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Shrubs Strongly Influence Snow Properties in Two Subarctic Watersheds

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ABSTRACT

Understanding changes in snow distribution in permafrost ecosystems is fundamental to predicting their response to future climate change. The expansion of tall shrubs into tundra ecosystems can trap snow and insulate permafrost ecosystems during the winter, but the overall insulation effect is dependent upon many ecosystem properties. To study shrub–snow–ground interactions, small temperature sensors were deployed at two research sites on the Seward Peninsula of Alaska, USA, during the 2019–2020 winter. Snow temperatures were used to extrapolate multiple metrics, including freezing n-factors, the snow insulation effect, snow cover duration, and the length of the snowmelt period. Statistical and spatial analysis showed that shrub patches were a dominant control on all snow metrics. Within shrub patches, average ground temperatures were 2.1°C warmer, snow persisted 50 days longer, snow insulation was double, and a longer, later spring snowmelt period occurred compared to nonshrubby areas. Site-level differences contributed relatively little to variation in snow metrics, indicating that shrub presence is an overarching driver of snow–ground interactions at the locations examined. Shrub expansion, which is anticipated under climate change, will strongly impact future permafrost distribution and Arctic energy, water, and carbon cycles through snow–shrub–ground feedbacks.

1 | Introduction

Snow plays a fundamental role in the Arctic energy balance through its seasonal persistence, water storage capacity, and ground thermal regulation. Snow in the Arctic is an important component of the Earth's energy balance; its high albedo during the fall, winter, and spring acts to reflect energy back to the atmosphere, affecting local and global surface temperatures [1–4]. Snow also acts as a water reservoir, retaining water during winter for release in spring, which provides an important moisture source during drier summer months [5]. Snow can act as an insulating layer, buffering frozen ground from extremely low winter air temperatures [6]. In the high latitudes, the depth of the snow layer is a controlling factor of the geographic extent of continuous and discontinuous permafrost zones [7].

Snow precipitation is anticipated to change variably across the Arctic as the climate warms [8, 9], which has implications for energy and water balances, vegetation community composition, and ground insulation of permafrost [10, 11]. Increasing spatial and temporal heterogeneity in snow precipitation is projected for many areas of the Arctic [10]. Resulting changes in snowpack depth, density, and distribution will impact the timing of many ecological and hydrologic processes. For example, deeper snow is associated with delayed spring snowmelt and increased runoff [12], which can affect phenology and vegetation reproduction [13] and result in a shift in the timing of hydrologic events [14].

In addition to precipitation regime shifts, climate change has impacted other Arctic ecosystem properties which change snowpack properties and distribution. The range and density of shrub species are expanding in tundra ecosystesms, which predicted to change snow cover distribution across the Arctic [15]. Shrub expansion increases the presence of tall vegetation on a landscape of relatively short statured tundra plants, which can enhance snow trapping [16],causing deeper snow and greater insulation of frozen soils [17]. Because of complex and interconnected ecosystem dynamics, the net impact of shrub expansion on ground thermal dynamics is not yet clear. Many studies show higher winter ground temperatures underneath shrub patches in comparison to barren tundra [18, 19], but in the summertime, shading, higher evapotranspiration, and delayed snowmelt in shrub patches can cause a cooling of ground temperatures [20, 21]. Recent work has also shown that low shrubs in a Canadian tundra site cool the ground during the winter compared to the predicted impacts of snow insulation, as frozen stems transfer heat from the ground to the snow, though this trend reverses as air temperatures rise in the spring [22]. These studies highlight the impact of local variables like topographic position, microclimate, and soil properties on snow accumulation and correspondently, its effects on the ground temperature regime. Thus, untangling the effects of changing vegetation and site-level controls on snow accumulation and ground thermal regimes requires additional research.

Changes in the local ground thermal regimes in the Arctic can have regional and global consequences. Increasing ground temperatures lead to permafrost thaw, which creates major geophysical disruptions to Arctic ecosystems and local human infrastructure through ground subsidence and thermokarst formation [23]. Additionally, permafrost soils contain 33% of global soil organic carbon, potentially impacting the global carbon cycle with thaw and subsequent microbial degradation [24]. Observational and experimental evidence show that snow cover can strongly control ground temperature, which impacts the stability and persistence of permafrost. Farquharson et al. [25] observe that snow depth is a dominant control on talik formation in permafrost soils across Alaska. Snow fence experiments show that deeper snow raises ground temperatures and increases the depth of unfrozen soil atop permafrost [26]. Improved understanding of snowpack insulation on permafrost has been cited as a critical goal for representation of permafrost in earth system models [27]. Thus, understanding changes in snow distribution will improve understanding of future of permafrost distribution.

Monitoring metrics of snow processes, such as the depth and persistence of snow through the winter and timing of snowmelt can be used to understand how vegetation changes impact snow distribution and ground thermal regimes in a changing Arctic. These snow metrics represent important spatial and temporal controls on energy and water cycles, but manually measuring them can be expensive, physically demanding, and time consuming. It is difficult to access remote arctic field sites during the winter, which in turn limits the spatial and temporal scale of measurements. Properties like snow depth and snow water equivalent can be monitored continuously and remotely at stations like the Snow Telemetry (SNOTEL) sites, but this network covers a limited spatial extent, measuring only a small proportion of the vast Arctic region. Arctic monitoring stations are prone to data quality issues (e.g., short, discontinuous records with erroneous values) due to their remote nature and harsh winter conditions [28, 29]. Remote sensing products derived from optical and near infrared satellite sensors (e.g., Landsat, MODIS, and Planet) have been used to estimate snow covered area, but these measurements are limited by high winter cloud cover in Arctic regions [30] and are not always available at required spatial or temporal resolutions. To address these challenges, previous studies have shown the effectiveness of using small, inexpensive ground surface temperature (GST) sensors deployed underneath the snowpack to capture snow processes continually through the winter [31–35].

In this study, we deployed ~100 small temperature sensors during the 2019–2020 winter at two heights above the ground as well as within and outside of shrub patches to examine the impacts of site and vegetation on the interaction of snow and ground thermal dynamics. Sensors were placed at two intensively studied watersheds on the Seward Peninsula of Alaska, USA, as part of the Next-Generation Ecosystem Experiments (NGEE) Arctic project. We used ground and snow temperatures measured by small, cost-effective sensors and air temperatures to extrapolate snow metrics that capture the effects of snow insulation (GST, freezing n-factor, and insulation effect of snow) and snow cover duration (length of snow cover and the length and end of the spring snowmelt period) for the 2019–2020 winter. Our two main hypotheses are the following:

1. Temperature sensors placed within shrub patches will measure a higher GST, a greater snow cover duration, smaller freezing n-factor, greater insulation effect of snow, and longer, later spring snowmelt period compared to temperature sensors placed outside shrub patches.
2. Site (Teller or Kougarok) will explain a greater proportion of variation in snow metrics than placement within or outside shrub patches, because both locations vary in their aspects, elevation, and local ecosystems that also effect snow accumulation and the interaction with the ground thermal regime.

2 | Methods

2.1 | Site Description

The Teller 27 Catchment site (hereby referred to as "Teller," 2.3 km^2) and the Kougarok 64 Hillslope site (hereby referred to as "Kougarok," 2.5 km^2) are located near the town of Nome in the Seward Peninsula, Alaska, USA (Figure 1). Both sites are located in the discontinuous permafrost zone [36].

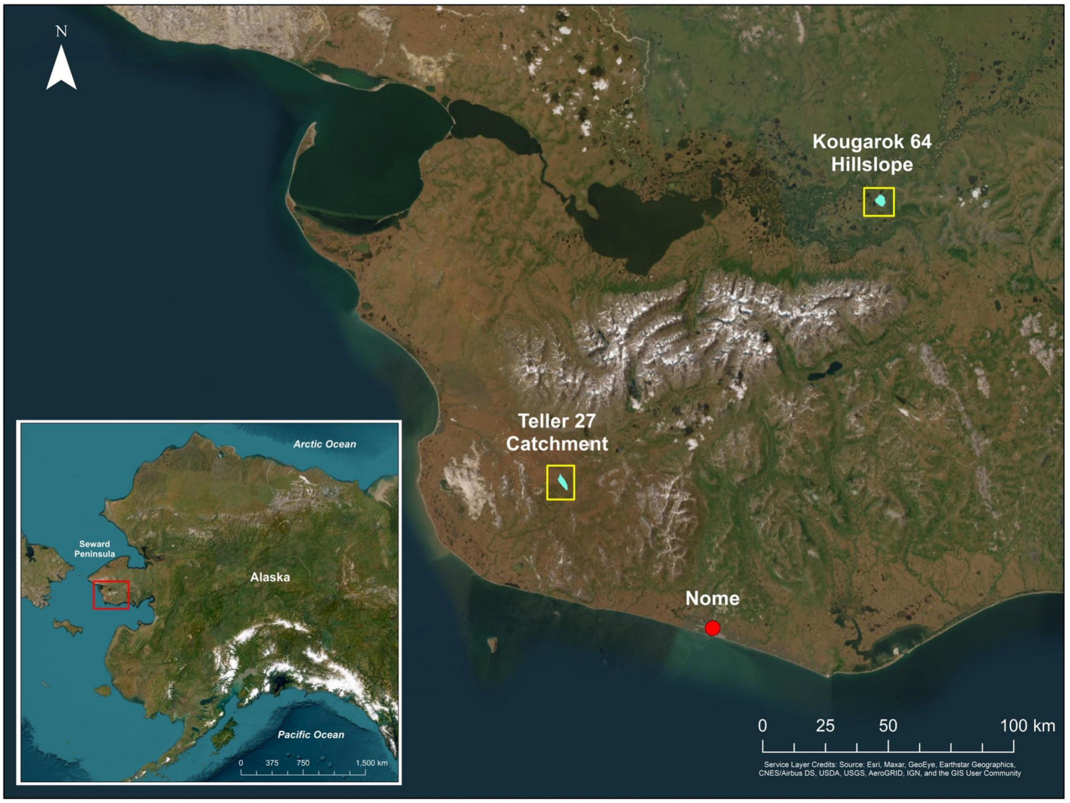

FIGURE 1 | Temperature sensors were deployed at the Teller 27 Catchment and the Kougarok 64 Hillslope, located on the Seward Peninsula, Alaska, USA. [Colour figure can be viewed at wileyonlinelibrary.com]

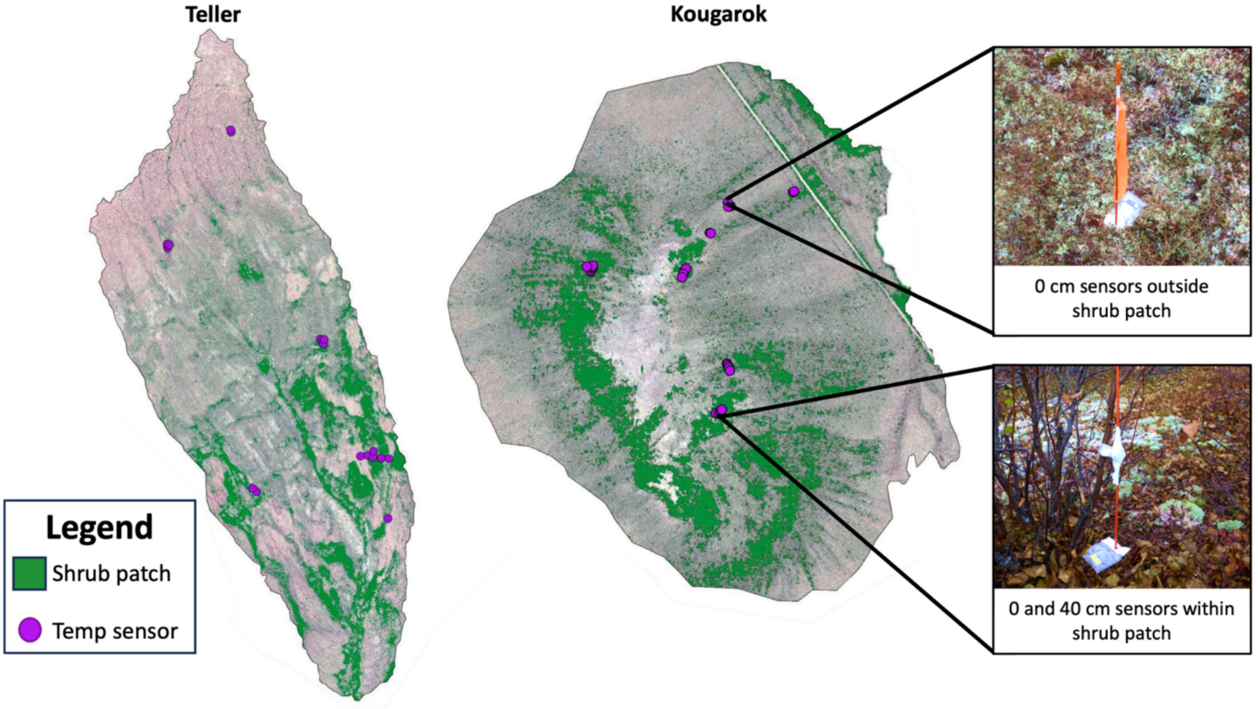

FIGURE 2 | Temperature sensor locations and shrub patches mapped at the Teller and Kougarok sites. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 | Summary of all measurements collected.

Measurement	Date range	Number of observations				Mean (standard deviation)			
Site:		**Kougarok**		**Teller**		**Kougarok**		**Teller**	
Within or outside shrub patch:		Within	Outside	Within	Outside	Within	Outside	Within	Outside
GST (°C)	Oct 2019–Jun 2020	11	15	10	9	−3.06 (5.71)	−5.23 (8.94)	−1.38 (5.11)	−4.04 (7.43)
Freezing n-factor (unitless)	FDD, from Oct 2019–Jun 2020	11	15	10	9	0.45 (0.09)	0.61 (0.10)	0.60 (0.18)	1.00 (0.19)
Snow cover duration at 0 cm (days)	Oct 2019–Jun 2020	11	15	10	9	177 (19)	97 (53)	173 (10)	126 (27)
Snow cover duration at 40 cm (days)	Oct 2019–Jun 2020	12	14	9	7	120 (57)	23 (44)	118 (55)	30 (23)
Insulation effect of snow (unitless)	Oct 2019–Jun 2020	11	15	10	9	0.55 (0.12)	0.26 (0.14)	0.58 (0.09)	0.33 (0.09)
Spring snowmelt length (days)	Apr 15, 2020–May 31, 2020	11	15	10	9	26.3 (11.58)	4.5 (9.42)	29.4 (4.35)	19.6 (10.32)

Note: The "Number of observations" columns indicate the number of unique temperature sensors with calculated metrics (not the total number of days of data). All metrics reported in this table were calculated by using GST sensors, except for snow cover duration at 40 cm, which was calculated using sensors placed 40 cm above the ground.

The Teller site, located northwest of Nome approximately 25 km off the coast of the Bering Sea, is a mild sloping watershed with elevation ranging from 53 to 279 m. A stream drains flow from spring and wetland features in the mid-central region of the catchment. From 2016 to 2019, the average maximum snow depth at Teller was 90 cm across the watershed [37, 38]. The average annual air temperature since 2016 was −1.3°C [39]. An average thaw depth of 79 cm was recorded across six subsites at Teller in August of 2019 [40], and permafrost extent is generally characterized as nonexistent or deep [41]. Taller vegetation at Teller, considered shrubs in this study, are predominantly willow (*Salix* spp.), with heights between 0.5 and 3 m (mean = 1.5 m) [42–44]. Shrub distribution at Teller is shown in Figure 2.

Farther inland, Kougarok is characterized by hillslope topography, where hydrologic flow is disparate and all topographic aspects are represented. Elevation ranges from 18 to 107 m. In 2018 and 2022, the average maximum snow depth was 23 cm across the site, with low to no snow cover on the ridge of the hillslope [45, 46]. At Kougarok, the average annual temperature since 2017 was −1.6°C, slightly colder than the coastal Teller site [47]. The average thaw depth at Kougarok in August 2019 was 63 cm [40]. The shallower thaw depth is reflected in the presence of near-surface permafrost at most subsites along the hillslope [41]. The dominant shrub type at Kougarok is tall alder (*Alnus viridis* spp. *fruticosa*), which lines the edges of the ridge near the hillslope peak [48]. Shrub heights are slightly taller than at Teller and range from 0.5 to 3 m (mean = 2 m) [44]. Shrub distribution across the Kougarok site is shown in Figure 2.

2.2 | Temperature Sensor and Climate Data

In October 2019, 100 iButton temperature sensors (DS1921G-F5# Thermochron, iButton Link, Whitewater, WI; accuracy: ±1°C; precision 0.5°C) were deployed on stakes along transects within or outside of shrub patches, at two heights above the ground (0 and 40 cm; Figure 2). We refer to temperature sensors placed at 0 cm as GST sensors. Sensors were placed in clusters at NGEE Arctic's intensively sampled subsites to better characterize ground temperatures coincident with other monitoring, though for this study, we focused on the effects of shrub presence and site. Sensors were programmed to record temperature every 4 h. Due to COVID-related travel restrictions, sensors were collected from the field later than planned (October 2020 and 2021). Sensors that failed to collect temperatures for the whole study period and sensors with internal clocks that were off by more than 4 h at the time of download were removed from the dataset. Table 1 includes details on which sensor heights were used as data input for snow process calculations.

Air temperature data were collected from two meteorological stations situated at or nearby the study sites. Daily air temperature [39, 47] was considered homogenous across the site, and unique air temperature values were not applied for each snow temperature sensor location. The 2019–2020 winter season was defined as October 2019 to June 2020, which accounted for the entire local snow cover period, as snowfall began in October and melted out completely at both sites by June 2020. Spring is defined as April 15 through June 1. These dates are not traditionally used to represent a hydrologic or calendar period but instead represent local snow cover duration and melt off for the 2019–2020 winter.

2.3 | Snow Metrics Calculations

We drew on multiple previously published methods applying low-cost temperature sensors to extrapolate important snow metrics and understand the influence of shrubs on snow and ground thermal dynamics [31–35]. Six different snow metrics were calculated from temperature sensor measurements during the 2019–2020 winter and are described below. Metrics were categorized as describing snow insulation, GST (°C), the freezing n-factor (unitless), the insulation effect of snow (unitless), snow duration, snow cover duration (count of days), and the spring snowmelt duration (count of days) and end date (Julian day). Calculations of snow cover duration, the insulation effect of snow, and the length of the snowmelt period rely on the assumption that when snow covers a temperature sensor, it is buffered from diurnal fluctuations in air temperature by the insulating snow layer [49, 50] (Figure S1).

2.3.1 | Freezing n-Factor

The freezing n-factor is a metric used to examine differences between surface and air thermal regimes during freezing temperatures and has been used in permafrost ecosystems to examine the ground energy balance [51–53]. Mathematically, the freezing n-factor (n_f) is the ratio of freezing degree days (FDDs) at the ground surface compared to FDD of the air (Equation 1).

$$n_f = \frac{FDD_{surface}}{FDD_{air}}. \tag{1}$$

We calculated freezing n-factors for each GST sensor during the snow cover season (October 1, 2019, to June 1, 2020), to quantify how GSTs were decoupled from subzero air temperatures. FDDs were calculated as the sum of mean daily GST or air temperature from meteorological stations at the Teller and Kougarok sites when daily temperatures were below 0°C.

2.3.2 | Insulation Effect of Snow Cover

The insulation effect of snow cover was calculated following methods presented in Staub and Delaloye [34] (Equation 2). We calculated the snow insulation index (unitless) from the standard deviation of the mean weekly GST (GST_{SDweek}) and the standard deviation of the weekly mean air temperature ($AirT_{SDweek}$). This snow insulation index is restricted to days where the average GST is below 0.5°C ($GST_{day} \leq 0.5$) to avoid noise from small, short snow events in the summer and fall.

$$Snow\ Insulation\ Index\ [0, \ldots, 1] = \frac{(AirT_{SDweek} - GST_{SDweek})}{(AirT_{SDweek} + GST_{SDweek})} \wedge GST_{day} \leq 0.5. \tag{2}$$

The snow insulation index ranges from 0 to 1, where a value of 1 indicates high ground insulation and that the GST is fully decoupled from the air temperature. A time series of snow cover and insulation for two GST sensors are plotted in Figure S2.

2.3.3 | Snow Cover Duration

The presence or absence of snow cover on any day was calculated using measurements from a temperature sensor [32] (Table 1). When the sensor was covered with snow, the daily temperature fluctuation was significantly dampened [32, 34]. The sensor was considered snow covered if the 24-h temperature variance of the sensor was less than 1°C for more than 3 days [31, 32]. Snow cover duration was calculated for GST sensors and temperature sensors 40 cm above the ground (Table 1). The total number of days spent under snow was summed for all snow cover days between October 1, 2019 (following sensor deployment) and June 1, 2020 (following the last sensor being free from snow cover). This method was validated by calculating the duration of snow cover at GST sensors during a period of known snow cover (Supporting Information S1). Our validation showed that during this period, sensors within shrub patches captured 98% of snow cover days and sensors outside shrub patches captured 94% of snow cover days.

2.3.4 | Length and Timing of Spring Snowmelt

During periods of snowmelt, GSTs are expected to remain close to 0°C because of water's thermodynamic properties and the process of phase change from solid to liquid. Here, we define the spring snowmelt period as the amount of time that the bottom of the snowpack hovers around 0°C (Equation 3). The length and end date of spring snowmelt was calculated for all GST sensors using an equation adopted from Staub and Delaloye [34] (Equation 3). This method compensates for minimal temperature fluctuations that may occur during snowmelt.

$$Snowmelt = \begin{cases} 1 \ if \left|GST_{day}\right| \leq th_{sm} \wedge \left(GST_{SDweek\_prior} \leq \frac{th_{sm}}{2} \vee GST_{SDweek\_after} \leq \frac{th_{sm}}{2}\right) \\ 0 \ if \left|GST_{day}\right| > th_{sm} \vee GST_{SDweek\_prior} > \frac{th_{sm}}{2} \vee GST_{SDweek\_after} > \frac{th_{sm}}{2} \end{cases}. \quad (3)$$

In Equation (3), a GST sensor experienced snowmelt (Snowmelt = 1) if the mean daily temperature was less than a threshold value based on the resolution of the sensor, and the standard deviation of the temperature the previous week and the following week remained below the threshold value. GST_{day} is the mean of all temperatures collected by a GST sensor over the course of 24 h. A threshold value (th_{sm}) of 1°C was used to account for the coarse thermal resolution of the iButton sensors used in this study. GST_{SDweek_prior} and GST_{SDweek_after} are the standard deviations in GST in the week preceding and following each GST_{day} value.

2.4 | Data Manipulation and Statistical Analysis

Data manipulating and statistical testing were done in R, version 4.4.1 [54]. Data were manipulated using the tidyr and dplyr packages [55, 56], lubridate [57] package for dates and times, and visualized using the ggplot2 package [58]. Location of temperature sensor (within or outside shrub patches) and site (Teller or Kougarok) were considered independent variables for statistical analyses. The influence of shrub patch placement (within or outside shrubs), site (Teller and Kougarok), and site by shrub interactions on all measured snow metrics were examined with linear models (lm function). Models were checked to ensure they met assumptions of normality, linearity, and heteroskedasticity using the performance package [59]. The amount of variation accounted for by the independent variables (r^2) relied on analysis of variance (aov function) and Tukey test (tukey.test function) for post hoc testing and interpretation [60].

3 | Results

3.1 | Measurements of Snow Metrics

Of the 100 temperature sensors deployed, 93 were recovered from the field and after data quality checks and cleaning, and 89 were suitable for analysis. GSTs and calculated snow metrics (freezing n-factor, insulation effect of snow, snow cover duration, length, and end of spring snowmelt period) are summarized in Table 1, grouped by site and location (within or outside shrub patches). We found that diurnal fluctuations in temperature were significantly dampened in temperature sensors that were covered by snow (Figure S1). Detailed descriptions of each of these snow metrics are reported in the following subsections.

3.2 | Snow Insulation Metrics

3.2.1 | GST

During the entire period of snow cover, GSTs within shrub patches were warmer (−2.6°C) than outside shrub patches (−4.7°C; $p < 0.001$; Figure 3a). GST was greater at Teller than Kougarok ($p < 0.001$; Figure 3a), consistent with historically warmer air temperature from meteorological stations, and the greater extent of near-surface permafrost at Kougarok [41, 61]. There was no significant interaction effect between site and shrubs on GST and only weak evidence that GST within shrub patches differed between the two sites ($p < 0.1$; Figure 3a). The range of GST values inside shrub patches was smaller than the range of GSTs outside (Figure 3a), indicating there was less insulation from air temperature variations outside of shrubs.

GST also varied seasonally depending on the timing of snow cover. In the late fall and early winter months, before snow accumulated in October and November 2019, there was no difference in GSTs placed within or outside shrub patches. Following snow accumulation and until snowmelt began in mid-April and early-May, GSTs within shrub patches were significantly warmer

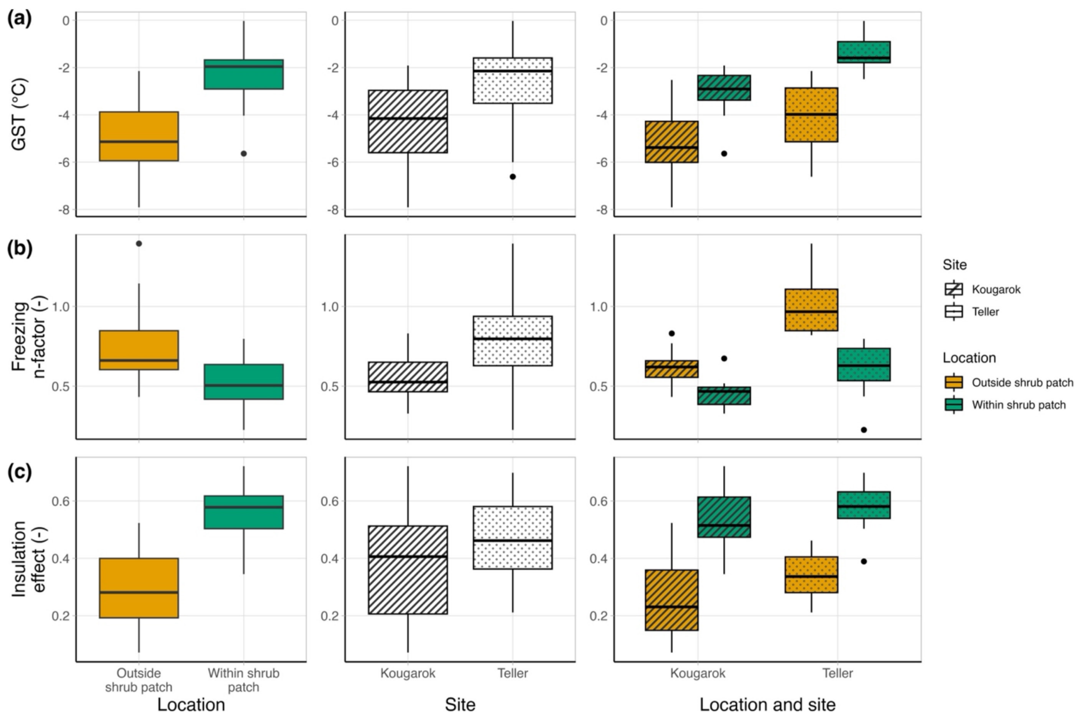

FIGURE 3 | Boxplots showing the (a) mean ground surface temperature (GST,°C) during the snow cover period (October–June), (b) the freezing n-factor (unitless), and (c) the insulation effect of snow (unitless). Solid lines inside the boxes represent the median values. The upper and lower ends of the boxes represent the 75th and 25th percentiles, respectively. The whiskers represent 1.5 times the interquartile range above or below the 25th or 75th percentiles. Box color represents placement of temperature sensors within (green) or outside (orange) shrub patches. Dashed boxes represent temperature sensors from Kougarok and dotted boxes represent temperature sensors at Teller. [Colour figure can be viewed at wileyonlinelibrary.com]

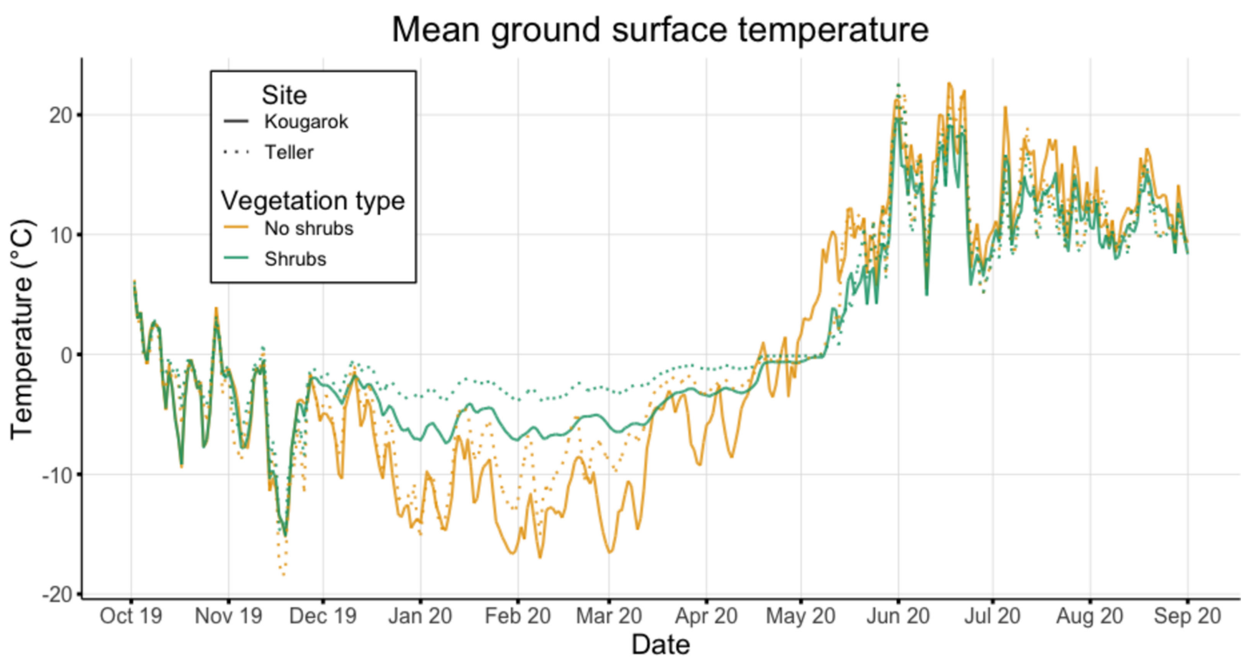

FIGURE 4 | Average daily ground surface temperature of sites in shrub patches (green lines) and ground surface temperature outside shrub patches (orange lines) between October 2019 and September 2020. Solid lines represent ground temperatures at Kougarok and dotted lines represent ground temperatures at Teller. [Colour figure can be viewed at wileyonlinelibrary.com]

($p < 0.001$). After snowmelt, GSTs outside of shrub patches were warmer ($p < 0.001$; Figure 4). This pattern continued into the summer months (June 1 to September 1), where shrub patches had cooler GSTs (12.1°C) than shrub-free sites (13.4°C, $p < 0.001$; Figure 4).

3.2.2 | Freezing n-Factor

A freezing n-factor near 1 indicates small differences between air and surface temperatures for a given amount of time. An n-factor less than 1 indicates that surface temperatures are warmer than air temperatures and, as applied in this study, that there is greater ground surface insulation during the winter. Within shrub patches, the freezing n-factor averaged 0.50, compared to 0.66 outside of shrub patches ($p < 0.001$; Figure 3b). Freezing n-factors also differed significantly by site. Kougarok had a significantly smaller freezing n-factor than Teller ($p < 0.001$), likely a result of colder winter air temperatures and differences in ecosystem and soil types at the two study sites. Some sensors outside of shrub patches had freezing n-factors greater than 1, indicating that the surface temperature was cooler than the air temperature during the winter.

3.2.3 | Insulation Effect of Snow

GST sensors within shrub patches showed significantly greater snow insulation throughout the 2019–2020 winter (Figure 3c). The insulation effect of snow was significantly higher ($p < 0.001$) within shrub patches during the snow cover period from October 2019 to June 2020 (mean insulation within shrub patch = 0.57, outside shrub patch = 0.28; Figure 3c), a result of deeper or denser snow cover. The insulation effect of snow was slightly higher at Teller ($p < 0.05$), but the interaction between site and shrubs had no impact on the insulation effect of snow. Site and location within or outside shrub patches accounted for 59% of the variation in insulation ($p < 0.001$).

The insulation effect of snow was higher in shrub patches both earlier in the winter and later in the spring than outside of shrub patches (Figure 6a). Following snowpack onset, the insulation effect of snow increased three times faster within shrubs than outside of them. Insulation varies throughout the winter both within and outside of shrub patches, likely as a function of both air temperature and thickness or density of snow cover. However, insulation is consistently higher within shrub patches, especially in April and May during peak snow cover at Teller and Kougarok [37, 38, 45, 46].

3.3 | Snow Cover Metrics

3.3.1 | Snow Cover Duration

Snow cover duration varied significantly ($p < 0.001$) within and outside of shrub patches, at both temperature sensor heights (GST sensors and sensors at 40 cm above the ground; Figure 5a,b). Based on GST sensors, shrub patches spent an average of 169 days under snow, while areas outside of shrub patches averaged 113 days (Figure 5a). Measurements from 40 cm above the ground surface indicate that shrub patches maintained deeper snowpacks for longer. Shrub patches spent an average of 138 days with at least 40 cm of snow, compared to 25 days outside shrub patches (Figure 5b). Snow cover duration also varied by site (Teller or Kougarok) for both temperature sensor height placements ($p = 0.1$; Figure 5a,b), consistent with historically deeper snowpack at Teller. We found no significant interaction between site and shrubs for snow cover duration at GST or 40-cm sensors.

For GST sensors, location within or outside shrub patches, site, and the interaction between them account for 46% of the

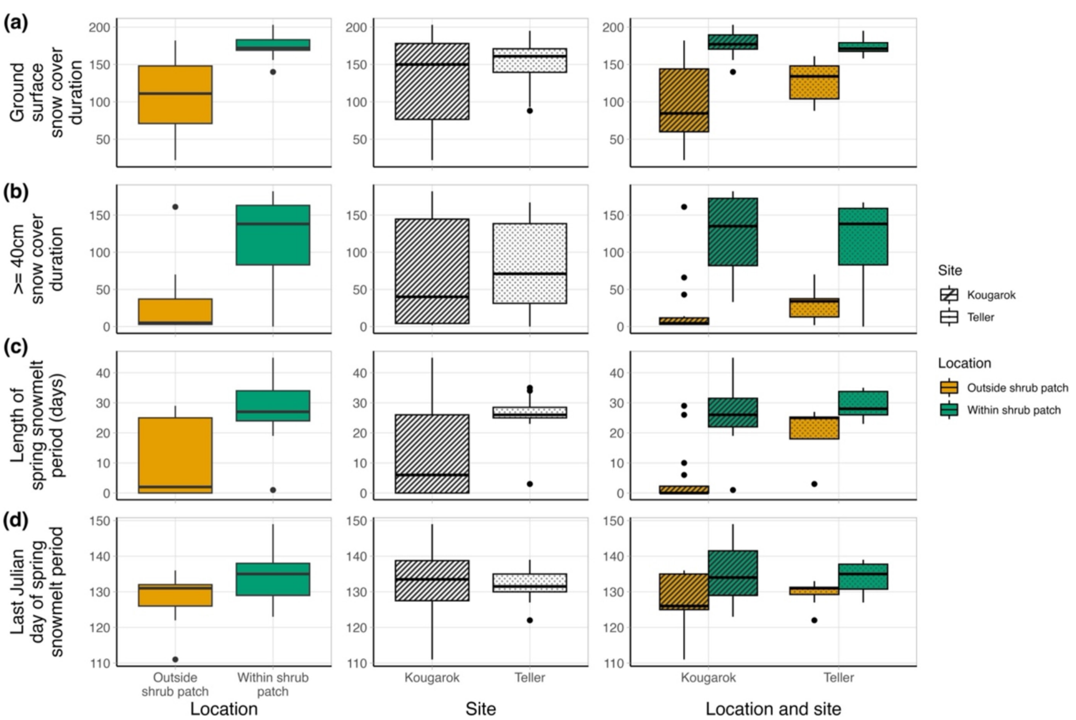

FIGURE 5 | Boxplots showing (a) Duration of snow cover on GST sensors (count of days), (b) the duration of at least 40 cm of snow cover (count of days), (c) the length of the spring snowmelt period for GST sensors (count of days), and (d) the end of the spring snowmelt period (Julian day). Solid lines inside the boxes represent the median values. The upper and lower ends of the boxes represent the 75th and 25th percentiles, respectively. The whiskers represent 1.5 times the interquartile range above or below the 25th or 75th percentiles. Box color represents placement of temperature sensors within (green) or outside (orange) shrub patches. Dashed boxes represent sensors from Kougarok and dotted boxes represent sensors from Teller. [Colour figure can be viewed at wileyonlinelibrary.com]

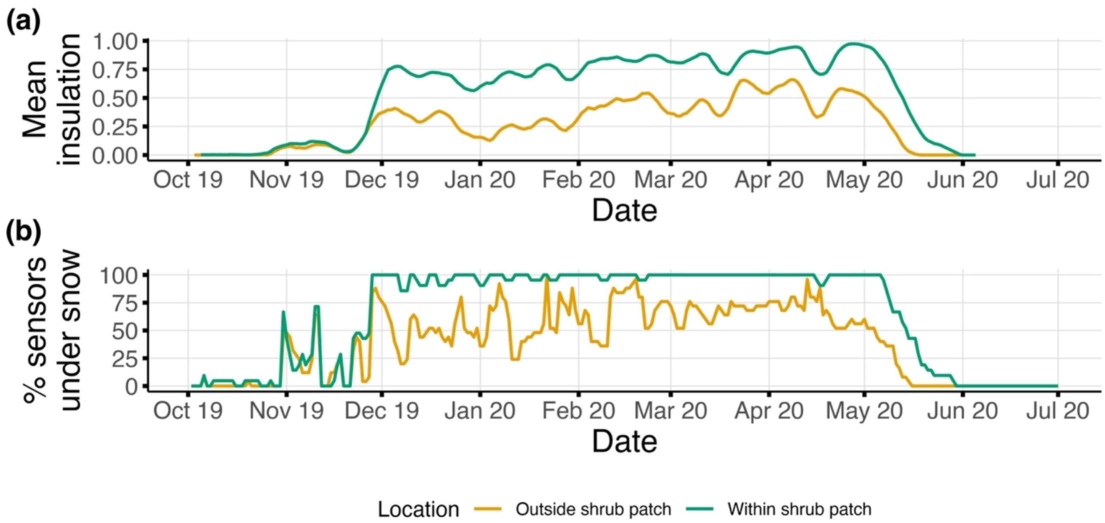

FIGURE 6 | (a) Average mean insulation effect of snow (unitless) for all GST sensors and (b) the percentage of GST sensors under snow over time (%) for the 2019–2020 winter. Green lines represent temperature sensors within shrub patches and orange lines represent temperature sensors outside of shrub patches. [Colour figure can be viewed at wileyonlinelibrary.com]

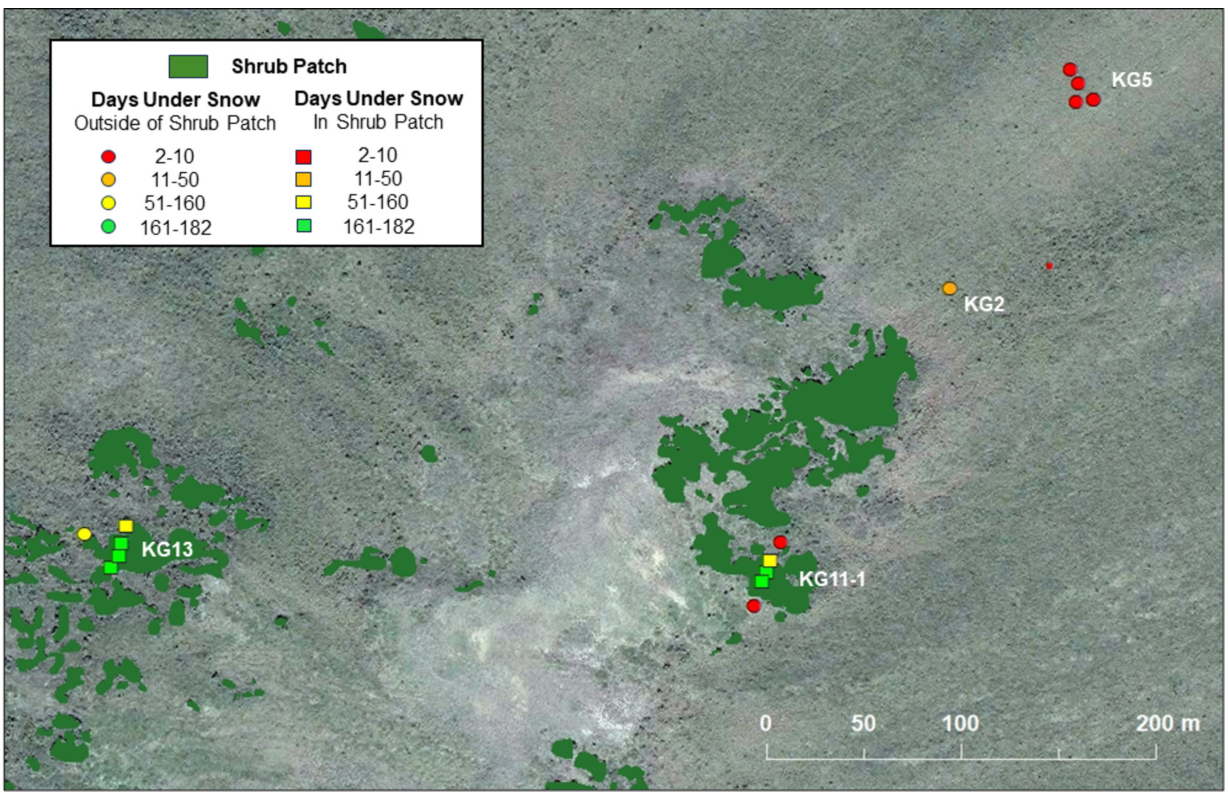

FIGURE 7 | Forty-centimeter temperature sensors at Kougarok colored by the duration of snow cover during the 2019–2020 winter. The symbol shape indicates if the temperature sensor is located within (square symbols) or outside a shrub patch (round symbols). [Colour figure can be viewed at wileyonlinelibrary.com]

variance in snow cover duration ($r^2=0.46$, $p<0.01$). Shrubs alone explain 45% of the variation in ground surface snow cover duration ($r^2=0.45$, $p<0.001$). For sensors placed at the 40-cm height, location within or outside shrub patches, site, and the interaction between them explain 47% of the variation in the duration of snow cover ($r^2=0.47$, $p<0.001$). Shrubs alone explain 50% of the variation in the duration of at least 40 cm of snow ($r^2=0.50$, $p<0.001$), indicating better model fit when excluding site as a predictor variable.

While snow accumulation began around the same time for sensors within and outside shrub patches, more sensors within shrubs were covered by snow from mid-to-late October onward, an effect of wind redistribution and snow trapping. Consistent snow accumulation occurred for all sensors by early December (Figure 6b). Overall, shrub patches maintained snow cover longer in the spring, with a late-May melt off outside shrub patches and early-June melt off inside shrub patches (Figure 6b).

Snow metrics were tightly coupled to the distribution of shrubs on the landscape. Forty-centimeter sensors placed just outside (less than 2 m) of a shrub patch spent approximately 100 fewer days under snow cover (Figure 7) than sensors inside the shrub patch, indicating vastly different snowpack characteristics occurring in close proximity. GST sensors placed in shrub patches also spent longer under snow cover than those placed outside of shrub patches. Spatially, the distribution of shrubs and snow metrics were tightly coupled.

3.3.2 | Length and End Date of Spring Snowmelt

The snowmelt period was defined as the length of time a GST sensor hovered around 0°C during the period of snowmelt (April 15, 2020–May 31, 2020; Equation 3). We found strong evidence for a significantly longer snowmelt period within shrub patches (27 days) compared to outside shrub patches (2 days; $p < 0.001$). The snowmelt length varied by site ($p < 0.001$), with Teller having a longer snowmelt period (Figure 5a), possibly driven by the historically deeper snowpack at this site. Additionally, there was evidence that the interaction of site and shrubs affected the length of snowmelt ($p < 0.05$; Figure 5a), where shrub patches at Kougarok impacted snowmelt length more strongly than they did at Teller.

The timing of snowmelt was also impacted by placement within or outside shrub patches. We found evidence ($p < 0.1$) that sensors within shrub patches experienced snowmelt that ended 5 days later compared to sensors outside shrub patches (Figure 5b). There was no evidence for an impact of site or the interaction between shrubs and site on the end date of spring snowmelt.

4 | Discussion

Shrubs were a dominant control on all snow metrics in this study. Contrary to our hypotheses, we only found minimal evidence that the site (Teller or Kougarok) impacted most snow metrics. Inside shrub patches, there was less variance in all snow metrics reported, regardless of the site and other unmeasured environmental controls (e.g., precipitation regimes, landscape position, and topography; Figures 3 and 5). In this study, shrubs alone were the best predictor of the duration and depth (as measured by 40-cm sensors) of snow.

Shrub coverage is predicted to increase by up to 150% in the Arctic [62, 63]. If wind redistribution moves snow to areas with shrubs, it can be trapped by relatively tall vegetation, leading to an increase in the spatial heterogeneity of snow depths and as a result, ground thermal regimes [20, 64, 65] (Figure 7). Our results support growing evidence that Arctic shrub expansion has the potential to change snow distribution, which has major implications for permafrost ecosystem water and energy balances.

4.1 | Snow Insulation Metrics

Ground temperature and the insulation effect of snow during the 2019–2020 winter were both strongly affected by the presence or absence of shrubs. Within shrub patches, ground temperatures were approximately 2.1°C warmer, experienced twice the insulation effect of snow, and had lower freezing n-factors compared to locations outside shrub patches (Figure 3). Our finding of warmer ground temperatures underneath shrubs supports the vast majority of findings in Arctic environments experiencing shrub expansion [65–67].

Warmer winter ground temperatures in shrub patches will have impacts for biogeochemical cycling in Arctic ecosystems. Despite cold temperatures and snow cover, permafrost ecosystems emit significant CO_2 during the winter months [24, 65, 68]. Wintertime emissions can offset growing season carbon uptake and may push permafrost systems towards sources, rather than sinks, of carbon. According to published temperature sensitivities of microbial carbon mineralizers [69], a 2.1°C increase in winter GSTs like we observed in this study could lead to an increase in microbial decomposition. Using Moni et al.'s estimations, the increase in microbial decomposition in this study system could be up to 5% assuming uniform soil temperature cascades [69], though further research could improve carbon mineralization estimates. Such increases have consequences for permafrost carbon vulnerability and the global carbon cycle because of disproportionate stores of soil carbon in the high latitudes.

However, the net impact of shrub expansion on the carbon balance of permafrost ecosystems is not clear. In this study, spring snowmelt triggered a reversal in GST warming patterns (Figure 4), during which shrubs patches were ~1.5°C cooler than nonshrub areas, a result of residual snow cooling from deeper snow in shrub patches, summer shading, and canopy cooling through evapotranspiration from leafy, woody vegetation [20]. Winter warming was ~1°C greater and persisted a full month longer than the summer cooling effect. Thus, lower summer carbon emissions caused by ground cooling in shrub patches are unlikely to balance out carbon losses triggered by warmer GSTs in winter, especially when considering that winter carbon fluxes make up at least half of the annual carbon flux in the Arctic [68]. An additional carbon balance complexity is that tall shrubs have greater carbon uptake through photosynthesis than low-lying forbes, grasses, and shorter statured shrubs [70]. It is important to consider the net impact of shrub presence on GST because the balance between winter ground warming, summer ground cooling, and plant carbon uptake will influence the relative losses of permafrost carbon from microbial respiration.

In addition to shrubs, site also impacted metrics of snow insulation, though it contributed a small fraction of variance explained in linear modeling of the snow insulation effect. GSTs were warmer at Teller than Kougarok, and freezing n-factors at Kougarok were significantly smaller than Teller (Figure 3). The effects of colder winter air temperatures and the greater presence of near-surface permafrost at Kougarok are visible in the colder GST measurements. GSTs can be influenced from belowground by differences in soil conductivity, moisture, or nonshrub vegetation parameters like a thick insulating moss layer. The exposed ridge and shallow, rocky soils at Kougarok could have lower soil conductivity than Teller soils, causing a greater impact of snowpack insulation on GST at Teller. The difference in snow insulation metrics between sites indicates that ecosystem properties like microclimates and topographic position play a role in the impact of snow processes on ground thermal dynamics. These results show the importance of site-level factors in some snow–ground insulation interactions and support findings that shrub structure and soil properties will also modulate the effect of GST insulation via thermal bridging, which can cause shrub patches to have cooler GSTs than models predict [22].

4.2 | Snow Cover Metrics

Locations within shrub patches experienced deeper (as measured by days with at least 40 cm of snow cover) and longer snow cover (Figure 5). We found that placement within or outside shrubs explained approximately half of the variation in snow cover duration, making it a major control on snow distribution at these sites. These findings have substantial consequences for the future of the water balance for tundra ecosystems. Though snow depth was not directly measured in this study, previous findings at the Teller and Kougarok sites indicate that snow depth varies more between sites than snow density. In this regard, snow density tends to be less variable spatially [71–73] and is an important predictor of snow water equivalent [37, 38, 45, 46]. Shrub locations had deeper, more insulating snow, and thus likely had greater snow water equivalents [15]. Continued shrub expansion will alter the distribution of water on the landscape and the timing and duration of melt events. Increasing snow water inputs within shrub patches add to increased patchiness in snow water distribution and will impact Arctic communities (e.g., through winter road and land access) and ecosystems.

The Arctic energy balance depends on a myriad of factors, including radiation, vegetation stature, and snowpack, which could change with shrub expansion. Snow cover strongly increases albedo compared to bare tundra [74], and higher winter albedo increases the radiation emitted out of the ecosystem [75]. Again, complex and interconnected ecosystem dynamics make the net energy balance following shrub expansion unclear. Tall shrubs can have lower albedo branches that emerge above the snowpack. Despite trapping more snow, taller shrubs could decrease albedo during the melt season as their dark branches become exposed and ultimately speed up snowmelt. Concurrently, shrub heights are likely limited in these ecosystems due to nutrient limitation [48] which could pose an upper limit to the albedo effect. The net impact on the energy balance depends on vegetation stature and snowpack conditions and will require further research to untangle.

Though we observed differences in snow duration between Teller and Kougarok, site was not a dominant control on snow cover duration. We expected a larger impact of site because Teller and Kougarok have difference in their precipitation, microclimates, and topographic positions that impact snow distribution and depth [22]. The lack of a strong site impact indicates that spatial distribution and variation in snow duration is tightly coupled to the distribution of shrubs on the landscape. With shrub expansion, the Arctic could experience landscape-level snow redistribution, causing enhanced patchiness in the distribution of snow, increasing the heterogeneity of tundra ecosystems [67, 76]. We showed that locations only meters apart can have vastly different snow cover duration, thermal regimes, and melt-off times based on shrub presence (Figure 7). To improve snow representation in models, it will be important to have high resolution spatial products that show vegetation height because this property is so tightly coupled to snow distribution.

4.2.1 | Snowmelt

Shrubs impacted the timing and length of snowmelt. Snow within shrub patches melted off later than snow outside shrub patches, with a longer snowmelt period that extended later into the spring likely driven by a deeper snowpack (Figure 5). These observed shifts during the shoulder seasons support other studies that indicate the importance of transitional seasons under future Arctic change. Shoulder seasons are recognized as becoming increasingly important for changing phenology, hydrology, and hydrogeochemisty in a warmer Arctic [77–79]. Shrubs have the potential to delay snowmelt and runoff, impacting the timing of the water cycle, plant reproduction, and plant productivity [80–82], which alters water resource availability for communities in the North [83]. Delayed snowmelt can extend soil moisture conditions to the rainy season and increase groundwater discharge [84]. However, in warmer months, woody vegetation has higher rates of evapotranspiration [85] and soils underneath shrubs tend to have lower moisture throughout the growing season [86]. The timing and net change in soil moisture conditions could become more variable in space with increased shrub expansion.

We observed a lengthening of the snowmelt period in shrub patches. Many snow fence experiments that increase snow depth report a later snowmelt period but vary in the response of the length of the snowmelt period [26, 87, 88]. We found that shrub patches had extended snowmelt periods (Figure 5), but location within or outside shrubs was a weaker explanation of spring snowmelt period length and end date than it was for the snow insulation and other snow cover duration metrics. Radiation and air temperature have been found to be more important controls on snow disappearance date than snow depth [89], possibly explaining why site was a stronger predictor of snowmelt period than it was for other snow metrics. Additionally, GSTs used to infer snowmelt period can be impacted by soil texture [90], and nonshrub vegetation parameters like moss thickness, which helps to explain why location within or outside shrub patches alone had less of an effect on snowmelt period than other snow metrics measured in this study. Even though site played a role in snowmelt duration, the small delay in the timing of snowmelt we observed in shrub patches does have ecosystem consequences. Snow fence experiments show that delayed melt causes delays in plant flowering, which has cascading effects on other ecosystem dynamics like plant–pollinator interactions [91] and seasonal biomass accumulation.

Our findings of a prolonged snowmelt period also have impacts for permafrost carbon storage. We defined the snowmelt period as when the GST (bottom of the snowpack) maintained temperatures of approximately 0°C for a prolonged period (Equation 2). While we only measured GSTs, the effects of GST do cascade through the soil. The period where subsurface soil temperatures hover at 0°C is termed the zero-curtain period. In permafrost soils, this state of soil conditions has been linked to high CH_4 and CO_2 emissions [92, 93]. With shrub expansion, soils above permafrost that spend more time in the zero-curtain period could see greater carbon emissions from microbial decomposition and subsequent evasion during the spring melt-off period.

4.3 | Limitations

While we observed strong differences in snow metrics within and outside shrub patches, there are limitations to this study from the instrumentation and methods, validation techniques, and unmeasured variables that impact snow properties and ground thermal dynamics. First, this study utilized inexpensive temperature sensors to capture snow metrics, which have limitations related to the accuracy, precision, and storage size of these instruments. We measured large (~2°C) differences in temperatures inside and outside of shrub patches, but if those differences had been smaller, we may not have been able to capture them. We programmed the temperature sensors to measure every 4 h, which allowed for measurements through the winter, and even some summer measurements, but metrics that require finer resolution measurements (i.e., hourly) were limited by the length of data collection and storage. While this is a limitation of the study, the low cost of these sensors makes it easy to deploy many sensors over a large area and should be considered for future use in combination with higher quality sensors.

Restrictions due to COVID-19 prevented us from validating our methods with higher resolution, manual snow depth measurements. To address this issue, we focused on using methods to measure binary (snow cover or no snow cover) indices of snow cover to measure the duration of snow in the winter. This method for calculating daily snow cover is based on the daily standard deviation of temperature being below a 1°C threshold for three consecutive days [31]. One study found that this method is effective when testing the validity of this threshold across Arctic ecosystem types in Canada [32]. Many studies have shown that different ecosystem types will require different thresholds for snow cover that would bias results [35, 94, 95]. García-Maroto et al. found that applying four different methods and thresholds (e.g., using 2-day standard deviation of the temperature sensor) for determining sensor snow coverage give different results of snow thickness [94]. However, their analysis found greater variation in extrapolating snow thickness when using sensors distributed along a pole as opposed to measuring the duration of snow cover at the base of the snowpack, as applied in our study. The daily standard deviation method we used [31] likely underestimates snow cover duration, which is discussed by publications that apply this method [31, 32, 94] and is corroborated by our validation of the method during peak snow cover (see Section 2 and Supporting Information S1), which showed a 2%–4% underestimation of snow cover duration.

Snowpack properties like density are variable with snow thickness and across ecosystem and vegetation types, while snow depth is considered more variable than snow density [71–73]. However, snow density can impact the snow metrices derived in this study [73, 96–98]. While GST sensors within and outside of shrub patches had a relatively high success rate (average 96% success rate; Supporting Information S1), we found that GST sensors outside of shrub patches were slightly worse at capturing snow cover (94% success rate; Supporting Information S1) during peak snow depth than sensors within shrub patches (98% success rate; Supporting Information S1). The slightly lower success rate of snow cover outside of shrub patches is likely due to shallower snowpacks, which insulate less against daily air temperature fluctuations, leading to challenges in capturing when snow is present. While there may have been differences in snow properties between vegetation types that led to differential success of the threshold method, we were still able to capture drastic differences in snow cover within and outside of shrub patches.

Finally, this study focused specifically on the impact of shrubs and site on snow metrics, but surface temperature dynamics are also impacted by belowground processes driven by highly heterogenous soil characteristics [99], not just by aboveground snow and vegetation characteristics. For example, we saw evidence of cooler ground temperatures at Kougarok, which has more near-surface permafrost than Teller. Differences in permafrost distribution were discussed as potentially contributing to site differences in GSTs, but this study was not designed to test the interaction between permafrost and vegetation changes.

4.4 | Future Directions

While shrub presence was a strong and dominating control on all snow metrics observed in this study, there was still variability and a range of responses observed, especially for areas without shrubs. Kougarok, a hillslope site with measurements on all topographic aspects, had greater variation in GST (Figure 3a), snow insulation effect (Figure 3c), snow cover duration (Figure 5a,b), and snowmelt timing (Figure 5c,d), pointing to landscape position as another important predictor of snow distribution. Locations outside shrubs at both sites had greater range of observed values for most snow metrics observed, indicating that when shrubs are not present, other environmental drivers become more important for snowpack characteristics. Future research should focus on understanding what other ecosystem properties become important controls on snow processes to further improve models of snow distribution.

No direct measurements of snow depth were collected during this study, which made validation of metrices challenging. Future analysis should focus on a stronger validation of snow metric calculations to better constrain the error in measurements like snow cover duration. While validation was a challenge in this study, it points to the importance of developing methods presented herein, which allow for data collection while sites are inaccessible. Additional work has and will expand on these methods and incorporate estimates of snow water equivalent, snow distribution modeling [33, 34] and machine learning to measure snow depth continuously through a winter [100]. The methods published in this study are foundational to be able to confidently collect snow depth data throughout the winter and across the watersheds, regardless of site accessibility [15, 101].

5 | Conclusions

Taller vegetation, like the alder and willow shrubs at Teller and Kougarok, is projected to experience range expansion in a warmer Arctic. Our results suggest that taller vegetation greatly impacted the winter and summer GST, the insulation effect of snow, snow duration, and the length and end date of the spring snowmelt period at field sites on the Seward Peninsula of Alaska. This is corroborated by a combined observational and modeling study that showed that vegetation cover strongly influences the distribution of snow cover across the Teller watershed.

Our findings have implications for the future of the Arctic. Higher ground insulation from shrubs trapping snow has the potential to warm and thaw permafrost and increase microbial decomposition of soil organic carbon, which has far-reaching impacts for the global climate cycle. The spatial distribution of shrubs and snowpack characteristics snow metrics were tightly coupled, indicating the potential for increased heterogeneity of snow distribution with shrub expansion. Though shrub patches strongly controlled these snow metrics, more research is needed to evaluate other environmental effects on snowpack characteristics for improved prediction of snow distribution in the Arctic.

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Data Availability Statement

Snowpack measurements used to characterize sites are available from a publicly available repository, the United States Department of Energy's Environmental System Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE), which is accessible at https://ess-dive.lbl.gov/ (Wilson et al. [45], https://doi.org/10.5440/1593874; Wilson et al. [38], https://doi.org/10.5440/1592103; Bennett et al. [37], https://doi.org/10.5440/1798170). Meteorological data used to calculate snow metrics are also available on ESS-DIVE (Busey et al. [39], https://doi.org/10.5440/1437633) and the International Arctic Research Center's data repository (Busey et al. [47], http://monitors.iarc.uaf.edu/data/uaf_sp/k-met/). iButton temperature data are also available on ESS-DIVE (https://doi.org/10.5440/1996564).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.