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Environmental and vegetation control on the active layer and soil temperature in an Arctic tundra ecosystem in Alaska

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Abstract. Permafrost soils contain approximately twice the amount of carbon than the atmosphere, which could be released as global warming continues. Increasing global temperatures have in fact the potential to result in increased permafrost degradation, and carbon loss into the atmosphere. To properly understand the potential release of the carbon stored in permafrost soils, it is critical to understand the environmental and vegetation control on the development of active layer, the upper soil layer that thaw during the growing season in the Arctic. Arctic tundra ecosystems are dominated by mosses, which compose approximately 40% of the vegetation, and have a critical role in regulating the heat condition into the soil. Given their importance, the role that mosses play on permafrost degradation should be investigated in more details. This study measured soil temperature together with thaw depth, a range of environmental variables, and moss thickness, to identify the most important controls on the development of the active layer across 124 plots in continuous permafrost tundra ecosystems. We found that a thicker moss layer insulated the soil and resulted in cooler temperatures deeper in the soil, despite warmer surface temperatures. A thicker moss layer was associated with a deeper depth of thaw, likely for the higher growth of mosses in the drier and warmer topographically higher elevation areas. The protective role of mosses was only relevant for the first ~3

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cm of the green moss layer, suggesting that the living moss layer was more important in regulating soil temperature, possibly through a higher ability to retain water. Soil moisture was in fact an important control on surface and deeper soil temperatures, with wetter soils been associated with cooler surface temperatures because of the higher evaporative cooling, and warmer deeper temperatures likely because of the larger heat conduction to deeper soils. Overall, this study highlights the importance of a green living moss layer on soil temperature and thaw depth. Mosses are among the most vulnerable vegetation to hydrological changes, given their lack of a rooting system, and their sensitivity to climate change should be considered when predicting the response of permafrost thaw to climate change.

Short summary

Permafrost soils contain twice the amount of carbon than the atmosphere, and its release could majorly affect global temperatures. This study found that a thicker moss layer resulted in cooler temperatures deeper in the soil, despite warmer surface temperatures. The top green living moss layer was the most important in regulating the soil temperatures and should be considered when predicting the response of permafrost thaw to climate change.

1 Introduction

Northern high-latitude ecosystems are characterized by the presence of permafrost, a soil layer that remains frozen for at least two consecutive years (Permafrost Subcommittee 1988). The active layer (also known as the thaw depth) is the layer of soil of variable depth found directly above the permafrost which only thaws during the summer (Permafrost Subcommittee 1988). The depth of this active layer depends on a combination of factors, including abiotic factors such as air temperatures, solar radiation, and soil moisture, which may increase subsurface heat and associated belowground thermal difference (Dafflon et al. 2017; Fisher et al. 2016; Permafrost Subcommittee 1988; Schuur et al. 2015; Williams et al. 2020). Vegetation also has a role in the development of the active layer by potentially decreasing heat transfer below the surface by serving as a layer of insulation when dry or increasing heat transfer when wet (Beringer et al. 2005; Blok et al. 2010; Blok et al. 2011; Hayashi et al. 2007; Hrbáček et al. 2020; Park et al. 2018; Porada et al. 2016). Globally, permafrost and the active layer currently store

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an estimated 15 gigatons of carbon (Koven et al. 2011; Schurr 2019). The increasing severity of climate change currently threatens the stability of this sequestered carbon (Miner et al. 2022; Schaphoff et al. 2013; Schuur et al. 2008). The release of the vast carbon stored in these high-latitude soils can potentially affect the climate at the global scale through positive feedback loops in which increased atmospheric carbon may further greenhouse emissions and permafrost degradation (Davidson and Janssens 2006; Schuur et al. 2008). These positive feedback loops further contribute to the rapid change in climate in the northern high-latitude ecosystems known as "Arctic amplification" (Dai et al. 2019).

Given the large carbon store of permafrost soils (Hugelius et al. 2014), it is critical to improve understanding of the environmental and vegetation controls on active layer development. Mosses compromise approximately 40% of the Arctic sedge tundra and exist in "mats" alongside other forms of vegetation directly above permafrost soils and their associated ice wedges (Euskirchen et al. 2009). Mosses play a significant role in regulating thaw depths by reducing the heat penetration belowground when dry or increasing it when wet (Beringer et al. 2005; Blok et al. 2010; Blok et al. 2011; Hayashi et al. 2007; Hrbáček et al. 2020; Park et al. 2018). Mosses retain a unique adaptation to desiccation that allows them to desiccate while remaining alive and to create a layer of tissue, which thermally insulates soils (Blok et al. 2011; Park et al. 2018). The dried mats have an insulation effect with increased moss community coverage and layer thickness associated with lower soil temperatures in deeper soil layers and a shallower active layer depth (Blok et al. 2011; Park et al. 2018; van der Wal et al. 2001). A wetter moss layer should result in increased heat conduction in the soil and a deeper active layer depth (Hayashi et al. 2007; Hrbáček et al. 2020; Park et al. 2018).

The overall control that mosses and other environmental drivers have on permafrost degradation is still not fully understood (Fisher et al. 2018; Luo et al. 2016). The Arctic is experiencing warmer temperatures and increased precipitation between August to October (Boisvert and Strove 2015, Fujinami et al. 2016). The resulting increase in moisture availability can increase thermal conduction in deeper soil layers in turn supporting thawing of the soil (Beringer et al. 2005; Blok et al. 2011; Hayashi et al. 2007; Hrbáček et al. 2020; Park et al. 2018). This increase in thermal conduction may lead to increased permafrost soil thawing which in turn would lead to increased releases of greenhouse gas emissions (Miner et al. 2021; Schaefer et al. 2014;

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van Huissteden and Dolman 2012). Therefore, an increased depth of thaw can create a positive feedback loop which can further exacerbate the effects of climate change in the Arctic.

To further our understanding of the controls on the development of the active layer, a range of environmental drivers and vegetation characteristics should be investigated, including soil moisture, solar radiation, and air and soil temperatures together with the thickness of the moss mat across the fine scale, micro topographically variable polygonal tundra ecosystems. The goal of this research is to identify the biotic and abiotic controls regulating soil temperature and the thawing of the active layer across a range of microtopographic areas in a wet sedge arctic tundra ecosystem in Alaska. We expect thicker mosses to be associated with shallower depth of thaw and decreased belowground temperatures. We anticipate moss patches with increased soil water content to be associated with deeper depth of thaw as well as increased belowground temperatures given an increase in heat conduction with higher soil moisture.

2 Methods

2.1 Study Sites

The sites of this research are near Utqiaġvik, Alaska (formerly known as Barrow), which is the largest town in the Alaskan North Slope Borough. Our team has been maintaining several micrometeorological and eddy covariance towers in Utqiaġvik over the last decades (Zona et al., 2016). This research was conducted near two of these eddy covariance towers, which were in operation from 2005-2009 (Fig. 1b, the US-Ben (North), and US-Bec (Central) sites, established during the Biocomplexity Experiment, see Zona et al., 2009; Zona et al., 2012). Environmental drivers (such as air temperature and photosynthetic active radiation (PAR)) measured from another tower still operational since 2005 (US-Bes), in close proximity to the US-Ben and US-Bes sites, were also included in this study. The locations of the US-Bes, US-Bec, and US-Ben are: 71.2809N, -156.5965W; 71.28316N, -156.60342W; and 71.28628N, -156.60424W respectively (Zona et al., 2009). These sites are located in a drain lake basin ecosystem with vegetation classified as wet sedges tundra dominated by mosses, lichens, and graminoids with patches of water and partially to fully submerged patches of vegetation (Davidson et al., 2016). Given the proximity of these sites (US-Ben and US-Bec being within 662-meters and 356-meters of US-Bes respectively), we assume that the air

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temperature and PAR collected in US-Bes were representative of the US-Ben and US-Bec sites. Access to US-Bes, US-Bec, and US-Ben sites was facilitated by the establishment of boardwalks during the Biocomplexity experiment in summer 2005 (Zona et al., 2009). These boardwalks allowed sampling across the sites while limiting disturbance. Data was collected every two meters in both US-Ben and US-Bec across 124-meters transects that parallel historical water table data collection (Zona et al., 2012), for a total of 62 plots in US-Ben and 62 in US-Bec.

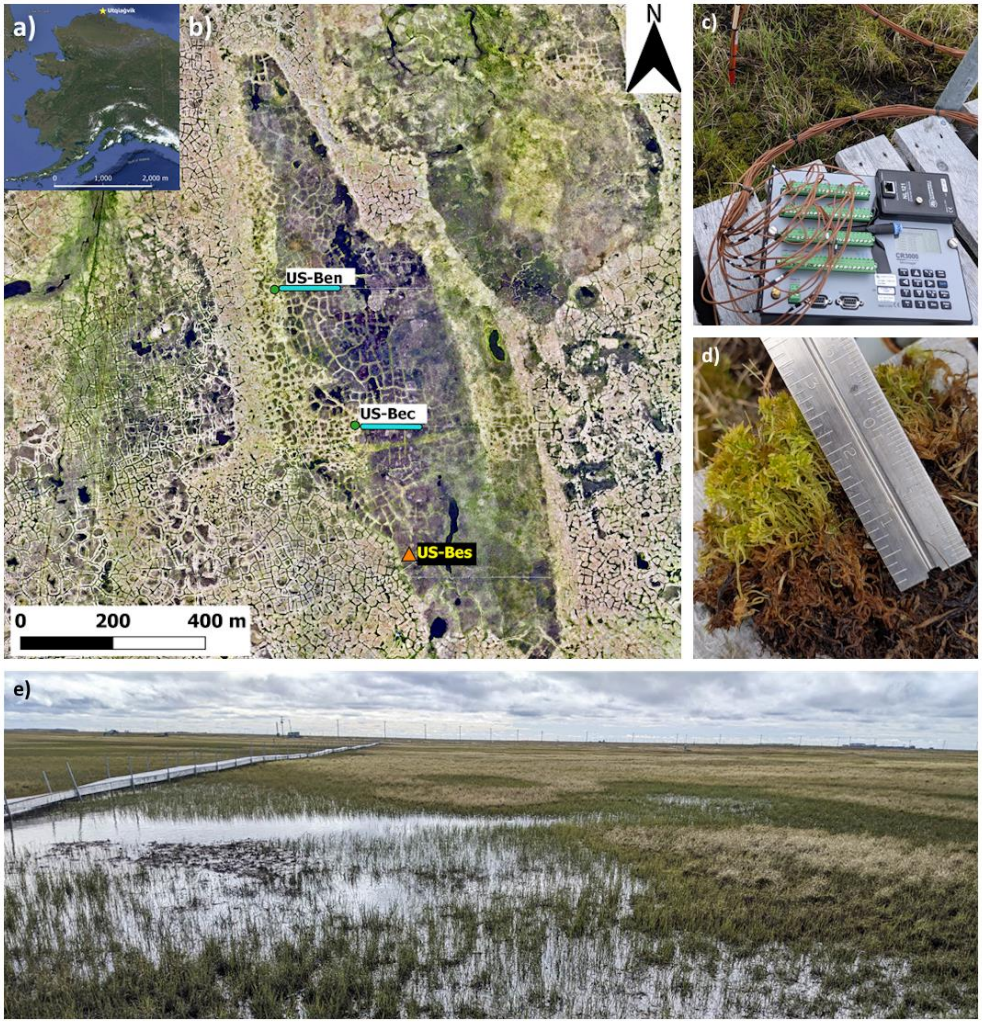

Figure 1: Study site: (a) Map of Alaska showing the general location of Utqiaġvik accessed via ©Google Earth Pro Copernicus/Landsat satellite imagery (2023). (b) A high-resolution orthorectified camera imagery mosaic acquired by the National

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Ecological Observatory Network (NEON) Airborne Observation Platform (AOP) highlighting the US-Ben and US-Bec transects (with the transect lengths highlighted in blue) and the US-Bes tower site. (c) The CR3000 datalogger with 21 thermocouples for belowground and air temperature recordings every centimetre. (d) A cross section of the moss layer showing the total (lowest brown point to surface) moss layer thickness and green (living) moss layer thickness. (e) A photograph of the research site, showing the boardwalk used for sampling.

2.2 Vegetation and environmental controls

The data collection was performed at 2-meter intervals along two 124-meter transects at US-Bec and US-Ben (Fig. 1b). In each of these plots we recorded the thickness of the total moss layer and the thickness of the green living moss layer. A previous in-depth vegetation analysis from our team showed that the general region where this data was collected was composed primarily of graminoids as the dominant vascular plant group, and by mosses such as *Sphagnum sp*. and *Drepanocladus sp.* (Davidson et al., 2016). We also collected data on the dominant moss genus at every point and found *Sphagnum sp.* and *Drepanocladus sp.* to be the dominant genera at our sites with most of the plots being *Sphagnum sp.* (N = 55) or some combination of predominantly *Sphagnum sp.* and *Drepanocladus sp.* (N = 46) and a limited number of plots with only *Drepanocladus sp.* (N = 21). The moss layer thickness and genus identification were recorded in sections of approximately 25-square cm (5 cm x 5 cm) in each of the 2-meter plots only once (i.e., the first week of July in 2021 for all plots and a subset of these plots on the first week of July in 2022) during the peak season (i.e., the first week of July to the second week of August 2021) to reduce the disturbance to the moss layer. These sections were carefully removed using a serrated knife trying to limit damage to surrounding vegetation. Afterwards, the thickness of the moss mat was measured with a ruler (Fig. 1d), and the samples were reinserted into the sampling locations.

In each of the plots for each of the sites (N=62 US-Ben, and N=62 for US-Bec) we also recorded moss and soil temperature every cm from 1 cm below the surface until 20 cm below ground on a weekly basis using type T thermocouples connected to a CR3000 datalogger (Campbell Scientific, Logan, UT, USA). These temperature profiles allowed us to determine how the presence and thickness of the moss layer affected the thermal difference across the moss and soil layers. These 21

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thermocouples were attached to a fiberglass probe, which facilitated insertion in the moss layer and soil. Each point was measured for approximately 3 minutes as the temperature readings stabilized within the first couple of minutes. We also collected soil water content (percent water) weekly in the first 5-cm of the moss or soil layer using a FieldScout TDR300 (Spectrum Technologies, Aurora, IL, USA) and 5-cm rods (Beringer et al., 2005; Hayashi et al., 2007; Hrbáček et al., 2020). The FieldScout was calibrated using local water samples to account for nutrients which may influence conductivity. Thaw depth and water table levels were also collected weekly in each of the sampling plots using a metal and wooden probe respectively with markings indicating intervals of 1-cm depths. Water table measurements were collected inside PVC pipes (with holes every 1 cm) previously installed along the transects (Zona et al., 2009; Zona et al., 2012) in each of the sampling locations. This data collection was repeated for a second field season in a subset of the plots (N = 20 in Summer 2022 vs. N = 124 in Summer 2021) to reduce disturbance to the sites; samples collected in these different years were compared, showing good agreement between the measured moss thickness in the 2021 and 2022 field seasons (R^2 = 91.82%, p-value < 0.001, 2022 Moss Thickness (cm) = 1.01967 * 2021 Moss Thickness (cm) + 0.228272).

Environmental variables collected by the eddy covariance US-Bes tower, included PAR, air temperature, local surface and subsurface soil temperature, relative humidity, wind speed, and net radiation. Elevation above sea level was collected in each of the sampling plots at US-Ben and US-Bec with a dGPS as reported in Zona et al. (2012). These measurements described the microtopography of each of the sampling plots and allowed us to test the role on microtopography on the environmental conditions, vegetation, and active layer development.

3 Statistical Analysis

All statistical analyses were conducted using R version 4.2.0 (R Core Team, 2022); the caret, leaps, and MASS packages (Kuhn, 2022; Lumley and Miller, 2022; Posit Team, 2022; R Core Team, 2022; Venables and Ripley, 2002), and stepwise multiple regressions and univariate regressions (both linear and nonlinear) were used to test for and model the relationships between the deepest (minimum given the negative sign) thaw depth (D_{thaw}) or the temperature difference between 1 and 15 cm

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147 belowground (dT_{1_15}) and environmental predictors, and to evaluate the collinearity in predictors. For the stepwise multiple
148 regressions, we tested the correlations between predictor variables, given that covarying variables can create issue when
149 included together in the same model; variables that met cutoff points ($-0.65 \geq r \geq 0.65$ and p-value < 0.05) were not included
150 together in the stepwise multiple regression models. Data from both 2021 and 2022 were aggregated by both site and distance
151 along each transect. The predictor variables included median, maximum, and minimum values of water table level, soil water
152 content, temperature at 15 cm belowground, 10 cm belowground, 5 cm belowground, 1 cm belowground, 5 cm aboveground,
153 green moss layer thickness, total moss layer thickness, and PAR. Deviation from the mean elevation (dz) was calculated as a
154 simple difference between each elevation point and the mean elevation. dT_{1_15} was calculated as the difference in temperatures
155 recorded at 1 cm belowground and 15 cm belowground; -15 cm was selected as it was the thaw depth most consistently
156 represented at most of the sites during the entire collection period. We used the median dT_{1_15} for each plot along each transect
157 for both 2021 and 2022, given that only one elevation value was recorded for each plot. We tested the influence of moss genus
158 on the statistical analysis but did not find it significant, so we did not include it in the results.

159 dT_{1_15} was modelled as a function of the median air temperature, dz, the soil water content, and both the midsummer green
160 and total moss layer thicknesses. We tested the relationship between D_{thaw} as a function of dz, median water table level, median
161 soil water content, maximum soil temperatures, median local air temperatures, 2021 midsummer green and total moss layer
162 thicknesses, median PAR, and dT_{1_15}. dT_{1_15} was regressed against the median water table level, median soil water content,
163 D_{thaw}, median local air temperatures, green and total moss layer thicknesses, median PAR, and dz. We tested the collinearity
164 of predictor variables; covarying variables ($-0.65 \geq r \geq 0.65$ and p-value < 0.05) were not included together in the stepwise
165 regression models, and each variable was also tested separately in a univariate model to rank their relative importance as
166 explanatory variable.

167 To evaluate the environmental controls on either thaw depth, and soil temperature (at -1 cm and -15 cm depth), we tested a
168 variety of non-linear regressions, including different order polynomial and logarithmic regressions, given that ecological
169 processes can have complex relationships (Zona et al., 2023). However, when evaluating these models, we did not find an
170 ecological explanation for the statistical models with the highest explanatory power which were at the time third order

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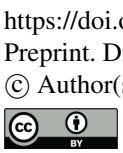
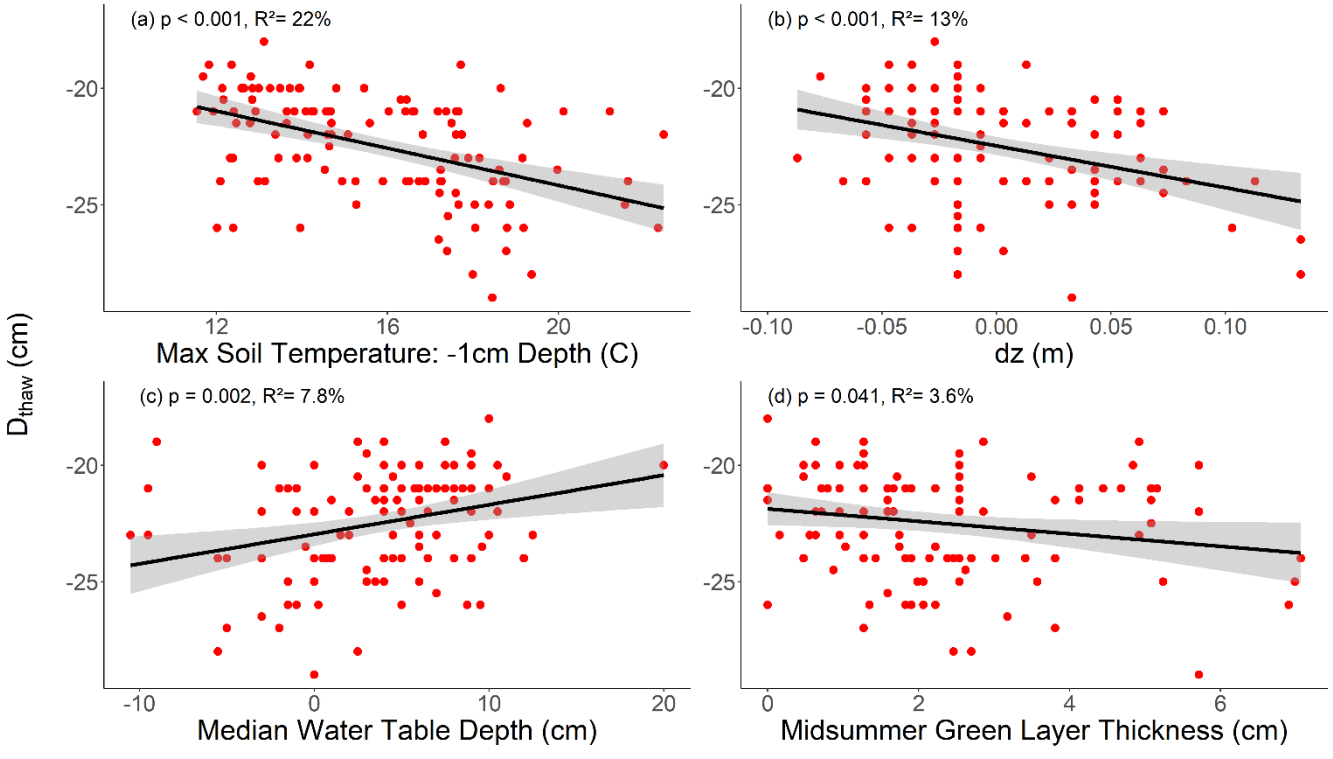


171 polynomial models. Therefore, we applied piecewise regressions to test the occurrence of a breakpoint in the linear regressions,
172 using the segmented package in R (Muggeo, 2003; 2008). When the occurrence of a breakpoint was significant, we included
173 separate linear regressions for the two datasets separated by the breakpoint.

174

175 **4 Results**



176

177 **Figure 2: Relationship between the deepest thaw depth (D_{thaw}) and the indicated variables for the entire study period (summer 2021**
178 **and 2022) and for both study sites combined, demonstrating a) a negative relationship between the maximum soil temperature at -**
179 **1 cm depths and deepest thaw depth, b) a negative relationship between the deviation from the mean elevation (dz) and the deepest**
180 **thaw depth, c) a positive relationship between water table level and the deepest thaw depth, and d) a negative relationship between**
181 **green moss layer thickness during the middle of the 2021 summer and the deepest thaw depth.**

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Several environmental variables were strongly correlated (Table S1). The strongly correlated variables ($-0.65 \geq r \geq 0.65$ and p-value < 0.05) were not included together in the regression models of D_{thaw}, dT_{1_15}, and soil temperature at -1 and -15 cm. See Table S1 for details on the correlation coefficients and p-values among those variables.

The maximum temperature for each measurement point aggregated across both years at -1 cm belowground had the highest explanatory power in the stepwise model of the deepest thaw depth for each measurement point aggregated across both years (p-value < 0.001, R^2 = 22%, Akaike information criterion (AIC) = 500, Table 1). A similar result was obtained from the comparison of univariate regressions, where the maximum soil temperature at -1 cm had the highest explanatory power on the variability of thaw depth. The stepwise model for dT_{1_15} identified the median soil water content, deepest thaw depth, and dz as the only significant variables among the variables tested (i.e., median soil water content, the deepest thaw depth, median air temperature, total moss layer thickness, and the dz, p-value < 0.001, R^2 = 45%, AIC = 525, Table 2). A complete list of the statistics of the univariate models are included in Tables 3 and 4.

Table 1: Statistics of the stepwise linear regression model of the deepest thaw depth (cm) for summer 2021 and 2022 across all the plots, which selected the maximum soil temperature at -1 cm depth as the variable with the highest explanatory power and the only significant predictor. Included are the regression coefficient, R^2, p-value, the Akaike information criterion (AIC).

Deepest Thaw Depth				
Variable	**Coefficient**	**R^2**	***p*-value**	**AIC**
Maximum Soil Temperature – -1 cm	-0.40	22%	< 0.001	500

Table 2: Statistics of the stepwise linear regression model of the temperature difference between the 1 and 15 cm depths (dT_{1_15}) which selected the following variables as those with the highest explanatory power. Included are the coefficients, R^2, p-values, and the Akaike information criterion (AIC). The overall *p*-value for the entire model was < 0.001.

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Temperature Difference				
Variable	**Coefficient**	**R^2**	***p*-value**	**AIC**
Median Soil Water Content	-0.09		0.003	
Deepest Thaw Depth	-0.33	45%	0.001	525
Deviation from the Mean Elevation (dz)	27.94		< 0.001	

After ranking and comparing all models including the variables listed in Table S1, maximum soil temperatures at -1 cm, dz, median water table level, and green moss layer thickness explained the largest percentage of variation in the deepest thaw depth (Fig. 2). Soil temperature alone explained about 22% of the variability in the deepest thaw depth (Table 1). Similarly, dT_{1_15} was mostly explained by the dz, soil water content, and green and total moss layer thicknesses (Fig. 3). The dz had the highest explanatory power explaining 34% of the variability in dT_{1_15} (Fig. 3), and the addition of soil water content and the deeper thaw depth increased the explanatory power to 45% (Table 2).

Table 3: Statistics of the univariate simple linear regressions of the deepest thaw depth and the indicated variables including the entire dataset. The variables are ranked based on the simple linear model's R^2 value. Included are the R^2, p-value, the Akaike information criterion (AIC), and the breakpoint if statistically significant.

Deepest Thaw Depth				
Predictor Variable	**Breakpoint**	**R^2**	**p-value**	**AIC**

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Maximum Soil Temperature – -1 cm	N/A	Linear: 22%	Linear: < 0.001	Linear: 500
Belowground Temperature Difference	N/A	Linear: 19%	Linear: < 0.001	Linear: 504
Median PAR	N/A	Linear: 13%	Linear: <0.001	Linear: 512
Difference from Mean Elevation	N/A	Linear: 13%	Linear: < 0.001	Linear: 513
Median Water Table Level	N/A	Linear: 7.8%	Linear: 0.002	Linear: 519
Maximum Soil Temperature – 5 cm	N/A	Linear: 7.1%	Linear: 0.004	Linear: 520
Green Moss Layer Thickness	N/A	Linear: 3.6%	Linear: 0.041	Linear: 524

211

212 **Table 4. Statistics of the univariate simple linear and piecewise regressions of the temperature difference (dT_{1_15}) and the indicated**
213 **variables including the entire dataset. Included are the R^2, p-value, the Akaike information criterion (AIC), and the breakpoint if**
214 **statistically significant. The significance in the difference between models is included in the column "ANOVA" only when the p-**
215 **value was less than 0.05 (e.g., the significance in the difference between the linear (L) and the piecewise (PW) was 0.005 for the**
216 **median local air temperature). The best models are highlighted in bold.**

Thermal Difference

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Variable	Breakpoint	R^2	p-value	AIC	ANOVA
Median PAR	N/A	**Linear: 43%**	**Linear: < 0.001**	**Linear: 523**	
Median Local Air Temperature	x = 12.6	Linear: 41%	Linear: < 0.001	Linear: 528	
		x < 12.6: 12%	**x < 12.6: < 0.001**	**x < 12.6: 539**	**L-PW: 0.005**
		x > 12.6: 50%	**x > 12.6: 0.049**	**x > 12.6: 36.7**	
Median Water Table Level	x = -1.1	Linear: 40%	Linear: < 0.001	Linear: 530	
		x < -1.1: 6.3%	x < -1.1: 0.330	x < -1.1: 67.3	**L-PW: < 0.001**
		x > -1.1: 42%	**x > -1.1: < 0.001**	**x > -1.1: 448**	
Difference from Mean Elevation	N/A	**Linear: 34%**	**Linear: < 0.001**	**Linear: 541**	
Minimum (Deepest) Thaw Depth	N/A	**Linear: 19%**	**Linear: < 0.001**	**Linear: 566**	
Median Soil Water Content	x = 74.4	Linear: 15%	Linear: < 0.001	Linear: 570	
		x < 74.4: 0.36%	x < 74.4: 0.725	x < 74.4: 167	**L-PW: < 0.001**
		x > 74.4: 19%	**x > 74.4: < 0.001**	**x > 74.4: 381**	
Green Moss Layer Thickness	x = 3.1	Linear: 14%	Linear: < 0.001	Linear: 572	
		x < 3.1: 21%	**x < 3.1: < 0.001**	**x < 3.1: 439**	**L-PW: < 0.001**

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		x > 3.1: 4.6%	x > 3.1: 0.294	x > 3.1: 125
Total Moss Layer Thickness	N/A	**Linear: 7.0%**	**Linear: < 0.001**	**Linear: 581**

217

218 We found a negative relationship between the green moss layer thickness and deepest thaw depth (Fig. 2d, *p*-value = 0.041,
219 R^2 = 3.6%) and a positive relationship between the green (Fig. 3c, *p*-value < 0.001, R^2 = 21% when the green layer thickness
220 was below 3.1 cm) or total layer thickness (Fig. 3d, *p*-value < 0.001, R^2 = 7.0%) and dT_{1_15}. A positive relationship was
221 observed between green (Fig. 4b, *p*-value < 0.001, R^2 = 9.7%) or total layer thickness (Fig. 4a, *p*-value = 0.031, R^2 = 4.0%)
222 and the maximum soil temperature at the surface, but a negative relationship between increasing green (Fig. 4e, *p*-value =
223 0.002, R^2 = 7.9%) (or total layer thickness, Fig. 4d, *p*-value = 0.006, R^2 = 6.3%) and the maximum soil temperature at -15 cm
224 depths. We observed a negative relationship between the deepest thaw depth and dz (Fig. 2b, *p*-value < 0.001, R^2 = 13%) and
225 a positive relationship between dT_{1_15} and dz (Fig. 3a, *p*-value < 0.001, R^2 = 34%). We noticed a negative relationship between
226 soil temperatures at -1 cm depths and deepest thaw depth (Fig. 2a, *p*-value < 0.001, R^2 = 22%). We observed a positive
227 relationship between increasing green moss layer thickness (Fig. 6b, *p*-value < 0.001, R^2 = 13%), or total moss layer thickness
228 (Fig. 6a, *p*-value < 0.001, R^2 = 15%), and dz.

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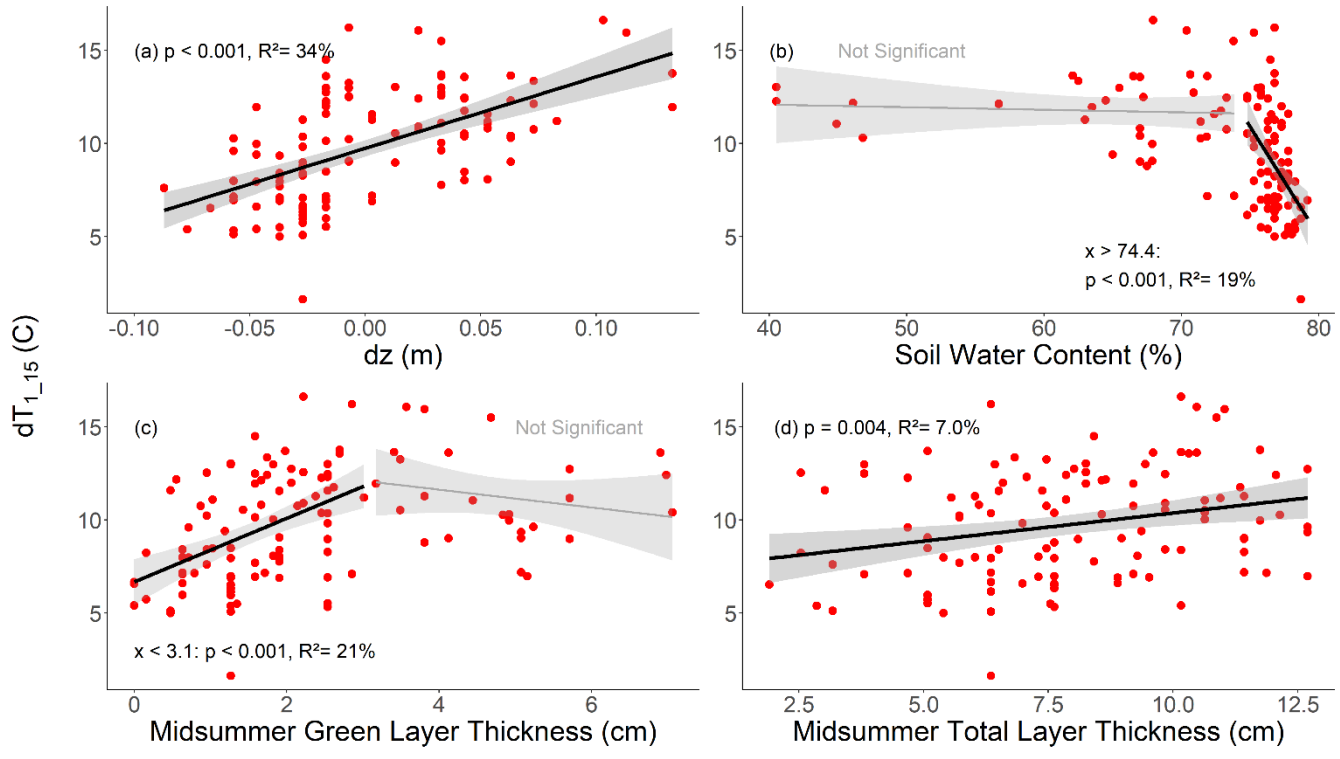

Figure 3: Relationship between the temperature difference (between soil temperature at -1 cm and at -15 cm belowground) and the indicated variables for the entire sampling period (summer 2021 and 2022) across all the sampling plots, showing a) a positive relationship between the deviation from the mean elevation (dz) and the temperature difference, b) a negative relationship between soil water content and the temperature difference when soil water content is greater than 74.4%, c) a positive relationship between the green moss layer thickness during the middle of the 2021 summer and the temperature difference when the green moss layer thickness was less than 3.1 cm, and d) a positive relationship between the total moss layer thickness and the temperature difference.

Soil water content (soil water content) had a negative relationship with temperature difference when soil water content was greater than 74.4% (Fig. 3b, *p*-value < 0.001, R^2 = 19%) and no significant relationship below that threshold. While soil temperatures at -1 cm were negatively associated with soil water content past a threshold of 74.3% (no significant relationship was noted prior to this threshold), the temperature deeper in the soil (15 cm below ground) was positively correlated with soil water content past a soil water content of 76.4% (Fig. 4). A positive relationship was seen between water table level and deepest thaw depth (Fig. 2c, *p*-value = 0.002, R^2 = 7.8%).

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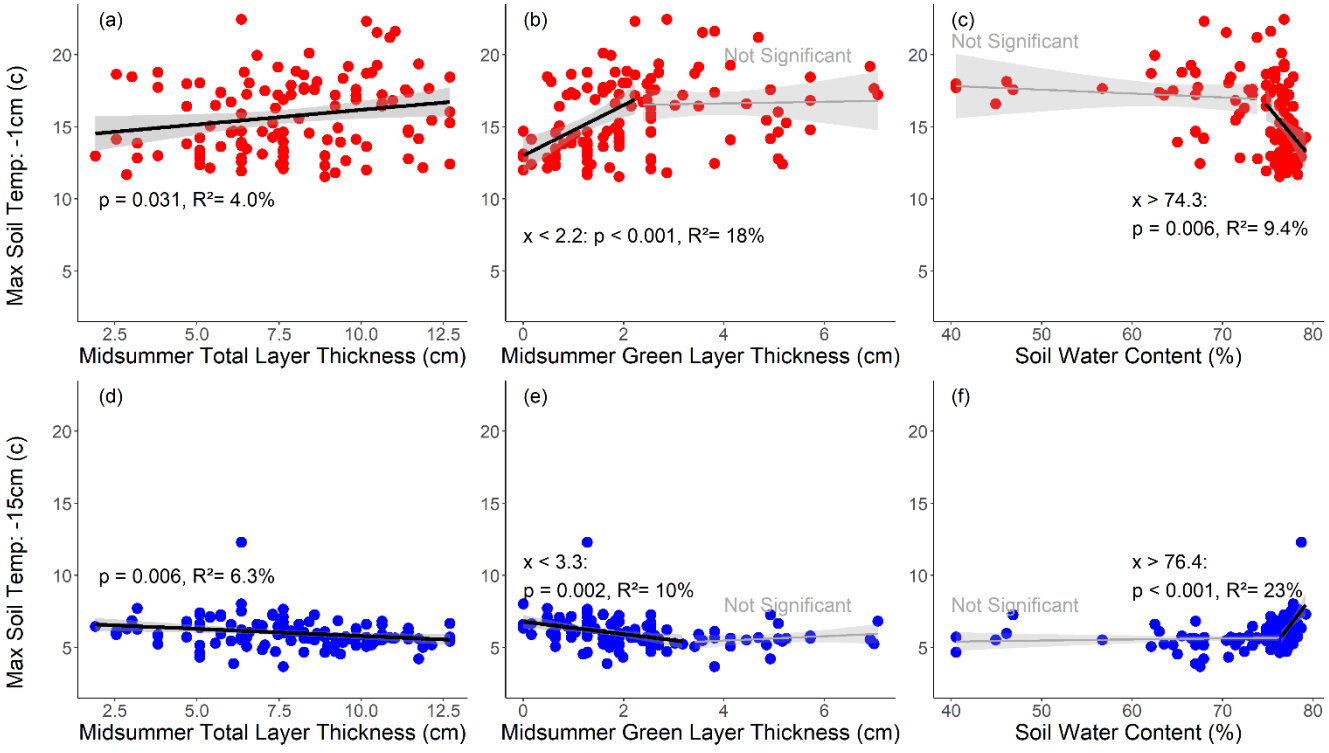

Figure 4: Relationships between the maximum soil temperature and the indicated variables for the entire periods of measurements aggregated (summer 2021 and 2022), and for all the sampling plots. While green and total moss layer thicknesses was positively associated with higher temperatures closer to the surface (a and b), thicker moss layers were associated with cooler temperatures at deeper depths (d and e). As the percent soil water content increased, the superficial temperatures decreased (c) but temperature in deeper soil layers increased (f).

Given the significant relationship between soil temperature and relative elevation, we conducted a two-sample t-test to compare surface temperatures at -1 cm depth across both transects in areas above and below the mean elevation. There was a significant difference in temperature between areas above the mean elevation (4.2 cm) and below the mean elevation. The median temperature of higher elevation areas was (M = 17.3 ± 4.3 ˚C) and those below the mean elevation (M = 14.8 ± 4.9 ˚C); t(107.85) = 5.8, p < 0.001, Fig. 5. Another two-sample t-test showed percent soil water content was lower in areas with elevations above the mean elevation (M = 70.6 ± 17.4%) compared with areas below the mean elevation (M = 74.7 ± 12.8%) (p = 0.007), as shown in Fig. 5, and summarized in Fig. 7.

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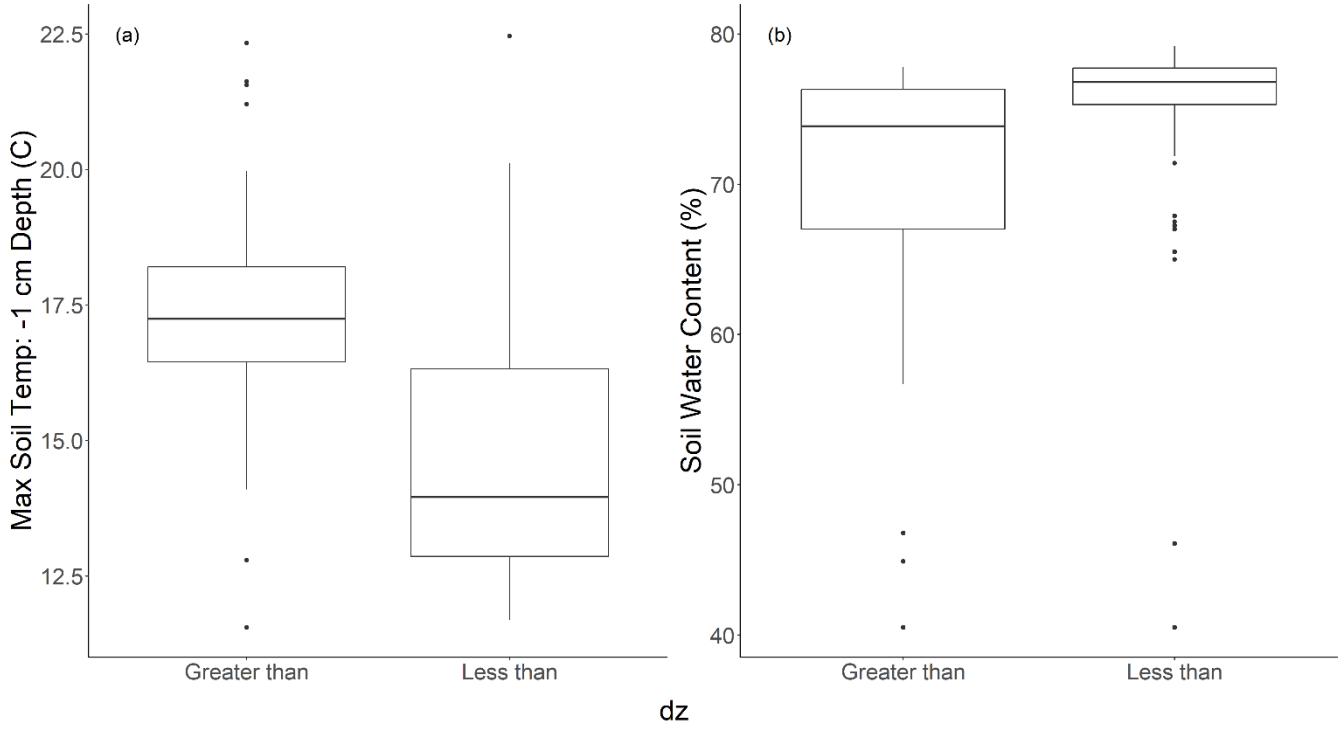

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256

257 **Figure 5: Comparison of (a) maximum soil temperature ranges at a -1 cm depth and (b) soil water content based on the deviation**
258 **from the mean elevation (dz) grouped by areas greater than and less than the mean elevation for the entire periods of**
259 **measurements (summer 2021 and 2022), and for all the sampling plots. a) Areas with higher elevations had a higher observed**
260 **average soil temperature. b) Areas with lower observed average soil water content.**

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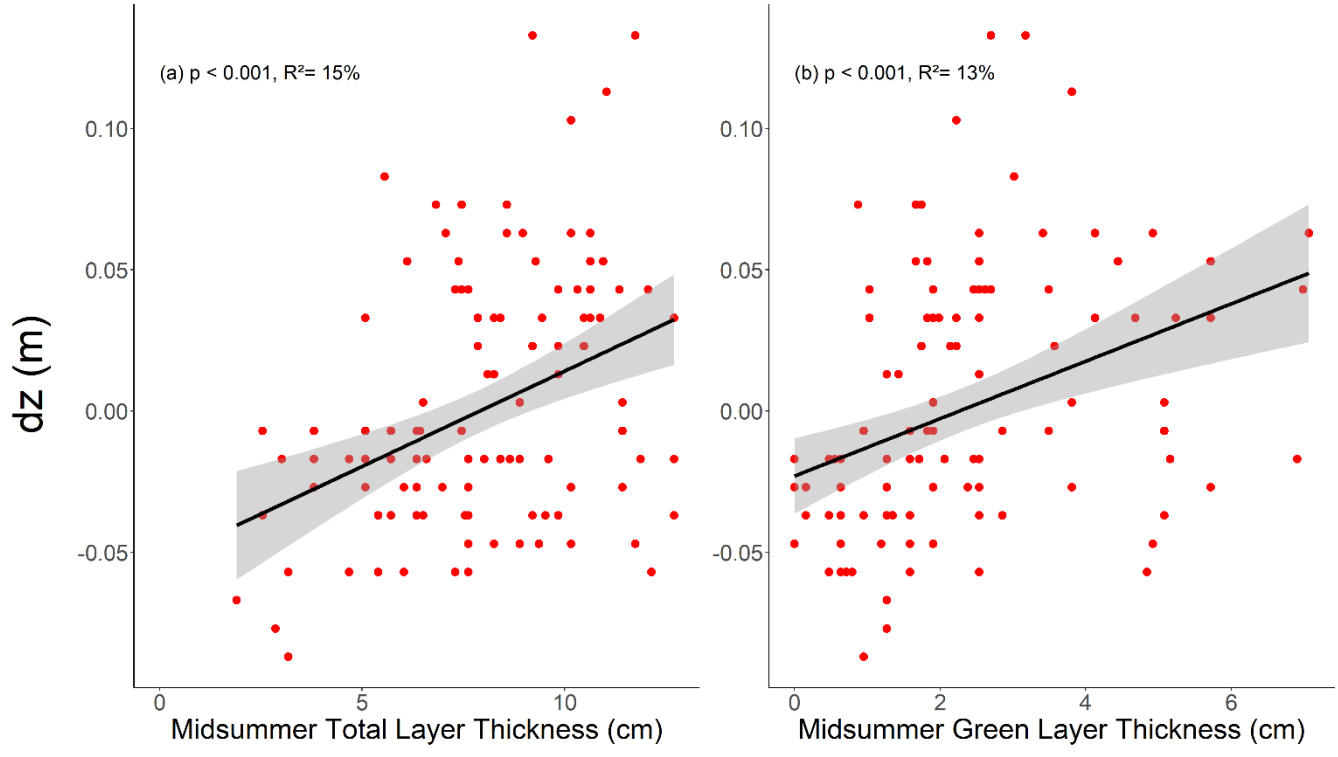

Figure 6: Relationships between (a) increasing midsummer (2021) total layer thickness or (b) midsummer (2021) green layer thickness and the deviation from the mean elevation (dz) suggesting the occurrence of a thicker moss layer in higher topographic areas.

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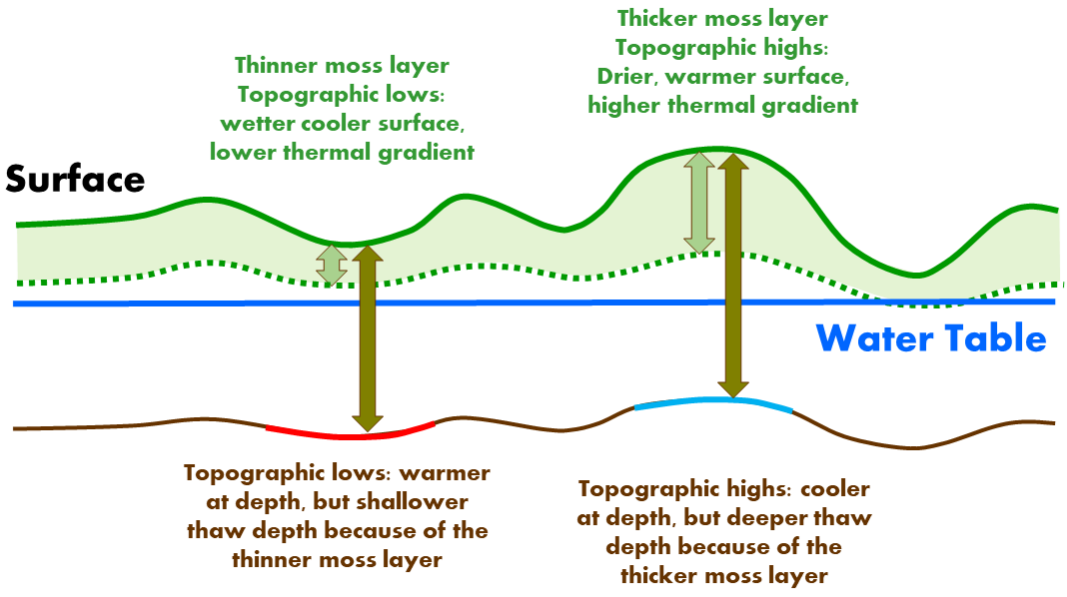

Figure 7: A visual summary of the relationships highlighted by the regression analyses highlighting how thinner moss layers have a seemingly shallower depth of thaw and lower surface but higher belowground temperatures as opposed to thicker moss layers that have higher surface temperatures and seemingly deeper depth of thaw but lower belowground temperatures.

5 Discussion

We found that moss layer thickness, microtopography, and soil moisture exerted important controls on soil temperature profiles. Microtopographic lower elevation areas had higher soil water content and lower temperature gradients than topographic highs. Thicker green moss layers co-occurred with cooler deep (-15 cm below the surface) soil temperature, which is consistent with a higher thermal insulation (Beringer et al., 2005; Fisher et al., 2016; Hrbáček et al., 2020; Soudzilovskaia et al., 2017). Thicker mosses insulate the soil (Blok et al., 2011; Chadburn et al., 2015; Heijmans et al., 2022; Hrbáček et al., 2020; Park et al., 2018) as shown by the cooler deeper soil temperature, even with warmer near surface (i.e. -1 cm) temperatures. Moss thickness was higher in higher elevation areas possibly because their higher surface temperature

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might have stimulated moss growth, in these temperature limited ecosystems (Harley et al., 1989; Bengtsson et al., 2021). Near surface temperature was the main control on thaw depth, consistent with previous studies (Dafflon et al., 2017; Schuur et al., 2015). Soil moisture was also a very relevant control on soil temperature, with opposite relationships for the near surface and deeper soil temperatures. Cooler near surface temperature co-occurred with higher soil moisture and could be explained by the higher evaporative cooling of a wetter moss layer (Heijmans et al., 2004a, b) and by the higher thermal conductivity and rates of heat transfer to lower soil layers. The higher thermal conductivity and heat penetration in wetter soils could also explain the higher soil temperature in deeper soil layers (-15 cm) (Soudzilovskaia et al., 2013; Fisher et al., 2016; Hrbáček et al., 2020; Soudzilovskaia et al., 2017; Curasi et al., 2016; Hinkel and Nelson, 2003; Hinkel et al., 2001; Shiklomanov et al., 2010).

We observed a significant breakpoint, and different linear regressions for the shallower (~2-3 cm) than deeper green (living) moss layers in describing the relationship between green moss layer thickness and temperatures at -1 cm and -15 cm. This would suggest that the top living layer of mosses has the most relevant role in regulating soil temperature. The larger importance of the top moss layer in insulating the soil is consistent with the reported significant relationship between the top ~15-20 cm of the moss layer moss layer thickness and permafrost thaw (Douglass et al., 2008). The significance in the breakpoint was only observed for the relationship between the green layer thickness and soil temperatures (at -1 cm and at -15 cm depth), while no significant breakpoint was observed in the relationship between the total moss thickness and soil temperatures. This is likely because of the higher water retention of the handlike structures (papillae) present in the green moss layer (Clymo, 1970; Dykas, 2018), which could increase their importance in regulating the heat transfer. Similarly, the lack of a significant response between temperatures at -1 and -15 cm and soil moisture until approximately 74.3% and 76.4% respectively, is consistent with the observed exponential relationship between the thermal conductivity and relative moisture content reported for bryophytes and lichen in permafrost ecosystems, with a steeper relationship at higher moisture levels (Porada et al., 2016). Overall, the relationship between deviation from mean elevation (dz) and moss thickness together with the relationships between moss thickness and -15 cm temperatures confirms that microtopography dominated ecosystem functioning in these arctic tundra ecosystems (Zona et al., 2011; Wilkman et al., 2018).

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303 **6 Conclusion**

304 The results of this study support the importance of mosses and soil moisture to insulate permafrost. A thicker moss layer is
305 associated with warmer near surface temperature but with cooler deeper soil temperature and larger thermal gradient because
306 of higher thermal insulation. Future studies should better define the role of moisture on heat penetration to deeper soil layers,
307 across a wider range of soil moisture, as this study was mostly focused on very wet ecosystems. Additionally, a wider range
308 of moss thickness together with the role of other vegetation types should be considered when modelling the soil temperature
309 and thaw depth to understand the controls on the integrity of permafrost.

310

311 **7 Data Availability**

312 Donatella Zona, & Kevin Gonzalez. (2023). *Environmental and vegetation control on active layer and soil temperature in an*
313 *Arctic tundra ecosystem in Alaska*. Arctic Data Center. urn:uuid:0e00e7c3-d2a1-4065-bba6-3c664b983990.

314

315 **8 Author Contribution**

316 DZ and WCO acquired funding to support the project leading to this publication. DZ conceptualized the project with KG
317 conducting the investigation process involving data collection. KG conducted formal analysis with contributions from DZ
318 and TB. KG prepared the manuscript with contributions and critical review from all co-authors. All co-authors provided
319 feedback on the data analysis and contributed to writing the manuscript.

320

321 **9 Competing Interests**

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322 The authors declare that they have no conflict of interest.

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330 Commerce.

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