RC1: 'Comment on egusphere-2025-3236', Anonymous Referee #1, 25 Aug 2025

Comment 1.0

Du et al. have submitted an interesting paper that investigates the spatial heterogeneity of the active layer thickness for a region on the North Slope of Alaska. The study combines field sampling, remotely sensed imagery and modelling. The analysis considers the relative influence of various climate and environmental factors on active layer conditions at different spatial resolutions. The study has potential to contribute to improved prediction of active layer thickness in a warming climate. However, I do have some concerns and comments that should be addressed for the manuscript to be acceptable for publication.

Response 1.0

Thanks for the careful review and insights into the study! We revised our manuscript accordingly. Please check our point-by-point responses below. All revisions were marked in blue.

Comment 1.1

Several previous studies have considered the relative influence of environmental factors on the ground thermal regime through analysis of field data collected across environmental gradients and some of the conclusions in the manuscript are not new. Recent papers, including those by some of the coauthors of the submitted manuscript have also considered quantification of active layer at multiple scales in Alaska (e.g. Brodylo et al. 2024). A better description of the novelty and advancement in knowledge of the submitted manuscript compared to earlier studies would be beneficial.

Response 1.1

As the reviewer pointed out, recent studies have focused on resolving multi-resolution ALT patterns and their environmental linkages using multi-sensor remote sensing (Brodylo et al., 2024; Hantson et al., 2025). Compared with the existing studies, our study differs in three respects, which include (a) advancing from transect-based (1-dimensional) sampling to intensive 2-dimensional grid-cell sampling, which provided a more comprehensive representation of spatial variability to support multi-resolution analysis; (b) characterizing ALT patterns in the unique Arctic-foothills tundra environment, thereby complementing existing studies for Interior Alaska (Brodylo et al. 2024) and the Seward Peninsula (Hantson et al. 2025); and (c) quantifying resolution-dependent uncertainties in ALT retrievals, offering additional support for improved interpretation of multi-resolution ALT products derived from remote sensing and process-based simulations for the changing Arctic.

In the revision, we added the following in the Discussion section.

"Recent studies have focused on resolving multi-resolution ALT patterns and their environmental linkages using multi-sensor remote sensing (Brodylo et al., 2024; Hantson et al., 2025). Compared with the existing studies, our study differs in three respects, which include (a) advancing from transect-based (1-dimensional) sampling to intensive 2-dimensional grid-cell sampling, which provided a more comprehensive representation of spatial variability to support multi-resolution analysis; (b) characterizing ALT patterns in the unique Arctic-foothills tundra environment, thereby complementing existing studies for Interior Alaska (Brodylo et al. 2024) and the Seward Peninsula (Hantson et al. 2025); and (c) quantifying resolution-dependent uncertainties in ALT retrievals, offering additional support for improved interpretation of multi-resolution ALT products derived from remote sensing and process-based simulations for the changing Arctic".

Comment 1.2

The manuscript would benefit from a better description of the study plots and the broader region considered, such as information on surficial materials, vegetation and topography. Since the focus of the paper is spatial heterogeneity, it would be useful for the reader to have information on the spatial heterogeneity of the factors that are considered in the analysis within the study plots and in the broader area considered.

Response 1.2

As suggested, we revised the Study Region section to include a general description of the surrounding region, and more detailed information for the study plots. The revisions are also presented below.

"Our study focused on the Imnavait Creek (68.6167° N, 149.3167° W) area within the Alaskan North Slope tundra foothills region (Fig. 1). The study region experiences a cold climate with a mean annual temperature of -7.4°C, ranging from an average of -17°C in January to 9.4°C in July (Schramm et al., 2007). Annual precipitation averages 340 mm, two-thirds of which falls as light rainfall during the summer (Schramm et al., 2007). The dominant vegetation consists of water-tolerant plants like tussock sedges and mosses, grasses and low shrubs (Schramm et al., 2007). Vegetation and soil patterns vary with slope, aspect, and drainage conditions, exhibiting a patchy distribution across the study domain (Hinkel and Nelson, 2003). The region is also characterized by diverse glacial landforms, including deposits, stream networks, and bedrock outcrops (Hinkel and Nelson, 2003). The region has gently rolling terrain, with elevations ranging from ~750 m to 980 m. Vegetation and soil patterns vary with slope, aspect, and drainage conditions, exhibiting a patchy distribution across the study domain (Hinkel and Nelson, 2003). The region is also characterized by diverse glacial landforms, including deposits, stream networks, and bedrock outcrops (Hinkel and Nelson, 2003). Increasing ALT was observed from both in-situ measurements at the Circumpolar Active Layer Monitoring (CALM) sites (https://www2.gwu.edu/~calm/data/north.htm) and regional ALT records (Liu et al., 2024).

The local study area consisted of four intensively sampled field plots (Plot 3, Plot 4, Plot 5, and Plot 6 in Fig. 1; 90m ×90m each) distributed across an elevation gradient along west facing hill slopes, and surrounded by a larger (5 km by 5 km) landscape domain used for analyzing ALT across different resolutions (Fig.1; Table 1). The field plots are dominated by tussock-forming sedges and moss-lichen mats, along with scattered dwarf birch shrubs, and riparian grasses (Fig. 1-2). The common species identified near the ALT sampling points include dwarf birch (*Betula nana*), alpine blueberry (*Vaccinium uliginosum*), black bearberry (*Arctous* spp.), crowberry (*Empetrum nigrum*), and *Arctostaphylos uva-ursi*, among other less-recognizable species. Our soil coring samples indicated high organic matter content of the topsoil (0-10 cm depth) for Plots 3, 4 and 5, with the respective values of 77.3%, 75.1%, and 71.8%, contrasting with a relatively low value of 45.5% for Plot 6.

Plot 3 and Plot 4 are located on west-facing downhill slopes characterized by gradual elevation changes (10-15 m across the plot), small water tracks, and scattered glacial erratics. Plot 3 is crossed by multiple drainage features that are transverse to the Kuparuk River (Fig. 1). These features are evident in the topography as well as the vegetation, with alternating bands of dwarf willow, grasses, and tussocks. Standing water is present in many places, as are glacial erratics, particularly along the drainage channels. Plot 4 is more homogeneous in vegetation character and height, consisting mostly of grass tussocks and moss, with some larger glacial erratics present.

Plots 5 and 6 are on the east side of the access road and are more level than Plots 3 and 4. Plot 5 is located at a valley bottom and is partitioned by Imnavait Creek, which winds directly through the middle of the plot. Shallow drainage channels transverse to Imnavait Creek are found on the west side of the plot, while the east side is upland and drier. Vegetation cover in Plot 5 follows the typical mix of grasses, mosses, and sedges, with some moss forming humps about 20 cm tall, while shrub density and height increase close to the creek. Along Imnavait Creek there are taller (0.5-1.0 m) birch shrubs and more grasses. Plot 6 is characterized by widespread subsurface rocks (Fig. 1) and overall short-statured grass-sedge tussocks and mosses, lichens, small bunchgrasses, *Arctous spp*., and alpine blueberry, interrupted by areas of bare rock and gravel. Bare areas are common in the center of the plot."

Table 1. Summary of surface and soil conditions for the sampling plots

Name	Plot 3	Plot 4	Plot 5	Plot 6
Elevation	810 m	846 m	855 m	875 m
vegetation	dwarf willow, grasses, and tussocks	grass tussocks and moss	mix of grasses, mosses, and sedges	grass tussocks and mosses
Organic matter content	77.3%	75.1%	71.8%	45.5%
Unique characteristics	ephemeral, drainage features	homogeneous in vegetation character and height	located in a valley bottom and partitioned by Imnavait Creek	widespread subsurface rocks
ALT	49 cm	39 cm	44 cm	58 cm

Comment 1.3

An improved presentation of results would be beneficial especially for comparison of ALT from field measurements and the modelled results. It is difficult for example, for the reader to compare the measured values to the ML outputs in figure 4 as the study plot area isn't clear. The text refers to ALT variability near water bodies, but the results presented (i.e. maps) do not allow the reader to see this. Consideration of the accuracy of the models in terms of the entire area covered is fine but it is useful to consider which areas of the study area and under what conditions the accuracy is better. (see below for additional comments)

Response 1.3

Thanks for pointing out the issues. We addressed each issue as follows:

To address the comment "It is difficult for example, for the reader to compare the measured values to the ML outputs in figure 4 as the study plot area isn't clear", Figure 4 was re-plotted to improve presentation and comparison, and ensure ALT measurements and ML predictions were mapped over the same overlapping areas for each study plot. The updated Figure 4 is also presented below.

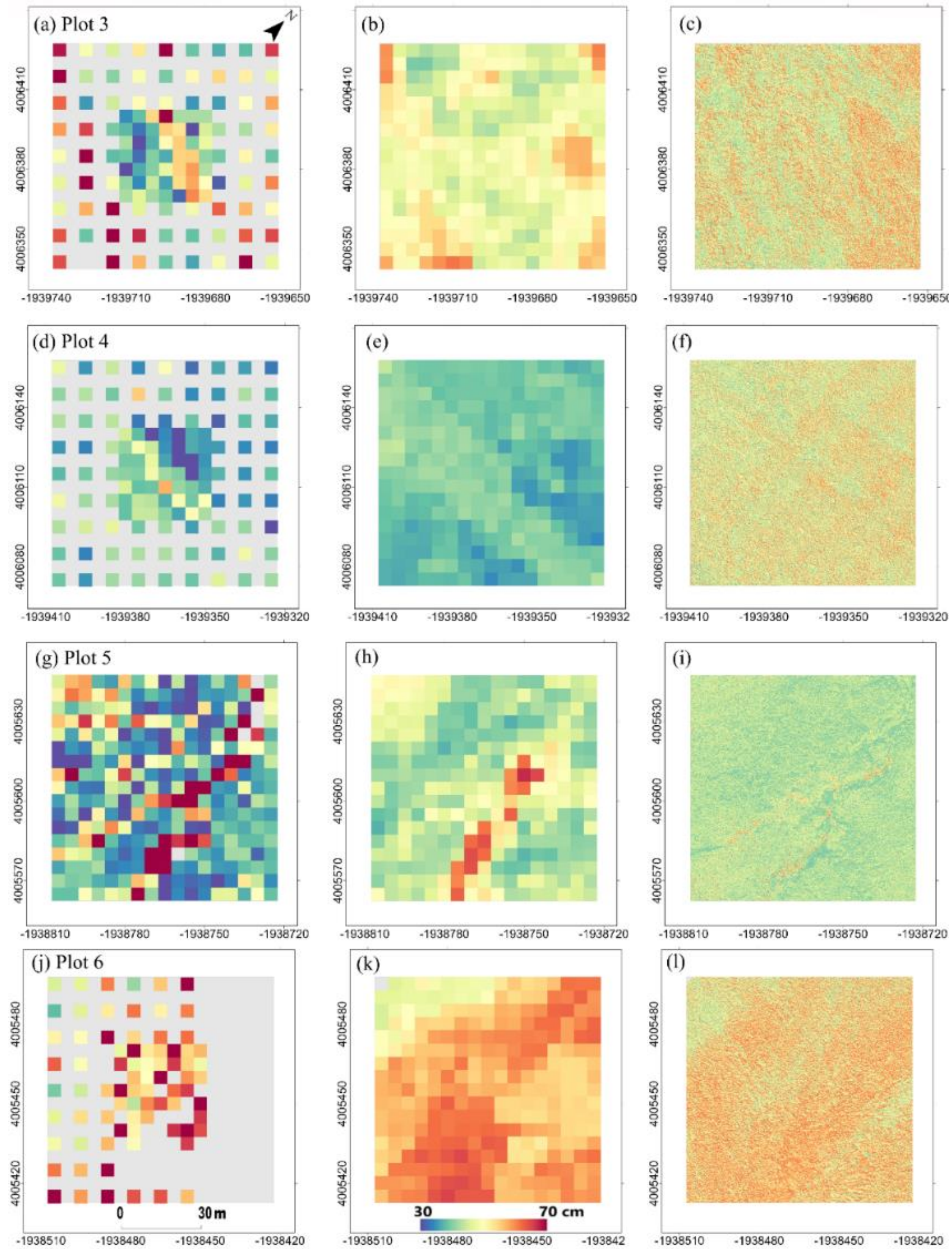

Figure 4: Comparisons of ALT spatial patterns derived from field measurements (a, d, g, j), 5-m machine learning outputs (b, e, h, k), and 0.1-m machine learning estimates (c, f, i, l) for the intensively sampled plots (grey shading indicates areas without sampling). The map was plotted using Canada Albers Equal Area Conic projection.

To address the comment “The text refers to ALT variability near water bodies, but the results presented (i.e. maps) do not allow the reader to see this”, we re-plotted Figure 4 (please refer to the figure above) for improved presentation and added the following in Section 4.1.1 to specify (a) the areas with substantial ALT variations near water bodies and (b) the differences of the ML-results in different resolutions:

“Specifically, higher ALT values are visible along Imnavait Creek within Plot 5, as shown by the red pixels in the field measurements (Fig. 4g), 5-m ML predictions (Fig. 4h), and 0.1-m ML results (Fig. 4i). However, field sampling revealed substantial ALT variation within individual 5-m grid cells, with a standard deviation of up to 32 cm as distance from the watercourse increases. These meter- to sub-meter variations are only resolved in the 0.1-m results (Fig. 4i), which distinguish the high ALT values along the creek (red pixels) from the lower values in adjacent areas (blue pixels). Similarly, the stripe patterns of ALT in Plot 4 associated with alternating bands of dwarf willow, grasses, and tussocks (Fig. 1; Section 2) are clearly defined in the 0.1-m predictions (Fig. 4c) but are not discernible in the 5-m results (Fig. 4b). For Plot 6 where overall high ALT is observed (Fig.4 j, 4k, and 4i), heterogeneity is only captured by the 0.1-m results (Fig. 4l). The pattern of interspersed lower-ALT (non-red) pixels within high ALT areas (Fig. 4l) is likely associated with widespread clusters of underlying rocks and complex vegetation cover observed in the field (Fig. 1; Section 2)”.

To address the comment “Consideration of the accuracy of the models in terms of the entire area covered is fine but it is useful to consider which areas of the study area and under what conditions the accuracy is better”, we added the following in Section 4.1.1 for clarifying the model performance and uncertainties.

“Considering the larger ALT variability and more diversified surface conditions at 0.1-m resolution relative to the 5-m resolution, the RF model trained using limited 5-m data set may not be able to fully capture the 0.1-m ALT variations, leading to inconsistency of the overall ALT patterns between the 5-m and 0.1-m results (e.g., Plot 4; Fig. 4d, 4e, 4f) and additional uncertainties in the multi-resolution analysis. In addition, the RF predictions tended to be centralized, which may underestimate larger ALT values (e.g., fewer dark red pixels with ALT higher than 65 cm in Fig. 4h and 4i than the measurements in Fig. 4g) and overestimate smaller ones relative to the measurements (e.g., dark blue pixels with measured ALT smaller than 35 cm in Fig. 4g but not in the ML predictions in Fig. 4h and 4i)”.

Comment 1.4

In the discussion and conclusions, general statements are made but it is unclear how the results and analysis support these statements. There needs to be a clearer link between results and conclusions.

Response 1.4

Thanks for the comment. We revised Section 5.1 to provide more in-depth analysis for interpreting our ALT observations and model analysis. The revisions are presented below.

"Consistent with previous studies, our field observations and RF estimates (section 4.1.1) confirmed that greater ALT is most common in areas with standing water or adjacent to creeks (e.g., Plot 5; Fig. 4g, 4h, 4i), where wet conditions enhance soil thermal conductivity in foothills tundra (Grant et al., 2017; Clayton et al., 2021) despite increased latent heat required for thawing. Relatively larger ALT was also found in the vicinity of subsurface rocks (e.g., within 1-m distance) (e.g., Plot 6; Fig. 5j, 5k, 5l), whose high thermal conductivities facilitate heat propagation and summer thawing (Bonnaventure et al., 2013). Relatively lower ALT was recorded under shrubs, which likely cool the ground in summer through canopy shading (Lawrence and Swenson, 2011) and in winter through the thermal bridging effect (Domine et al., 2022). However, shrubs can also have a counteracting influence on ALT by promoting snow accumulation; whereby, the deeper snow layer insulates the ground, leading to warmer winter soil temperatures (e.g., Palmer et al., 2012; Morse et al., 2012; Kropp et al., 2020) which can result in a deeper active layer when this winter warming effect outweighs the summer shading effect of the shrubs (Way and Lapalme, 2021). A thick moss layer may also slow active layer thaw through its insulating capacity (Schuuring et al., 2024), though no specific descriptions of the moss layer were made in our sampling.

In the Imnavait Creek area, the thickness of the organic layer increases from hill crests to foot slopes. The thicker organic layer provides enhanced thermal insulation, leading to a shallower active layer downhill (Walker and Walker, 1996). Accordingly, Plots 3 and 4 on west-facing downhill slopes and Plot 5 in the valley bottom exhibited overall high soil organic matter content (~75%) and relatively low ALT (~44 cm). In contrast, the higher-elevation Plot 6 had lower organic matter (~46%) and a higher ALT (~58 cm). Besides terrain-controlled organic matter distribution, topography also affects ALT through its impacts on runoff and drainage, soil temperature, snow properties, and vegetation types (Walker and Walker, 1996, Li et al., 2017). Accordingly, topography information including slope (17.40%) and aspect (13.44%) are among the most important factors shaping ALT variations in the ML- and drone-based analysis, while surface features including vegetation, water bodies, and soil properties determined from the multi-spectral reflectance and optical-NIR indices, all showed important contributions to the 5-m ALT predictions over the sampling plots (7.24% to 14.05%; section 4.1.1).

It is noted that additional radar (L-band 1.26 GHz) observations from UAVSAR helped to enhance the performance of the first RF model (e.g., R increased from 0.78 to 0.81), but were not used in the subsequent scaling analysis (section 3.1.2). For the features selected for radar-based ALT predictions, red-edge reflectance (16.67%), HV-polarized radar backscatter (16.04%), aspect (15.33%), and HH-polarized radar backscatter (15.04%) contributed most to the predictions, while the red band (13.34%), slope (11.99%), and green band (11.57%) observations were relatively less important. The sensitivity of radar backscatter to vegetation biomass, surface water bodies, and soil wetness likely enhanced the ALT estimation.

For the ML- and satellite-based analysis, terrain factors (elevation, slope, and aspect) collectively dominate the ALT predictions (64.89% contribution) at 10-m resolution. The broad ALT patterns over the surrounding region (Fig. 5a) largely align with terrain-driven variability (section 4.1.2), as also observed in a previous study (Hinkel and Nelson, 2003). In general, south-facing slopes in the Northern Hemisphere receive more solar radiation than north-facing slopes, leading to warmer soil and larger ALT. However, the study region is characterized by gentle terrain slopes and west facing aspects (Fig. 5). Besides the terrain-controlled organic matter distribution observed over the Imnavait Creek area, direct solar radiation loading is higher around the hill tops and lower in downslope areas (Hinkel and Nelson, 2003), thus promoting larger ALT conditions in the uplands (Fig. 5). Topography therefore exerts a direct influence on the general thaw pattern as shown in the regional ML analysis".

Added references:

Walker, D. A. and Walker, M. D.: Terrain and vegetation of the Imnavait Creek watershed, Landscape function and disturbance in Arctic Tundra, pp. 73-108, Berlin, Heidelberg: Springer Berlin Heidelberg, 1996.

Li, A., Tan, X., Wu, W., Liu, H. and Zhu, J.: Predicting active-layer soil thickness using topographic variables at a small watershed scale, Plos one, 12(9), p.e0183742, 2017.

Comment 1.5

The organization of some sections of the manuscript could be improved including Section 2 and 4.1 – see further comments below. Tables could also be considered for summarizing ALT conditions for study plots etc.

Response 1.5

As suggested, Section 2 was revised for improving the structure, and providing a general description for the study region and more details for the sampling plot conditions. Table 1 summarizing the plot surface and ALT conditions was also added.

The updated Section 2 is also presented below.

"Our study focused on the Imnavait Creek (68.6167° N, 149.3167° W) area within the Alaskan North Slope tundra foothills region (Fig. 1). The study region experiences a cold climate with a mean annual temperature of -7.4°C, ranging from an average of -17°C in January to 9.4°C in July (Schramm et al., 2007). Annual precipitation averages 340 mm, two-thirds of which falls as light rainfall during the summer (Schramm et al., 2007). The dominant vegetation consists of water-tolerant plants like tussock sedges and mosses, grasses and low shrubs (Schramm et al., 2007). Vegetation and soil patterns vary with slope, aspect, and drainage conditions, exhibiting a patchy distribution across the study domain (Hinkel and Nelson, 2003). The region is also characterized by diverse glacial landforms, including deposits, stream networks, and bedrock outcrops (Hinkel and Nelson, 2003). The region has gently rolling terrain, with elevations ranging from ~750 m to 980 m. Vegetation and soil patterns vary with slope, aspect, and drainage conditions, exhibiting a patchy distribution across the study domain (Hinkel and Nelson, 2003). The region is also characterized by diverse glacial landforms, including deposits, stream networks, and bedrock outcrops (Hinkel and Nelson, 2003). Increasing ALT was observed from both in-situ measurements at the Circumpolar Active Layer Monitoring (CALM) sites (https://www2.gwu.edu/~calm/data/north.htm) and regional ALT records at 1-km resolution, which were generated using machine learning by combining in situ ALT observations with a suite of observational biophysical variables (Liu et al., 2024).

The local study area consisted of four intensively sampled field plots (Plot 3, Plot 4, Plot 5, and Plot 6 in Fig. 1; 90m ×90m each) distributed across an elevation gradient along west facing hill slopes, and surrounded by a larger (5 km by 5 km) landscape domain used for analyzing ALT across different resolutions (Fig.1; Table 1). The field plots are dominated by tussock-forming sedges and moss-lichen mats, along with scattered dwarf birch shrubs, and riparian grasses (Fig. 1-2). The common species identified near the ALT sampling points include dwarf birch (Betula nana), alpine blueberry (Vaccinium uliginosum), black bearberry (Arctous spp.), crowberry (Empetrum nigrum), and Arctostaphylos uva-ursi, among other less-recognizable species. Our soil coring samples indicated high organic matter content of the topsoil (0-10 cm depth) for Plots 3, 4 and 5, with the respective values of 77.3%, 75.1%, and 71.8%, contrasting with a relatively low value of 45.5% for Plot 6.

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Plots 5 and 6 are on the east side of the access road and are more level than Plots 3 and 4. Plot 5 is located at a valley bottom and is partitioned by Imnavait Creek, which winds directly through the middle of the plot. Shallow drainage channels transverse to Imnavait Creek are found on the west side of the plot, while the east side is upland and drier. Vegetation cover in Plot 5 follows the typical mix of grasses, mosses, and sedges, with some moss forming humps about 20 cm tall, while shrub density and height increase close to the creek. Along Imnavait Creek there are taller (0.5-1.0 m) birch shrubs and more grasses. Plot 6 is characterized by widespread subsurface rocks (Fig. 1) and overall short-statured grass-sedge tussocks and mosses, lichens, small bunchgrasses, *Arctous spp*., and alpine blueberry, interrupted by areas of bare rock and gravel. Bare areas are common in the center of the plot.

As part of the NASA Arctic Boreal Vulnerability (ABoVE) field campaign, our study used ABoVE standard projection, which is Canada Albers Equal Area projection (https://above.nasa.gov/implementation_plan/standard_projection.html), for data visualization and analysis.

Table 1. Summary of surface and soil conditions for the sampling plots

Name	Plot 3	Plot 4	Plot 5	Plot 6
Elevation	810 m	846 m	855 m	875 m
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ALT	49 cm	39 cm	44 cm	58 cm

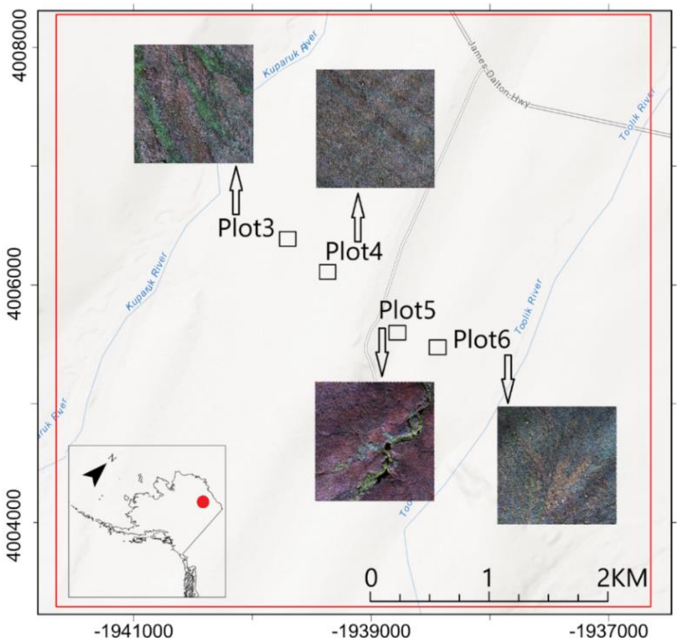

Figure 1: The study region encompasses an Arctic tundra area (68.6167°, -149.3167°; red dot in the inset) in the northern foothills of the Brooks Range, Alaska. The region consists of four intensively sampled plots (Plot 3, Plot 4, Plot 5, and Plot 6; 90 m x 90 m each) with their corresponding true-color RGB (red-green-blue) drone images displayed alongside alongside for visual inspection only, and surrounded by a larger 5km by 5km study region (red rectangle) used for analyzing ALT scaling effects. The map was plotted using Canada Albers Equal Area Conic projection.

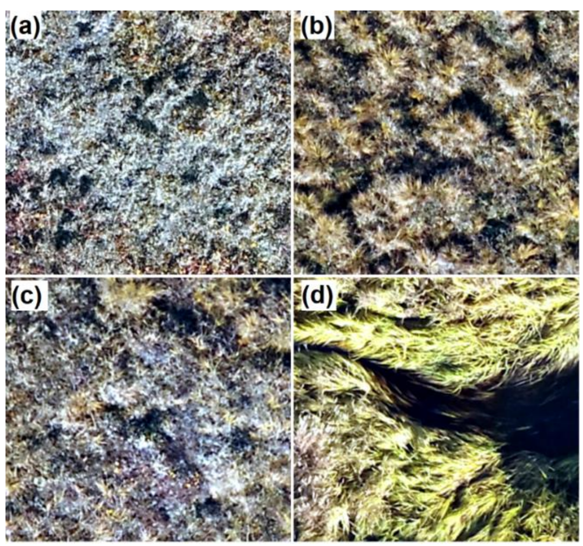

Figure 2: The study region contains characteristic tundra vegetation types, including dwarf shrubs (a), tussock-forming sedges (b), moss-lichen mats (c), and riparian grasses along watercourses (d). The images (0.7cm resolution) were acquired from a drone-based RGB camera.

”

In addition, Section 4.1.1 was re-organized to present results for each plot first before giving overall statistics. We also described the field sampling results first before comparing them with the RF model estimates.

Comment 1.6

The authors appear to confuse scale and resolution. Scale and resolution are not the same thing. The authors refer to scale (e.g. finer, coarser scales) in the manuscript, but this is incorrect, and references should be made to resolution.

Response 1.6

As suggested, we used "resolution" instead of "scale" in the revision throughout the manuscript.

Comment 1.7

Editorial revisions have been suggested to improve clarity. Additional comments for the author's consideration are provided below.

Response 1.7

We thank the reviewer for the constructive editorial revisions. We have implemented all suggested changes to enhance the manuscript's readability.

Comment 1.8

Additional Comments

Title – It might be sufficient to have a shorter title: "…..over Arctic-foothills tundra, North Slope Alaska" and delete the last part. I think you should mention the location as the study is specific to a region.

Response 1.8

As suggested, the title was shortened as "Assessing spatial heterogeneity of active layer thickness over Arctic-foothills tundra, North Slope Alaska"

Comment 1.9

L16 – Revision suggested for first sentence" Changes in active layer thickness are used as an indicator of permafrost degradation" (I don't think the ECV part is necessary).

Response 1.9

As suggested, the first sentence was revised as “Changes in active layer thickness (ALT) are used as an indicator of permafrost degradation”.

Comment 1.10

L17-18 – A thickness doesn’t deepen, revise to: “Increases in ALT can….” Infrastructure damage results from ground instability so maybe that should be mentioned as changes in ALT do not directly cause infrastructure damage.

Response 1.10

As suggested, the sentence was revised as “Increases in ALT can lead to increased greenhouse gas emissions, altered hydrology and ecology, ground instability, and …”

Comment 1.11

L33 – It should be clear that you are referring to atmospheric warming here rather than permafrost warming.

Response 1.11:

The reviewer is correct. We revise the sentence as “Permafrost in the northern high latitudes is undergoing rapid changes driven by enhanced atmospheric warming at roughly four times...”

Comment 1.12

L34-37 – Consider revising the sentence. Some of these things are a result of permafrost degradation while other things mentioned may promote it. Deepening of a layer doesn’t sound right so refer to thicker active layer.

Response 1.12: The sentence was re-written for improved clarity as below.

“Complex environmental changes that accompany degrading permafrost include widespread earlier spring thawing and lengthening of the thaw season, shifts in seasonal snow cover properties, contrasting wetting and drying patterns, vegetation greening and browning, and increasing disturbances. Permafrost degradation, which involves active layer (layer on top of permafrost that undergoes seasonal freeze/thaw) thickening, may lead to ground surface deformation”.

Comment 1.13

L40 – Biskaborn et al. (2019) was not about GHG emissions, so I suggest you delete it. You could also consider citing the review paper of Miner et al. (2022).

Response 1.13: Thanks for the suggestion. We removed the reference "Biskaborn et al. 2019" and cited "Miner et al., 2022".

Added Reference:

Miner, K. R., Turetsky, M. R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A. D., Fix, A., Sweeney, C., Elder, C. D., and Miller, C. E.: Permafrost carbon emissions in a changing Arctic, Nature Reviews Earth & Environment, 3, 55-67, doi:10.1038/s43017-021-00230-3, 2022.

Comment 1.14

L41-42 – The accepted definition of the active layer comes from the IPA glossary (van Everdingen et al. 1998) so that should probably be cited. Establishment of active layer thickness as an essential climate variable is described in Smith and Brown (2009) so this is probably better reference than what you use.

Response 1.14: We followed the reviewer suggestion and revised the sentence as below. **"**Active layer thickness (ALT), defined as "the thickness of the layer of the ground that is subject to annual thawing and freeing in areas underlain by permafrost" (Van Everdingen et al. 1998), is an essential climate variable for monitoring permafrost degradation (Smith and Brown 2009)".

Added reference:

Van Everdingen, R.O. ed.: Multi-language glossary of permafrost and related ground-ice terms in Chinese, English, French, German, Icelandic, Italian, Norwegian, polish, Romanian, Russian, Spanish, and Swedish. International Permafrost Association, Terminology Working Group, 1998.

Smith, S. and Brown, J.: Permafrost: permafrost and seasonally frozen ground, T7. Global Terrestrial Observing System GTOS 62, Food and Agriculture Organization of the United Nations (FAO), Rome, 2009.

Comment 1.15

L44 – You could just refer to spatial and temporal variability.

Response 1.15: As suggested, the sentence was revised as "Accurate mapping of ALT spatial and temporal variability is critical for understanding impacts of climate change…"

Comment 1.16

L47-49 – You are essentially saying that local microclimate is important.

Response 1.16: The reviewer's summary is correct. However, we prefer keeping the original sentence and providing readers more detailed descriptions of the factors affecting local scale ALT heterogeneity.

Comment 1.17

L55 – Are you referring to process models that determine ALT here? – Obu et al. (2019) model simulates TTOP not ALT.

Response 1.17: To be more accurate, we removed the reference Obu et al. 2019.

Comment 1.18

L61-66 – ALT is inferred from information acquired using these techniques. In the case of geophysical techniques, there can be other factors that result in similar signals. Most geophysical techniques are used to determine frozen/unfrozen interfaces, but this also requires knowledge of geology etc. to make the interpretations. Techniques like InSAR are used to determine changes in surface elevation but freezing and thawing are not the only reason movements of the ground occur. Other remote sensing techniques provide information that is used with thermal models to simulate ALT etc. It is difficult to say that any of these techniques are direct measures of ALT, and you should probably say that they are used to infer or provide data for models to estimate ALT.

Response 1.18: Thanks for the comments! Accordingly, we added the sentence below for a more accurate summary of the remote sensing techniques in estimating ALT.

"In sum, the remote sensing techniques provide information necessary to infer or model ALT."

Comment 1.19

L75-77 - Inferred through modelling?

Response 1.19: To be clearer, the sentence was re-written as below:

"Considering its dependence on surface conditions (Kelley et al., 2004), ALT can also be indirectly inferred from optical vegetation observations and relatively high-frequency radar backscatter signals using regression analysis (Gangodagamage et al., 2014; Widhalm et al., 2017)."

Comment 1.20

L85 – Do you mean “characterize” or “assess” rather than clarify? I think other studies have determined the various controls. Are you investigating the relevant importance of these?

Response 1.20: We revised the sentence as “…assess the underlying environmental controls on ALT patterns manifesting at different resolutions…”. This was done by analyzing the relative importance of the RF predictors and the in-situ ALT measurements.

Comment 1.21

L87-115 – Study Region section. Normally this would include a general description of the regional setting – climate, geology, vegetation etc. and then details of the study plots would be provided. This section could benefit from better organization.

Response 1.21:

Thanks for the suggestion. We revised the Section 2 Study Region section to include a generate description of the surrounding region, and more detailed information for the study plots. The revisions are also presented below.

“Our study focused on the Imnavait Creek (68.6167° N, 149.3167° W) area within the Alaskan North Slope tundra foothills region (Fig. 1). The study region experiences a cold climate with a mean annual temperature of -7.4°C, ranging from an average of -17°C in January to 9.4°C in July (Schramm et al., 2007). Annual precipitation averages 340 mm, two-thirds of which falls as light rainfall during the summer (Schramm et al., 2007). The dominant vegetation consists of water-tolerant plants like tussock sedges and mosses, grasses and low shrubs (Schramm et al., 2007). Vegetation and soil patterns vary with slope, aspect, and drainage conditions, exhibiting a patchy distribution across the study domain (Hinkel and Nelson, 2003). The region is also characterized by diverse glacial landforms, including deposits, stream networks, and bedrock outcrops (Hinkel and Nelson, 2003). The region has gently rolling terrain, with elevations ranging from ~750 m to 980 m. Vegetation and soil patterns vary with slope, aspect, and drainage conditions, exhibiting a patchy distribution across the study domain (Hinkel and Nelson, 2003). The region is also characterized by diverse glacial landforms, including deposits, stream networks, and bedrock outcrops (Hinkel and Nelson, 2003). Increasing ALT was observed from both in-situ measurements at the Circumpolar Active Layer Monitoring (CALM) sites (https://www2.gwu.edu/~calm/data/north.htm) and regional ALT records (Liu et al., 2024).

The local study area consisted of four intensively sampled field plots (Plot 3, Plot 4, Plot 5, and Plot 6 in Fig. 1; 90m ×90m each) distributed across an elevation gradient along west facing hill slopes, and surrounded by a larger (5 km by 5 km) landscape domain used for analyzing ALT across different resolutions (Fig.1; Table 1). The field plots are dominated by tussock-forming sedges and moss-lichen mats, along with scattered dwarf birch shrubs, and riparian grasses (Fig.

1-2). The common species identified near the ALT sampling points include dwarf birch (*Betula nana*), alpine blueberry (*Vaccinium uliginosum*), black bearberry (*Arctous* spp.), crowberry (*Empetrum nigrum*), and *Arctostaphylos uva-ursi*, among other less-recognizable species. Our soil coring samples indicated high organic matter content of the topsoil (0-10 cm depth) for Plots 3, 4 and 5, with the respective values of 77.3%, 75.1%, and 71.8%, contrasting with a relatively low value of 45.5% for Plot 6.

Plot 3 and Plot 4 are located on west-facing downhill slopes characterized by gradual elevation changes (10-15 m across the plot), small water tracks, and scattered glacial erratics. Plot 3 is crossed by multiple drainage features that are transverse to the Kuparuk River (Fig. 1). These features are evident in the topography as well as the vegetation, with alternating bands of dwarf willow, grasses, and tussocks. Standing water is present in many places, as are glacial erratics, particularly along the drainage channels. Plot 4 is more homogeneous in vegetation character and height, consisting mostly of grass tussocks and moss, with some larger glacial erratics present.

Plots 5 and 6 are on the east side of the access road and are more level than Plots 3 and 4. Plot 5 is located at a valley bottom and is partitioned by Imnavait Creek, which winds directly through the middle of the plot. Shallow drainage channels transverse to Imnavait Creek are found on the west side of the plot, while the east side is upland and drier. Vegetation cover in Plot 5 follows the typical mix of grasses, mosses, and sedges, with some moss forming humps about 20 cm tall, while shrub density and height increase close to the creek. Along Imnavait Creek there are taller (0.5-1.0 m) birch shrubs and more grasses. Plot 6 is characterized by widespread subsurface rocks (Fig. 1) and overall short-statured grass-sedge tussocks and mosses, lichens, small bunchgrasses, *Arctous spp*., and alpine blueberry, interrupted by areas of bare rock and gravel. Bare areas are common in the center of the plot".

Comment 1.22

L88-89 – Normally a more general description of regional climate would be presented first, and this sentence seems out of place (see previous comment). Provide reference period for statements such as this and be clear that it is air temperature (rather than permafrost temperature) that is rising by the amount indicated.

Response 1.22: To be clearer, the sentence was deleted in the revision.

Comment 1.23

L100 – information on map projections should be provided in the figure caption.

Response 1.23: As suggested, we deleted the sentence and provided the map projection information in the figure caption.

Comment 1.24

L105 – Figure 1 – If the images include the plot area, then it should be clear what area of them is covered by the plot. The orientation of the plots and images differ so it is difficult for the reader to see the characteristics of the plots. It is also unclear if the scale of map and the images is the same.

Response: Figure 1 was re-plotted to show the same overlapping areas of the sampling plots and the corresponding drone images. We also clarified in the figure caption that the drone images did not use map scales and were for visual inspection only.

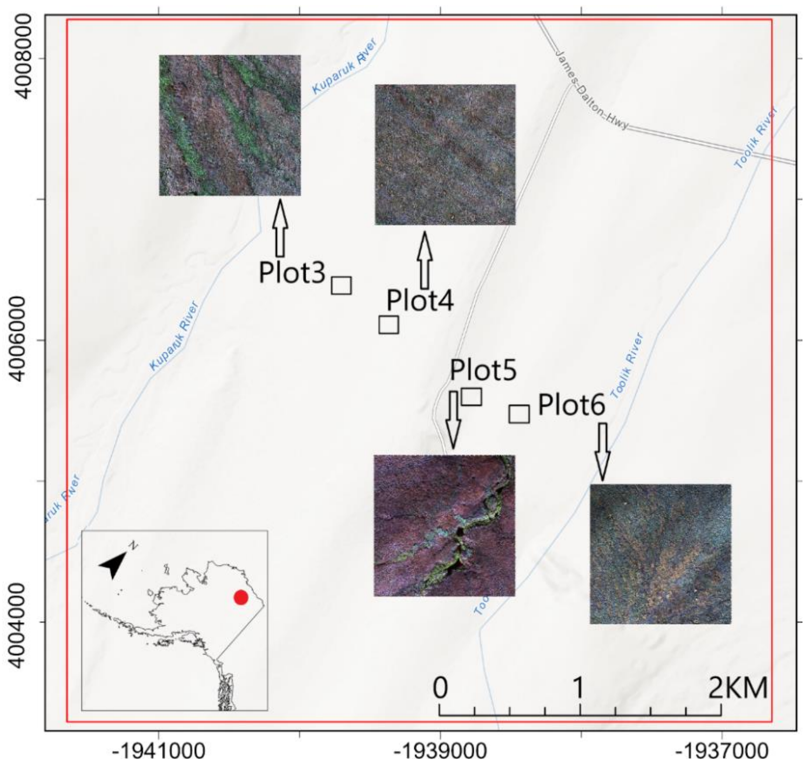

Figure 1: The study region encompasses an Arctic tundra area (68.6167°, -149.3167°; red dot in the inset) in the northern foothills of the Brooks Range, Alaska. The region consists of four intensively sampled plots (Plot 3, Plot 4, Plot 5, and Plot 6; 90 m x 90 m each) with their corresponding true-color RGB (red-green-blue) drone images displayed alongside for visual inspection only, and surrounded by a larger 5 km by 5 km study region (red rectangle) used for analyzing ALT scaling effects. The map was plotted using Canada Albers Equal Area Conic projection.

Comment 1.25

L125-126 – It would be better to indicate that mechanical probing to the depth of refusal was used to determine the depth of the frost table. Essentially that is what is done when probing is conducted.

Response 1.25: Thanks for the suggestion. We added the sentence below accordingly.

"The mechanical probing to the depth of refusal was used to determine the depth of the frost table".

Comment 1.26

L129-131 – Revision suggested: "Additional observations were made including vegetation type and distribution, occurrence of standing and running water…." Observation of subsurface rocks is mentioned but were there also descriptions of organic layer thickness or surficial materials which are relevant for interpretation of results.

Response 1.26: As suggested, the sentence was revised as "Additional observations were made including vegetation types, occurrence of standing and running water, and appearance of subsurface rocks".

In addition, we also took soil core samples for quantifying organic layer for the sampling plots. The following sentence was added:

"Soil organic layer properties (section 2) were also estimated from soil cores taken within the sampling plots".

Comment 1.27

L169-170 – The way this is written it sounds like ALT is directly determined through remote sensing. Don't you mean that the RF method is used with parameters determined through remote sensing to estimate ALT. Doesn't the ALT used to develop the model come from the field observations?

Response 1.27: To be more accurate, the sentence was re-written as below.

"The RF method has been widely used with parameters determined through remote sensing to estimate land parameters such as soil moisture, vegetation optical depth, and ALT…".

Comment 1.28

L224-255 Section 4.1.1 – It would be better to present results for each plot first and then compare them before giving overall statistics. Clearly there are differences between the plots, and they should be described first. A better presentation of the results of the field sampling should be provided before presenting results of the RF models and the comparison to observed ALT.

Response 1.28: As suggested, section 4.1.1 was re-organized to present results for each plot first before giving overall statistics. In addition, field sampling results were presented before comparing with RF model estimates. The revised section was also given below.

"The ALT values sampled across all plots have a mean of 45.9 cm and a standard deviation of 11.9 cm. Relatively low ALT (39.3 cm) was typically found in areas dominated by non-riparian shrubs, while larger ALT occurred in soils near standing water (61.0 cm), along creeks (78.2 cm) (e.g., Fig. 4g), and around rocks (70.0 cm) (e.g., Fig. 4j).

The resulting 5-m and 0.1-m ALT maps were compared with the field measurements (Fig. 4). The 5-m ALT maps (Fig.4b, 4e, 4h, 4k) captured the primary ALT patterns observed from the field measurements (Fig. 4a, 4d, 4g, 4j) including elevated ALT along the perimeter of Plot 3, consistently low ALT throughout Plot 4, high ALT values following the water tracks in Plot 5, and generally deep ALT in Plot 6. The 0.1-m results revealed significantly finer variations (Fig. 4c, 4f, 4i, and 4l), resolving ALT patterns associated with small water tracks (e.g., Fig. 4i), discrete vegetation patches (Fig. 4c, 4l), and widespread clusters of underlying rocks (Fig. 4l) that were not discernible at 5-m resolution. Specifically, higher ALT values are visible along Imnavait Creek within Plot 5, as shown by the red pixels in the field measurements (Fig. 4g), 5-m ML predictions (Fig. 4h), and 0.1-m ML results (Fig. 4i). However, field sampling revealed substantial ALT variation within individual 5-m grid cells, with a standard deviation of up to 32 cm as distance from the watercourse increases. These variations within individual 5-m grid cells are only resolved in the 0.1-m results (Fig. 4i), which distinguish the high ALT values along the creek (red pixels) from the lower values in adjacent areas (blue pixels). Similarly, the stripe patterns of ALT in Plot 4 associated with alternating bands of dwarf willow, grasses, and tussocks (Fig. 1; Section 2) are clearly defined in the 0.1-m predictions (Fig. 4c) but are not discernible in the 5-m results (Fig. 4b). For Plot 6 where overall high ALT is observed (Fig.4 j, 4k, and 4i), heterogeneity is only captured by the 0.1-m results (Fig. 4l). The pattern of interspersed lower-ALT (non-red) pixels within high ALT areas (Fig. 4l) is likely associated with widespread clusters of underlying rocks and complex vegetation cover observed in the field (Fig. 1; Section 2).

Considering the larger ALT variability and more diversified surface conditions at 0.1-m resolution relative to the 5-m resolution, the RF model trained using limited 5-m data set may not be able to fully capture the 0.1-m ALT variations, leading to inconsistency of the overall ALT patterns between the 5-m and 0.1-m results (e.g., Plot 4; Fig. 4d, 4e, 4f) and additional uncertainties in the multi-resolution analysis. In addition, the RF predictions tended to be centralized, which may underestimate larger ALT values (e.g., fewer dark red pixels with ALT higher than 65 cm in Fig. 4h and 4i than the measurements in Fig. 4g) and overestimate smaller ones relative to the measurements (e.g., dark blue pixels with measured ALT smaller than 35 cm in Fig. 4g but not in the ML predictions in Fig. 4h and 4i).

Overall, the first RF model was able to reproduce the sampled ALT at 5-m resolution with a RMSE of 6.53 cm and strong correlation (0.78). Among all the predictors, slope (17.40%), red-edge reflectance (14.05%), aspect (13.44%), and NIR reflectance (12.64%) were the most important features contributing to ALT predictions. The contributions from other predictors including green band (9.91%), blue band (9.43%), NDWI (8.48%), red band (7.41%), and NDVI (7.24%) were also important. The RF model applied to the 0.1-m predictor features was able to capture the high-resolution ALT variability and details missed by coarser-resolution results.

”

Comment 1.29

L236-240 – These features do not appear to be visible on the maps in Figure 4 so difficult for the reader to see how you arrive at these interpretations. There appears to be substantial difference between Plot 5 (g) observed ALT and modelled (e) – observed values appear to be less than modelled.

Response 1.29:

For better comparisons between the 5-m and 0.1-m results, Figure 4 was re-plotted and additional explanations were provided to address the discrepancies between the ALT results and possible uncertainties as below.

“…The 0.1-m results revealed significantly finer variations (Fig. 4c, 4f, 4i, and 4l), resolving ALT patterns associated with small water tracks (e.g., Fig. 4i), discrete vegetation patches (Fig. 4c, 4l), and widespread clusters of underlying rocks (Fig. 4l) that were not discernible at 5-m resolution. Specifically, higher ALT values are visible along Imnavait Creek within Plot 5, as shown by the red pixels in the field measurements (Fig. 4g), 5-m ML predictions (Fig. 4h), and 0.1-m ML results (Fig. 4i). However, field sampling revealed substantial ALT variation within individual 5-m grid cells, with a standard deviation of up to 32 cm as distance from the watercourse increases. These variations within individual 5-m grid cells are only resolved in the 0.1-m results (Fig. 4i), which distinguish the high ALT values along the creek (red pixels) from the lower values in adjacent areas (blue pixels). Similarly, the stripe patterns of ALT in Plot 4 associated with alternating bands of dwarf willow, grasses, and tussocks (Fig. 1; Section 2) are clearly defined in the 0.1-m predictions (Fig. 4c) but are not discernible in the 5-m results (Fig. 4b). For Plot 6 where overall high ALT is observed (Fig.4 j, 4k, and 4i), heterogeneity is only captured by the 0.1-m results (Fig. 4l). The pattern of interspersed lower-ALT (non-red) pixels within high ALT areas (Fig. 4l) is likely associated with widespread clusters of underlying rocks and complex vegetation cover observed in the field (Fig. 1; Section 2).

Considering the larger ALT variability and more diversified surface conditions at 0.1-m resolution relative to the 5-m resolution, the RF model trained using limited 5-m data set may not be able to fully capture the 0.1-m ALT variations, leading to inconsistency of the overall ALT patterns between the 5-m and 0.1-m results (e.g., Plot 4; Fig. 4d, 4e, 4f) and additional uncertainties in the multi-resolution analysis. In addition, the RF predictions tended to be centralized, which may underestimate larger ALT values (e.g., fewer dark red pixels with ALT higher than 65 cm in Fig. 4h and 4i than the measurements in Fig. 4g) and overestimate smaller ones relative to the measurements (e.g., dark blue pixels with measured ALT smaller than 35 cm in Fig. 4g but not in the ML predictions in Fig. 4h and 4i)”.

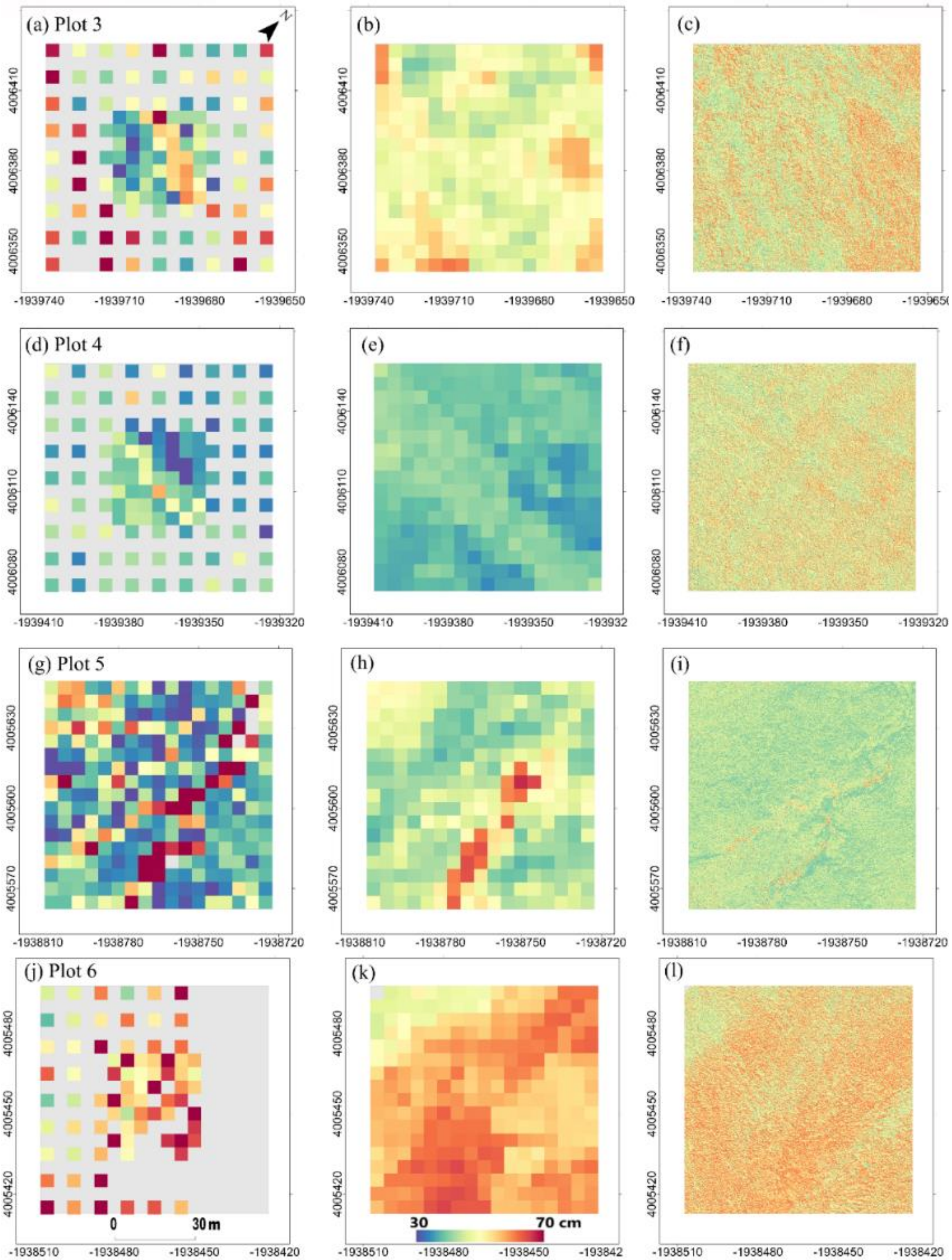

Figure 4: Comparisons of ALT spatial patterns derived from field measurements (a, d, g, j), 5-m machine learning outputs (b, e, h, k), and 0.1-m machine learning estimates (c, f, i, l) for the intensively sampled plots (grey shading indicates areas without sampling). The map was plotted using Canada Albers Equal Area Conic projection.

Comment 1.30

Figure 4 – The presentation does not allow the reader to compare the observed to the model outputs as it is unclear how the plot area in first column fits on the maps in the other two columns. The plot area should be clearly shown on the other plots. For plot 6 the rest of the plot area should be shown in (j) with grey shading for example to indicate area that couldn't be probed.

Response 1.30: As suggested, Figure 4 was re-plotted for improved comparisons between the ALT results. In addition, grey shading was added to indicate areas without sampling.

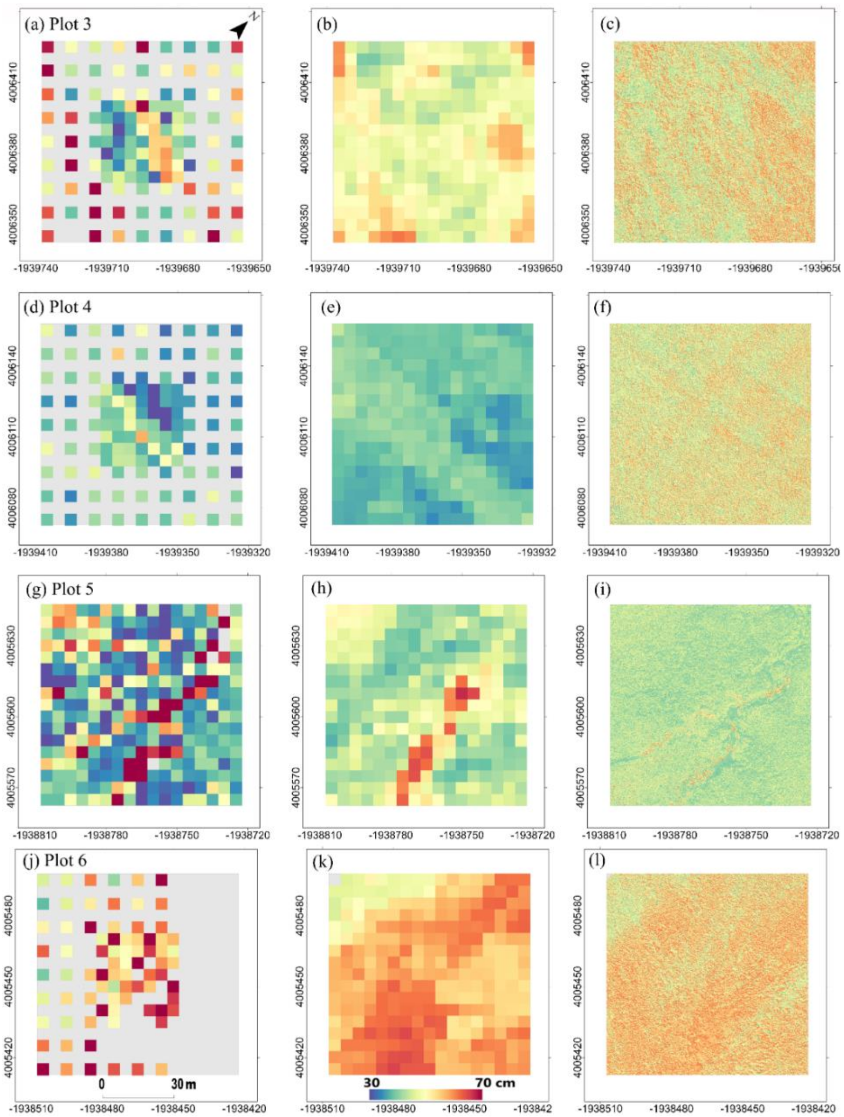

Figure 4: Comparisons of ALT spatial patterns derived from field measurements (a, d, g, j), 5-m machine learning outputs (b, e, h, k), and 0.1-m machine learning estimates (c, f, i, l) for the intensively sampled plots (grey shading indicates areas without sampling). The map was plotted using Canada Albers Equal Area Conic projection.

Comment 1.31

L245-255 – We would expect warmer conditions and greater ALT on south facing vs north facing slopes – can you say anything about this based on observed results. Note that some of the factors considered are related. For example, vegetation will depend on elevation and aspect. Drainage and therefore surface wetness (affects vegetation) will depend on topography.

Response 1.31: We expanded the discussion to address the ALT control from topography and its interactions with other factors as below.

"In the Imnavait Creek area, the thickness of the organic layer increases from hill crests to foot slopes. The thicker organic layer provides enhanced thermal insulation, leading to a shallower active layer downhill (Walker and Walker, 1996). Accordingly, Plots 3 and 4 on west-facing downhill slopes and Plot 5 in the valley bottom exhibited overall high soil organic matter content (~75%) and relatively low ALT (~44 cm). In contrast, the higher-elevation Plot 6 had lower organic matter (~46%) and a higher ALT (~58 cm). Besides terrain-controlled organic matter distribution, topography also affects ALT through its impacts on runoff and drainage, soil temperature, snow properties, and vegetation types (Walker and Walker, 1996, Li et al., 2017). Accordingly, topography information including slope (17.40%) and aspect (13.44%) are among the most important factors shaping the ALT variations in the ML- and drone-based analysis, while the surface features including vegetation, water bodies, and soil properties determined from the multi-spectral reflectance and optical-NIR indices, all showed important contributions to the 5-m ALT predictions over the sampling plots (7.24% to 14.05%; section 4.1.1).

…

For the ML- and satellite-based analysis, terrain factors (elevation, slope, and aspect) collectively dominate the ALT predictions (64.89% contribution) at 10-m resolution. The broad ALT patterns over the surrounding region (Fig. 5a) largely align with terrain-driven variability (section 4.1.2), as also observed in a previous study (Hinkel and Nelson, 2003). In general, south-facing slopes in the Northern Hemisphere receive more solar radiation than north-facing slopes, leading to warmer soil and larger ALT. However, the study region is characterized by gentle terrain slopes and west facing aspects (Fig. 5). Besides the terrain-controlled organic matter distribution observed over the Imnavait Creek area, direct solar radiation loading is higher around the hill tops and lower in downslope areas (Hinkel and Nelson, 2003), thus promoting larger ALT conditions in the uplands (Fig. 5). Topography therefore exerts a direct influence on the general thaw pattern as shown in the regional ML analysis".

Comment 1.32

L262-264 – Words like "rapid" and "slower" imply that a change over time is being considered but that is not the case here. It would be better to refer to is a smaller increase in uncertainty at coarser (or lower) resolution (note on you map in Figure 4 the x axis appears to be the resolution, not scale – resolution and scale are not the same thing).

Response 1.32: As suggested, the sentence was re-written to be more rigorous as below. In addition, the X-axis label was revised as "Spatial resolution (m)".

"Uncertainties increase as spatial resolution becomes coarser. However, this increase is most pronounced when moving from high resolutions (e.g., sub-meter to 1 m) and becomes smaller at coarser pixel sizes (e.g., 100 to 1000 m)".

Comment 1.33

L276-278 – "Coarser scale" is incorrect, it should be "coarser resolution". Air temperature affects surface temperature (as do local environmental factors that affect microclimate) which influence the ground thermal regime (ground temperature) and therefore active layer conditions.

Response 1.33: Thanks for the interpretation and correction. We used "resolution" instead of "scale", and expanded the sentence by adopting the reviewer's interpretation. The revised sentences are given below.

"Regional ALT dynamics at kilometer or coarser resolutions are primarily governed by air temperature, which affects surface temperature, and further influences soil thermal regimes and therefore active layer conditions (Gangodagamage et al., 2014; Peng et al., 2023). Local ALT variations at finer resolutions (sub-meter to 100 m) are highly complex (Gangodagamage et al., 2014) since soil thermal regimes are further modified by local environmental factors that fine-tune the microclimate".

Comment 1.34

L275-302 – Section 5.1 – There are a lot of general statements from the literature, but very little analysis is presented to show the relative importance of the various factors mentioned. Information on snow cover, soil texture, groundwater flow etc. has not been presented and it is unclear how these things may vary over the study area. You mention that ALT is greater in areas with standing water or adjacent to creeks but not clear from results presented (e.g. maps) that this is the case.

Response: We revised Section 5.1 to provide more in-depth analysis to interpret our ALT observations and model analysis, and clearer links between the interpretation and our observations/predictions. The revisions are presented below.

"Consistent with previous studies, our field observations and RF estimates (section 4.1.1) confirmed that greater ALT is most common in areas with standing water or adjacent to creeks (e.g., Plot 5; Fig. 4g, 4h, 4i), where wet conditions enhance soil thermal conductivity in foothills tundra (Grant et al., 2017; Clayton et al., 2021) despite increased latent heat required for thawing. Relatively larger ALT was also found in the vicinity of subsurface rocks (e.g., within 1-m distance) (e.g., Plot 6; Fig. 5j, 5k, 5l), whose high thermal conductivities facilitate heat propagation and summer thawing (Bonnaventure et al., 2013). Relatively lower ALT was recorded under shrubs, which likely cool the ground in summer through canopy shading (Lawrence and Swenson, 2011) and in winter through the thermal bridging effect (Domine et al., 2022). However, shrubs can also have a counteracting influence on ALT by promoting snow accumulation; whereby, the deeper snow layer insulates the ground, leading to warmer winter soil temperatures (e.g., Palmer et al., 2012; Morse et al., 2012; Kropp et al., 2020) which can result in a deeper active layer when this winter warming effect outweighs the summer shading effect of the shrubs (Way and Lapalme, 2021). A thick moss layer may also slow active layer thaw through its insulating capacity (Schuuring et al., 2024), though no specific descriptions of the moss layer were made in our sampling.

In the Imnavait Creek area, the thickness of the organic layer increases from hill crests to foot slopes. The thicker organic layer provides enhanced thermal insulation, leading to a shallower active layer downhill (Walker and Walker, 1996). Accordingly, Plots 3 and 4 on west-facing downhill slopes and Plot 5 in the valley bottom exhibited overall high soil organic matter content (~75%) and relatively low ALT (~44 cm). In contrast, the higher-elevation Plot 6 had lower organic matter (~46%) and a higher ALT (~58 cm). Besides terrain-controlled organic matter distribution, topography also affects ALT through its impacts on runoff and drainage, soil temperature, snow properties, and vegetation types (Walker and Walker, 1996, Li et al., 2017). Accordingly, topography information including slope (17.40%) and aspect (13.44%) are among the most important factors shaping ALT variations in the ML- and drone-based analysis, while surface features including vegetation, water bodies, and soil properties determined from the multi-spectral reflectance and optical-NIR indices, all showed important contributions to the 5-m ALT predictions over the sampling plots (7.24% to 14.05%; section 4.1.1).

It is noted that additional radar (L-band 1.26 GHz) observations from UAVSAR helped to enhance the performance of the first RF model (e.g., R increased from 0.78 to 0.81), but were not used in the subsequent scaling analysis (section 3.1.2). For the features selected for radar-based ALT predictions, red-edge reflectance (16.67%), HV-polarized radar backscatter (16.04%), aspect (15.33%), and HH-polarized radar backscatter (15.04%) contributed most to the predictions, while the red band (13.34%), slope (11.99%), and green band (11.57%) observations were relatively less important. The sensitivity of radar backscatter to vegetation biomass, surface water bodies, and soil wetness likely enhanced the ALT estimation.

For the ML- and satellite-based analysis, terrain factors (elevation, slope, and aspect) collectively dominate the ALT predictions (64.89% contribution) at 10-m resolution. The broad ALT patterns over the surrounding region (Fig. 5a) largely align with terrain-driven variability (section 4.1.2), as also observed in a previous study (Hinkel and Nelson, 2003). In general, south-facing slopes in the Northern Hemisphere receive more solar radiation than north-facing slopes, leading to warmer soil and larger ALT. However, the study region is characterized by gentle terrain slopes and west facing aspects (Fig. 5). Besides the terrain-controlled organic matter distribution observed over the Imnavait Creek area, direct solar radiation loading is higher around the hill tops and lower in downslope areas (Hinkel and Nelson, 2003), thus promoting larger ALT conditions in the uplands (Fig. 5). Topography therefore exerts a direct influence on the general thaw pattern as shown in the regional ML analysis".

Added reference:

Walker, D. A. and Walker, M. D.: Terrain and vegetation of the Imnavait Creek watershed, Landscape function and disturbance in Arctic Tundra, pp. 73-108, Berlin, Heidelberg: Springer Berlin Heidelberg, 1996.

Li, A., Tan, X., Wu, W., Liu, H. and Zhu, J.: Predicting active-layer soil thickness using topographic variables at a small watershed scale, Plos one, 12(9), p.e0183742, 2017.

Comment 1.35

L282-285 – Revise "deeper ALT" to "greater ALT" (a thickness can't be deeper – same issue with shallow ALT). Latent heat is also an important factor with respect to the effect that wet conditions have on the ground thermal regime.

Response 1.35: As suggested, the sentence was revised as below.

"Consistent with previous studies, our field observations and RF estimates (section 4.1.1) confirmed that greater ALT is most common in areas with standing water or adjacent to creeks (e.g., Plot 5; Fig. 4g, 4h, 4i), where wet conditions enhance soil thermal conductivity in foothills tundra (Grant et al., 2017; Clayton et al., 2021) despite increased latent heat required for thawing. Relatively larger ALT was also found in the vicinity of subsurface rocks (e.g., within 1-m distance) (e.g., Plot 6; Fig. 5j, 5k, 5l), whose high thermal conductivities facilitate heat propagation and summer thawing (Bonnaventure et al., 2013)".

Comment 1.36

L287-290 – Note that shrubs can promote snow accumulation and other studies have shown that this leads to warmer winter ground temperatures (e.g. Palmer et al. 2012; Morse et al. 2012; Way and Lapalme 2021; Kropp et al. 2020) – winter conditions will influence ALT and it is not as simple as implied in the text. Way and Lapalme (2021) also showed that the insulating effect of snow outweighs the shading effect of shrubs.

Response 1.36: For a more rigorous analysis, we added the following discussions on the shrub impacts as below.

"Relatively lower ALT was recorded over the shrubs, which likely cool the ground in summer through canopy shading (Lawrence and Swenson, 2011) and in winter through thermal bridging effect (Domine et al., 2022). However, shrubs can also have a counteracting influence on ALT by promoting snow accumulation; whereby, the deeper snow layer insulates the ground, leading to warmer winter soil temperatures (e.g., Palmer et al., 2012; Morse et al., 2012; Kropp et al., 2020) which can result in a deeper active layer when this winter warming effect outweighs the summer shading effect of the shrubs (Way and Lapalme, 2021)".

Added references:

Kropp, H., Loranty, M. M., Natali, S. M., Kholodov, A. L., Rocha, A. V., Myers-Smith, I., Abbot, B. W., Abermann, J., Blanc-Betes, E., Blok, D. and Blume-Werry, G.: Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems, Environmental research letters, 16(1), p.015001, 2020.

Morse, P. D., Burn, C. R., and Kokelj, S. V.: Influence of snow on near-surface ground temperatures in upland and alluvial environments of the outer Mackenzie Delta, Northwest Territories, Canadian Journal Earth Sciences, 49: 895-913. doi:10.1139/E2012-012, 2012.

Palmer, M. J., Burn, C. R., and Kokelj, S. V.: Factors influencing permafrost temperatures across tree line in the uplands east of the Mackenzie Delta, 2004–2010, Canadian Journal of Earth Sciences, 49: 877-894. doi:10.1139/E2012-002, 2012.

Way, R. G., and Lapalme, C. M.: Does tall vegetation warm or cool the ground surface? Constraining the ground thermal impacts of upright vegetation in northern environments, Environmental Research Letters, 16: 054077. doi:10.1088/1748-9326/abef31, 2021

Comment 1.37

L306 – I think you mean greater uncertainty in ALT at sub-metre resolution.

Response 1.37: The ALT uncertainty increases with coarser spatial resolution, but the increase is greater at finer spatial resolutions. We revised the sentence for improved clarity as below.

"Our analysis revealed a greater increase in ALT spatial uncertainty at the sub-meter resolutions"

Comment 1.38

L322-323 – This is a general statement but not a conclusion of your study – there was no investigation of GHG emission, infrastructure issues etc.

Response 1.38: The sentence was deleted in the revision to avoid confusion.

Comment 1.39

L350 – References – check URL links numbers as some of them do not seem to work. I noticed this with a few ERL publications.

Response 1.39: Thanks for the careful check. All the URL links were checked and updated to make sure they are workable.

Comment 1.40

L599 – Biskaborn et al. has many more coauthors so "and coauthors" should be added after the last author given. Same comment for Obu et al. in line 457.

Response 1.40: The two references were not cited in the revised manuscript. For a few other references with many more coauthors, we added "and co-authors" as suggested.

Comment 1.41

References cited in comments

Kropp, H. et al., 2021. Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems. Environmental Research Letters, 16: 015001. doi: 10.1088/1748-9326/abc994

Miner, K.R., Turetsky, M.R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A.D., Fix, A., Sweeney, C., Elder, C.D., and Miller, C.E. 2022. Permafrost carbon emissions in a changing Arctic. Nature Reviews Earth & Environment, 3: 55-67. doi:10.1038/s43017-021-00230-3

Morse, P.D., Burn, C.R., and Kokelj, S.V. 2012. Influence of snow on near-surface ground temperatures in upland and alluvial environments of the outer Mackenzie Delta, Northwest Territories. Canadian Journal Earth Sciences, 49: 895-913. doi:10.1139/E2012-012

Palmer, M.J., Burn, C.R., and Kokelj, S.V. 2012. Factors influencing permafrost temperatures across tree line in the uplands east of the Mackenzie Delta, 2004–2010. Canadian Journal of Earth Sciences, 49: 877-894. doi:10.1139/E2012-002

Smith, S. and Brown, J., 2009. Permafrost: permafrost and seasonally frozen ground, T7. Global Terrestrial Observing System GTOS 62, Food and Agriculture Organization of the United Nations (FAO), Rome.

Way, R.G., and Lapalme, C.M. 2021. Does tall vegetation warm or cool the ground surface? Constraining the ground thermal impacts of upright vegetation in northern environments. Environmental Research Letters, 16: 054077. doi:10.1088/1748-9326/abef31

Response 1.41: Thanks for summarizing the references, which were also cited in the revision to support the study.