

Response to Reviewer 2

In black: Reviewer comments.

In blue: Response to reviewer.

This manuscript addresses the pressing issue of assessing the informative value of remote sensing (RS) data for studying landscape changes in subarctic tundra with sporadic permafrost. The importance of research in this area is primarily due to the need to identify areas (regions) of the most likely and intense landscape transformation and permafrost degradation due to climate change. Clearly, large-scale, detailed, and systematic observations can only be carried out using RS, while ground-based observation data from localized areas is necessary for training and validating satellite imagery results.

We sincerely thank the Reviewer for the constructive assessment of our manuscript. We fully acknowledge the comments raised and consider them valuable guidance for improving our study. We believe that the proposed revisions will substantially enhance the scientific quality of the manuscript. We provide below a detailed response to the Reviewer comments.

Using a local area in northern Finland as a case study, the authors attempted to link long-term Landsat satellite observations with ground-based observations characterizing landscape heterogeneity, with a focus on identifying the characteristics of the palsa mire zone, beneath which permafrost is observed. The stated objective is too general and does not fully align with the content and conclusions of the study, as, in particular, there is no information indicating the representativeness of the small study area (402 km²) in relation to the whole of northern Finland. The authors should clarify the knowledge gap this study aims to address.

We thank the Reviewer for this valuable comments. We would like to emphasize that the aim of this study was not to analyze changes in the selected indices across the whole of Finland or a substantial part of the country, but rather to improve our understanding of the processes occurring within the marginal permafrost zone, which is among the most rapidly changing environments under ongoing climate change. Therefore, 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?

Studies predicting changes in permafrost highlight the fact that it will disappear completely by the end of the 21st century in marginal zones (Leppiniemi et al. (2023). Answering provided above questions and specifically identifying the differences between palsa mires and peatlands with no ground ice could contribute to a better understanding of how the environment responds to the total disappearance of permafrost. The studied area differs from continuous and discontinuous zones of the Arctic, where the active layer deepens but permafrost will not predicted to disappearing entirely, and when permafrost will still shape water permeability. Similar marginal permafrost zones occur in other regions where permafrost is undergoing spatial contraction, including North America, Siberia, Tibet and Mongolia. We therefore believe that the results presented in this study can contribute new insights to the current state of knowledge and to the broader discussion of environmental changes occurring within marginal

permafrost zones. In the revised manuscript, we will clearly state that our study area represents a case study rather than a random sample intended to represent the whole of Northern Finland. We will also revise the formulation of the study objectives.

The study area analyzed in this work was selected after preliminary studies of available literature, because it encompasses a zone of documented sporadic and isolated permafrost (Gisnås et al., 2017) with the presence of palsas (Seppälä, 2006) which, in addition to the earlier studies mentioned above, have also been documented in recent research by Finnish authors (Leppiniemi et al., 2025; Ruuhijärvi et al., 2022). As a result, the area containing active palsas at different stages of preservation and degradation (Leppiniemi et al., 2025; Tammilehto et al., 2024) was selected. The size and location of the study area were selected so that the entire area could be covered by a single satellite scene. This allowed us to minimize data gaps in the analyses, which are a frequent limitation when using satellite imagery from the 1980s and 1990s. At the same time, the intentionally selected and relatively small study area of 402 km² allowed us to reduce the influence of other potentially confounding factors, such as deep drainage systems associated with the margins of larger valleys or negative postglacial landforms, the presence of large water bodies, substantial differences in elevation and the related orographic effects on temperature and precipitation, as well as regional climatic differences. Such factors could otherwise mask differences in the satellite-derived indices observed between palsa mires and the surrounding environments. Thus, the selection of the study area was intentional and was preceded by a review of the relevant literature and a preliminary assessment of satellite scene availability.

The study area's descriptions include excessively detailed descriptions of lithological features and soil properties, which are not clearly related to the analyzed parameters. At the same time, no information is provided on the characteristics, presence, absence, or transformation of permafrost in areas grouped into three soil types (palsa, organic soils, and mineral soils), making it impossible to relate the obtained results to the heterogeneity of geocryological conditions.

We thank the Reviewer for this valuable comment. We agree that the description of the study area included overly detailed lithological information that was not directly related to our analyses. In the revised manuscript, we will shorten these sections to information necessary to understanding obtained results. At the same time, we will expand the description of the transformation of permafrost in the study area that have recently been investigated by Finnish researchers (Leppiniemi et al., 2025).

Satellite imagery data was analyzed using the NDVI, NDWI, MNDWI, NDMI, and LST indices for areas without water bodies. Unfortunately, the authors poorly understand the meaning and information content of these indices. The NDWI and MNDWI indices are not intended to characterize the surface moisture of land areas and vegetation. Interpreting them as indicators of vegetation or soil moisture can lead to erroneous conclusions. These indices (NDWI and MNDWI) were developed to identify water bodies and are calculated based on the differences in the reflectance spectrum of water compared to the spectra of other surface types. Higher NDWI and MNDWI values are attributed to water bodies, while lower values are attributed to all other surface types.

The NDWI index (Green-NIR/Green+NIR) is essentially an inverted (reversed) version of the NDVI index (NIR-Red/NIR+Red), since the Green and Red channels are located close to each other in the overall spectrum and differ only slightly in reflectance. This is confirmed by the authors' results, according to which all average values and long-term distributions of the NDWI index with a high negative correlation

invert the values and distributions of the NDVI index. The NDWI index will always be negatively correlated with the NDVI, including regardless of vegetation moisture. The authors' analysis of NDWI as an indicator of vegetation moisture led to a contradiction.

We thank the Reviewer for this valuable comment. We would like to clarify that, in our study design, NDWI and MNDWI were intended from the outset to characterize water conditions rather than to provide a direct measure of soil or vegetation moisture. We agree, however, that this distinction may not have been sufficiently clear in some parts of the manuscript, which could have led to an incorrect interpretation. We would also like to clarify that one of the objectives of our study was to comprehensively test a broad range of remote sensing indices, including NDWI and MNDWI, in order to map changes in water conditions across the study area, as illustrated by the difference maps provided in the Supplementary Material. In addition, these indices were used to assess whether open-water bodies had developed in areas previously occupied by palsas. This is particularly relevant in such a dynamic environment, where palsa degradation may be associated with contrasting hydrological responses, including the formation of open-water surfaces (Vasile et al., 2026). In the revised manuscript, we will distinguish the description and application of these indices more clearly and rigorously. Specifically, we will emphasize that NDWI and MNDWI are used to assess the dynamics of water conditions and the occurrence of open-water surfaces, whereas moisture conditions are evaluated using the dedicated NDMI index.

We also agree with the Reviewer regarding the correlation between NDVI and NDWI. It is well established that visible light is strongly absorbed by chlorophyll pigments, resulting in low reflectance in the red region (~5%) and a small reflectance peak in the green region (~10%), whereas multiple internal scattering within the leaf mesophyll is responsible for the high reflectance observed in the near-infrared (NIR) region (~40-50%) (Knippling, 1970). This relationship will also be clarified and corrected in the final version of the manuscript.

The authors write: (341) «... the median NDVI in each period is notably higher for palsa mires (0.46–0.52) than for other organic soils (0.40–0.48) or mineral soils (0.37–0.43) (Figures 7 and S18). This indicates that biomass productivity is highest within palsa mires. There is a similar increase through P1, P2 and P3 for the soil moisture index (NDMI)...». Hence, the conclusion is that palsa mires are characterized by high moisture (as measured by NDMI). According to the authors' results, the NDVI index correlates well and positively with the surface moisture index NDMI, which is confirmed by the results in earlier publications by other authors.

At the same time, the authors write: (570) «It is also interesting that NDWI values were lowest on palsa mires as compared to the other substrate types, which may be due to their unique relief. Their ice core elevates these formations above the mire level, which forces a natural slope of the terrain. As a result, water does not accumulate on the tops of the palsas but flows down to the lower depressions.» From these two fragments of text, it is unclear whether the humidity in palsa bogs is high or low.

In fact, the NDWI values in the palsa swamps are the lowest for the same reason as the highest NDVI values. The vegetation here has higher green phytomass and, consequently, higher surface moisture (including NDMI).

It should be noted that the NDMI index clearly characterizes moisture content only at the surface of the vegetation cover. The NDMI index clearly cannot characterize the moisture content of the soil beneath the vegetation, since the penetration depth of solar radiation at these wavelengths does not

exceed 0.6 cm. The relationship between moisture content at the surface of the vegetation and in the soil is not always clear, so the NDMI index cannot be considered a soil moisture indicator, but only an indicator of surface moisture.

We thank the Reviewer for these valuable comments and for the precise clarification. Our interpretation regarding water runoff from the elevated palsa surfaces is consistent with the behavior of the NDWI, which, as the Reviewer correctly points out, primarily indicates the absence of surface water in these areas. We also agree with the important methodological point that NDMI reflects the moisture status of the vegetation cover rather than soil moisture itself. To eliminate the apparent contradiction between the higher NDVI/NDMI values and the low NDWI values observed on palsas, we will clearly distinguish between these processes in the revised manuscript. Specifically, we will explain that high NDMI values on palsas reflect the moisture content of the vegetation biomass, whereas low NDWI values result from the absence of standing surface water on their elevated surfaces. In addition, we will consistently replace any imprecise references to “soil moisture” in relation to NDMI with the more accurate term “vegetation moisture,” which more appropriately reflects the spectral information provided by satellite data.

The authors write that at the stage of processing remote sensing data, spectral differences between generations of Landsat satellites were corrected, and for this purpose, the intersensor calibration equations proposed by (Roy et al. 2016) were used. However, the work (Roy et al. 2016) presents formulas for correcting data obtained from the OLI (Landsat 8) and ETM+ (Landsat 7) radiometers and there is no information on intersensor correction between the data of these radiometers and the data of the TM radiometer (Landsat 5). At the same time, there are publications indicating a difference in the spectral response of the ETM+ and TM radiometers, which is manifested in particular by higher values of the NDVI and NDMI indices according to the ETM+ radiometer data compared to the TM radiometer. It is also known that these differences in the spectral response depend on the types of surface and vegetation of the analyzed areas. The authors do not provide information on the correction of the TM radiometer data. In most cases, neglecting this type of correction leads to overestimated values of the slopes of long-term trends in the NDVI and NDMI indices when using data from all three types of radiometers - TM, ETM+ and OLI. Thus, the average values obtained by the authors NDVI and NDMI indices and the slopes of the trends of these indices may be erroneous due to the lack of a stage of intersensor correction of TM radiometer data.

We particularly appreciate the Reviewer emphasis on the need to strengthen the methodological rigor of the processing and interpretation of the remote sensing data. We would like to clarify that our analysis employed a harmonization approach based on the methodology of Roy et al. (2016), which was developed for the OLI and ETM+ sensors. Previous studies (e.g., Crichton et al., 2025) indicate that differences in spectral response between the TM (Landsat 5) and ETM+ (Landsat 7) sensors for indices such as NDVI are marginal at high latitudes. Moreover, the application of the Roy et al. (2016) approach to Landsat 5 data used in previous studies in multi decadal time series studies (e.g., Fassnacht et al., 2019; Hong et al., 2024; Pei et al., 2022). We agree, however that the description provided in the original manuscript may have been too brief and insufficiently clear regarding the specific treatment of the TM sensor (Landsat 5). In the revised manuscript, we will expand the section describing the data preprocessing procedure and clearly explain that the adopted approach is based on established and widely used procedures for cross-sensor harmonization reported in the literature.

Unfortunately, the authors do not provide specific formulas from (Jimenez and Sobrino, 2003) by which they calculated the LST temperature and the LSE emissivity of the surface.

In the revised manuscript, we will expand the section describing LST and LSE by including the specific formulas and equations used in our calculations.

To statistically analyze and characterize long-term trends in index changes, the authors propose linear mixed-effects models (LMM), justifying this approach by the hierarchical nature of the data (the nature of the hierarchy is not explained) and the absence of data for some years. The authors do not provide specific formulas for converting the original data into data corresponding to LMM, which precludes the possibility of verifying the results of the statistical analysis and long-term trends using LMM. The authors' LMM results do not allow for direct comparison with those of other authors using more common statistical and regression analysis methods (t-statistics, Mann-Kendall tests, ordinary least squares (OLS), and the slope of the trend line using Sen's method), which are used, among other things, to analyze long-term trends with missing data for some years.

According to the authors' results, all index trends (Fig. 5, Table 2) have very high significance levels ($p < 0.001$), including for LST, which raises doubts given the observed data scatter. In this regard, the reviewer conducted a statistical analysis, in particular, of the LST trend (Fig. 5) based on the attached remote sensing dataset (<https://doi.org/10.5281/zenodo.20817134>) using OLS and t-statistics to assess the significance level. The result for LST: $\beta = -0.016$; $0.1 < p < 1$. The LST trend is insignificant and cannot be analyzed as a pattern. Elimination of one LST value (1985) leads to a change in the sign of β . Such a significant difference in the significance level of the LST trend based on the t-statistic from that shown in Table 2 ($p < 0.001$) cannot be attributed to the specifics of the LMM analysis. In this regard, the results of the statistical analysis for other indices also raise doubts.

We are very grateful to the Reviewer for this detailed statistical assessment, that helped us to trace and identify the reasons behind very high significance levels ($p < 0.001$) and address it appropriately in the improved version of the LMM model. We agree that the initial LMM specification underestimated the uncertainty associated with the temporal effect. The original model:

$$\text{Index} \sim \text{year} + (1 \mid \text{POINT_FIN})$$

accounted for repeated observations at the same sampling locations but did not account for year-specific variation shared among observations obtained in the same year. We therefore revised the model by treating sampling point and observation year as crossed random intercepts:

$$\text{Index} \sim \text{year_c} + (1 \mid \text{POINT_FIN}) + (1 \mid \text{YEAR})$$

where year_c is centred calendar year representing the long-term linear trend, POINT_FIN accounts for repeated measurements at the same location, and YEAR accounts for deviations shared by observations from the same year.

The revised model confirms the reviewer concern - although the estimated LST slope remains negative and very similar in magnitude ($\beta = -0.0257^\circ\text{C yr}^{-1}$), but it is not statistically significant after accounting for year-level variation ($p = 0.604$, 95% CI includes zero). A simple OLS regression of annual spatial

mean LST gives essentially the same conclusion ($\beta \approx -0.026$, $p \approx 0.60$). Thus, we no longer interpret LST as exhibiting a significant long-term trend.

Along with LST we reanalysed the remaining indices and noted change in the strength of inference: NDVI ($p = 0.049$), NDWI ($p = 0.006$), and NDMI ($p = 0.013$) retain detectable linear temporal trends, whereas MNDWI ($p = 0.666$) does not. We will therefore revise Fig. 5, Table 2, and the corresponding parts of Results, Discussion and Conclusions.

Table 2. Revised: Temporal trends in remote-sensing indices, 1985-2024 according to the revised LMM with random intercepts for sampling point and year

Index	Trend (β /year)	95% CI	p-value	Marginal R^2	Conditional R^2
NDVI	0.001795	0.00009 to 0.00350	0.049	0.069	0.863
NDWI	-0.001959	-0.00325 to -0.00067	0.006	0.119	0.871
MNDWI	0.000243	-0.00085 to 0.00133	0.666	0.002	0.767
NDMI	0.002545	0.00068 to 0.00441	0.013	0.071	0.885
LST	-0.025750	-0.12191 to 0.07041	0.604	0.006	0.931

After this change we would like to keep LMM as the primary analysis because it retains the repeated spatial observations and explicitly accounts for both sampling-point and year-level dependence but to facilitate comparison with more conventional time-series approaches, we will additionally report annual-level trend analyses as sensitivity checks (including OLS and non-parametric trend estimates) alongside the LMM results. To be sure that the improved model is accurate as an additional sensitivity analysis, we repeated the temporal trend assessment using annual spatial means and three conventional approaches: OLS regression, the Mann-Kendall test, and Sen's slope estimator. These analyses were broadly consistent with the our revised LMM results: NDWI and NDMI showed significant monotonic trends, whereas MNDWI and LST showed no significant trends. For LST, annual OLS yielded $\beta = -0.026 \text{ } ^\circ\text{C yr}^{-1}$ ($p = 0.600$), closely matching the revised LMM estimate ($\beta = -0.0257 \text{ } ^\circ\text{C yr}^{-1}$, $p = 0.604$). NDVI showed only weak evidence of a positive trend: the LMM and OLS results were marginally significant, whereas the Mann-Kendall test was not ($p = 0.119$).

We noticed the potential problems in reproducing full data processing of complicated analysis. Furthermore, we sincerely thank the Reviewer for such a careful and detailed check of the data. Thanks to this thorough inspection, we realized that an incorrect dataset was mistakenly uploaded to Zenodo (data prior to atmospheric correction and harmonization by Roy et al. (2016)). The correct dataset has already been uploaded to the Zenodo repository belonging to the article (doi.org/10.5281/zenodo.22904043).

Data were only reshaped from the published wide point-by-year format to a long point-year format, where missing point-year observations are omitted rather than imputed, and calendar year is centred.

The exact analysis-ready dataset and complete R scripts and the complete mathematical model specification used to reproduce the revised results will be archived and linked in the revised Code and Data Availability section.

According to the reviewer, the manuscript is overloaded with statistical analysis methods, graphics, and tables that duplicate fairly simple and obvious conclusions about the relationships between the indices themselves, as well as between the indices and predictors. The text is excessively replete with repetitions and unexplained terms (environmental gradient, environmental control, fixed effect,

sampling point, random intercept, continuous predictor, predictor redundancy, heat load). The text also contains many complex phrases, which significantly complicate understanding and obscure the essence of the conclusions (e.g. (409),... the joint variation in standardised point-level mean values of RS indices was strongly structured by environmental conditions; (414) ...This indicates that the environmentally structured component of RS variability was organised mainly along a single dominant gradient.).

We agree that, in its current form, the manuscript is overloaded with overlapping statistical analyses and figures, which obscures the main message of the study, and that some parts of the text are unnecessarily complex. To improve the readability, clarity, and overall style of the manuscript, we will reorganize and streamline the material by removing repetitive or redundant analyses and figures that lead to essentially the same conclusions. We will also simplify complex wording, including the passages indicated by the Reviewer, replacing it with clearer and more direct scientific language. In addition, we will ensure that key statistical and environmental concepts are clearly defined and explained at their first occurrence in the text.

The "Discussion" section provides overview information that is clearly unrelated to the results obtained. The authors do not provide specific information on long-term permafrost transformation trends in the study area, so repeating well-known conclusions about these processes is unnecessary. The "Results" section provides an interpretation of the data, which should be included in the discussion. General information about the potential and limitations of RS data application in the Arctic is well known. Authors should consider the potential and limitations of the methods used in their work if they are original or are being applied for the first time in similar conditions.

Thank you for that comment. We will substantially revise and reorganize both sections in the revised manuscript. First, we will remove interpretative elements from the Results section and retain only the presentation of the results. Second, we will revise the Discussion by removing general and widely established information on permafrost transformation and by giving the section a much more focused structure. The revised Discussion will concentrate exclusively on the direct interpretation of our findings, their relation to the specific trends in satellite-derived indices observed within the study area, and a critical assessment of the specific strengths and limitations of the methods applied under the conditions of the marginal permafrost zone.

Comments on the authors' conclusions:

(637) 1. Temporal trends in the vegetation index (NDVI) and moisture indices (NDMI, MNDWI) increased throughout the entire study period, in contrast to the water index (NDWI) and surface temperature (LST), which decreased towards the end of the study period.

Comm: The NDWI index mirrors the NDVI index; LST trends are insignificant and cannot characterize a decrease in surface temperature.

(640) 2. A strong positive correlation between the vegetation index (NDVI) and the moisture index (NDMI) was found and a negative correlation between the vegetation index (NDVI) and the water index (NDWI).

Comm: The positive correlation between NDVI and NDMI is well known for both tundra vegetation and other landscape types. The explanation for the negative correlation between NDVI and NDWI is given above.

(642) 3. Spatial differentiations in individual indices and in trends over the period 1985–2024 were found.

Comm: Spatial differentiation of indicators is obvious, as it is related to landscape heterogeneity. Differentiation in trends (direction and rate of change) by soil category is not obvious (Fig. 6). Numerical values are not provided.

(643) 4. Discrepancies were found between the air temperature trend (continuous increase) and the surface temperature index trend (decrease at the end of the period).

Comm: The LST trend is insignificant. Overall, the conclusion is trivial, as it is known that LST depends not only on air temperature but also on evapotranspiration, humidity, and surface thermophysical properties.

(645) Distinct environmental factors were identified that determined the multivariate structure of remote sensing indices. Of these, soil categories, DTW2, and DEM were the strongest and most consistent predictors across all three subperiods from 1985 to 2024.

Comm: The conclusion is unclear. Do these predictors influence the average index values or their long-term trends?

(647) The importance of soil categories and the DTW2 parameter increased significantly in the last period (P3: 2013–24), indicating the progressive intensification of environmental control over the spectral signal.

Comm: The conclusion is unclear. The spectral signal always depends on surface conditions. If there is no information on changes in soil conditions and DTW2, then how can we talk about an increase in their importance?

(648). These results also confirmed the clear thermal and hydrological distinctiveness of palsa mires, which throughout the study period retained an environmental character that was entirely distinct from the other organic soils (i.e., dystic histosols, sapric histosols) and the mineral soils (dystic leptosols, endogleyic podzols, hypersclletic leptosols).

Comm: According to the authors, palsa swamps differ from other organic and mineral soils only by their higher average NDVI and NDMI values, which is known and typical for any peatlands with a high content of ice inclusions.

(652) The use of Landsat images, being characterised by high spatial resolution (30 metres), enabled the detection of even small spatial changes, which is important due to the heterogeneous and mosaic landscape of the young glacial landscape of northern Finland.

Comm: It is well known that remote sensing data characterizes the heterogeneity of any landscape.

(654) At the same time, the Landsat mission provides a long time series of images, which allowed for the analysis of changes over as much as 40 years. The approach used can be easily applied to other study sites, which can help understand and quantify changes in dynamically changing permafrost areas, including those at the margins of its range.

Comm: The authors' approach is well-known, but what's new is unclear?

We agree with the Reviewer criticism that the Conclusions should be more concise and precise and should place greater emphasis on the aspects of our study that are genuinely novel and specific to the study area. To revise this section, we will remove broad statements concerning, among other aspects, non-significant LST trends and restrict the Conclusions to statistically significant findings. We will also clarify the role of the environmental predictors (soil categories, DTW2, and DEM) and their actual influence on the observed index values and trends, avoiding vague or overly general statements. Instead of reiterating well-established points regarding the advantages of Landsat data or landscape heterogeneity, we will more clearly emphasize the novelty of our study, namely the analysis of approximately 40 years of environmental change in specific palsa landforms in northern Finland in comparison with other peatlands and mineral soils. A significant contribution of our study is the assessment of whether the direction and magnitude of environmental changes at palsa sites differ from those observed in other peatlands and mineral soil environments.

Summary

Overall, of all the results obtained by the authors, the differences in the average NDVI and NDMI indices for the three soil categories, with the highest index values for palsa, are considered the most reliable and informative. Palsa bog zones represent typical peatlands with a higher content of ice inclusions. This result is not original, as similar results by other authors have been reported, confirming anomalously high NDVI and NDMI indices in peatlands with higher moisture/ice content in the thawed soil layer and higher ice content below the seasonal thaw layer. No obvious differences in the trends in index change for the three soil types were identified. In the reviewer's opinion, this work does not contain fundamentally new results and is not recommended for publication, including due to errors and inconsistencies in the remote sensing data analysis.

We thank the Reviewer for this final summary and for the valuable perspective on our work. We also appreciate the acknowledgement that the results concerning the mean NDVI and NDMI values for palsa mires are robust. Despite the Reviewer critical assessment, we respectfully disagree with the conclusion that the study provides no novel contribution to the existed knowledge. We would like to emphasize that the scientific value of our study lies in its 40-year temporal perspective (1985-2024), which enables us to track long-term environmental changes within the marginal permafrost zone of northern Finland, as well as in the comparison of different substrate categories within a consistent spatial framework. This is a specific environment in which permafrost occurs as isolated patches surrounded by permafrost-free terrain. In our view, such conditions differ substantially from those of tundra peatlands located within the discontinuous and continuous permafrost zones. The differences presented between palsa mires and ice-free peatlands, in the context of the widely observed ongoing degradation of palsas (Leppiniemi et al., 2025), may indicate how environmental conditions defined by remote sensing indices (NDVI, NDMI) could change when palsa mires transform into non permafrost boreal peatlands. In the revised manuscript, we will present the novelty and implications of these findings more explicitly and precisely. At the same time, we would like to emphasize that, to the best of our knowledge, we have not identified previous studies that analyze multi-decadal changes in ice-cored peatlands, specifically palsa mires characteristic of the marginal permafrost zone, using a comparable approach that distinguishes among different soil or substrate categories and addressed to comparable number of palsa mires. Several detailed long-term investigations have focused on individual mire complexes or a limited number of study areas (e.g. Verdonen et al. (2023)), whereas broader inventories and spatial assessments have primarily examined palsa distribution and morpho-

ecological condition (e.g. Leppiniemi et al. (2025)). After revising the manuscript in accordance with the Reviewer valuable comments and addressing the methodological and interpretative limitations identified in the review, including a more precise distinction between the functions and interpretation of RS indexes, we hope that the revised manuscript will meet the scientific and methodological standards required for publication in Biogeosciences.

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