Dear Editor,

Thank you for considering our manuscript egusphere-2024-141 (“Multitemporal UAV LiDAR detects seasonal heave and subsidence on palsas”) for publication in The Cryosphere. We have been through all feedback provided by you and the reviewers, and we are glad to report that all comments led to changes in the manuscript one way or the other.

In the below, we provide a point-to-point reply to each comment/question raised in RC2, and we specify the changes that were implemented in the manuscript for each of them.

Q = Question / comment raised

A = Answer / details of the changes made

LXXX–XXX refers to the line numbers of text in the revised manuscript.

General comments:

Q1: The paper is well written. However, I think the opening paragraph in particular is the weakest part of the writing because it is trying to address too many points with too little detail. I recommend splitting this paragraph into two (e.g. 1: The ecological and climatic importance of permafrost, and 2: threats to permafrost environments).

A1: First of all, we thank the reviewer for stating that the paper is well written. They suggest splitting up the first paragraph of Chapter 1 as it tries to address to many points, without enough details. After their comment, we agree with that some of the points deserve more detail and that the paragraph can be split up in two. The main focus of our study are the seasonal palsa dynamics and the use of UAV LiDAR for monitoring permafrost environments. We therefore try to not create too long of an introduction regarding the general loss and threats to permafrost regions. While the 'ecological and climatic importance of permafrost' is inherently linked to the 'threats to permafrost environment', we have followed the suggestion and spit up the first paragraph.

In the first, we have now addressed the important role of peatlands in the permafrost zone related to their carbon stocks.

L25–33 In the face of accelerating climate change, permafrost – defined as ground that remains at or below 0 ◦C for at least two consecutive years (Harris et al., 1988) – is warming at a global scale (Biskaborn et al., 2019). Permafrost regions hold approximately 50% (1300±200 Pg) of the world's terrestrial carbon, making them vital to the global climate system (Hugelius et al., 2020). A significant amount (415±150 Pg carbon) is stored in northern peatlands, nearly half of which is affected by permafrost (Hugelius et al., 2020). In the discontinuous and sporadic permafrost zones, peatland permafrost can be found in palsa mires, consisting of peat plateaus and palsas. Palsas are peat mounds with a core of perennially frozen soil (Seppälä, 1986). Palsa mires are a sensitive and heterogeneous ecosystem, which are vulnerable to increased air temperatures and precipitation in the Arctic (Luoto et al., 2004).

The second paragraph now includes more examples of threats to palsa mires as permafrost environment.

L34–50 The climatic space for palsas, typically with a mean annual air temperature between -3 °C and -5 °C and mean annual precipitation <450 mm, according to Luoto et al. (2004a), is projected to disappear in Fennoscandia by the end of the 21st century (Fewster et al., 2022). In recent studies, an increasing lateral degradation rate of palsas is reported (Borge et al., 2017; Mamet et al., 2017; Olvmo et al., 2020) which may have far-reaching consequences for these ecosystems and biodiversity of the subarctic region (Luoto et al., 2004; Swindles et al., 2015). For example, the loss of palsas can lead to the decline of specialized plant species that are adapted to the unique, dry conditions of palsas. Additionally, animals that depend on these habitats, such as certain bird species and small mammals are affected (Luoto et al., 2004). In addition to the threat to biodiversity, the degradation of palsas also impacts reindeer herding, berry picking and transport for local communities, as these elevated, often dry, parts of the landscape shrink and become more fragmented. The transition from a palsa to a lower lying, wet fen, is also associated with an increase in CH4 and CO2 emissions (e.g. Łakomiec et al., 2021; Pirk et al., 2024; Swindles et al., 2015; Voigt et al., 2019) as the stored carbon in these peatlands is subject to microbial re-mobilization when permafrost thaws. The climatic feedback mechanism further highlights the need for continued monitoring of these environments. Therefore, palsa mires are a priority habitat of the EU Species and Habitat Directive (EUNIS -Factsheet for Palsa Mires, 2013). However, in Sweden only about half (47%) of the total palsa area is situated within a protected area (Backe, 2014).

Q2: Given the limited spatial and temporal scope of the paper, some further work is needed to contextualise the findings at these sites with other literature from the region. I note that comparisons are already made with site-specific studies using LiDAR but in Alaska and Canada. Within Scandinavia, methodological comparisons are made with other studies (e.g. use of InSAR vs LiDAR) but the findings of these studies could also be incorporated to better understand trends at this site and the region. Whilst InSAR is broadly agreed to underestimate rates, there is confidence in the direction of vertical trends, which can still make for valuable contextual information. I recommend taking a look at the very recently published paper from Valman et al. (2024) [https://doi.org/10.5194/tc-18-1773-2024], which looks at the subsidence of the same site of Vissátvuopmi (and across the same palsa mire complex more broadly) except using InSAR from 2017-2021. It could provide a site history and context of subsidence trends prior to your study embarking in 2022 (may be useful at lines 258-267).

A2: The reviewer states that the paper can be improved by providing more context of other studies done in the region. We value this comment and have taken several approaches in order to contextualize our findings. First of all, we have provided more context of Vissátvuopmi as part of the eight named palsa complexes in Sweden using the findings of Valman et al. (2024):

L90–95 Located near the Finnish border, and just southwest of the Könkämäeno river, Vissátvuopmi is the largest, of the in total eight named, coherent palsa mire complexes in Sweden (ca. 150 ha of palsa area; Backe, 2014) at N 68°47’50”, E 21°11’30” (Fig. 1). According to InSAR data from 2017, 55% of the total area of these eight palsa complexes is subsiding, compared to 98% of the Vissátvuopmi area (Valman et al., 2024). Though notably, only Vissátvuopmi and Árbuvuopmi (northwest of Vissátvuopmi) are not part of the EU Natura 2000 network.

Next, in order to further contextualize our results, we include the findings by de la Barreda-Bautista et al. (2022) and the recently published Valman et al. (2024), as the reviewer suggested. We have noticed this recent publication and agree that it provides as very suitable context of longer-term subsidence of palsa complexes in the region.

L339–351: de la Barreda-Bautista et al. (2022) reported a maximum subsidence rate of 1.5 cm, from InSAR data, between 2017 and 2020 on a palsa plateau at ca. 100 km from the Vissátvuopmi palsa complex. Due to the coarser spatial resolution (20 m) of the data, it is likely to underestimate actual heave and subsidence values of smaller isolated features such as palsas. Over the same period and location, they observed 25 cm subsidence from DEMs created with UAV photogrammetry. InSAR subsidence has also been analyzed at the Vissátvuopmi palsa complex (Valman et al., 2024). They found that Vissátvuopmi and the adjacent Árbuvuopmi are the fastest subsiding complexes of the eight studied in northern Sweden, with maximum subsidence rates of -8.9 and -9.9 mm yr-1 between 2017 and 2021. While the absolute values are not comparable with subsidence rates from our UAV LiDAR data due to the large discrepancy in spatial resolution, they give an important context of the subsidence trend across the entire palsa complex in the years right before our study period. The fact that Vissátvuopmi is among the most quickly deforming complexes and at the same time does not hold a protected status, emphasizes the importance of studies conducted here.

Finally, we have incorporated a more in-depth comparison with the findings from Olvmo et al. (2020), who provide annual (lateral) decay rates, at the same palsas that we studied, based on historical orthophotos. We have used orthophotos that were created with UAV photographs at the same day as the LiDAR surveys to delineate the palsas and find the area of the palsas in September 2023. We were then able to compare annual decay rates from 2010–2016 and 2016–2023 on the Dome and Ridge palsa.

L387–394: Olvmo et al. (2020) found an average annual decay rate (loss of palsa area) of -0.74 %a−1 and -2.45 %a−1 for the Dome and Ridge palsas respectively, for the period 2010–2016. Using the palsa area from Olvmo et al. (2020) in 2016 and the extent in 2023 from our study, we can calculate a new annual decay rate. For the period 2016–2023, we found respective rates of -3.27 %a−1 and -1.55 %a−1. The -2.53 %a−1 change in decay rate on the Dome palsa can be largely explained by the degradation hotspot, which covered ca. 2.6% of the total palsa area. The slight decrease in annual decay rate on the Ridge palsa could be explained by a stabilization of degraded areas. When excluding the degradation hotspot on the Dome palsa, the Ridge palsa lost a larger percentage of its extent, similar to Olvmo et al. (2020).

Specific comments:

Q3: L21: replace “helps in” with “facilitates”

A3: We agree with the suggestion and made the adjustment

L21–22: It facilitates tracking the ongoing effects of climate change and highlights palsa dynamics that would not be captured by annual measurements alone.

Q4: L45: it would be useful to include a definition of ‘lateral erosion’ and ‘vertical subsidence’ and differentiate between the two here.

A4: We agree with the reviewer that a more elaborate definition of ‘lateral erosion’ and ‘vertical subsidence’ will improve this part of the Introduction chapter. The revised text is as follows:

L51–55: The degradation of permafrost in palsas is indicated by both lateral erosion and vertical subsidence. Lateral erosion refers to the horizontal shrinkage of the permafrost body along the edges of palsas, often resulting in the formation or expansion of connected water bodies, i.e. thermokarst lakes (Martin et al., 2021). Vertical subsidence, on the other hand, involves the downward sinking of the ground surface as a result of the melting of excess ground ice, leading to a drop in surface elevation.

Q5: L79-81: I would reserve stating findings until the discussion/conclusion.

A5: After revising the Introduction, we agree that this belongs in the Conclusions and have removed this sentence.

Q6: L92: I am not familiar with what an ATV is. Please define.

A6: We have now included the definition of ATV, all-terrain vehicle.

L105–106 An all-terrain vehicle (ATV) track runs over the northeastern part of the palsa,

Q7: L116: Please define HOBO weather station.

A7: HOBO is a datalogger brand by Onset Computer Corporation. Their weather stations are widely used for environmental monitoring. In order to clarify this, we have changed the text.

L130–132: In September 2022, a HOBO® U30-NRC (Onset Computer Corporation) weather station was set up in the nearby settlement of Saarikoski, ca. 1.5 km from the study site (see Fig. 1b for location of the two weather stations).

Q8: L152: change ‘m2’ to ‘m^2’

A8: We thank the reviewer for pointing out this mistake and have fixed it.

L171–172: Similarly, flights over the Dome palsa yielded a slightly larger coverage area of 53993 m^2 compared to the Ridge palsa,

Q9: L206: “palsas palsa” repeated twice in caption

A9: Thank you again for finding this language mistake. We also took the opportunity to fix the incorrect naming of fig. 5c and d from ‘DTM’ to ‘difference map’. We have adjusted the caption.

L238–242: Figure 5. DTMs of the Dome (a,b) and Ridge (d,e) palsas on UAV LiDAR scans in September 2022 and September 2023. The black lines represent the extent of the palsas, based on orthomosaics from the same day as the UAV LiDAR surveys. The difference maps (c,f) show the topographical changes over one year, with the palsa extent from the September 2022 flights in black The dashed box in (c) shows the ‘degradation hotspot’ on the Dome palsa.

Q10: L212: two full stops here – please remove one.

A10: We have removed the second stop.

L270–272: The snow thickness is up to ca. 2.0 m at the eastern margin of both palsas and 1.0 to 1.5 m in the depressions, while the crests remain snow-free (also see Fig. 1d).

Q11: L228: could you clarify what you mean by “deepening” here? I presume this is referring to snow depth?

A11: The ‘deepening’ here refers to the subsidence that occurred in the all-terrain vehicle (ATV) track. This was the only part in the text that the term ‘deepening’ was used and we replaced it by ‘subsidence’ in order to be consistent.

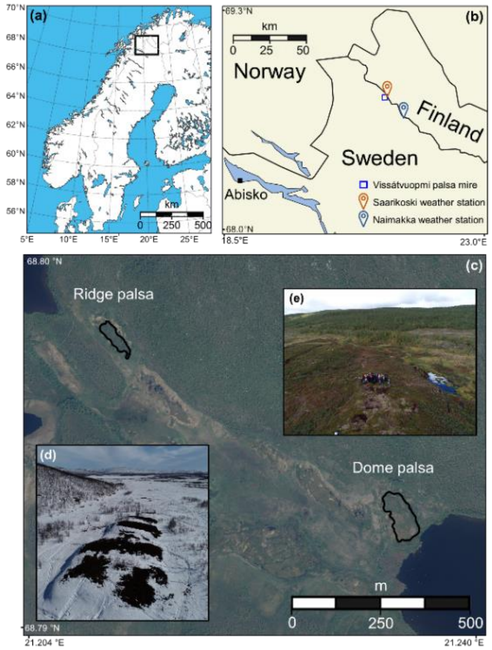
L267–269: The ATV track that crosses the Dome palsa shows a subsidence of 0.2–0.3 m just over the time period in this study (at ca. 27–29 m in Fig. 7e).

Q12: L276-277: Glad to see that you have taken this into account – I would be intrigued to find out more about how you corrected for this effect? Elevational changes in the mire could be partially independent of the palsa elevational changes because 'mire breathing' may reflect water table level change (if water table rises above ground level) rather than ground surface level change at some points during the seasonal cycle. I am not sure if this is the case at the sites you have investigated. In any case, some site context may be useful here to establish whether water tables typically rise above mire surface level here and how you would have corrected for this. If so, it's possible this could have further implications for lateral erosion rates? You may prefer to address this in the methods.

A12: We thank the reviewer for pointing out that the Method section was missing details on this part. These two palsas are close to a mountain and surrounded by mostly dry, walkable terrain and water tables typically do not rise above the mire surface in most of the surroundings of the two studied palsas, except for thermokarst lakes (or ponds) that border the palsa. To clarify this, we have first made adjustments in the Study site chapter:

L99–101: Water tables typically do not rise above the mire surface in most of the surroundings of the two studied palsas, except for thermokarst ponds that border the palsas

Additionally, we made the orthophoto of the site (Fig. 1c) clearer, by moving the site photos (Figs. 1d and 1e):



The polygons around the palsas that we used to transform the elevation to height are carefully drawn on the areas that were dry at the moment of all the flights and thus no open water is included. That means that changes in the water table, where above the ground surface, are not interfering with the normalization calculation. An important note to make is that the definition of a palsa is morphological and thus per definition the height above the surroundings is the height of the palsa.

The Methods chapter is now changed as follows:

L218–226 For each DTM, the mean elevation of the palsa's surrounding was computed and subtracted from the DTM, which normalizes the elevation of the palsa into the height above the surroundings. Since the definition of palsas is morphological (Harris et al., 1988), the height above its surroundings is per definition the height of the palsa. For the normalization, we used the previously mentioned orthophotos to create a polygon around each palsa, for which the mean elevation was taken per LiDAR flight. Areas containing open water at any of the time steps, either thermokarst lakes directly around the palsas or other ponds, were not included in these polygons. The transformation from elevation to height, simplifies the comparison between the data from the different flights.

The final point made by the reviewer regards whether the water that surrounds the palsas has further implications for lateral erosion rates. There is indeed consensus that this is the case. E.g. Martin et al. (2021) and Sjöberg et al. (2016) describe the importance of lateral water and associated heat fluxes for permafrost degradation. From our frequent field visits, we know that the Ridge palsa is surrounded by relatively larger and deeper thermokarst ponds compared to the Dome palsa, which affects water and heat fluxes into the palsa. By comparing the lateral extent from our study to that in in Olvmo et al. (2020), we find a higher annual decay rate in the Dome palsa between 2016 and 2023 (while they found the opposite for the period 2010–2016). However, this difference can be entirely explained by the degradation hotspot on the Dome palsa, for which the initiation is not fully known. To find a more direct effect of the water bodies on the lateral erosion rates, we need to conduct geophysical investigations of the interior of the palsas and their surroundings.

These points are now also discussed in the main text, also as part of Q2 in this response, where we aim to contextualize our findings with data from previous studies in the region.

L387–398: Olvmo et al. (2020) found an average annual decay rate (loss of palsa area) of -0.74 $\%a^{-1}$ and -2.45 $\%a^{-1}$ for the Dome and Ridge palsas respectively, for the period 2010–2016. Using the palsa area from Olvmo et al. (2020) in 2016 and the extent in 2023 from our study, we can calculate a new annual decay rate. For the period 2016–2023, we found respective rates of -3.27 $\%a^{-1}$ and -1.55 $\%a^{-1}$. The -2.53 $\%a^{-1}$ change in decay rate on the Dome palsa can be largely explained by the degradation hotspot, which covered ca. 2.6% of the total palsa area. The slight decrease in annual decay rate on the Ridge palsa could be explained by a stabilization of degraded areas. When excluding the degradation hotspot on the Dome palsa, the Ridge palsa lost a larger percentage of its extent, similar to Olvmo et al. (2020). Again, lateral water fluxes greatly affect ground temperatures and permafrost degradation (Martin et al., 2021; Sjöberg et al., 2016; Walvoord & Kurylyk, 2016). Therefore, smaller palsas are relatively more susceptible to lateral erosion through heat and water fluxes, provided by surrounding thermokarst ponds, compared to larger palsas (e.g. Borge et al., 2017).

L355–359: The Ridge palsa is surrounded by relatively larger and deeper thermokarst ponds, which could enhance vertical subsidence more centrally in the palsas as a result of increased heat transfer to the palsa core. To find out if the higher subsidence on this palsa is a robust signal and what processes are responsible for this, continued annual LiDAR surveys and observations of the palsa's interior via geophysical imaging are needed.

Q13: L279: replace "been" with "used".

A13: We agree with the language suggestion and have changed the sentence accordingly.

L328–329: While other studies have applied multitemporal LiDAR for detecting permafrost dynamics, they have used terrestrial LiDAR scanning

Q14: L289-307: you could also consider higher winter precipitation rates contributing to greater thaw over the following summer season, especially with warmer winter temperatures so that rain falls instead of snow. This could compromise snow depth over the winter and therefore increase the length of the following thaw period. It's possible that this can be seen from the weather station data in Figure 2, where it looks like there is lower average snow depth and greater winter precipitation rates in the winter season 2022/2023.

A14: We appreciate the effort of the reviewer to explain the findings of our study, especially regarding the 'degradation hotspot' in the nw part of the Dome palsa. The suggestion of higher winter precipitation rates (and a longer thawing season) playing a part in initiating this degradation, is valuable. We therefore included the following text:

L373–377: Additionally, the precipitation in this winter was greater than the previous winter, which may have caused additional warming of the ground, either via a thicker snowpack (T. Zhang, 2005) or latent heat brought by rainfall (Putkonen & Roe, 2003). This falls in line with Olvmo et al. (2020), who conclude that increased winter precipitation is one of the main causes of rapid palsa degradation in the study region.

It is important to note that the snow depth is recorded at ca. 1.5 km from the palsas, where local topography affects the snow distribution in a different way than directly on the palsa surface. Hence the slightly differing snow depth between the different winters may not reflect the snow depth on the palsas. Also, a thicker snowpack is generally related to increased ground temperatures and active layer thickness due to the insulating effect of snow. The increased precipitation (both as rain and snow), as suggested by the reviewer, could thus contribute to a warmer soil.

Q15: L319: two commas, remove one.

A15: We have removed the second comma.

L407: In this study, GCPs were not used, however,

Q16: L366: insert “of” between “degradation palsas”

A16: We thank the reviewer for this final language suggestion and have adjust the text.

L458–460: This substantial permafrost degradation occurred between September 2022 and April 2023 which suggests that the degradation of palsas is not limited to the summer months.

Additional references

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