

Dear Editor,

We have provided our responses to the reviewers' comments below. Our responses are marked in **green** and added/modified manuscript text with **bold green** in the response letter. The line numbers in the response letter refer to the track-changes version of the manuscript.

On behalf of all coauthors,
Kind regards,
Iuliia Burdun

Anonymous Referee #1, 14 May 2026

The article titled “Detecting long-term canopy change and vegetation shifts in northern peatlands using LAI and climate data” explores the vegetation trajectory, namely greening and browning trends, across northern peatlands using satellite-based measurements. The study found that while greening was more common than browning across northern peatlands at the local scale, overall canopy change across the circumpolar region was not statistically significant. Instead, vegetation responses appeared to be shaped by complex interactions among temperature, moisture availability, existing canopy composition, and longer-term climate oscillations, highlighting that peatland responses to climate change are spatially variable rather than uniformly increasing in productivity.

I think additional attention should be paid to two main areas:

1. Expansion and clarification of the statistical methods
2. Improving the readability and overall digestibility of the study

Generally, this work appears to make a meaningful contribution to the field, and I appreciated the use of mostly accessible and publicly available datasets. Overall, I believe the authors present a relatively complete and thoughtful study, but I recommend revisions prior to publication.

Thank you for the overall positive feedback. We have carefully considered your recommendations and revised the manuscript to improve readability.

While there are several areas where this manuscript may benefit from minor revisions, I believe the greatest payoff would come from improving the readability of the paper, which from my perspective may require more substantial attention. The findings and methods presented here have relevance across multiple disciplines and have the potential to be of interest beyond a strictly scientific audience, yet some portions of the manuscript are challenging to follow. I believe the paper would be strengthened by reducing reliance on nonessential acronyms, uncommon or highly field-specific terminology, and assumptions that readers already possess the necessary background knowledge, some of which does not feel fully established in the introduction.

- We removed the following acronyms: PDO (from abstract – P1, L24)), CDR (P3, L84), AMWG (P11, L290), CI (P11, L290), GLS (P12, L321), SSE (P12, L332).
- We improved the Introduction clarity and removed not-introduced details about our methodology.

In addition, aspects of the statistical approach would benefit from further explanation. While the analyses themselves appear appropriate and seem to be robust, portions of the statistical methodology are described at a level that can feel somewhat opaque, making it difficult for readers to fully understand the rationale behind certain analytical choices or how specific models were implemented. Similarly, some of the statistical results are presented in a way that can feel somewhat "blackbox," where readers are asked to accept the outputs without sufficient interpretation of what those results mean in a practical or ecological context. Providing clearer explanations of method selection, assumptions, and interpretation of key statistical outputs would make the findings more accessible and strengthen confidence in the conclusions.

First, we added the motivation for statistical methods to improve the readability of the manuscript:

- P9, L247: **First, we separated short-term variability from the regular seasonal cycle and long-term change in LAI, air temperature, and precipitation.**
- P10, L256: **We then tested whether LAI anomalies were associated with temperature and precipitation anomalies at the pixel level.**
- P10, L266: **Finally, we assessed whether LAI anomalies were associated with PDO.**
- P10, L274: **A single long-term trend can mask breakpoints, where the direction of LAI change reverses during the study period. We therefore examined whether each pixel-level LAI anomaly time series followed one of three trend shapes following Higgins et al...**
- P11, L293: **For LAI anomaly time series with supported curvatures, we then fitted the bent-cable model to identify the timing and direction of the main change in LAI anomalies, i.e. breakpoints:...**
- P11, L309: **To estimate long-term greening and browning trends of LAI, we modelled LAI change through time while accounting for both temporal autocorrelation within each pixel and spatial autocorrelation across 1,244,063 pixels.**

Second, we added the equations and R packages where they were missing, which increases the reproducibility of our results:

- P10, L258: **Specifically, using the ppcor package in R, we calculated: (i) the partial correlation between LAI and air temperature anomalies, controlling for precipitation anomalies, $\rho_{LAI,T|P,i}$ (Eq.1), and (ii) the partial correlation between LAI and precipitation anomalies, controlling for air temperature anomalies, $\rho_{LAI,P|T,i}$ (Eq.2).**

The results themselves are interesting and have the potential to be widely applicable but would benefit from revisions to the written text to make this work more digestible and improve the communication of what are ultimately compelling findings.

We agree with your suggestion to improve the manuscript's written text. For this, we have rewritten most of the manuscript sections (specifically the Abstract, Introduction, Methods, Results, and Conclusions). We hope that the modified version is more digestible and better communicates findings. We have described our modifications in more detail below under your specific comments.

In addition to the above general comments I have the following specific feedback:

1. Line 8: “Peatlands store vast amounts of carbon, yet their canopies are changing under northern warming.” The use of “yet” makes it seem like these are directly in contrast or in spite of, which I’m not sure is the strongest way to begin the abstract.

We rephrased it to (P1, L8): **Northern peatlands store vast amounts of carbon, part of which might be released to the atmosphere as climate warming alters peatland canopies.**

2. Line 16-17: cup-shaped trends and hat-shaped trends, would consider more layperson language in abstract since I think these results are interesting and tell a story, but this language may lose some readers. In the main text you have opportunity to define these terms for the reader but there isn’t room for that context in the abstract.

We removed “cup-shaped” and “hat-shaped” from the Abstract, so the new text looks like this (P1, L24): **These non-linear trends differed by region: trends in which LAI first decreased and then increased were concentrated in West Siberia, whereas trends in which LAI first increased and then decreased were widespread across Europe, northeastern Asia, and Canada.**

3. Line 24: suggest leaving Carbon as Carbon rather than C for readability, doesn't seem like there's any benefit to shortening

We replaced "C" with "carbon" in the abstract and throughout the main text for readability (P2, L47 and L53).

4. Line 25-30: expand on background context, especially status quo vegetation, shifts to vegetation, and carbon sink vs source.

We elaborated further on the background information and hope that it now provides a clear connection between vegetation and carbon in peatlands (P2, L39-55).

5. Line 33: either in previous paragraph or here further explain the idea of vegetation self-engineering, also worth expanding/tying back into this in the discussion section more explicitly

We agreed the self-engineering part should be explained in more detail, and we added the following text in the Introduction section (P2, L41): These ecosystems are built and sustained by plants that engineer waterlogged, nutrient-poor and oxygen-limited conditions; **among them, Sphagnum mosses are especially important because they help maintain the acidic conditions under which peat accumulates (Turetsky et al., 2025). By slowing the decomposition of plant remains, these conditions allow carbon-rich peat to accumulate over long timescales rather than be rapidly returned to the atmosphere.**

6. Line 37: either in previous paragraph or here, explain the relationship between specific vegetation types and carbon sink vs source. I think general relationships are known but I think intricacies are important to the story being told through the rest of this paper.

We thank the reviewer for this suggestion. We agree that the relationship between vegetation change and carbon dynamics is important. Because our study analyses remotely sensed LAI trajectories rather than species-level vegetation composition, we did not expand the Introduction into a detailed review of individual vegetation types. Instead, we clarified the functional mechanism most relevant to our analysis:

P2, L50: **Such vegetation shifts can reduce peatland productivity and carbon sequestration (Bragazza et al., 2012; Keane et al., 2025), partly by accelerating the decomposition of carbon-rich organic matter through changes in soil enzyme activity (Bragazza et al., 2012).**

P3, L75: **Yet in peatlands, greening trends may not have the same ecological meaning as in forests or tundra. In forests or tundra, more leaf area often indicates higher productivity; in peatlands, it may instead reflect the expansion of vascular plants at the expense of Sphagnum mosses, with potential consequences for peat-forming function and carbon sequestration.**

We also explicitly mention the role of peatland vegetation and carbon sequestration in the Discussion:

P20, L461: **Moreover, greening trends can even coincide with declines in terrestrial carbon storage, for example, where forest cover decreases, and understory vegetation becomes more visible to satellite sensors (Lorantý et al., 2018; Rautiainen et al., 2007; Rautiainen and Lukeš, 2015).**

7. Line 41: New paragraph to break things up but start with something other than "Because"

We have started a new paragraph and revised the opening so that it no longer begins with "Because" (P2, L63): **Given that** these changes occur over decades and across continental

scales, only satellite remote sensing enables consistent monitoring of vegetation properties, including canopy greenness, structure, and productivity (Myers-Smith et al., 2020).

8. Line 54: suggest briefly but directly explaining how LAI will get you to these greening and browning trends in very plain language

We added the following explanation in the Introduction section (P3, L84): **LAI is an Essential Climate Variable that describes canopy foliage amount and is defined as one half of the total green leaf area per unit horizontal ground surface area (Chen and Black, 1992; Leaf Area Index, 2026). In simple terms, higher LAI means more green leaf area above the ground, whereas lower LAI means less green leaf area. We therefore interpret increases in LAI over time as greening and decreases as browning.**

9. Line 73: wonder if it would be useful to include these datasets in a table with summary information for each.

We structured the listed datasets as bullet points for better readability and added information about the peatland areas they include (P4, L116):

1. **PEATMAP, an amalgamated global peatland distribution dataset compiled from national, regional, and global sources (Xu et al., 2018), for which we retained all cells with peatland cover above 0%, resulting in a potential peatland envelope of ~5,700,559 km² within the study domain;**
2. **Open Street Map (OSM) for which we derived polygons tagged as “Wetland” (OpenStreetMap, 2025) downloaded on 02 May 2024 that cover ~606,699 km² in the study domain;**
3. **ESA WorldCover 2021 – global land cover product at 10 m resolution, based on Sentinel-1 and 2 data (ESA WorldCover 10 m 2021 v200, 2026), for which we derived pixels classified as “Herbaceous wetland” (class 90) with ~1,582,232 km² coverage in the study domain; and**
4. **Global Peatland Map 2.0 – 1 km resolution that indicates locations of peatlands that cover ~7,456,109 km² in the study domain, combining areas with a peat in soil mosaic and peat-dominated areas (Global Peatland Database, 2026)**

10. Line 77-83: expand on how each of the datasets came together to create final dataset and overcome the limitations you identified.

We added the following text (P5, L131): **Thus, the final peatland mask included areas supported by at least two global datasets and also located within the Global Peatland Map 2.0. Because peatland locations remain uncertain, we used agreement among global datasets as a conservative criterion: areas were retained only when they were supported by multiple sources. Our resulting peatland mask covered ~535,017 km² of conservatively mapped peatland area. This approach prioritises higher-confidence peatland areas...**

11. Figure 1: Better explanation needed (and/or different language in legend) in both caption and main text for reader to understand “number of pixels within hexagons”.

We added the following explanation in the figure caption (P6, L156): **The colour scheme indicates the number of LAI pixels with peatland coverage of 90% or greater and without wildfire detected between 2001 and 2023.**

12. Figure 1: might be worth putting lakes/water bodies on as a contextual layer so readers who have a specific area of interest can orient themselves and quickly look at trends in that

area. This would be especially helpful in the large contiguous landmasses of Canada/Alaska and Siberia.

We have added water bodies to all maps in the manuscript (Figures 1, 3-5).

13. Figure 1: somewhat surprised to see areas that appear to not have peatlands based on this map, even at this resolution, especially in NW Canada and CE Siberia. I know your data sources are described but I wonder if more explanation might be worthwhile or even a description of any limitations by using the methods you did.

In addition to the above-mentioned extended description of the peat mask – we added the following text (P5, L148): **The final number of pixels for our analysis was 1,244,063 which captures more than half of our conservative peat mask area (Fig. 1). Therefore, our analysis should not be interpreted as an exhaustive assessment of all northern peatlands, but as an assessment of peatland-dominated, unburned pixels where the LAI signal is least likely to be confounded by mixed land cover or recent fire disturbance.**

We added a more detailed description of the studied pixels to be transparent about the spatial domain of our research:

P1, L11: **We assessed vegetation change across the peatland-dominated 500 m pixels north of 45 °N, defined as pixels with at least 90% mapped peatland cover and no detected wildfire during 2001–2023, using gap-filled, sensor-independent LAI climate data record.**

P3, L81: Here, we address this gap by analysing **long-term vegetation changes across peatland-dominated 500 m pixels north of 45 °N, defined as pixels with at least 90% mapped peatland cover and no detected wildfire during 2001–2023...**

P23, L571: **This study quantified long-term LAI-based greening and browning across peatland-dominated, unburned 500 m pixels north of 45°N between 2001 and 2023, and tested whether these patterns were associated with climatic, ecological, and protection-related factors. By focusing on mapped peatlands rather than on the broader Arctic and boreal domain, we provide, to our knowledge, the first multi-decadal, peatland-specific assessment of canopy change based on a gap-filled, sensor-independent LAI climate data record.**

Additionally, we note that some studied pixels (no wildfire between 2001 and 2023 and >90% peat coverage) occur in northwestern Canada and central-eastern Siberia, as shown in the figure below, where each green point represents one studied pixel. However, these pixels are relatively sparse due to limited agreement among the input datasets, limited wildfire occurrence between 2001 and 2023, and high peatland fragmentation. In such fragmented landscapes, peatlands were often not represented by 500 m pixels with more than 90% mapped peatland cover.



14. Figure A1: this symbology (colour scheme) doesn't seem intuitive

We agree that alternative colour schemes are possible; however, we would prefer to retain the current scheme because it is consistent with Fig. 5 in the main manuscript, where blue indicates decreases and red indicates increases.

15. Line 113: expansion on these correlation methods? Is PDO with no time lag expected? Is there any concern of the possibility of the multiple comparisons or multiplicity problem emerging? How was this dealt with?

We added the following explanation (P6, L170): We estimated pixel-based Pearson correlations between detrended anomalies of LAI and those indices with a time lag from 0 to 6 months, **assuming the lag effect within the same phenological year (Zhang et al., 2019).** **This screening was used to identify the index and lag with the strongest spatially coherent association with LAI anomalies, rather than to conduct pixel-level hypothesis testing.** Since the PDO without time lag had the highest absolute values of the Pearson correlation coefficient (ranging from -0.33 to 0.37), we used it in further analysis.

16. Line 142: “continent information to account for continental differences in vegetation sensitivity to climatic parameters” such as?

We added this explanation (P7, L203): **In this sense, the continent was used to capture a large-scale regional context that was not fully represented by climate data, elevation, or tree cover.**

17. Line 160: I found this a bit confusing maybe expand or clarify.

We agree that the text caused confusion, so we decided to rephrase it (P8, L220): This approach ensured that all areas **recorded in the World Database on Protected Areas as having some form of protected-area designation at the start of, or during** our 2001–2023 satellite record were represented...

18. Line 164 (methods section as a whole): I think further detail throughout the methods would improve the possible replicability of this study. I feel further detail would be particularly beneficial in 3.1, 3.3, and 3.4.

We have substantially expanded and clarified the Methods section. First, we added a general description of our workflow at the beginning of the Methods section, together with Figure 2

(P9, L240). Second, we added equations and the package name where they were missing (P10, L262). Thirdly, we removed field-specific abbreviations: AMWG (P11, L305), CI (P11, L291), GLS (P12, L321), SSE (P12, L332). Finally, we improved the digestibility of text in section 3.

19. Line 207: similar comment to line 113

We rephrased the text so that it explicitly states that temporal and spatial autocorrelation were accounted for using the package remotePARTS (P11, L309): **To estimate long-term greening and browning trends of LAI, we modelled LAI change through time while accounting for both temporal autocorrelation within each pixel and spatial autocorrelation across 1,244,063 pixels. This was done using the remotePARTS package in R (Ives et al., 2021) that reduces sensitivity to autocorrelation in satellite time series (Ploton et al., 2020).**

20. Line 207-222: I think there should be expansion into the statistical methods used, either here or elsewhere. These methods feel a bit “blackbox” to me and I think further detail is needed.

We agree that the statistical workflow needed to be described more transparently. We have therefore expanded Section 3.3 to explain the remotePARTS workflow step by step (P12, L314): first estimating pixel-level trends with AR(1) errors, then estimating spatial covariance from residuals, and finally fitting partitioned spatial generalised least squares models to obtain map-scale inference while accounting for spatial non-independence. We also clarify how candidate models were compared using pooled likelihood-ratio F-tests and how the final model was selected.

We note that remotePARTS is an established published framework rather than a method newly developed in this study, and we added an explicit reference to the relevant methodological paper for those who are interested in more detail (P12, L335): **Further details about the hypothesis testing with the remotePARTS package can be found in the original paper by Morrow and Ives (2025).**

Finally, we added a more explicit reference to Tables A1 and A2 in the Supplementary Materials (P12, L332): **The final model is summarised in Table A1, and the intercept-only map-level trend model used to test the overall LAI trend is summarised in Table A2.**

21. Line 224: expand and include some of this basic mapping approach alongside figure 1, which is introduced before any discussion on pixels or hexagons

We added the following explanation in the figure caption (P6, L155): **The colour scheme indicates the number of LAI pixels with peatland coverage of 90% or greater and without wildfire detected between 2001 and 2023.**

22. Figure 2: more contrast and/or larger figure panels may be beneficial here

We changed the colour palette in Figure 2 (now Figure 3) and increased the panel sizes.

23. Figure 2: also might be worth putting lakes/water bodies on as a contextual layer so readers who have a specific area of interest can orient themselves and quickly look at trends in that area. This would be especially helpful in the large contiguous landmasses of Canada/Alaska and Siberia.

We have added water bodies to all maps in the manuscript (Figures 1, 3-5).

24. Line 246: strongly recommend further description of “cup-shaped” and “hat-shaped” and even “linear” to better describe the patterns you have observed as cup/hat are not mainstream

enough descriptors to be used standalone. I think this is particularly important given that the plots in figure 3 don't appear as the classic, textbook examples (often financial) you would see in statistics texts. Improving the description and communication of statistics in this paper would be beneficial

We added the following description in:

- Result (P15, L364): **Here, linear refers to pixels with no detected change in trend direction, cup-shaped refers to pixels where LAI anomalies first declined and then increased, and hat-shaped refers to pixels where LAI anomalies first increased and then declined.**
- Conclusions (P24, L587): **Cup-shaped trends, where LAI first declined and then increased, were concentrated in West Siberia, whereas hat-shaped trends, where LAI first increased and then declined, were widespread across Europe, northeastern Asia, and Canada.**

25. Figure 5: improve tie-in with main text and expand on description of results seen in figure
We expanded the description of Figure 5, now Figure 6, as follows: (P18, L412):

Nevertheless, pixels overlapping drained lakes showed a higher proportion of increasing LAI trends: 94.5% of overlapping pixels had increasing trends, comprising 1,185 pixels with linear increasing trends, 758 with cup-shaped increasing trends, and 256 with hat-shaped increasing trends. Although linear increasing trends accounted for the largest number of overlapping pixels, the relative share of drained-lake overlap was highest for cup-shaped increasing trends, and the overlapping pixels were predominantly located in Asian peatlands. Given the limited and spatially clustered sample, this pattern should be interpreted as exploratory and not generalised.

26. Line 294 (long-term trends in LAI): any consideration for the reasons behind this? Some discussion on vegetation in following sections but wonder if it's worth tying in works by Loranty et al. (2018), Wang and Friedl (2019), Dearborn et al. (2021), Walker et al. (2021), and Carpino et al. (2025) who discuss specific changes to forest cover in this section of the discussion to strengthen the applicability? Are there vegetation successional changes associated with permafrost thaw? Are there species shifts related to the transition from more forest-dominated to more-wetland dominated peatlands in some of these areas? The discussions are much stronger for the following sections than for this section so it is worth adding to this section.

We agree that Section 5.1 previously focused more on comparison with previous greening/browning estimates than on the ecological interpretation of the observed LAI trends. We added the following paragraph (P20, L457): **Observed greening and browning trends in this study should not be interpreted as direct indicators of change in peatland productivity. In boreal and Arctic ecosystems, disturbances can affect vegetation trends, producing browning after tree loss and greening during post-disturbance recovery (Wang and Friedl, 2019). Although we minimised wildfire effects by excluding burned pixels, we did not account for insect defoliation and associated tree mortality (MacLean, 2016), or for disturbances related to peatland drainage and restoration. Moreover, greening trends can even coincide with declines in terrestrial carbon storage, for example, where forest cover decreases, and understory vegetation becomes more visible to satellite sensors (Loranty et al., 2018; Rautiainen et al., 2007; Rautiainen and Lukeš, 2015). In permafrost peatlands, thaw adds a further pathway of vegetation reorganisation, including shifts in dominant tree species and transitions between forested and wetland states (Carpino et al., 2021; Dearborn et al., 2021). Therefore, the widespread positive LAI trends observed here likely integrate multiple forms of vegetation**

change, rather than representing a single uniform greening mechanism. Some of these possible mechanisms are discussed in more detail in the following sections.

Anonymous Referee #2, 30 May 2026

The authors around Iuliia Burdun present a study on LAI trends and anomalies on northern peatlands in relation to climate variables for the period 2001-2023. The manuscript is well-written, addresses a relevant topic and is based on a well-executed analysis. It fits the scope of the journal and the quality of the study is generally suited for publication. However, in the present form the manuscript is not as convincing as it could/should be, due to some minor and -from my perspective- one major deficiency, which the authors should clarify in a revised version. Especially the relevance may be further improved. I look forward to such new version and believe it can contribute to an increased understanding on the global trends in these relevant ecosystems.

We thank the reviewer for this positive assessment. We have revised the manuscript to address the reviewer's minor comments and a major concern.

My main concern is related to the masking of study area and a potential bias towards greening trends: the masking approach requires at least one "recent" product to show peatland area as defined from visible land cover, i.e. a related vegetation class and, hence, some harder to detect peatlands may be excluded (as long as we define peatlands from the depth of organic soil). This would be different with the global peatland map alone. I could imagine that the masking will exclude more pixels that underwent browning, which may be lost in the recent vegetation signals. Masking may have been different at the beginning of the analysed time period. Likewise, areas affected by fires are excluded, which may also affect a mainly pixels under settings more likely to show browning (higher risk of burning). Ideally, the authors try to take a detailed look on excluded areas and show for some examples if such bias does or does not exist. The minimum requirement -for me- would be a convincing discussion how this may affect the results. (I am aware of the greening-to-browning-ratio argument in line 308f. However, if this is the only argument for the estimates, then the justification of the paper suffers, that we need a closer look on peatlands, only.)

We thank the reviewer for raising this important point. We agree that our masking approach may introduce a bias because it prioritises peatland areas that are visible in recent land-cover or wetland datasets and supported by multiple sources. As the reviewer notes, this means that peatlands that are harder to detect from current vegetation or land-cover signals, including fragmented, degraded, recently burned, or strongly altered peatlands, may be underrepresented. We also agree that excluding burned pixels may remove some areas that are more likely to show browning or abrupt canopy loss. Therefore, the analysed domain should not be interpreted as the full northern peatland domain.

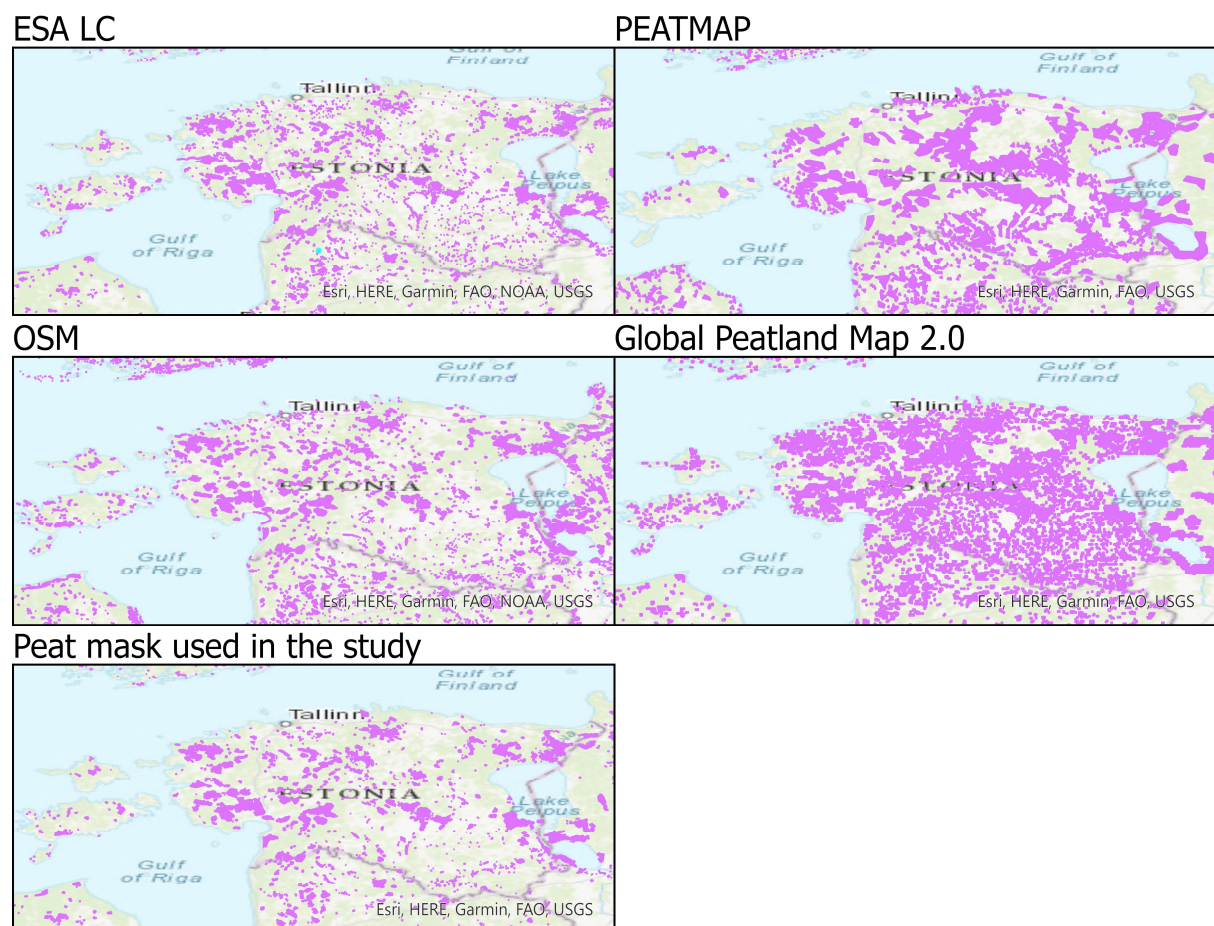
We have revised the manuscript to make this limitation explicit. In the Abstract, we now define the study domain as "**peatland-dominated 500 m pixels north of 45°N, defined as pixels with at least 90% mapped peatland cover and no detected wildfire during 2001–2023**" (P1, L11), rather than implying that the analysis covers all northern peatlands. In the Data section, we also expanded the description of the peatland mask, reporting the area covered by the input datasets and clarifying that the final mask retained only areas supported by multiple sources and located within the Global Peatland Map 2.0 (P4, L124). This conservative mask covered approximately 535,017 km². We further clarify that, after applying the 90% peatland-pixel condition and excluding burned pixels, the final analysis should be interpreted as an assessment of peatland-dominated, unburned pixels where the LAI signal is least likely to be confounded by mixed land cover or recent fire disturbance (P5, L157).

We agree that using the Global Peatland Map 2.0 alone would have resulted in a broader potential peatland domain. However, many areas in this broader domain include mosaic or low-fraction peatland landscapes, where a 500 m LAI signal may be strongly influenced by

adjacent non-peatland land covers, open water, forest edges, or agricultural land. Because the aim of our study was not to estimate total northern peatland extent, but to analyse long-term LAI trajectories in pixels where the satellite signal can be more confidently attributed to peatland vegetation, we retained the conservative mask. This choice increases internal validity but reduces spatial representativeness.

As an illustrative example, the figure below shows the coverage of Estonian peatlands in the datasets used in this study: ESA WorldCover herbaceous wetlands (~1,693 km²), PEATMAP (~9,318 km²), OSM wetlands (~2,599 km²), Global Peatland Map 2.0 (~10,170 km²), and the peat mask derived in our study (~1,394 km²). Although the estimated peatland area differed substantially among datasets, with Global Peatland Map 2.0 indicating approximately six times larger coverage than ESA WorldCover herbaceous wetlands, the main spatial pattern was broadly consistent across datasets and was retained in our final peat mask. This example illustrates that our conservative mask reduced the mapped area while preserving the major spatial structure of peatland distribution. However, this comparison does not rule out trend-related bias in excluded areas, which we now explicitly discuss as a limitation:

P20, L455: However, it also means that fragmented, small, recently burned, edge-dominated, and mosaic peatlands are likely underrepresented, potentially biasing greening–browning estimates.



Additionally, to address the reviewer's concern, we have added an explicit cautionary discussion. We now state that our mapped and analysed peatland area is smaller than the potential peatland domain indicated by PEATMAP and Global Peatland Map 2.0, and that this difference reflects our conservative domain definition rather than a revised estimate of northern peatland extent:

P1, L11: We assessed vegetation change across the peatland-dominated 500 m pixels north of 45 °N, defined as pixels with at least 90% mapped peatland cover and no detected wildfire during 2001–2023, using gap-filled, sensor-independent LAI climate data record.

P3, L81: Here, we address this gap by analysing long-term vegetation changes across peatland-dominated 500 m pixels north of 45 °N, defined as pixels with at least 90% mapped peatland cover and no detected wildfire during 2001–2023...

P23, L571: This study quantified long-term LAI-based greening and browning across peatland-dominated, unburned 500 m pixels north of 45°N between 2001 and 2023, and tested whether these patterns were associated with climatic, ecological, and protection-related factors. By focusing on mapped peatlands rather than on the broader Arctic and boreal domain, we provide, to our knowledge, the first multi-decadal, peatland-specific assessment of canopy change based on a gap-filled, sensor-independent LAI climate data record.

Below some recommendations of minor urgency which may further improve the manuscript:

1. Line 27 – also the changes in hydrology as such alter the C dynamics, esp. emissions. Here it sounds as if the reorganisation of plant communities is the driver of C dynamics, which only accounts for sequestration.

We have rephrased that text so now it looks like this (P2, L43): **By slowing the decomposition of plant remains, these conditions allow carbon-rich peat to accumulate over long timescales rather than be rapidly returned to the atmosphere.**

However, under a warming, drying climate, together with anthropogenic drainage, the conditions that sustain peatland may shift, causing plant communities to reorganise (Liu et al., 2023) and altering the processes that regulate peatland carbon dynamics (Bansal et al., 2023; Virkkala et al., 2025; Yuan et al., 2024).

2. Line 28 – with a focus on peatlands > 45 North you should also mention the active drainage of peatlands together with the fact that the masking excludes peatlands under different management from this study (may come in data section, but should be clear).

- We have added the following clarification about masking limitation in the Abstract (P1, L11): **We assessed vegetation trajectories across the peatland-dominated 500 m pixels north of 45 °N, defined as pixels with at least 90% mapped peatland cover and no detected wildfire during 2001–2023...**
- We added the drainage impact in the following text (P2, L45): **However, under a warming, drying climate, together with anthropogenic drainage, the conditions that sustain peatland may shift, causing plant communities to reorganise (Liu et al., 2023) and altering the processes that regulate peatland carbon dynamics (Bansal et al., 2023; Virkkala et al., 2025; Yuan et al., 2024).**

3. Line 49 – mention those “other ecosystem types”, ideally in relation to their greening-browning trends detected by others.

We agree that the phrase “other ecosystem types” was too vague. We revised this sentence so now it looks like this (P3, L70): **Consequently, global and semi-global mapping of greening and browning trends has mostly been focused on broad terrestrial vegetation types, e.g., forests, tundra, shrublands, grasslands, where greening has often been linked to warming, carbon dioxide fertilisation, or land-use change, while browning has been associated with drought, heat stress, disturbance, and vegetation mortality (Barichivich et al., 2013; Cai et al., 2025; Forzieri et al., 2017; Lian et al., 2020; Piao et al., 2019; Zhu et al., 2016)**

4. The final paragraphs of the introduction may be re-organized: Move sentence “This provides...” (line 54) to the very end of the introduction; state the hypothesis before the research questions; formulate the research questions as objectives (so far they are pretty weakly formulated research questions, especially #1)

We reorganised the final part of the Introduction so now it looks like this (P3, L94):

Specifically, our objectives were to:

- (1) quantify the direction, magnitude, spatial distribution, and temporal dynamics of LAI-based greening and browning across peatland-dominated, unburned 500 m pixels north of 45°N over 2001–2023; and**
- (2) test whether the identified LAI-based greening and browning patterns were associated with climatic, ecological, and protection-related factors, including temperature, precipitation, decadal climate variability, recent lake drainage, tree-cover type and density, and protection status.**

This provides, to our knowledge, the first multi-decadal, peatland-specific assessment of canopy trends.

5. Introduction in general – it reads a little that the “gap” is the main motivation for the analysis, please try to further strengthen the arguments why this study is needed and what may be learned from this focus on peatlands.

We agree that the Introduction should make the relevance of a peatland-specific analysis clearer. We therefore expanded the explanation of why peatland vegetation is important for peatland carbon dynamics

P3, L75: Yet in peatlands, greening trends may not have the same ecological meaning as in forests or tundra. In forests or tundra, more leaf area often indicates higher productivity; in peatlands, it may instead reflect the expansion of vascular plants at the expense of Sphagnum mosses, with potential consequences for peat-forming function and carbon sequestration.

6. Section 2.1 – please be clearer, how you define peatlands and how this is related to wetlands and masking classes and what your mask in the end includes from the greater entity “peatland”, what it does not include and what this means for the presented results (this may fit in the discussion!). See my main concern.

In the revised text, we now list the four input datasets separately and report their mapped areas within the study domain: PEATMAP cells with peatland cover >0%, OSM polygons tagged as wetland, ESA WorldCover herbaceous wetland pixels, and Global Peatland Map 2.0, including peat-dominated and peat-in-soil-mosaic areas (P4, L125). We also clarify that OSM and ESA WorldCover identify wetlands or wetland-like land cover rather than peatlands specifically, whereas PEATMAP and Global Peatland Map 2.0 are peatland-oriented products. We further clarified the masking workflow (P5, L131): **Thus, the final peatland mask included areas supported by at least two global datasets and also located within the Global Peatland Map 2.0. Because peatland locations remain uncertain, we used agreement among global datasets as a conservative criterion: areas were retained only when they were supported by multiple sources. Our resulting peatland mask covered ~535,017 km² of conservatively mapped peatland area. This approach prioritises higher-confidence peatland areas...**

We also clarified what this mask does not include (P20, L455): **However, it also means that fragmented, small, recently burned, edge-dominated, and mosaic peatlands are likely underrepresented, potentially biasing greening–browning estimates.**

We now explicitly state that our analysed area is smaller than the broader potential peatland domain indicated by PEATMAP and Global Peatland Map 2.0, and that fragmented, small, recently burned, edge-dominated, and mosaic peatlands are likely underrepresented.

7. 325ff – would this argumentation maybe ask for a split analysis where e.g. the last 10-15 years are looked at individually?

We agree that a split-period analysis would be valuable for directly testing whether the relative importance of moisture controls has changed over time. In the present manuscript, however, our aim was to estimate net LAI trends over the full 2001–2023 period, identify the main non-linear LAI trajectories, and test map-scale associations between LAI trends and climatic, ecological, and protection-related factors. A formal split-period or moving-window driver analysis would require an additional modelling framework and would shift the focus of the paper.

To avoid implying that the present analysis directly tests a temporal strengthening of moisture control, we revised the wording to present this interpretation as consistent with recent literature rather than as a result of our own split-period analysis (P20, L487): **However, recent evidence suggests that, over the past two decades, vegetation responses have become increasingly constrained by moisture balance, making water availability an important control on canopy dynamics (Chen et al., 2025), and may have facilitated the expansion of vascular plants in peatlands (Bu et al., 2011).**

8. The discussion should clearer show, why the separate analysis of peatlands was relevant and needed in addition to exiting studies, which leads over to the conclusion...

In the Introduction, we now clarify that peatlands require separate attention because LAI trends can be interpreted not only as changes in canopy leaf area, but also in relation to carbon sequestration (P3, L84).

In the Discussion, we expanded the interpretation of LAI trends to show why a peatland-specific framing matters. We now emphasise that greening and browning in peatlands should not be interpreted simply as direct indicators of productivity change (P20, L457): **Observed greening and browning trends in this study should not be interpreted as direct indicators of change in peatland productivity. In boreal and Arctic ecosystems, disturbances can affect vegetation trends, producing browning after tree loss and greening during post-disturbance recovery (Wang and Friedl, 2019).**

9. ... which is in the end a bullet summary and not a conclusion. Conclude by highlighting the value of the outcomes of the paper.

We have rephrased the Conclusions to highlight the value and main outcomes of the study (Section 6, P23).

10. I do agree to the comments of referee #1. I do not share the concern in the discussion that NDVI or similar should be included, but a short paragraph on LAI as compared to the mentioned indices may be added in the discussion

We have addressed Referee #1's comments. As suggested, we did not add NDVI or other indices to the analysis but we added a short mentioning on difference between LAI and NDVI (P19, L439): **Additionally, part of this difference in estimated greening may also stem from the vegetation metric itself: many previous studies were based on NDVI, which responds to canopy chlorophyll and saturates relatively early (Camps-Valls et al., 2021). By contrast, the LAI data used in our study is a biophysical measure of leaf area retrieved primarily through a physically based radiative transfer algorithm rather than from spectral greenness alone (Pu et al., 2024). Greening and browning expressed**

through these metrics are therefore not directly comparable, and this may help explain some of the divergence between our LAI-based results and earlier NDVI-based estimates. Yet our greening-to-browning ratio is consistent with a 3.6:1 greening-to-browning ratio in the Low Arctic observed before.

Kai Yan, 09 Mar 2026

This study detected long-term canopy change and vegetation shifts in northern peatlands using LAI and climate data. The innovation of the article is now reflected in the peatland map and conclusions about there is no significant trends in peatlands. The study is consistent with the journal's scope, supported by rich datasets and thorough analyses, and the topic holds clear scientific significance. Overall, this research has certain significance in long-term vegetation shifts in northern peatlands, but it still needs to be modified to improve.

Thank you for the overall positive feedback. We improved the manuscript following your recommendations.

Abstract

Q1: Lines 16-17: What is the means of Cup-shaped trends? And hat-shaped trends? These are not mentioned before. Pls delete is or explain more.

We have corrected it and now the text looks like this (P1, L24): **These non-linear trends differed by region: trends in which LAI first decreased and then increased were concentrated in West Siberia, whereas trends in which LAI first increased and then decreased were widespread across Europe, northeastern Asia, and Canada. Protected peatlands did not show different LAI trends once differences in climate and canopy were accounted for.**

1 Introduction

Q2: Lines 54-56: "This provides, to our knowledge, the first multi-decadal, peatland-specific assessment of canopy trends based strictly on mapped peatlands, rather than generic boreal or Arctic ecosystems." Could the author elaborate on this point? It's the most innovative aspect of the article and understanding it would be crucial for readers.

Thank you for pointing it out, we have explained the importance of peatland-specific assessment (P3, L75): **Yet in peatlands, greening trends may not have the same ecological meaning as in forests or tundra. In forests or tundra, more leaf area often indicates higher productivity; in peatlands, it may instead reflect the expansion of vascular plants at the expense of Sphagnum mosses, with potential consequences for peat-forming function and carbon sequestration.**

2 Data

Q3: Section 2.1: Authors listed some datasets, could you also list the link for these datasets?

We have added the references to all the datasets (P4, L116):

1. **PEATMAP, an amalgamated global peatland distribution dataset compiled from national, regional, and global sources (Xu et al., 2018), for which we retained all cells with peatland cover above 0%, resulting in a potential peatland envelope of ~ 5,700,559 km² within the study domain;**
2. **Open Street Map (OSM) for which we derived polygons tagged as "Wetland" (OpenStreetMap, 2025) downloaded on 02 May 2024 that cover ~ 606,699 km² in the study domain;**
3. **ESA WorldCover 2021 – global land cover product at 10 m resolution, based on Sentinel-1 and 2 data (ESA WorldCover 10 m 2021 v200, 2026), for which we derived pixels classified as "Herbaceous wetland" (class 90) with ~ 1,582,232 km² coverage in the study domain; and**
4. **Global Peatland Map 2.0 – 1 km resolution that indicates locations of peatlands that cover ~7,456,109 km² in the study domain, combining areas with a peat in soil mosaic and peat-dominated areas (Global Peatland Database, 2026)**

3 Methods

Q4: Can you provide a flowchart to help highlight the understanding of the entire study?

We have created a flowchart – Figure 2 on page 9.

Q5: Section 3.1: Can you add some formulas to help explain this part?

We have added Eq. 1 and 2 (P10, L262).

4 Results

Q6: Fig. 5: Numbers at bar ends give the count of overlapping pixels. However, this is quite confusing and should be deleted. Additionally, this figure should be optimized, and it looks significantly different from the other figures.

We expanded the description of Figure 5, now Figure 6 (P18, L420) so now the numbers at the bar ends are explained in the text: **Nevertheless, pixels overlapping drained lakes showed a higher proportion of increasing LAI trends: 94.5% of overlapping pixels had increasing trends, comprising 1,185 pixels with linear increasing trends, 758 with cup-shaped increasing trends, and 256 with hat-shaped increasing trends.**

We respectfully retained the figure layout because the numbers at the bar ends provide the sample size for each trend-shape class and help interpret the proportions shown in the bars. We also used the same plotting workflow and graphical settings as for the other figures, and therefore considered the figure style sufficiently consistent with the rest of the manuscript.

5 Discussions

Q7: The discussion is well designed. However, only LAI discussed here, can you discuss other metrics also (e.g., NDVI, EVI, and GPP)?

We have added a discussion of the difference between LAI and NDVI as a possible explanation for differences in greening estimates between our study and previous studies (P19, L439): **Additionally, part of this difference in estimated greening may also stem from the vegetation metric itself: many previous studies were based on NDVI, which responds to canopy chlorophyll and saturates relatively early (Camps-Valls et al., 2021). By contrast, the LAI data used in our study is a biophysical measure of leaf area retrieved primarily through a physically based radiative transfer algorithm rather than from spectral greenness alone (Pu et al., 2024). Greening and browning expressed through these metrics are therefore not directly comparable, and this may help explain some of the divergence between our LAI-based results and earlier NDVI-based estimates. Yet our greening-to-browning ratio is consistent with a 3.6:1 greening-to-browning ratio in the Low Arctic observed before (Berner et al., 2020).**