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Dear Editor-
Thank you for providing these constructive Reviewer comments to our manuscript titled "Comparing thaw probing, electrical resistivity tomography, and airborne lidar to quantify lateral and vertical thaw in rapidly degrading boreal permafrost."

We have provided a tracked change and a clean version of revised manuscripts to Copernicus web site and here we provide detailed information on how we addressed each comment. Original comments are in black, our responses are in blue text, and new/updated contents are provided as red text in quotation marks.

Di Wang
RC1: 'Comment on egusphere-2024-3997', Di Wang, 31 Mar 2025
This is interesting and timely work. Some comments:

1. The description of permafrost degradation is quite general, please provide some data (temperature increasing rate, extreme climate event frequency and severity) to support it.

We are not clear where the Reviewer suggests adding this information but we have edited the first paragraph of the Introduction and provided a new figure in SI (Figure 1) of climatology of air temperature, precipitation and snow since 1900 for our study area to support this:
"Permafrost is warming and degrading across earth's high latitudes. In interior Alaska this includes top-down thaw of near-surface permafrost (Douglas et al., 2021), increased permafrost temperatures and the formation of unthawed zones (taliks; Farquharson et al., 2022), and lateral expansion of thawed areas (Jorgenson et al., 2020). Mean annual air temperatures in the region have increased ~3C since the 1970s (Douglas et al., 2025) and summers are getting wetter (Jorgenson et al., 2020). The ongoing permafrost degradation affects hydrology (Marshall et al., 2021), ecological processes (Foster et al., 2019; Mekonnen et al., 2019), the carbon cycle (Douglas et al., 2014) and infrastructure (Hjort et al., 2022). With warming projected to accelerate over coming decades the spatial extent of permafrost thaw is expected to increase (Wolken et al., 2011)."

2. The literature review is more like a background description. Please explicitly highlight the novelty and necessity of combining thaw probing, ERT, and airborne lidar.

To address this, we have added the following to the end of the third paragraph of the Introduction. We also have detailed discussion of the pros and cons of each method and the effectiveness of a combined application of these three methods in the Discussion section 4.1:
"Combining ground-based geophysical measurements with airborne remote sensing observations provides an effective means for quantifying three-dimensional permafrost thaw (Minsley et al., 2015; Uhlemann et al., 2021). These typically include site-based

surface measurements of the depth of maximum summer season thaw (active layer) and cores of permafrost to quantify ice content."

3. It is not clear why these three technologies were selected. Please revise it.

We have added this sentence to the last paragraph in the Introduction:

"We focus on thaw probing, ERT, and airborne LiDAR methods because they are among the widest applied techniques to measure permafrost degradation."

4. The data collection periods are different among these three technologies. How do you compare them properly?

As we state in this revised version of the manuscript, we do not specifically apply the three methods to the same measurements/applications as they have their unique pros and cons. We have clarified some of the survey information to address this comment and some others. Specifically, in Section 2.2. Data collection, processing, and analysis. In 2.2.1 Field sampling design and measurements we have added this paragraph about topographic surveys:

"Topographic surveys of ground- and water-surface elevations usually were made using an auto-level and stadia rod at 1-m intervals along the four permanently marked transects. We estimate measurement accuracy to be within 3 cm for firm ground and within 10 cm for soft floating mats in bogs and fens. A survey-grade, differential global position system (DGPS) was used in 2012 at TF10 and in 2013 at TF01, TF10, and TF50 to determine ground elevations using a 15-second observation time at each 1-m interval. The data were post-processed using data from a base station in Fairbanks. We estimate the accuracy to be mostly with 10 cm in open areas and 30 cm in forested areas. For auto-level surveying, elevations were calculated relative to permanent benchmarks, where the elevations were determined through repeated measurements."

And, further down:

"Accuracy of the field probing depends on soil materials, unfrozen-water content in partially thawed soils, and depth. As the soils within the top 3 m were mostly peat and silt, shallow (<1 m) probing typically hit a hard refusal boundary (indicating frozen conditions) for stable permafrost; for these conditions we consider the accuracy to within 3 cm (given a "soft" mossy and litter-rich ground surface). Occasionally, in partially degrading permafrost near the surface (within 1.5 m) the probe encountered frozen ground with substantial unfrozen water content with refusal gradually becoming harder across a ~20 cm transition zone; we consider the accuracy under these conditions to be with 20 cm. Deep (2 to 5 m) probing is more problematic as friction along the entire probe increases: for these conditions we believe we can reliably detect a frozen boundary within 2 m, but by 5 m the friction/stickiness is such that probing becomes unreliable. At these depths, we are confident in the determination of unfrozen conditions, but have only low to moderate confidence assigning a refusal to be the result of frozen conditions. For these situations we repeatedly raise and thrust the probe downward and used our best judgement to assign frozen/unfrozen status. Differentiating persistent seasonal frost from very thin permafrost also is a challenge. Here we are confident that frost <30 cm thick at the end of summer is seasonal frost and frost >50 cm thick is permafrost; for in between thicknesses we have low confidence as to whether it is seasonal or permanent frost. In some areas we noted a thin frost layer (30 to 50 cm) to persist for 2 to 3 seasons, and we refer to this as multi-year frost. This multi-year frost is a common problem for probing ecosystem-driven permafrost in the boreal region."

And to start the next paragraph:
"We differentiated three quasi-stable permafrost conditions and four degradation stages using a system modified from Jorgenson (2021) to address the complicated nature of permafrost formation and degradation in boreal ecosystem-driven permafrost (Supplemental Information Table 1; Supplemental Information Fig. 5)"

And this reference has been added:
Jorgenson, M. T. (2021). Thermokarst. In J. Schroeder (Ed.), Treatise on Geomorphology, 2nd Edition (Vol. Vol. 4 Cryospheric Geomorphology, pp. 1-22). Amsterdam, The Netherlands Elsevier. https://doi.org/10.1016/B978-0-12-818234-5.00058-4.

5. Line 490: The limitations of each technology were discussed in detail; excellent work. However, the application of emerging ML is vague.

To address this we have added the following sentence at the end of 4. Discussion and Conclusions:
"Of particular interest are ways to combine these techniques with multiple airborne and spaceborne remote sensing products to identify relationships of key ground state variables that control permafrost stability like the depth of the snowpack, surface soil moisture, soil strength, surface water ponding, and seasonal subsidence."

6. Conclusion: Among these technologies mentioned, what is the most promising one?

This is a good comment. To address it we have added this to the abstract:
"No single method provides all the information typically needed to adequately assess permafrost undergoing change. For example, frost probing yields insight into top-down thaw, LiDAR allows the identification of vertical and lateral subsidence, and ERT can identify the presence/absence of permafrost at 10s of meters depth."
We also added relevant text in Section 4.1 when we discussed the pros and cons of each method.

And in the Conclusions, 4.2 Degradation and Aggradation Stages we have inserted this paragraph (with an addition sentence added below based on a comment by this Reviewer.
"No single method provides all the information typically needed to adequately assess permafrost undergoing degradation or aggradation. For example, frost probing yields insight into top-down thaw or indicate areas where near-surface permafrost is aggrading upward but with limited spot measurements. LiDAR allows the identification of vertical and lateral subsidence upon thaw or heave associated with aggradation at a relatively larger spatial coverage but is limited to surface measurements. ERT can identify the presence/absence of permafrost at 10s of meters depth but is not as well suited for survey-level measurements of permafrost bodies whether they are stable or changing.

A combined use of three methods is more effective to characterize permafrost degradation at multiple dimensions than the application of each individual method. Though our study focused on sites in Interior Alaska the methods we applied here can be used to survey and track changes in other permafrost terrains."

7. The findings were based on the condition in Alaska. If such knowledge is being transferred to other cold regions, what is the most important issue for localization?

This is a good comment. To address this, we have added:

In 4. Discussion at the end of the first paragraph we have edited/added:

"Permafrost in Interior Alaska has been slowly thawing for the past ~500 years with sporadic periods of accelerated thaw typically attributed to wildfire and subsequent permafrost stabilization or aggradation associated with forest succession (Jorgenson et al. 2001; Jones et al., 2013). Air temperature increases since the 1970s in Interior Alaska (Osterkamp, 2005) and across the Arctic (Smith et al., 2022) have lead to increased permafrost temperatures and widespread thaw. Numerous recent studies in Interior Alaska show an acceleration of permafrost degradation with deeper seasonal thaw depths (Douglas et al., 2020; Euskirchen et al., 2024), widespread talik expansion (Farquharson et al., 2022), and an increased thermokarst development (Douglas et al., 2021; Minsley et al., 2022; Brodylo et al., 2024). Studies from sites across the Arctic show increasing soil temperatures (Chen et al., 2022) and subsidence due to permafrost degradation (Streletskiy et al., 2024)."

These references have been added:

Chen X, Jeong S, Park CE, Park H, Joo J, Chang D, Yun J. Different responses of surface freeze and thaw phenology changes to warming among Arctic permafrost types. Remote Sensing of Environment. 2022 Apr 1;272:112956.

Smith SL, O'Neill HB, Isaksen K, Noetzli J, Romanovsky VE. The changing thermal state of permafrost. Nature Reviews Earth & Environment. 2022 Jan;3(1):10-23.

Streletskiy DA, Maslakov A, Grosse G, Shiklomanov N, Farquharson LM, Zwieback S, Iwahana G, Bartsch A, Liu L, Strozzi T, Lee H. Thawing permafrost is subsiding in the Northern Hemisphere-review and perspectives. Environmental Research Letters. 2024 Dec 24.

In 4.1 Relative strengths and weaknesses of different permafrost degradation measurements:

"Though our study focused on sites in Interior Alaska the methods we applied here can be used to survey and track changes in other permafrost terrains."

In the last paragraph of the Conclusions, we have added:

"Given the positive and negative aspects of ground surface surveys, airborne LiDAR, and geophysical investigations a coupled application of these methods is warranted to track permafrost thaw at similar locations or other permafrost regions."