7-23-2021

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To cite this article: Jiaying He *et al* 2021 *Environ. Res. Lett.* **16** 085004

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
17 January 2021

REVISED
7 June 2021

ACCEPTED FOR PUBLICATION
6 July 2021

PUBLISHED
23 July 2021



LETTER

# Impacts of wildfire and landscape factors on organic soil properties in Arctic tussock tundra

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**Keywords:** Arctic tussock tundra, wildfire, soil organic layer thickness, soil moisture, soil temperature

Supplementary material for this article is available online

## Abstract

Tundra ecosystems contain some of the largest stores of soil organic carbon among all biomes worldwide. Wildfire, the primary disturbance agent in Arctic tundra, is likely to impact soil properties in ways that enable carbon release and modify ecosystem functioning more broadly through impacts on organic soils, based on evidence from a recent extreme Anaktuvuk River Fire (ARF). However, comparatively little is known about the long-term impacts of typical tundra fires that are short-lived and transient. Here we quantitatively investigated how these transient tundra fires and other landscape factors affected organic soil properties, including soil organic layer (SOL) thickness, soil temperature, and soil moisture, in the tussock tundra. We examined extensive field observations collected from nearly 200 plots across a wide range of fire-impacted tundra regions in AK within the scope of NASA's Arctic Boreal Vulnerability Experiment. We found an overall shallower SOL in our field regions (∼15 cm on average) compared to areas with no known fire record or the ARF (∼20 cm or thicker), suggesting that estimations based on evidence from the extreme ARF event could result in gross overestimation of soil organic carbon (SOC) stock and fire impacts across the tundra. Typical tundra fires could be too short-lived to result in substantial SOL consumption and yield less robust results of SOL and carbon storage. Yet, repeated fires may amount to a larger amount of SOC loss than one single severe burning. As expected, our study showed that wildfire could affect soil moisture and temperature in the tussock tundra over decades after the fire, with drier and warmer soils found to be associated with more frequent and severe burnings. Soil temperature was also associated with vegetation cover and air temperature.

## 1. Introduction

Soil organic layer (SOL) is a crucial component controlling the physical and thermal mechanisms of vegetation growth, soil decomposition, and carbon balance across permafrost-dominated landscapes of the High Northern Latitudes (HNLs; Harris 1987, Harden *et al* 2006, Drobyshev *et al* 2010, Jiang *et al* 2015, Trugman *et al* 2016). Estimates in North America reported a total of 98.2 Gt soil organic carbon (SOC) pool in the Arctic, with 19.2 Gt in the surface layer, 42.1 Gt in the subsurface active layer, and 36.9 Gt in the permafrost (Ping *et al* 2008). Specifically, the tundra SOC amount in the North Slope of AK ranges between 16 and 94 kg C m$^{-3}$ (Michaelson *et al* 1996). Physical properties of the SOL are strongly associated with ecosystem functioning and carbon balance in the HNL. SOL thickness is an important indicator of the SOC storage in Alaskan tundra, given their strong positive relationships (Pastick *et al* 2014, Baughman *et al* 2015). It also affects the establishment and growth of boreal forests (Lafleur *et al* 2015, Trugman *et al* 2016) and alters soil temperature and moisture (Kasischke and Johnstone 2005). Furthermore, soil temperature and moisture can influence the hydrological and thermal processes in the SOL and permafrost (Fisher *et al* 2016, Schuh *et al* 2017). Therefore, monitoring those can enhance our understanding of soil carbon dynamics and permafrost degradation in the Arctic.

As the primary disturbance agent in the HNL, wildfire is a major driver affecting the organic soils and leading to soil carbon release and permafrost degradation. Fires can consume the organic soils and release a large amount of SOC directly through the combustion of the carbon-dense soil organic matter (SOM; Kasischke and Johnstone 2005, Verbyla and Lord 2008, Mack *et al* 2011, Kasischke and Hoy 2012, Bret-Harte *et al* 2013). Additionally, post-fire loss of organic soils can change soil water content and temperature and increase the depth of the active layer (Viereck 1982, Kasischke and Johnstone 2005, Potter and Hugny 2020). Through the interaction with fire, other environmental factors such as vegetation cover and drainage can also influence organic soil properties in fire-impacted ecosystems of the HNL (Wang *et al* 2000, Benscoter *et al* 2011, Pastick *et al* 2014). Thus, understanding fire impacts on the organic soils is critical for improving our knowledge about the Arctic future under the observed and projected warming.

Though less studied than that of the boreal forests, the SOL in the tundra plays an essential role in affecting the carbon balance and ecosystem functioning. Despite the low aboveground biomass accumulation in the tundra, wildfire has the potential to release large amounts of carbon primarily due to the widespread carbon-dense SOL (Scharlemann *et al* 2014). With rapid warming in the Arctic (Hinzman *et al* 2005, Loranty and Goetz 2012, Myers-Smith *et al* 2015, Berner *et al* 2020), climate change can further affect the tundra through its direct and immediate impacts on fire. Projections have shown that meteorological conditions in the tundra are likely to be more supportive of fire occurrence in the coming decades and subsequently increase burned area (Krause *et al* 2014, French *et al* 2015, Young *et al* 2017). Tundra soil carbon could also become more vulnerable to fire in the future (Baughman *et al* 2015, Jiang *et al* 2015). Since tundra ecosystems are not highly productive, such carbon release would not be counterbalanced after burning. With the potential increase in fire activity under climate warming (French *et al* 2015), tundra is likely to switch from a carbon sink into a net source with rapid consumption of the remaining SOC in the future.

Previous efforts have elaborated on understanding fire impacts on SOC in the tundra. More subtle effects on other soil properties are less understood, though short-term increases in soil moisture and temperature were found after burning in the tundra (Liljedahl *et al* 2007, Rocha and Shaver 2011, Jandt *et al* 2012). Nevertheless, most of them came from limited observations measured within the 2007 Anaktuvuk River Fire (ARF), which may not describe the general patterns of tundra fires. While this fire was unusually severe and burned 1039 $km^2$ for 2 months (Jones *et al* 2009), over 70% of the tundra fires are short-lived (often lasting less than 10 d), less severe, and smaller than 20 $km^2$ (French *et al* 2015). Measurements collected in the ARF tended to have thicker SOL or deeper SOL reduction than those from other tundra sites (Baughman *et al* 2015, de Baets *et al* 2016). Given the strong positive relationship between SOL thickness and SOC storage, the total storage or fire-induced loss of SOC may be overestimated for the tundra. An additional feature of observed tundra fires not captured by the ARF is a high reburn frequency with a small mean fire return interval of 10–20 years (Rocha *et al* 2012, French *et al* 2015). For instance, an area of 1904 $km^2$ in the Seward Peninsula burned more than once between 1950 and 2011 (Rocha *et al* 2012). Since fire has the potential to convert tundra to a reburn-prone landscape in the future (Rupp *et al* 2000), the lack of field observations on smaller and repeated tundra fires limits our understanding of their long-term impacts on organic soils.

Our primary goal is to explore the impacts of environmental factors, especially wildfire, on organic soil properties (i.e. SOL thickness, soil moisture, and soil temperature) in Arctic tussock tundra. To achieve this goal, we conducted a three-season field campaign from 2016 to 2018 within the scope of NASA's Arctic Boreal Vulnerability Experiment (ABoVE). We obtained an extensive range of measurements across a wide range of typical fire events in fire-prone tundra. Here we hypothesized that: (a) SOL thickness would reduce given more frequent and severe fire; (b) soil moisture would decrease with poor drainage and more frequent and severe burning; (c) organic soils would increase with denser vegetation cover, higher air temperature, and more frequency and severe burning; (d) soil properties would gradually recover long after burning.

## 2. Materials and methods

### 2.1. Study area

We focused on two representative tussock tundra regions in the Noatak River Valley (Noatak) and Seward Peninsula (Seward) of AK (figure 1(a)). Both sites have experienced rich wildfire records in history (French *et al* 2015) but were less studied than the ARF. With a relatively warmer and drier climate and more available surface fuels than the North Slope, these regions can be more vulnerable to burning in the future. Under rapid climate warming, shrubification, treeline shift, and increasing permafrost thawing in these regions may also alter the soil carbon dynamics apart from fire (Schuur *et al* 2009, Berner *et al* 2020).

Both regions share the same bioclimate subzone, vegetation species, topography, and substrate soil chemistry (Walker *et al* 2005). Located in the Brooks Range ecoregion (Nowacki *et al* 2003), the Noatak has a dry polar climate with widespread permafrost underneath the surface (Alaska Department of Fish

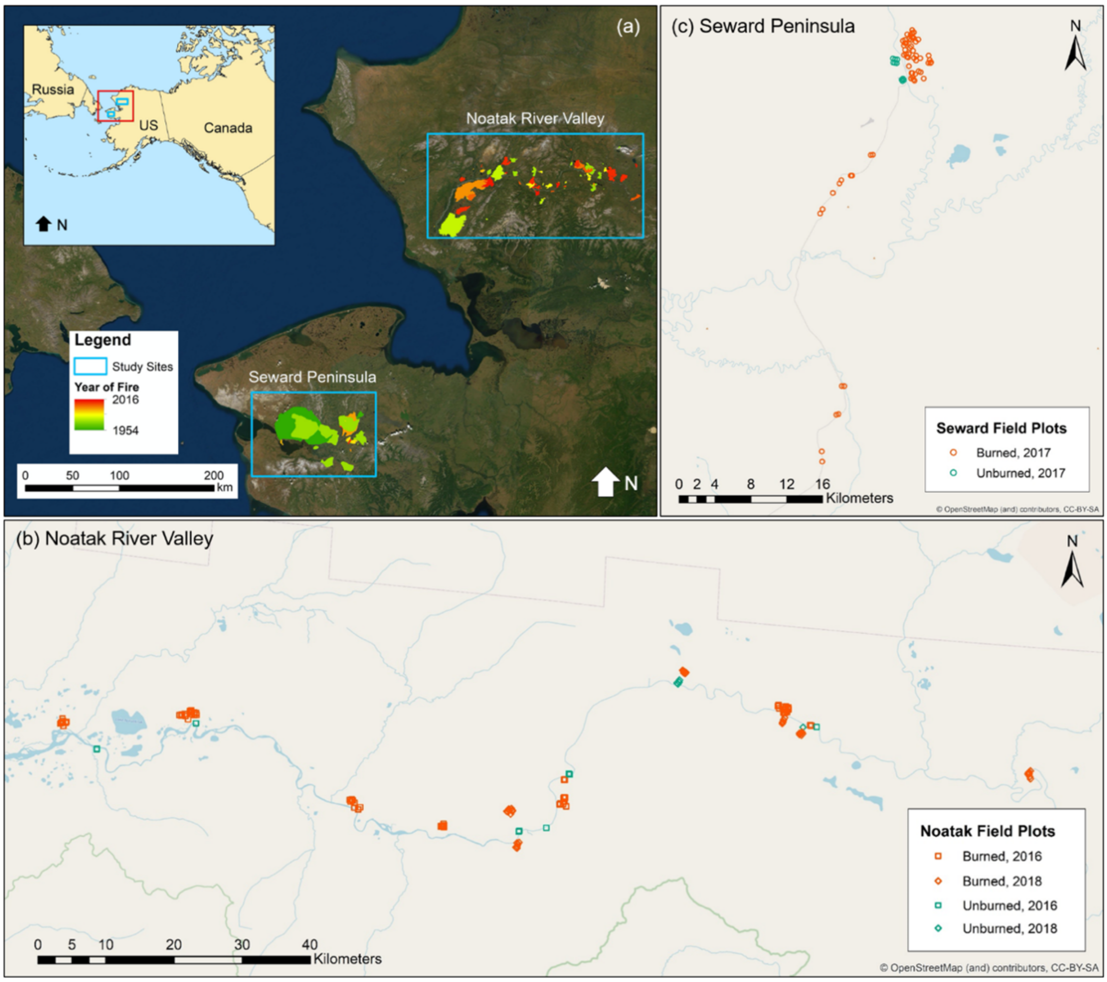


**Figure 1.** Study area and plots visited in our field campaigns: (a) fire records from AK Large Fire Database (ALFD) in the Noatak and Seward; (b) field plots visited in the Noatak River Valley in 2016 and 2018; (c) field plots visited in the Seward Peninsula in 2017.

and Game 2006). It is mainly covered by mixed shrub-sedge tussock tundra, with tall shrubs and willow thickets along rivers. Characterized by a moist polar climate, the Seward typically has wet and organic soils underlain by continuous permafrost. Vegetation communities like alpine dryas-lichen and moist sedge-tussock tundra dominate this region, while ericaceous and willow-birch shrubs in better-drained areas.

### 2.2. Field data collection

We conducted three field trips between late July and mid-August from 2016 to 2018 to collect a large and diverse set of measurements across various burning conditions (figure 1). To maximize the cost-efficiency of data collection, we designed a stratified randomized sampling scheme with different combinations of fire frequency, burn age, burn severity, and drainage type.

Although ALFD has maintained historical wildfire records since the 1940s (Olson *et al* 2011), these fire perimeters, particularly the older ones, only provide coarse delineations of the burned scars, which may introduce errors in determining fire-related variables. Therefore, we used ALFD as a reference to identify fire events and further mapped the detailed burned extents with Landsat imagery to verify the burned/unburned status (supplementary section 1.1.1 (available online at stacks.iop.org/ERL/16/085004/mmedia)). For each fire in the ALFD, we examined all available multispectral Landsat archives to select one cloud/snow-free image acquired during the growing season after burning. For fires that occurred after 1982, normalized burn ratio (NBR; García and Caselles 1991) was calculated for its effectiveness in identifying tundra burned areas (Loboda *et al* 2013). We classified its NBR into burned and unburned using a series of thresholds and selected the one that most resembled the actual burned extent as observed from the imagery. For earlier fires, however, only multispectral scanner (MSS) imagery is available and the lack of short-wave infrared bands of the MSS precluded the use of NBR. Although Chen *et al* (2020) recommended using global environmental monitoring index as a replacement of NBR for MSS data, we were not able to incorporate this index for field data collection since this study was published after our field trips. Instead, we adopted Tasseled-Cap Greenness (Kauth and Thomas 1976) following the NBR-based identification for burned area mapping with MSS data.

Fire frequency and burn age (number of years since the most recent burn) were directly derived from the mapping results.

To quantify burn severity (of the most recent burn), we adopted the categorical burn severity index (BSI) for its description of the ground surface (Bourgeau-Chavez *et al* 1994, 2020, Loboda *et al* 2013). BSI was calculated with NBR using an empirical method explicitly developed for the tundra (Loboda *et al* 2013). Ranging between 1 and 4, it represents the burn severity levels from the lowest to the highest, respectively (supplementary section 1.1.1). Since no feasible way exists for calculating BSI with MSS data, we were unable to provide it for older fires and excluded plots within those fires from statistical analyses related to burn severity. Drainage types were further classified as (a) flat-poorly drained, (b) flat-drained, (c) moderately-drained, and (d) well-drained (supplementary section 1.1.2), based on Kasischke and Hoy (2012).

We then identified 24 individual fires spanning a range of fire seasons between 1971 and 2015. Random points were generated across these fires based on the combinations of fire-related properties and drainage. We established 10 × 10 m plots using the randomized points as a south-east corner to collect a full suite of variables (supplementary section 1.1.3). SOL thickness was measured within a ∼0.3 × 0.3 m excavated soil pit from the top of the surface to the visually identified mineral soil layer. Within a ∼1 m radius of the south-east corner of each plot, we took three soil temperature ($T_{soil}$) measurements at 10 cm depth using Hanna digital soil thermometer. Five replicates of percent volumetric moisture content (%VMC) at both 6 cm and 12 cm depths were also recorded using Campbell Scientific Hydrosense II handheld probes to represent soil moisture. The measured %VMC was further calibrated to adjust the underestimation of soil moisture for the tundra (Jenkins 2019; supplementary section 1.2). Within each plot, we estimated fractional coverages of shrub, sedge/grass, and moss through ocular assessment. Meteorological variables of air temperature ($T_{air}$) and relative humidity (RH) were also recorded using Ambient Weather WM-4 digital handheld weather station in 2017 and 2018. In total, this dataset represents measurements acquired at 192 plots (159 burned and 33 unburned).

### 2.3. Statistical analyses

To test the hypotheses, we assessed the impacts of fire and other environmental factors on tundra organic soils using statistical tests and regression models. Fire-related properties, landscape-scale fractional vegetation covers, drainage types, and meteorological variables were considered as appropriate. We first compared the differences of organic soil properties by geographic region and site type. The distribution normality of our data was evaluated using the Shapiro–Wilk test. For normally distributed data, we chose the Welch's *t*-test for its insensitivity to unequal variance. Otherwise, the Mann–Whitney U test was used. We then examined linear relationships between fire-related and environmental variables and organic soil properties with correlation analyses. Pearson's *r* was calculated for continuous numerical variables, while Spearman's rank was used for others. Next, we developed hierarchical linear mixed-effect models (HLMs) with random effects for geographic region to support straightforward explanatory analyses to link specific fire-related or environmental variables to soil properties. Different scenarios were further explored for modeling $T_{soil}$ and %VMC combining various groups of variables (table 1).

**Table 1.** Scenarios and variable groups tested for modeling soil temperature and moisture.

| Scenarios | Variables |
|---|---|
| Group 1 | Fire-related + landscape-scale (vegetation cover and drainage) |
| Group 2 | Landscape-scale (vegetation cover and drainage) + meteorological |
| Group 3 | Fire-related + landscape-scale + meteorological |

## 3. Results

### 3.1. General patterns of organic soil properties

Spatial variations of SOL thickness existed with significantly shallower ($p < 0.05$) in the Noatak (12.9 ± 9.02 cm) than in the Seward (16.0 ± 9.92 cm; table S2.1). Our measurements ($\mu = 13.98$ cm; figure 2(a)) were lower than those in the North Slope (Mack *et al* 2011, Bret-Harte *et al* 2013). In particular, the average unburned SOL in the Noatak (14.64 cm) was 6.96 cm shallower than that from within the ARF (∼21.5 cm; Mack *et al* 2011). The SOL was consistently deeper at the unburned plots than the burned ($p < 0.05$), with differences of 2.11 cm and 3.9 cm in the Noatak and Seward, respectively. These were also lower than the 6.1 cm estimated from the ARF (Mack *et al* 2011).

Organic soils in the Seward ($\mu_{burned} = 4.6$ °C and $\mu_{unburned} = 4.1$ °C) were significantly warmer ($p < 0.05$; table S2.2) than in the Noatak ($\mu_{burned} = 2.6$ °C and $\mu_{unburned} = 3.3$ °C). For soil moisture, %VMC at 6 cm depth was generally high with an average of 67%, while %VMC at 12 cm depth showed a slightly lower mean value of 61% (figures 2(c) and (d); tables S2.1 and S2.2). Burned plots in the Noatak were significantly drier than in the Seward based on %VMC at either depth ($p < 0.001$; table S2.2), while this spatial variation

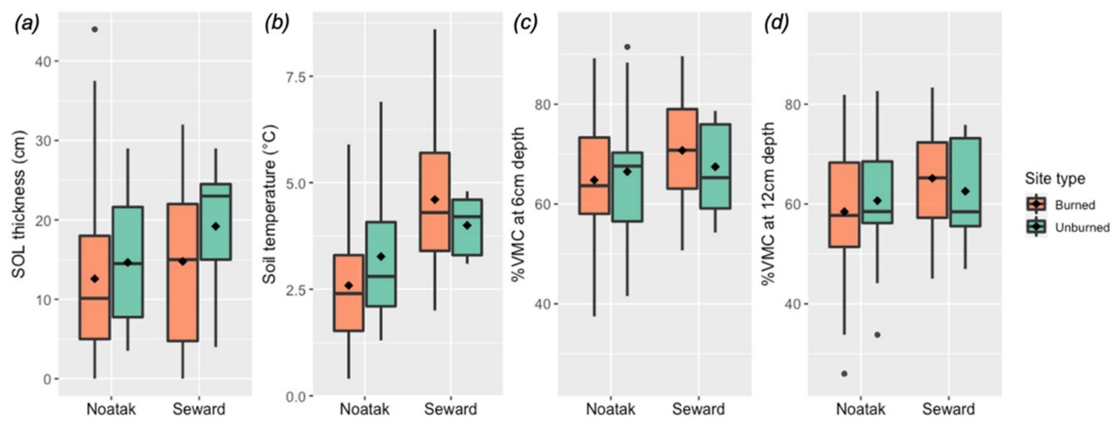


**Figure 2.** Boxplots of organic soil properties by geographic region and site type: (a) SOL thickness, (b) soil temperature, (c) %VMC at 6 cm depth, and (d) %VMC at 12 cm depth.

was not observed at the unburned sites. Unlike SOL thickness, $T_{soil}$ and %VMC at burned plots were not consistently lower or higher than the unburned (figures 2(b)–(d)).

### 3.2. Relationships between fire-related and environmental factors and organic soil properties

#### 3.2.1. SOL Thickness

The relationships between SOL thickness and fire-related and environmental variables vary across geographic regions. SOL thickness had a significant positive relationship with fire frequency ($p < 0.05$, rho = 0.21) in the Noatak while this relationship was negative in the Seward ($p = 0.1$, rho = −0.22; figure 3(a); table S3.1). SOL thickness was significantly correlated with burn age in the Seward (rho = 0.30, $p < 0.05$; figure 3(b)). However, such a correlation could not be found for the Noatak. Unexpectedly, our data showed a gradually thicker SOL with higher BSI in both regions (figure 3(c)). Negative relationship ($p < 0.1$; rho = −0.26) between SOL thickness and drainage was detected in the Seward (figure 3(d); table S3.1), where poorly drained plots had thicker SOL than the moderately-drained ones. In comparison, SOL thickness in the Noatak remained consistent among different drainage types.

Although the HLMs did not show strong predictive power in explaining the variance of SOL thickness (conditional $R^2 = 0.261$, marginal $R^2 = 0.195$), we found significant negative influences of fire frequency ($p < 0.1$) and burn age ($p < 0.05$) on SOL thickness across the tussock tundra (table 2). SOL became shallower as the tundra burns more frequently, while a weak negative relationship was found between SOL thickness and the burn age. We also found significant interaction terms ($p < 0.05$) between fire-related properties and drainage types in the HLM results: as the tundra regions became better drained, thicker SOL was observed as the burn age increased (figure S3.1).

#### 3.2.2. Soil temperature

Fire frequency showed positive correlations with $T_{soil}$ in both Noatak and Seward over 50 years (figure 4(a); table S3.2). This relationship was significant in the Seward with the correlation coefficient around 0.55 ($p < 0.001$). As fire frequency increased, $T_{soil}$ in the Seward rose from ∼4 °C to ∼6 °C. $T_{soil}$ was significantly negatively correlated with burn age ($p < 0.001$; table S3.2) with correlation coefficients of −0.59 and −0.38 for the Seward and Noatak, respectively. Burn severity, however, did not show strong linear relationships with $T_{soil}$. The drainage types were positively associated with $T_{soil}$ in the Noatak ($p < 0.05$; $r = 0.21$), while no correlation was found in the Seward. Additionally, $T_{soil}$ was strongly correlated with meteorological variables, with significantly positive and negative relationships ($p < 0.05$) with $T_{air}$ ($r \approx 0.6$) and RH ($r \approx -0.4 \sim -0.5$), respectively.

Shrub and moss fractional covers within plots were significantly related to $T_{soil}$ in the Noatak with negative and positive coefficients, respectively, while the relationships were insignificant for the Seward. We further examined the potential influence of primary soil substrate types on $T_{soil}$ using the Kruskal–Wallis test (figure 5). Not surprisingly, mean $T_{soil}$ differed significantly by soil substrate type in both regions ($p < 0.05$). Tundra areas covered with scorched moss or vegetation removed by fire tended to have warmer organic soils than those with healthy vegetation cover.

For $T_{soil}$ modeling, we tested multiple HLMs considering different scenarios (table 1). In general, $T_{soil}$ can be predicted with a high level of success with conditional $R^2$ values from all groups around 0.6 or higher (table 3(a)). When only considering fire-related and landscape-scale variables,

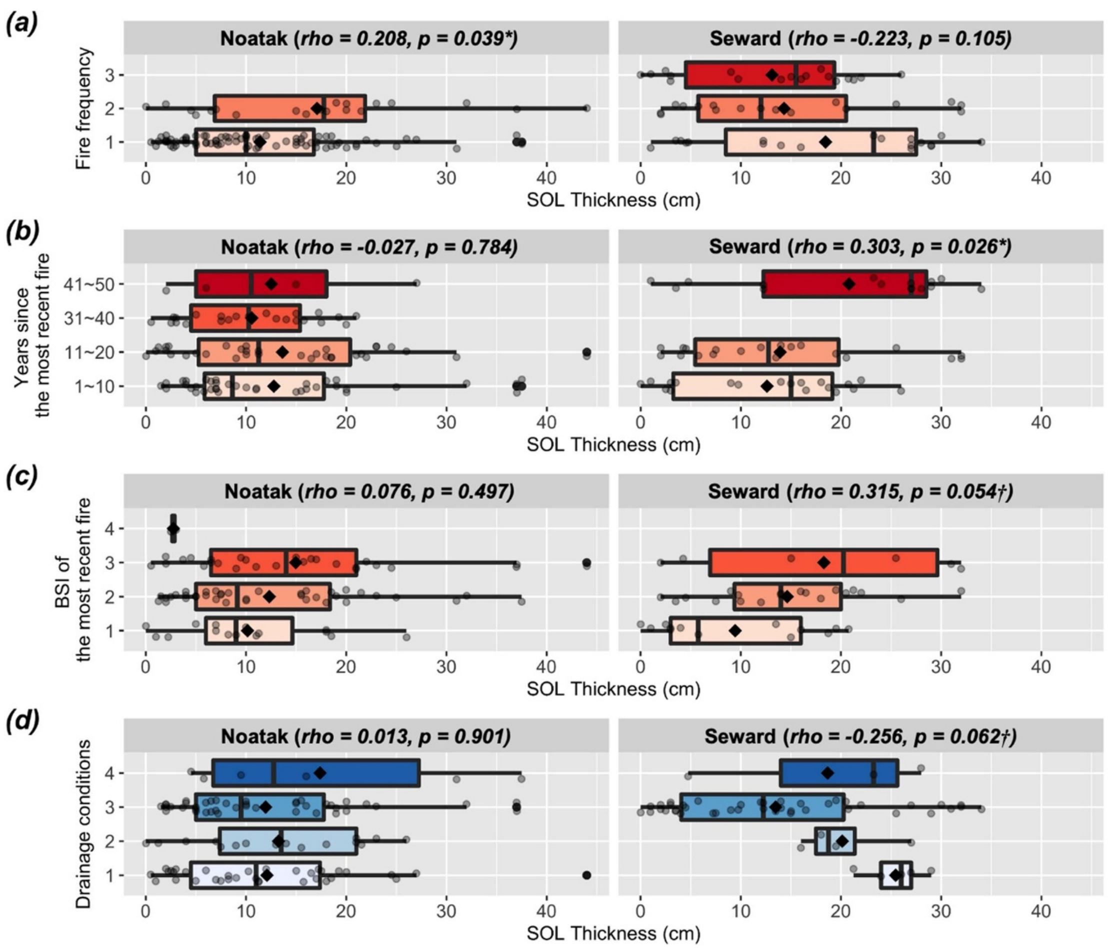


**Figure 3.** Box plots with jittered points for SOL thickness grouped by fire-related variables and drainage condition in the two regions: (a) fire frequency, (b) burn age, (c) BSI of the most recent fire, and (d) drainage type. Spearman's rank correlation coefficients and $p$-values are denoted next to the subtitles of the geographic regions with significance levels: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, and $\dagger p < 0.1$.

**Table 2.** Linear regression modeling results for SOL thickness ($n = 120$).

| Variables | Estimate | $t$ | $p$ |
|---|---|---|---|
| (Intercept) | 20.726 | 1.484 | 0.141 |
| Fire frequency | −7.674 | −1.874 | 0.064† |
| Burn age (years) | −0.680 | −2.427 | 0.017* |
| BSI (most recent) | 3.269 | 0.844 | 0.401 |
| Drainage | 3.949 | 1.233 | 0.220 |
| Shrub cover (%) | −0.198 | −1.607 | 0.111 |
| Herbaceous cover (%) | −0.113 | −0.974 | 0.332 |
| Moss cover (%) | −0.027 | −0.133 | 0.894 |
| Burn age:drainage | 0.318 | 2.214 | 0.029* |
| BSI:drainage | −3.277 | −2.365 | 0.019* |
| Frequency:BSI | 5.299 | 2.735 | 0.007** |

Notes: Significance levels of regression: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, and $\dagger p < 0.1$.

fire frequency and SOL thickness were found significant in explaining the variance of soil temperature ($p < 0.05$), with positive and negative relationships, respectively (table 3(b)). The inclusion of $T_{air}$ further improved the modeling performance, with conditional $R^2$ around 0.7: $T_{soil}$ increased significantly with higher $T_{air}$ ($p < 0.01$) and thinner SOL ($p < 0.1$). The shrub and sedge/grass covers showed negative and positive correlations with $T_{soil}$ in both regions (table S3.2). However, they did not show significance in predicting $T_{soil}$ within the HLMs.

### *3.2.3. Soil moisture*

The relationships between soil moisture and fire-related properties across the two geographic regions

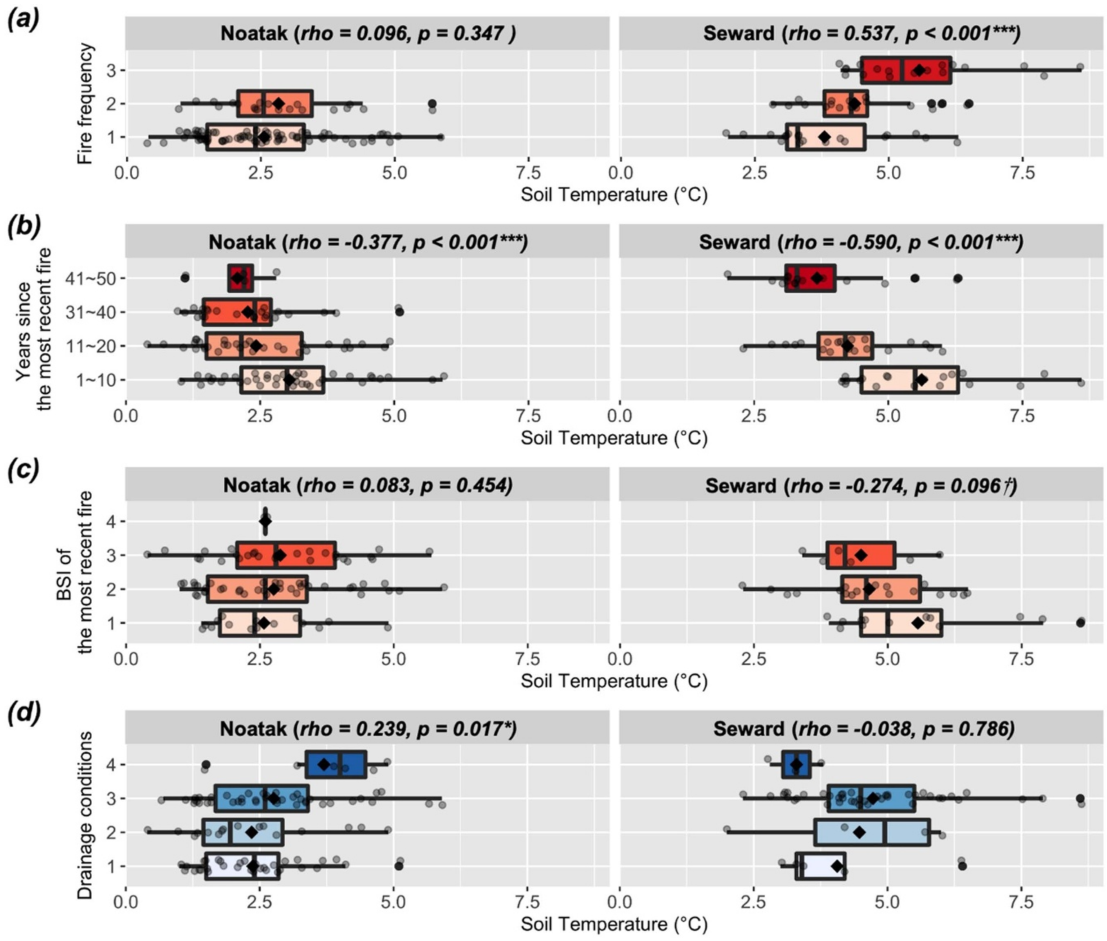


**Figure 4.** Box plots with jittered points for soil temperature grouped by fire-related variables and drainage condition in the two regions: (a) fire frequency, (b) burn age, (c) BSI of the most recent fire, and (d) drainage type. Spearman's rank correlation coefficients and $p$-values are denoted next to the subtitles of the geographic regions with significance levels: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, and $^{\dagger}p < 0.1$.

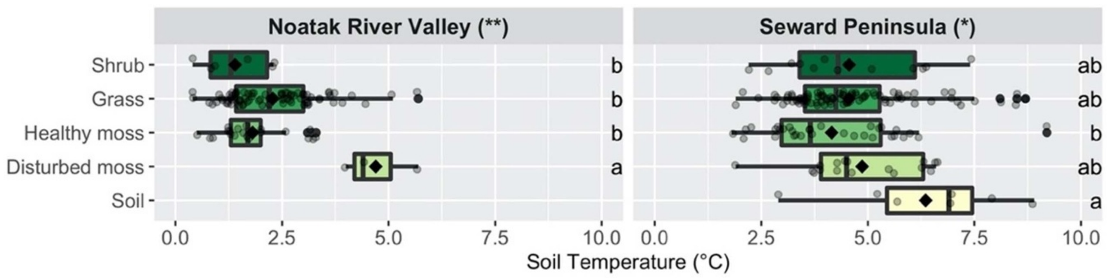


**Figure 5.** Box plot with jitter points for soil temperature grouped by major soil substrate types in the Noatak and Seward. Significance levels of Kruskal Wallis tests are denoted next to the subtitles of the geographic regions: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, and $^{\dagger}p < 0.1$. Results from the post hoc Dunn test were labeled as letters.

were similar (figures 6 and 7; tables S3.3 and S3.4). %VMC at 6 cm or 12 cm depth showed significant positive relationships with burn age (rho ≈ 0.3, $p < 0.05$), indicating a gradual increase in soil moisture over 50 years. In contrast, %VMC decreased with higher fire frequency ($p < 0.1$). Similarly, burn severity was negatively correlated with %VMC, indicating drier soils at more severely burned sites ($p < 0.01$). As expected, drainage showed negative correlations with %VMC. Additionally, %VMC showed negative and positive correlations with $T_{\mathrm{air}}$ and RH, respectively, with strong significance in the Seward ($p < 0.01$).

By considering the random effects of geographic region ($p < 0.01$), the HLM performances improved greatly for modeling %VMC (for %VMC at 6 cm depth, marginal $R^2 = 0.241$, conditional $R^2 = 0.592$; for %VMC at 12 cm depth, marginal $R^2 = 0.222$, conditional $R^2 = 0.638$) using independent variables from group 1. The HLMs revealed significant impacts of burn age, burn severity, and SOL thickness on

**Table 3.** HLM results for soil temperature at 10 cm depth ($n = 120$). RH was not included in modeling for its strong linear correlation with $T_{air}$.

(a) Overall statistics of HLMs developed for $T_{soil}$.

| Models | AIC | Marginal $R^2$ | Conditional $R^2$ |
|---|---|---|---|
| Group 1 | 262.268 | 0.195 | 0.595 |
| Group 2 | 251.569 | 0.154 | 0.768 |
| Group 3 | 260.381 | 0.179 | 0.688 |

(b) HLM results for fixed effects using variables from group 1.

| Variables | Estimate | $t$ | $P$ |
|---|---|---|---|
| Intercept | 2.492 | 1.509 | 0.137 |
| Fire frequency | 0.835 | 2.343 | 0.023* |
| Burn age (years) | 0.005 | 0.212 | 0.833 |
| BSI (most recent) | −0.062 | −0.248 | 0.805 |
| Drainage | 0.003 | 0.012 | 0.990 |
| SOL thickness (cm) | −0.049 | −2.634 | 0.011* |
| Shrub cover (%) | −0.001 | −0.068 | 0.946 |
| Herbaceous cover (%) | 0.007 | 0.477 | 0.635 |
| Moss cover (%) | 0.005 | 0.330 | 0.742 |

(c) HLM results for fixed effects using variables from group 2.

| Variables | Estimate | $t$ | $P$ |
|---|---|---|---|
| Intercept | 2.122 | 1.477 | 0.144 |
| Drainage | 0.049 | 0.336 | 0.738 |
| SOL thickness (cm) | −0.038 | −2.635 | 0.010* |
| Shrub cover (%) | −0.006 | −0.738 | 0.463 |
| Herbaceous cover (%) | 0.005 | 0.538 | 0.592 |
| Moss cover (%) | 0.013 | 1.112 | 0.269 |
| $T_{air}$ (°C) | 0.117 | 4.760 | <0.001*** |

(d) HLM results for fixed effects using variables from group 3.

| Variables | Estimate | $t$ | $p$ |
|---|---|---|---|
| Intercept | 2.549 | 1.533 | 0.131 |
| Fire frequency | 0.407 | 1.134 | 0.261 |
| Burn age (years) | −0.024 | −0.968 | 0.337 |
| BSI (most recent) | 0.008 | 0.033 | 0.974 |
| Drainage | −0.034 | −0.154 | 0.878 |
| SOL thickness (cm) | −0.033 | −1.828 | 0.073† |
| Shrub cover (%) | −0.002 | −0.186 | 0.853 |
| Herbaceous cover (%) | −0.003 | −0.31 | 0.818 |
| Moss cover (%) | 0.008 | 0.522 | 0.603 |
| $T_{air}$ (°C) | 0.097 | 3.106 | 0.003** |

Notes: Significance levels of regression: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, and †$p < 0.1$.

soil moisture (table 4). Older burns had consistently higher %VMC than more recent ones ($p < 0.001$). SOL thickness also showed significant positive relationships with %VMC ($p < 0.001$). In contrast, an increase in burn severity appeared to drive soil moisture down ($p < 0.001$). Negative relationships can be found between drainage and soil moisture. Different from the straightforward associations between soil moisture and the factors described above, drainage also influenced soil moisture by modifying the effects of fire-related variables with significant interactions ($p < 0.05$; table 4). The relationship between burn age or severity and soil moisture was moderated as the region became better drained (figures S3.3(a) and (b)). Although we expected strong impacts of real-time meteorological variables, the models excluding RH showed better performances (table S3.5).

## 4. Discussion

This study brings forward several important implications for understanding wildfires' impacts on organic soil properties in tussock tundra. First, we found that the SOL in the Noatak and Seward uniformly decreased after burning and was noticeably shallower than estimated previously in the North Slope

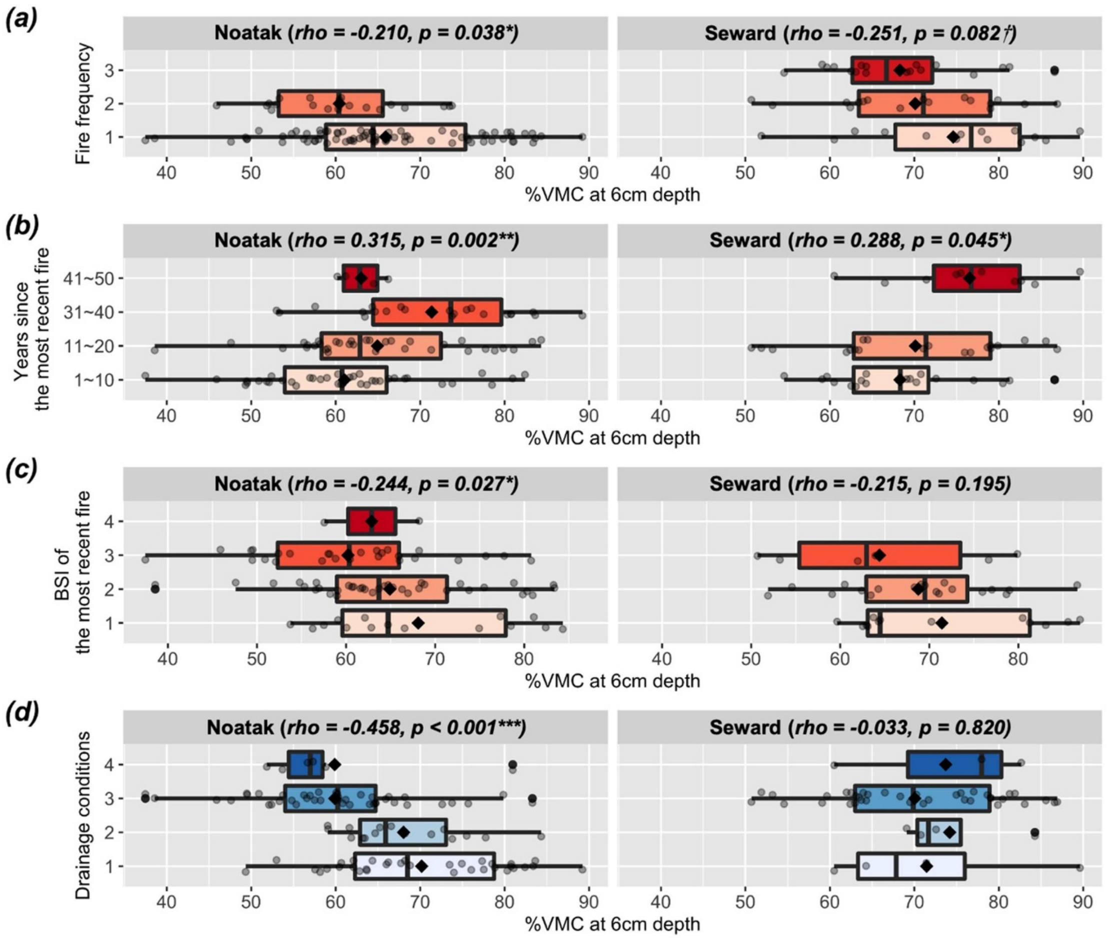


**Figure 6.** Box plots with jittered points for %VMC at 6 cm depth grouped by fire-related variables and drainage condition in the two regions: (a) fire frequency, (b) burn age, (c) BSI of the most recent fire, and (d) drainage type. Spearman's rank correlation coefficients and $p$-values are denoted next to the subtitles of the geographic regions with significance levels: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, and $^{\dagger}p < 0.1$.

(Mack *et al* 2011, Bret-Harte *et al* 2013). We believe that this could be explained by the exceptionally high fire activity historically in these regions (French *et al* 2015). The short fire return intervals, coupled with the extremely slow postfire SOM accumulation and litter decomposition rates in the tundra (Innes 2013, Michaelides *et al* 2019), likely result in uniformly shallow SOL over time. Considering the positive correlation between SOL thickness and SOC stock (Baughman *et al* 2015), our finding of an overall shallower tundra SOL than that measured at the ARF site correspondingly implicates that previous estimation might have overestimated SOL thickness in the vast expanse of Arctic tundra and thus exaggerated the actual tundra SOC pool.

Second, typically tundra fires (often less than 10 d; French *et al* 2015) can be too short-lived to result in considerable SOL consumption with substantial spatial variation and yield much less robust modeling results regarding the loss of SOC, compared to the severe combustion and extended smoldering observed on the ARF or boreal forest fires. The low aboveground biomass represented primarily by very fine flashy fuels (e.g. dried leaf litter of tussock grasses) carries the flaming front rapidly across the landscape without allowing for a substantial fire residency time over one area to support deep penetration of fire into the soil. Despite the limited soil consumption from a single transient and low- to moderate-severity tundra fire, we hypothesize that repeated fires may amount to higher levels of cumulative SOC consumption than one high-severity fire event does in the tundra, based on the fact that post-fire SOL is thicker within the perimeter of the particularly severe and long-lasting ARF (Mack *et al* 2011) than what we measured. To test this hypothesis, more field measurements in various tundra regions with differing wildfire history are required.

Third, we found that near-surface $T_{air}$ and SOL thickness were the most influential factors affecting tundra $T_{soil}$ according to statistical modeling results. Fire-reduced SOL loss can warm tundra soils by altering the soil thermal conductivity (Jiang *et al* 2015). The positive correlations between $T_{soil}$ and fire frequency and severity suggested that with more severe fires, organic soils in the tussock tundra would become warmer in the long run. This impact would dissipate as the burn age increases and the vegetation

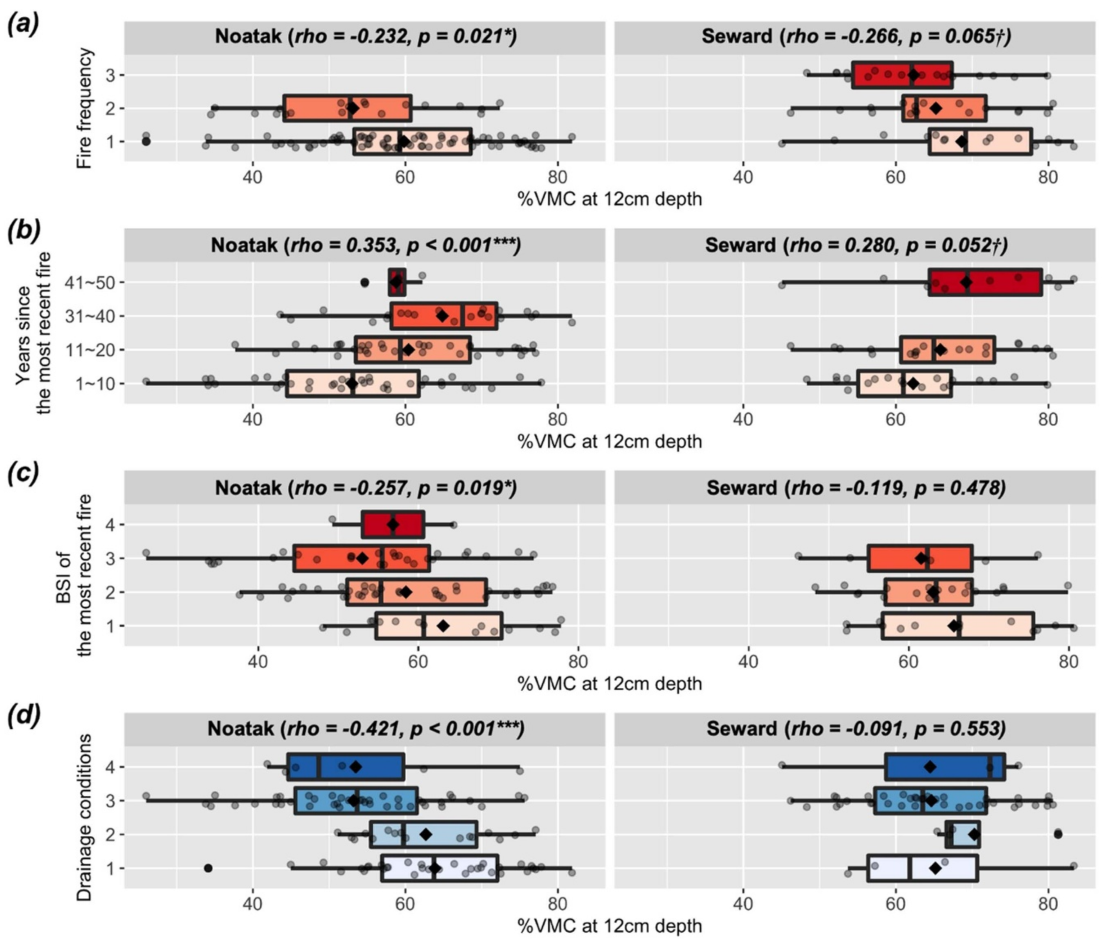


**Figure 7.** Box plots with jittered points for %VMC at 12 cm depth grouped by fire-related variables and drainage condition in the two regions: (a) fire frequency, (b) burn age, (c) BSI of the most recent fire, and (d) drainage type. Spearman's rank correlation coefficients and *p*-values are denoted next to the subtitles of the geographic regions with significance levels: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, and $\dagger p < 0.1$.

**Table 4.** HLM results for modeling %VMC using variables from group 1 ($n = 120$).

| | %VMC at 6 cm depth | | | %VMC at 12 cm depth | | |
|---|---|---|---|---|---|---|
| Variables | Estimate | $t$ | $p$ | Estimate | $t$ | $p$ |
| Intercept | 70.134 | 5.061 | <0.001*** | 70.007 | 4.529 | <0.001*** |
| Fire frequency | −3.061 | −1.620 | 0.108 | −3.743 | −1.815 | 0.072† |
| Burn age | 1.116 | 4.053 | <0.001*** | 1.056 | 3.527 | <0.001*** |
| BSI (most recent) | −11.759 | −3.499 | <0.001*** | −13.489 | −3.696 | <0.001*** |
| Drainage | −3.842 | −1.388 | 0.168 | −6.153 | −2.046 | 0.043* |
| SOL thickness | 0.344 | 3.849 | <0.001*** | 0.347 | 3.571 | <0.001*** |
| Shrub cover | 0.154 | 1.287 | 0.201 | 0.185 | 1.419 | 0.159 |
| Herbaceous cover | 0.201 | 1.813 | 0.073† | 0.181 | 1.504 | 0.136 |
| Moss cover | 0.119 | 0.602 | 0.548 | 0.246 | 1.142 | 0.256 |
| Burn age:drainage | −0.433 | −3.019 | 0.003** | −0.369 | −2.368 | 0.020* |
| BSI:drainage | 2.628 | 2.055 | 0.042* | 3.307 | 2.381 | 0.019* |

Notes: Significance levels of regression: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, and $\dagger p < 0.1$.

recovers. These relationships highlight the primary mechanism linking fire occurrence to increased $T_{soil}$ and deeper active layer (not discussed in this paper). Though fire-related variables did not show significance when modeled together with $T_{air}$, we hypothesize an implicit relationship through the linkages to SOL thickness and vegetation cover. The moss layer has a strong insulating effect that can cool the tundra organic soils during summer (Blok *et al* 2011, Migała *et al* 2014, Park *et al* 2018). The loss of moss after burning can therefore drive the increase of $T_{soil}$ in the tundra. Additionally, denser shrub canopies could reduce $T_{soil}$ during summer compared to herbaceous species by providing shades, though snow melting time and cloud cover may also contribute to this cooling effect (Blok *et al* 2010, Epstein *et al* 2013, Myers-Smith and Hik 2013, Juszak *et al* 2016).

In addition, our study established a notable connection between soil moisture and fire properties within burned areas, emphasizing the role of fire in altering tundra soil hydrology. We found a decrease of %VMC in plots with increases in fire frequency and severity via HLM modeling. We believe this is caused by the fact that repeated and severe burning could substantially modify soil structure and destruct soil aggregates through the combustion of SOM, further increasing soil water repellency and reducing soil water content (Neary *et al* 2005, Zavala *et al* 2014). The strong positive relationship between SOL thickness and soil moisture is also not surprising since thicker SOL can have stronger a water holding capacity (Kasischke and Johnstone 2005, Kane *et al* 2007). Fire can provide a drying-out environment in the tundra and further reduce soil moisture by increasing evapotranspiration rate, intensifying water repellency, and altering moss community composition after burning (DeBano 2000, Mkhabela *et al* 2009, Turetsky *et al* 2010, Kettridge *et al* 2014, Zavala *et al* 2014).

Though our finding contradicted previous results suggesting a substantial increase in soil moisture within 5–7 years following tundra fires (Liljedahl *et al* 2007, Jenkins *et al* 2014), this is likely caused by the different time scales we adopted. These studies evaluated the short-term change of soil moisture by comparing the burned and unburned sites. Soil water content can increase within a few years after burning due to permafrost thawing caused by fire-induced warming of SOL. Postfire snow cover can also recharge the moisture with more meltwater infiltrating into the soils than runoff (Sturm *et al* 2001). In contrast, we focused on assessing long-term soil moisture changes among the burned plots over 50 years. Since the postfire recovery of tundra soil ecosystems can last for decades (Heim *et al* 2021), it makes sense that we observed a gradually increasing trend of soil moisture.

As first-order analyses, we tested only the most obvious connections using straightforward methods. The statistical power of our analyses is constrained by the limited capability of satellite-based metrics to capture fire-related properties and drainage conditions. However, considering the difficulty of access and the lack of historical *in situ* observations in the tundra, satellite assessments at present provide the only viable option for deriving those properties at the ecosystem scale necessary to support such analyses. Since all input parameters can be derived from satellite observations, obtaining reasonably accurate wall-to-wall assessments of $T_{soil}$, the most predictable soil property, across circumpolar tundra appears realistic in the immediate future, providing invaluable insights into tundra ecosystem monitoring and modeling. With the advances in satellite and drone imagery, additional work in developing linkages between *in situ* observations and remote sensing-based metrics would enhance future research.

## 5. Conclusions

This study presents the first-order analysis of a large sample of organic soil properties across typical fire events in Arctic tussock tundra over the past ~50 years. Organic soils are overall shallower in tundra regions of active fire regimes than the ARF, suggesting that estimations or inferences across typical tundra fires based on evidence from this extreme event could result in gross overestimation of SOC stock and fire impacts on the carbon cycle or ecosystem functioning. Soil consumption may be less considerable during typical short-lived and fast-moving tundra fires. However, even these fires appear to impact soil moisture and temperature for decades after burning, partially through fire-induced SOL consumption. Additionally, soil temperature is also strongly influenced by weather and vegetation conditions. Fire occurrence tends to dry-out and warm organic soil in the tussock tundra with more recent and frequent burnings. Our dataset and findings can provide new insights into the tundra ecosystem functioning and improve ecosystem modeling capabilities.

## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

## Acknowledgments

This work is part of the NASA's ABoVE and was supported by the NASA Terrestrial Ecology program grant NNX15AT79A. The authors would like to thank Andrew Poley of the Michigan Technological Research Institute (Michigan Technological University) for contributing to data collection. The authors would also like to thank Garrett Jones of Arctic River Guides, LLC for logistical support in data collection.

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