details that are not directly relevant to the parameters analyzed in this study.

8. Consider defining abbreviations in figure and table captions, even if they have already been introduced in the main text. This would improve the readability of individual figures and tables and make them easier to interpret as stand-alone elements.

In the revised version of the manuscript, we will standardize the captions of all figures and tables and provide the full definitions of all abbreviations, ensuring that each graphical element can be understood independently.

Small corrections and suggestions:

- Line 8: "The palsa mires – peat hummocks with a..." (Add word "peat").
- Line 25: Maybe just: "...characterised by the palsa mires". (Probably no new palsas forming in the current climate.)
- Lines 68–69: A bit clumsy. Consider e.g.: "The analysis included only environmental parameters that were available in open databases."
- Line 71: "directions of changes" --> "trends"?
- Line 79: "Usjoki" --> "Utsjoki" (add t)
- Line 82: "young glacial landscape", please open more: when did the deglaciation happen in the study area?
- Lines 115–116: Does the mention of years 1999 and 2012 belong here (see minor comment no 3)

- Lines 145–146: Leppiniemi et al. (2025b) or references mentioned in Figure 1a?
- Line 156: “preliminary data mining” probably raises more questions from the reader so consider if this could somehow be rephrased.
- Lines 209–211: not sure if this is needed, could be removed?
- Line 271: Remove “Atmospheric”
- Line 275: Mention the numbers of the supplementary figures and tables referred.
- Lines 357–359: “It is also noteworthy that...” Could this sentence be removed as it repeats things already said?
- Lines 489–492: There is repetition in these lines, and the text is a bit stilted. Especially the part: “Important findings include that...”
- Line 550: "more humid" --> "moister" or "wetter"?
- Lines 598–601: Sentence is long and hard to follow, please rephrase.
- Lines 601 and 604: Both sentences start with “At the same time”. Rephrase at least one of the sentences to avoid repetition.

We thank the Reviewer for the all detailed comments. All minor errors and editing suggestions will be carefully addressed, revised, or supplemented in accordance with the Reviewer recommendations.

References:

Leppiniemi, O., Karjalainen, O., Aalto, J., Yletyinen, E., Luoto, M., and Hjort, J.: The morpho-ecological state of palsa mires in sub-arctic Fennoscandia: insights from high-resolution spatial modelling, CATENA, 257, 109203, <https://doi.org/10.1016/j.catena.2025.109203>, 2025.

Tammilehto, A., Härmä, P., Kallio, M., Törmä, M., Saikkonen, A., Tuominen, S., Impiö, M., Heikkinen, M., Kervinen, M., Jussila, T., Böttcher, K., Pääkkö, E., Kokko, A., Mäkelä, K., and Anttila, S.: Ylä-Lapin luonnon kaukokartoitus – Projektin loppuraportti osa 1 – Aineistot ja menetelmät, <https://julkaisut.metsa.fi/julkaisu/yla-lapin-luonnon-kaukokartoitus-projektin-loppuraportti-osa-1-aineistot-ja-menetelmat/> (last access: 30 March 2026), 2024.