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Greening of the Arctic: Plot-Scale Analysis of Interactions between Climate, Vegetation, and Permafrost at Toolik Lake, Alaska (1995 - 2017)

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GREENING OF THE ARCTIC: PLOT-SCALE ANALYSIS OF INTERACTIONS BETWEEN CLIMATE, VEGETATION, AND PERMAFROST AT TOOLIK LAKE, ALASKA
(1995 – 2017)

By

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ABSTRACT

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Greening of the Arctic: Plot-scale analysis of interactions between climate, vegetation, and permafrost at Toolik Lake, Alaska (1995 - 2017)

Chairperson: Dr. Anna E. Klene

Air temperatures across the Arctic have increased in recent decades, and through complex feedbacks, vegetation and permafrost (frozen ground) are actively responding as climate warming continues. This study investigates the trends and interactions of observed air, soil-surface temperature (SST), and active-layer thickness (ALT) at Toolik Lake on the Alaskan North Slope between 1995 and 2017, as well as vegetation change over time.

Time series between 1995 and 2017 at CALM site U12B, a 1 ha plot near Toolik Lake, reveal an increase (0.50 °C/decade) in mean summer (Jun-Aug) air temperatures and a decrease (-0.23 °C/decade) in mean summer SST. In winter (Dec-Feb), the plot experienced an overall increase (2.27 °C/decade) in SST and an increase (0.84 °C/decade) in air temperatures. In nearly every winter during the 23-yr observation period, mean SST at sensors positioned along the water track (WT) within the plot remained above -6°C. Since 2009, sensors in non-WT areas have recorded mean winter SST consistently above -8°C, an increase in mean winter SST across the tussock tundra that could have important implications for winter microbial activity. Deepening mean maximum ALT (1.9 cm/decade) reflects the annual warming air and SST (0.60 °C/decade and 0.90 °C/decade, respectively) at CALM site U12B.

Using airplane color-infrared aerial photographs (1995) and unmanned aerial vehicle (UAV) red-near infrared images (2017), normalized difference vegetation index (NDVI) maps were produced for peak greenness in August within the 1 ha plot. The WT, dominated by low shrubs, had the highest NDVI values compared to the surrounding tussock tundra. An increase in greenness along the edges of the WT in 2017 relative to 1995, as well as a visual comparison of the ortho-mosaics and photo-derived digital elevation models (DEMs), reveals the WT widening by nearly 4.5 m and greening of the shrubs adjacent to it, although shrub height and abundance were not directly measured. This increase in greenness could also be due to vegetation differences within (willow) and adjacent (dwarf birch) to the WT.

Incorporating air and soil-surface temperatures, ALT, and vegetation dynamics into a time series demonstrates the complexity of feedbacks in a changing Arctic environment. The results of this study are consistent with other studies reporting an increase in vegetation and biomass in this region. This increase in greenness (particularly within and adjacent to the WT), likely influences snow trapping and winter SST conditions, promoting overwinter decomposition and nutrient mineralization. These results may have strong implications for biogeochemical feedbacks and ecosystem processes.

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1 INTRODUCTION

Air temperatures in the Arctic (areas above 66°N) are increasing at more than twice the rate of the global mean (Overland et al., 2017), and climate models suggest that changes will continue to be more dramatic in polar regions relative to lower latitudes (Chapman and Walsh, 1993; IPCC, 2013). Permafrost (ground frozen for two or more consecutive years) underlies more than 24% of the land in the Northern Hemisphere and over 80% of the land in Alaska (Zhang et al, 2003). As Arctic air temperatures continue to rise and warm northern landscapes, greenhouse gases such as methane and carbon dioxide are released to the atmosphere through increased microbial activity and decomposition of soil carbon substrates - further fueling changes in climate (Schuur et al., 2008).

Historically, the Arctic was considered a carbon (C) sink, with vegetation absorbing more carbon for photosynthesis than was released through decay (Billings et al., 1981). Currently, the Arctic is generally considered carbon neutral as the C sink balances the C source (Ueyama et al., 2013). However, as the climate continues to warm, the Arctic could eventually become an overall source of carbon to the atmosphere (Abbott et al., 2016; Chaudhary et al., 2017). Vegetation typically acts as an insulating layer to soils, providing a buffer between air and soil-surface temperatures in the summer and trapping snow in the winter (Sturm et al., 2001; Nyland et al., 2012; Walker et al., 2003). Through these complex interactions, increases or decreases in Arctic vegetation (Arctic "greening" or "browning") will likely impact permafrost conditions as climate change continues.

The active layer (soil above permafrost that thaws seasonally) is where most ecological, hydrological, and biogeochemical processes in cold regions occur (Hinzman et al., 1991; Kane et al., 1991; Brown et al., 2000). Changes in the ground thermal regime also have an impact on ecological and terrain disturbances, potentially resulting in the disruption of existing infrastructure (roads, pipelines, buildings, etc.). Variations in seasonal thawing of permafrost at the interannual and multi-decadal scale are important for understanding the response of cold soils and permafrost to changes in climate, and for predicting future responses (Brown et al., 2000).

Permafrost thaw and active layer warming have important societal implications through increasing hazards by destabilizing the ground beneath local infrastructure (Hong et al., 2014) and through greenhouse gas emissions (Schuur et al., 2015). This study investigates the trends of observed air, soil-surface temperature, snow cover, and active-layer thickness at Toolik Lake on the Alaskan North Slope between 1995 and 2017, as well as vegetation change over time. This research aids in our understanding of the resulting biogeochemical feedbacks, ecosystem processes, and engineering implications of plot-level interactions on permafrost.

2 BACKGROUND

The number of permafrost studies in the Arctic increased around the 1960s, generally in response to the construction of oil fields and a growing concern of their influence on the surrounding environment (Raynolds et al., 2013). The International Biological Programme was an effort between 1964 and 1974 to conduct large-scale ecological and environmental studies (Webber et al., 1980). Study sites were established in the Arctic, including Alaska, and these locations (and subsequent similar efforts, e.g. International Tundra Experiment) serve as the basis for more recent studies, allowing for analysis of changes over time (Villarreal et al., 2012). These baseline field observations, combined with remote sensing, modelling, and continued field sampling allow for a more comprehensive understanding of the characteristics and drivers of changing vegetation, permafrost, and ecosystem dynamics at high northern latitudes.

2.1 Remote sensing of Arctic vegetation

Since the beginning of the Landsat program in 1972, satellite images have been used to calculate the Normalized Vegetation Difference Index (NDVI) (Tucker, 1979) where:

$$NDVI = (NIR - R) / (NIR + R) .$$

A combination of Advanced Very High Resolution Radiometer (AVHRR; 1.1 km resolution, global coverage twice daily (USGS, 2015)) and Moderate Resolution Imaging Spectroradiometer (MODIS; 500 m resolution, 16 day intervals (NASA, 2018))-derived

NDVI values were used to create remotely sensed productivity products (Prs) using the following equation:

$$Prs_{p,y} = \max(GSL_p^{-1} \sum_{i=t+1}^{t+\,GSL_p} NDVI_{p,y,i}),$$

where GSL is the growing season length, *p* is each grid cell, and *y* represents each year (Beck and Goetz, 2011). These NDVI and Prs values between 1982 and 2008 indicate an increasing trend in both shrub and non-shrub dominated areas. Remotely sensed NDVI values and the relationship between field-sampled aboveground phytomass and NDVI between 1982 and 2010 revealed an overall increase in Arctic tundra greening and vegetation productivity from 15% to over 30% in North America, as well as an average circumarctic increase of 19.8% in aboveground biomass (Epstein et al., 2012).

Analysis of AVHRR and MODIS images for the pan-Arctic domain also revealed an increase in growing season length by more than six days for tundra vegetation between 2000 and 2010, characterized by an earlier growing season onset (Zeng et al., 2011). An increasing trend in mean annual non-frozen season (1979-2010) of 2.4 days/decade for the northern vegetated region was also found by analyzing a global satellite record derived from overlapping scanning multi-channel microwave radiometer (SMMR) and special sensor microwave imager (SSM/I) 37 GHz frequency brightness temperatures (Kim et al., 2014). However, a longer growing season does not necessarily result in an increase in net vegetation growth due to confounding factors such as an increased risk of spring frost damage (Kimball et al., 2006; Inouye, 2008; Wipf et al., 2009). Regardless, these satellite remote sensing studies conclude that both growing season and aboveground biomass at northern latitudes have significantly increased over the past ~20 years.

Though the moderate to coarse resolution satellite-derived measurements used by these studies are useful for evaluating relative changes in Arctic vegetation dynamics, finer spatial information is needed to understand how changes are being realized on the ground in terms of tundra ecosystem structure and function. Field-based and finer resolution remote sensing data are necessary to verify satellite based remote sensing records in order to relate satellite records to landscape features. These studies will aid in the ability of satellite records to detect abrupt and subtle longer term changes in landscape characteristics.

2.2 Vegetation and soil processes

Mean summer air temperature generally decreases with latitude, accompanied by a shift in dominant vegetation type from forest to shrub to tundra along a northward latitudinal gradient (Walker, 1998). These factors influence the energy balance and temperature at the ground surface through insulation from solar radiation, which helps determine the depth of the active layer. In general, thaw depth decreases with latitude as landscape mean annual temperature becomes colder and winter solar radiation loadings become minimal to none (Nelson et al., 1997), though the spatial heterogeneity is substantial due to differences in soil, vegetation cover, topography, and microclimate conditions (Nelson and Outcalt, 1987).

In-situ NDVI measurements are often used as a proxy for aboveground biomass in arctic ecosystems (Kelley et al., 2004; Jia et al., 2003; Shippert et al., 1995). Using this method, Kelley et al. (2004) demonstrate that active layer thickness (ALT) was greater on sparsely vegetated frost boils than inter-boil areas with taller vegetation, supporting that with less insulation (and lower NDVI) there is greater heat transfer (Klene et al., 2001). However, Sturm et al. (2001) emphasize the influence even small shrubs can have on snow trapping and accumulation, as well as winter soil surface temperatures, ultimately leading to deeper active layer measurements. This demonstrates the complexity and variety of influencing factors, such as soil substrate, topography, weather, snow, and vegetation, which need to be considered at each individual plot.

Many recent studies have addressed the concept of 'greening of the Arctic' and changing ecosystem processes (Beck and Goetz, 2011; Zeng et al., 2011; Epstein et al., 2012; Kim et al., 2014). While satellite remote sensing and field studies indicate an expansion of shrub coverage, these studies suggest that expansion is greater in the sub-arctic and lower arctic zones (such as those found in most of Alaska). Regardless, the overall increase in aboveground tundra biomass has large implications for nearly all aspects of tundra ecosystems, including ALT, hydrology, wildlife, and human use of Arctic landscapes.

Satellite remote sensing techniques provide an overview of arctic trends; however, finer resolution remote sensing studies and field-based studies are necessary to accurately capture the high spatial and temporal variation of vegetation dynamics. Vegetation and permafrost respond locally to micro-scale variations in climate and site conditions (Nelson et al., 1998; Lachenbruch & Marshall, 1986). Models predicting changes in the Arctic use parameters at a coarse resolution which have difficulty accurately capturing the complex feedbacks between variables (Chadburn et al., 2017). Smaller, plot-scale studies are necessary for understanding the complex interactions between variables driving changes across the Alaskan North Slope (Elmendorf et al., 2012). Studies involving repeat high resolution color-infrared images, and other high resolution remote sensing techniques, could enhance the monitoring of small changes in vegetation dynamics at northern latitudes over time.

2.3 The Circumpolar Active Layer Monitoring (CALM) Network

The Circumpolar Active Layer Monitoring (CALM) network was developed in the early-1990s as a long-term observational program to assess changes and provide ground truth measurements for ALT in regional and global models. It was created to address concerns regarding the considerable potential for ecological and terrain disturbances in a continually warming climate (Burgess et al., 2000). With participants from 15 countries and more than 200 sites in both hemispheres, ALT and soil temperatures are monitored in-situ through mechanical probing and temperature loggers, respectively, each year.

The National Science Foundation's (NSF) Arctic Systems Science's (ARCSS) Flux Study established 1-hectare (100 m x 100 m) plots in the 1990s along the North Slope of Alaska where soil, vegetation, active layer, ecological, and microclimatic characteristics were inventoried (Weller et al., 1995; Reeburgh et al., 1998; Walker et al., 1998). NSF's CALM Project has continued monitoring in eight of these plots (Figure 1). As a result, time series of soil-surface and air temperatures, as well as ALT, are available from 1995-2017. In addition, 1 km^2 grids were established in the 1980s across Arctic Alaska for measuring ALT and providing the spatial and temporal distribution of ALT. These sites provide a uniquely long data set on the North Slope of Alaska, enabling time-series analysis.

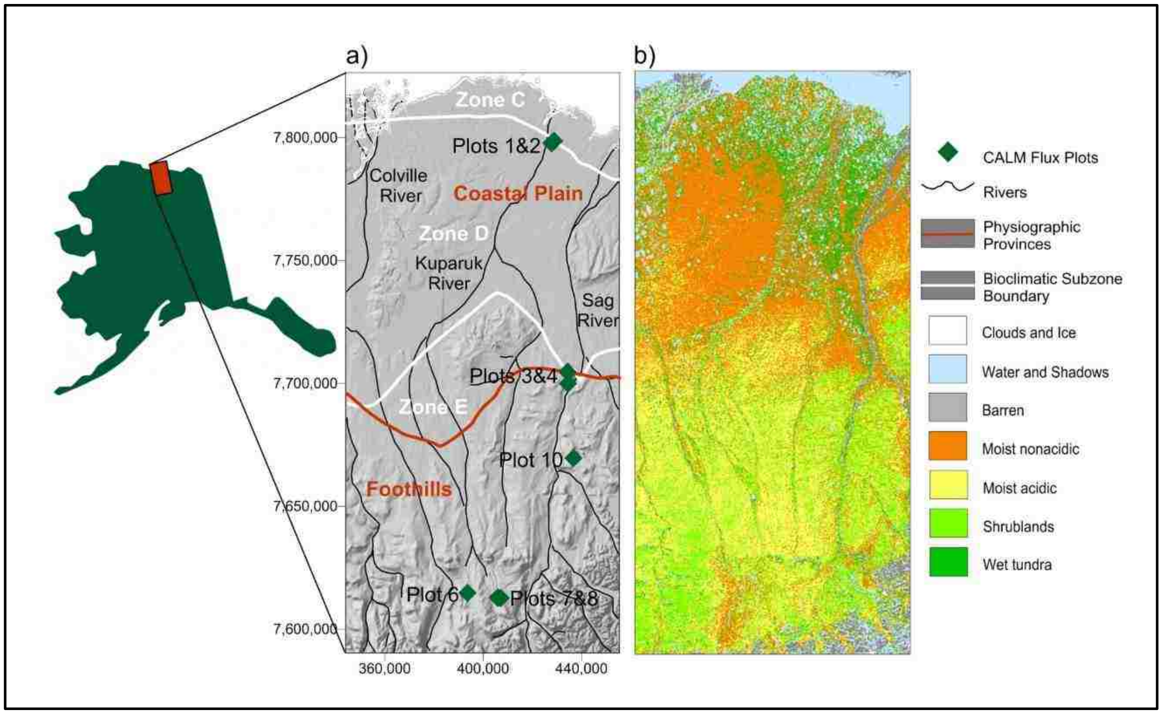

Figure 1. Map showing (a) bioclimatic subzones, physiographic provinces, and locations of 1 ha CALM Flux plots, and (b) vegetation type. Figure from Klene et al., 2015.

The past analysis of time-series at each of the 1-ha CALM plots revealed an increasing trend in mean summer (June-August) air temperatures, yet a shallower increase or slight decreasing trend in mean summer soil-surface temperatures (Klene et al., 2015). This growing difference between air and soil-surface temperatures raises the question of the driving force behind the decoupling of these variables. Annual measurements at these sites have included air and soil surface temperature, and ALT; however, no vegetation measurements have been taken since their establishment in 1995.

2.4 Temperature and ALT Relationship

The general relationship between end-of-season thaw depth and air temperature can be described by a variation of the Stefan solution (Stefan, 1891; Harlan and Nixon, 1978):

$$Z = E\sqrt{DDT}$$

where Z is the end-of-season thaw depth, DDT is the number of accumulated thawing degree days, and E is the "edaphic factor", representing the soil thermal properties, soil moisture, and the nature of surface cover (Nelson and Outcalt, 1987). DDT is calculated by summing all positive (>0°C) mean daily temperature over the period of thaw. This relationship (with variants of E) has been used to perform regional mapping of active-layer thickness (Nelson et al., 1997) and has been demonstrated as a valid approach for northern Alaska (Zhang et al., 1997; Romanovsky and Osterkamp, 1997; Nelson et al., 1998; Klene et al., 2001; Shiklomanov, 2001).

2.5 N-factors

The n-factor is the ratio of the sum of degree days per season at the soil-surface to those in the air at standard screen height. This index was originally used for construction and engineering purposes (Carlson, 1952), but has been adapted to natural landscapes to examine the relationship between air and soil temperatures, as well as the thermal properties of the ground surface (Lunardini, 1978; Klene et al., 2001). For calculating summer n-factors, the equation is:

$$n_t = \frac{DDT_{soil}}{DDT_{air}}$$

where n_t is the thaw-season n-factor and DDT are the summer (Jun-Aug) thawing degree-day sums (for soil surface and air in °C days). Winter n-factors can be calculated in the same manner, using the winter (Dec-Feb) freezing degree-day (DDF) sums for both soil surface and air. N-factors can range from zero to infinity, with values near 1 indicating little difference between the degree-day sums in the air and at the soil surface. Values below 1.0 indicate that air temperatures are higher than those at the soil surface.

3 STUDY AREA

The University of Alaska-Fairbanks' Toolik Field Station is located on the shores of Toolik Lake, approximately 125 km inland from the Arctic Ocean and nearly 600 km north of Fairbanks, Alaska (Figure 2). Long term ecological projects have been collecting a variety of data since 1975, and numerous long and short-term projects have been instituted since then (Hobbie, 2014). The area surrounding Toolik Lake consists of rolling foothills underlain by hundreds of meters of continuous permafrost. This low Arctic site is characterized by a tussock tundra and low shrubs, birches, and willows growing between tussocks or along the banks of streams and water tracks (Hobbie et al., 2017). Summers usually last between June and August; there is a mean annual temperature around -8 °C. Annual precipitation averages around 300 mm, mostly falling in the form of snow.

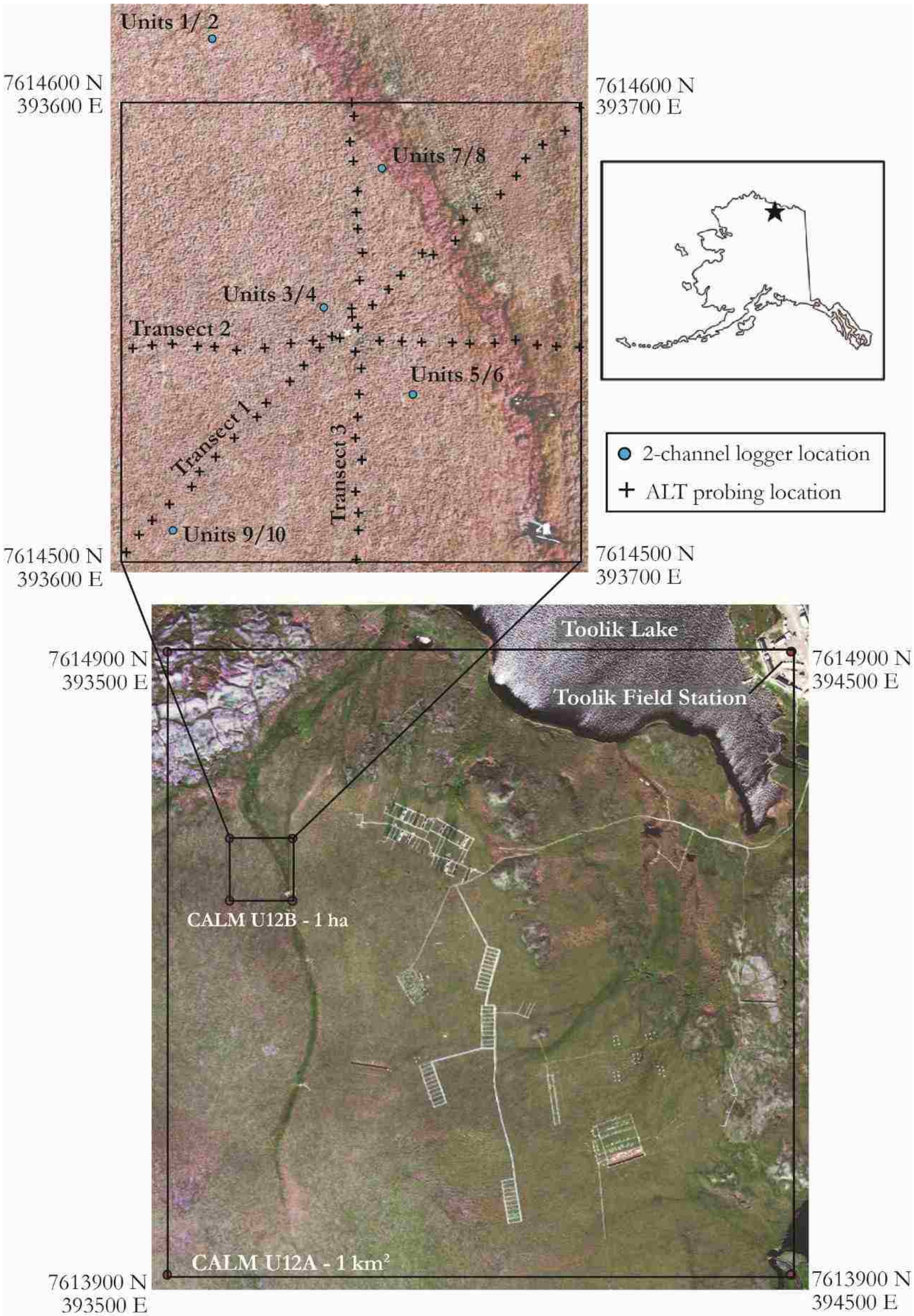

Figure 2. Location of 1-ha CALM site U12B nested within the 1 km^2 U12A or "ARCSS Grid", with ALT probing transects and temperature logger locations. Coordinates in NAD27 UTM zone 6N.

While CALM has been monitoring eight 1 ha plots (Figure 1) and ten 1 km^2 grids on the Alaskan North Slope since 1995, this study focuses specifically on CALM sites U12A (1 km^2 grid) and U12B (1 ha Flux Study Plot 6) at Toolik Lake (Figure 2). A description of U12B can be found in Walker and Bockheim (1995). CALM site U12B is a moist acidic tundra and water-track complex in the Arctic foothills province, near the University of Alaska-Fairbanks' Toolik Field Station (Figure 3). The CALM site U12B was chosen due to the extensive dataset available through the CALM Project, as well as the Toolik Field Station's ability to provide high-resolution imagery in summer 2017 for vegetation analysis.

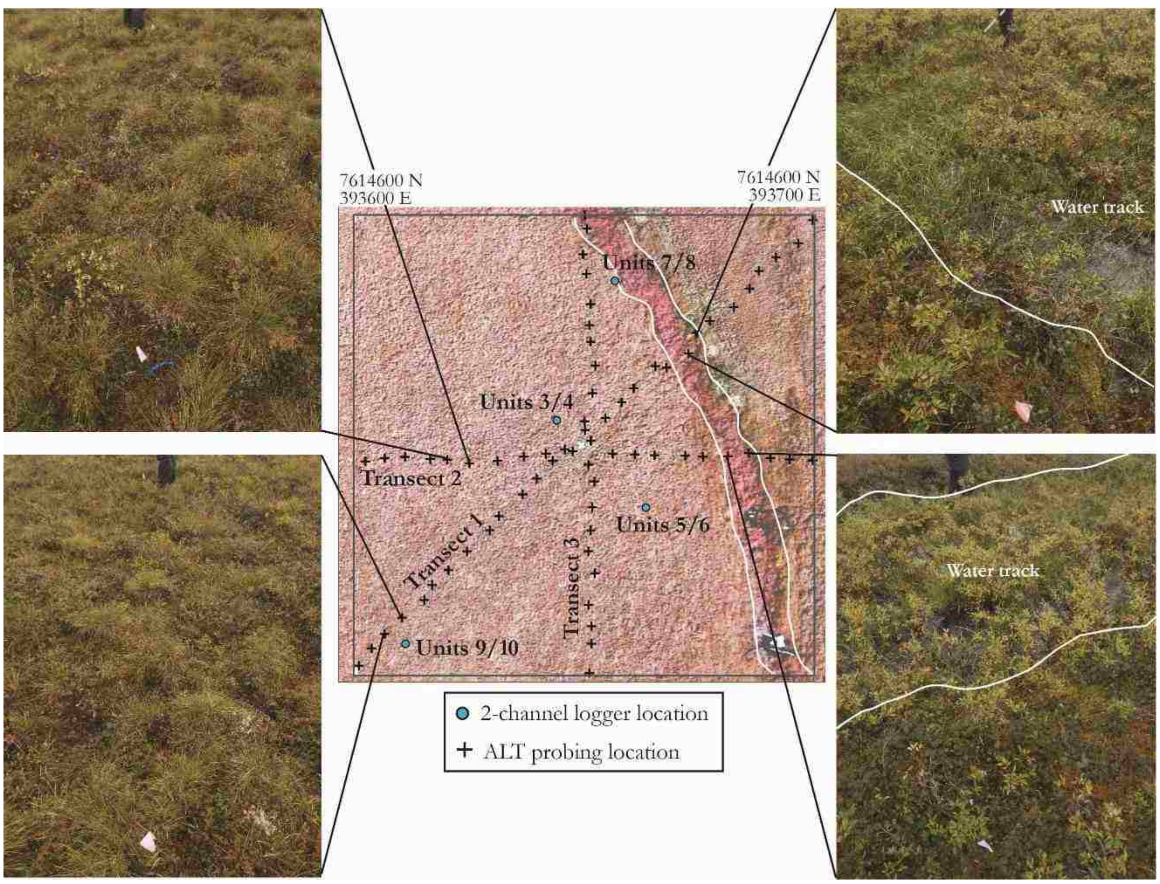

Figure 3. Vegetation examples along ALT transects from 2017 field campaign, with the two on the right showing the water track (outlined in white) with low shrubs, and the two left photos showing tussock tundra.

4 OBJECTIVES

This study investigates the trends of observed air, soil-surface temperature, snow cover, and ALT at Toolik Lake on the Alaskan North Slope between 1995 and 2017, as well as vegetation change over time. Using remote sensing techniques, vegetation changes were quantified in an attempt to better understand the micro-scale influence of climate and vegetation on permafrost. The main question investigated in this study is:

How has the interaction between climate, vegetation, snow, and permafrost changed at Toolik Lake on the North Slope of Alaska?

In order to answer this question, the following objectives were outlined:

Objective 1. Investigate trends in air and soil-surface temperature, snow cover, and ALT time-series (1995 – 2017).

Objective 2. Use near-infrared (NIR) aerial photographs (stereopairs) to quantify vegetation change at CALM U12B from 1995 to 2017 using modern photogrammetry.

Objective 3. Examine relationships between changes in vegetation characteristics in relation to air and soil-surface temperature, snow cover, and ALT time series.

5 METHODS

5.1 Air and soil-surface temperatures

At CALM site U12B, five 2-channel data loggers collect hourly temperature time series year-round, with 9 soil-surface and one air temperature sensor (Figure 1). Soil-surface temperature sensors are inserted at the base of the humic layer (top soil layer with partially decomposed organic components) and air temperature is measured 2 meters above the ground. Instrumentation has been replaced several times since initial installation, progressing from Onset Stowaway™, to HoboPro™, to the current Hobo U23 Pro V2™ dataloggers. Data are manually downloaded annually in August and batteries are replaced. Temperature data are processed into daily means, then mean summer (June-August) and winter (December-February) air and soil-surface temperatures are reported for the plot. When 5 or more of the 9 soil-surface temperature records are available, they are averaged to report the mean daily SST for the plot.

5.2 Active layer thickness (ALT) monitoring

Under the CALM protocol, mechanical probing is the standard basic approach used to obtain measurements of ALT. This is done in mid-August to capture the maximum seasonal thaw depth. At the 1-ha Flux Plot (CALM site U12B), ALT measurements are collected every 5 m along 3 transects (Figure 1), and every 100 m within the 1 km^2 grid. Probing is performed by inserting a 1 cm diameter graduated steel rod into the soil until resistance is met (Brown et al., 2000). Two measurements are taken at each probing location in the 1 km^2 grid, then these measurements are averaged for that point. When reporting maximum seasonal thaw across the entire grid or plot, all ALT measurements are averaged to produce one value, which can more easily be compared throughout time.

5.3 Snow cover duration

Methods for determining snow onset, snowmelt, and snow cover duration were modified from Lewkowicz (2008) by Pyne (2014) and applied at a series of sites along the CALM transect in northern Alaska. Hydrological years (Sept-Aug) were used to capture the entire winter season for each year. Daily soil-surface temperature amplitude and mean daily air temperature from in-situ loggers were used to determine snow-cover timing. The ground was considered snow covered if the mean daily air temperature was less than 0°C and soil-surface temperature amplitude was less than 1°C, between snow onset and snowmelt. Snow onset was considered the first day of five or more consecutive snow-covered days between August and November, so long as this period was not followed by ten consecutive snow-free days. Similarly, snowmelt was determined by finding the first day of five or more consecutive snow-free days in the spring, unless followed by 10 or more consecutive snow-covered days. Snow cover duration (SCD) was calculated as the number of days each year between snow onset and snowmelt.

5.4 Remote sensing of vegetation

For the photogrammetric analysis of vegetation at CALM site U12B, two color-infrared (CIR) aerial photographs were obtained by Quantum Spatial at 1:3000 resolution in August 1995. Markers were placed at each surveyed corner of the plot, as well as the center, to be used as ground control points (GCP). In August 2017, unmanned aerial vehicle (UAV) imagery (RGB and NDVI) of CALM site U12B was flown by the GIS office at the Toolik Field Station during peak vegetation (August) to capture the full extent of vegetation growth. DDT for each image acquisition was calculated to ensure comparable phenology between 1995 and 2017 (Figure 4). The 2017 NDVI images (Red + NIR) were taken using the MapIR©'s Survey 2 camera and RGB images were taken with a GoPro™. Five black and white targets were placed on the ground before image acquisition and differential GPS measurements were taken for each ground control point. Oblique ground photographs of the vegetation were also taken for each of the three transects at 5-meter intervals.

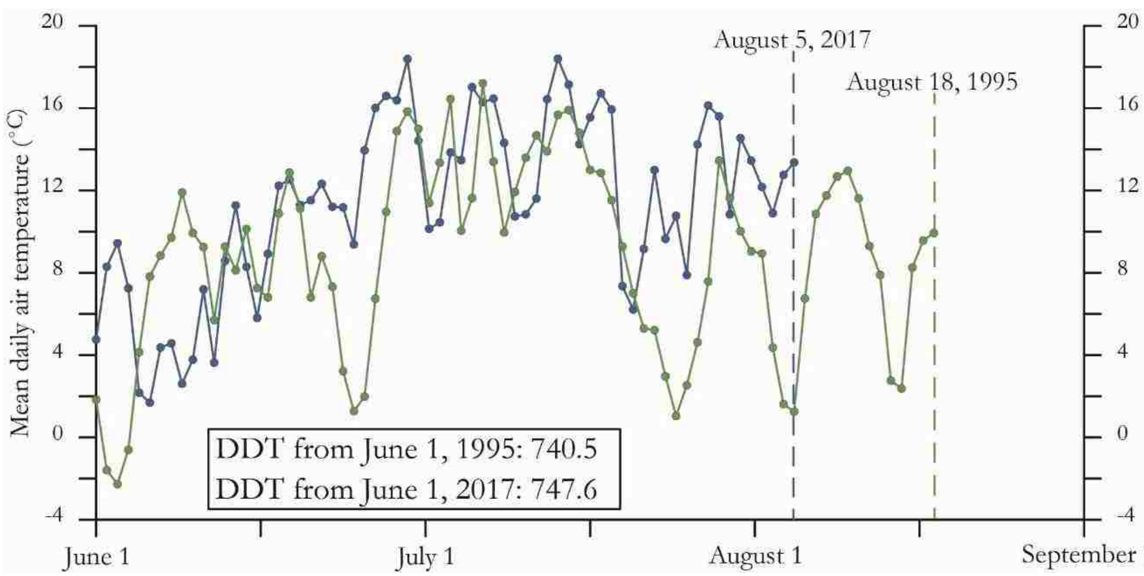

Figure 4. Mean daily temperature at CALM site U12B from June 1 until date of image acquisition in 1995 (green) and 2017 (blue) and degree days of thawing (DDT).

Pix4D©, an advanced photogrammetry software, was originally investigated as the primary software for analysis. However, problems were immediately encountered due to a minimum requirement of 3 images (only 2 are available from 1995) and a lack of flight plan information from 2017. This inhibited the software's ability to properly align the photos. By using low accuracy (25% photo resolution) alignment parameters in Agisoft Photoscan©, however, both the 1995 and 2017 photos were successfully aligned. GCPs

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were then used to georeference the images. Because the 1995 GCPs lacked a Z value (elevation), Z values were extracted from the 2017 DEM under the assumption that the corners of the plot remained stable. Using Photoscan, high density point clouds were produced, then the point clouds were used to create an orthomosaic and DEM for each year.

After the orthomosaics were produced, the NDVI processing function (with scientific output) from the Image Analysis toolbar in ESRI's ArcMap[©] was used to produce NDVI maps (using the Red and NIR bands for each image), with the orthomosaics as the input. The 2017 NDVI image was resampled to the same resolution (3.8 cm/pix) as the 1995 NDVI image using the bilinear resampling technique. The mean of each image was subtracted from each pixel value to help accommodate for differences in sensor and phenology between 1995 and 2017. Then, pixels in each map were reclassified by their standard deviation (SD; -3, -2, -1, 1, 2, 3), permissible due to the normal distribution of the dataset. The 1995 and 2017 images were then cross-tabulated utilizing the standard deviation and grouped based upon change between the 1995 and 2017 SD categories.

The "Classify Ground Points" tool in Photoscan was used to attempt to differentiate between ground points and non-ground points (i.e. vegetation canopy) to produce both a digital terrain model (DTM) and digital surface model (DSM); however, little distinction between them could be made. CloudCompare (2018) was also investigated as a software to aid in separating ground and vegetation surfaces, but due to the small vegetation height and lack of bare ground for reference, this was unsuccessful.

ArcGIS was used to perform necessary transformations to ensure all images and data were in the same projected coordinate system, NAD83 UTM Zone 6N. All 1995 data was originally collected using NAD27 UTM Zone 6N. ArcMap was used for organizing and visualizing all images and data to assess changes in vegetation between 1995 and 2017.

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6 RESULTS

6.1 Air and soil-surface temperature

Time series between 1995 and 2017 at CALM site U12B reveal an overall increase (0.51°C/decade) in mean summer (Jun-Aug) air temperatures and a slight decrease (-0.23°C/decade) in mean summer soil-surface temperatures (Figure 5; Table 1). In winter (Dec-Feb), CALM site U12B experienced an overall increase (2.27°C/decade) in soil-surface temperatures and a slight increase (0.84°C/decade) in air temperatures (Figure 5). There was an overall increase (0.90°C/decade) in annual (Sept-Aug) mean soil-surface temperature, with most of the increase occurring during the winter months. Missing daily air temperature data from 14 August 2013 to 15 August 2014 and from 11 December 2014 to 16 August 2015 were filled in using data from the Toolik Field Station's Environmental Data Center and a correlation equation ($y = 0.9634x + 0.2446$).

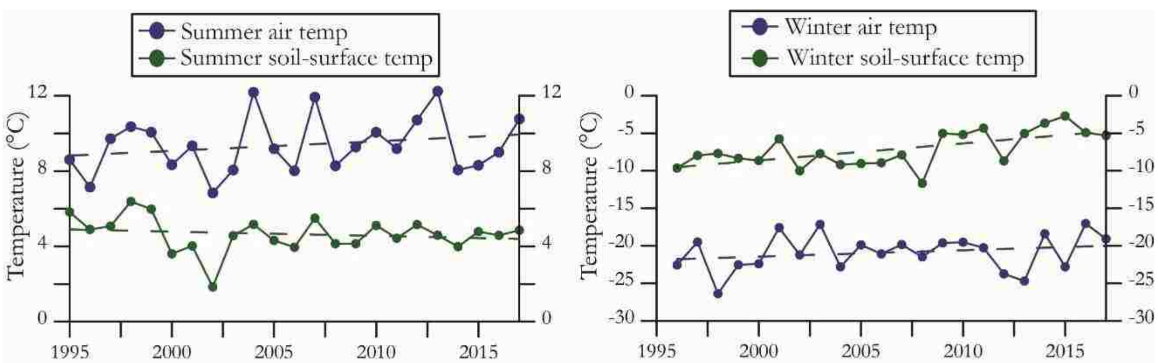

Figure 5. Graphs showing temperature trend for 1995-2017 of both mean air and soil-surface temperature for summer (Jun-Aug; left) and winter (Dec-Feb; right), respectively. Axes have different scales.

Table 1. Summary of trends in change per decade for each variable.

Variable	Trend	Variable	Trend
Summer air T	0.51 °C/decade	Summer N-factor	-0.02 /decade
Summer SST	-0.23 °C/decade	Winter N-factor	-0.10 /decade
Winter air T	0.84 °C/decade	ALT U12A	4.5 cm/decade
Winter SST	2.27 °C/decade	ALT U12 B	1.9 cm/decade
Summer $T_{surf} – T_{air}$	-0.59 °C/decade	SCD (w/1996)	14.3 days/decade
Winter $T_{surf} – T_{air}$	1.63 °C/decade	SCD (w/o 1996)	7.9 days/decade
Annual mean SST	0.90 °C/decade	Annual mean air T	0.60 °C/decade

Mean summer (Jun-Aug) and winter (Dec-Feb) soil-surface time series were produced for each individual sensor at CALM site U12B (Figure 6). Units 7 and 8 reported consistently warmer winter soil-surface temperatures than all other sensors, however, summer temperatures show little difference. The year 2008 had the coldest recorded mean winter temperature for all sensors.

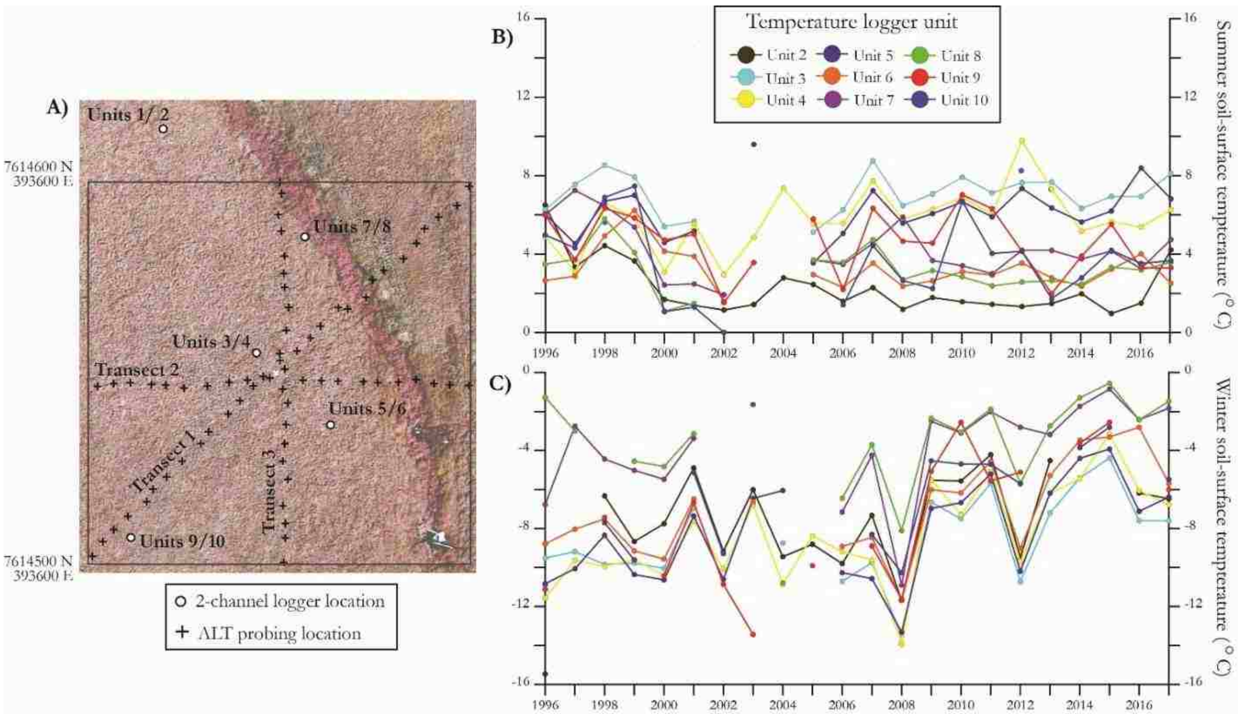

Figure 6. Location of 2-channel loggers within the plot (A), and corresponding summer (Jun-Aug) soil-surface temperature (B) and winter (Dec-Feb) soil-surface temperature (C) for Units 2-10.

6.2 N-factors and temperature difference

The difference ($T_{surf} – T_{air}$) plot (Figure 7) reveals an increase (1.63°C/decade; Table 1) in difference between soil-surface and air temperatures in winter, due to the soil warming 1.43 more degrees per decade than winter air temperatures over time. An increase (-0.59°C/decade) in the difference in summer is due to the soil becoming slightly cooler as the air temperatures warm over time.

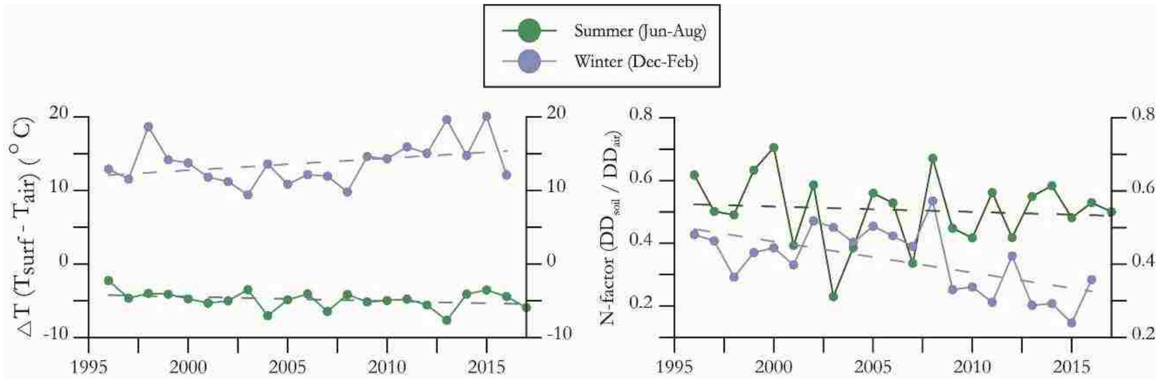

Figure 7. Graph displaying the difference between mean soil-surface temperature and mean air temperature (left) for both summer (Jun-Aug) and winter (Dec-Feb) for 1995-2017. Graph displaying the calculated n-factor using degree days (DD; right) for both summer (Jun-Aug; thawing) and winter (Dec-Feb; freezing) for 1995-2017.

N-factor plots (Figure 7) display an overall decreasing trend in n-factors for both winter (-0.10/decade) and summer (-0.02/decade), with a steeper negative change in the winter and a shallower negative trend in the summer (Table 1). This indicates an increasingly greater DD_{air} than DD_{soil} in both summer and winter, reflecting more warming in the air than soil during summer (0.73°C/decade), but less warming in the air than soil during winter (1.43°C/decade).

6.3 Active layer thickness

Between 1995 and 2017, the mean ALT at CALM site U12B increased by 7 cm, with maximum thickness in 2010 of 53 cm, and a minimum thickness in 2002 of 33 cm (Figure 8). Active layer measurements at CALM site U12A (1 km^2 grid) also display an overall increase in mean annual maximum ALT. Averages at both sites follow similar trends, with U12A experiencing an increasing trend of 4.5 cm/decade and U12B recording an increasing trend of 1.9 cm/decade (Table 1). Both sites recorded an ALT maximum in 2010, and an ALT minimum in 2002.

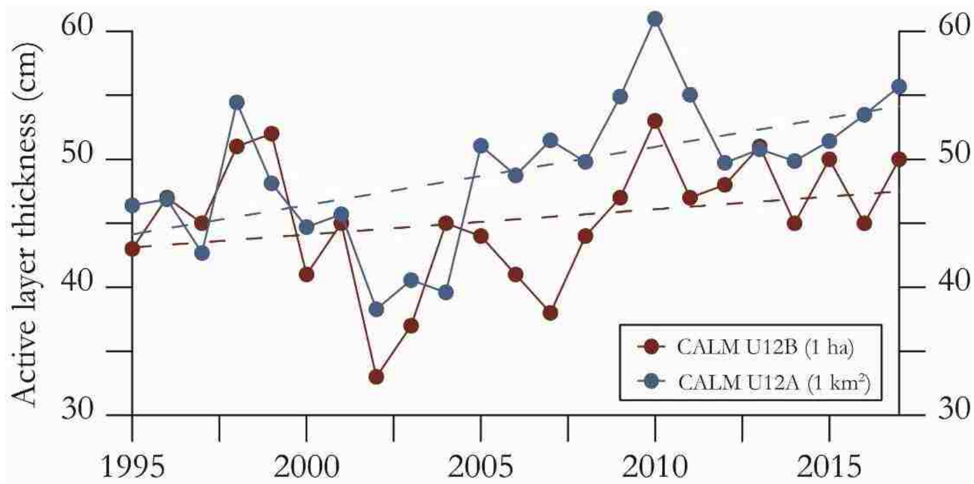

Figure 8. Graph showing mean active layer thickness at CALM site U12A and U12B for 1995-2017.

ALT measurements for the entire plot at 5 m intervals (441 pts total) were taken in August 1995. These measurements reveal that the deepest ALT were located in and around the water track (Figure 9).

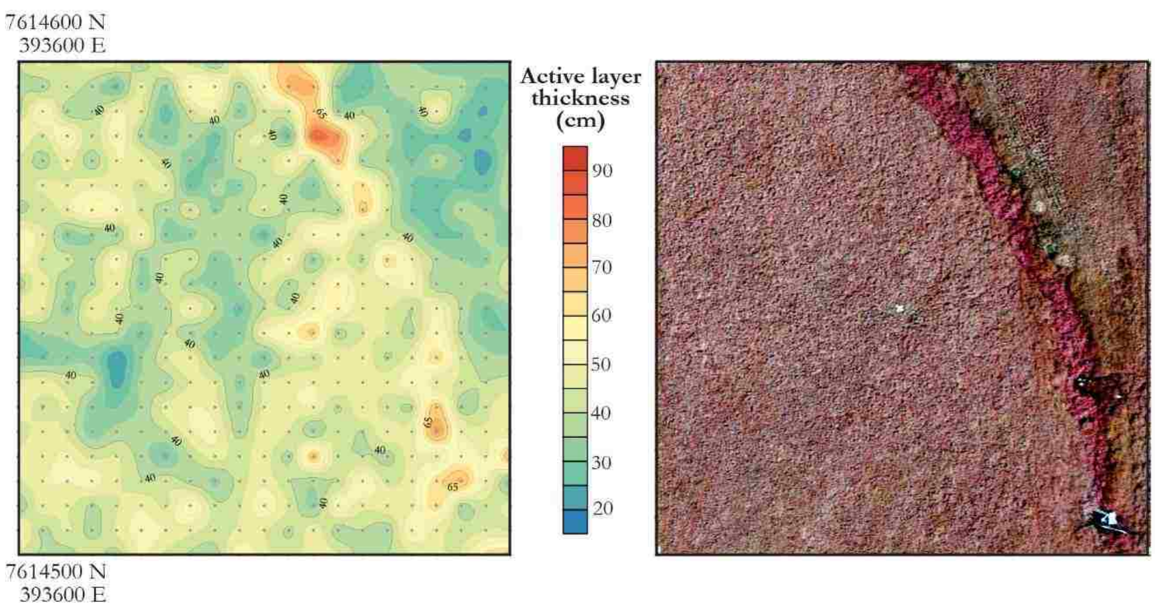

Figure 9. ALT depth (left) from mechanical probing every 5 meters in August 1995, and aerial photo from 1995 (right). ALT surface produced using ordinary point kriging gridding with weighted distances in Surfer©.

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6.4 Snow cover

There was an overall increasing trend in snow cover duration (SCD) of 14.3 days/decade at the 1 ha plot (Table 1), characterized by an earlier date of snow onset (mid-Sept) in more recent years and a fairly consistent snowmelt date in mid-May (Figure 10). The low SCD (184 days) in 1996 was due to a late date of snow onset, when 5 consecutive snow cover days did not occur until November 2. Excluding the 1996 hydrologic year results in an increasing SCD trend of 7.9 days/decade (Table 1). Missing daily air temperature data from 14 August 2013 to 15 August 2014 and from 11 December 2014 to 16 August 2015 were filled in using data from the Toolik Field Station's Environmental Data Center and a correlation equation (y = 0.9634x + 0.2446).

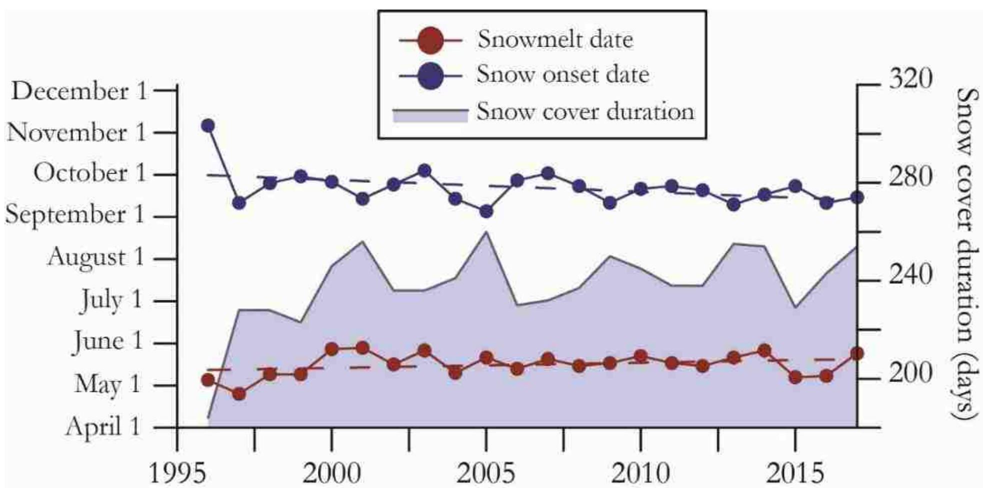

Figure 10. Snow onset, snowmelt, and snow cover duration for each hydrologic year as calculated from daily soil-surface amplitude and mean daily air temperature at CALM site U12B.

6.5 Vegetation

NDVI maps produced using CIR photos in 1995 and NIR + Red images in 2017 reveal the highest values are within the water track, where low shrubs are located. The circular, very low NDVI values on the northeast side of the water track in the 1995 NDVI map are due to International Tundra Experiment (ITEX) studies, which used enclosed hexagonal open-top chambers to study climate change impacts on tundra vegetation (Walker, 1996). Reflectance values from the chamber material or changes in phenology due to condition manipulation likely caused these low NDVI values. The very low values in the southeast corner of both maps are due to a wooden weir within the plot. Figure 10 shows changes in terms of standard deviation relative to the mean between 1995 and 2017, highlighting that the water track remained green in 2017, although relatively less green than in 1995. Between 1995 and 2017, 30.4 % of the plot changed from brown (lower than the mean) to green (higher than the mean), 13.4 % changed from green to brown, 23.6% shifted one SD but remained brown or green, and 32.6% of the plot remained within the same SD category (Figure 11). The strip on the east side of the water track indicating a change from brown to green (Figure 11) has an approximate width of 4.5 m. The areas covered by the ITEX studies were also greener relative to the rest of the plot in 2017 than in 1995. A strip running north-south in the northeast corner of the plot shows "greening" as well.

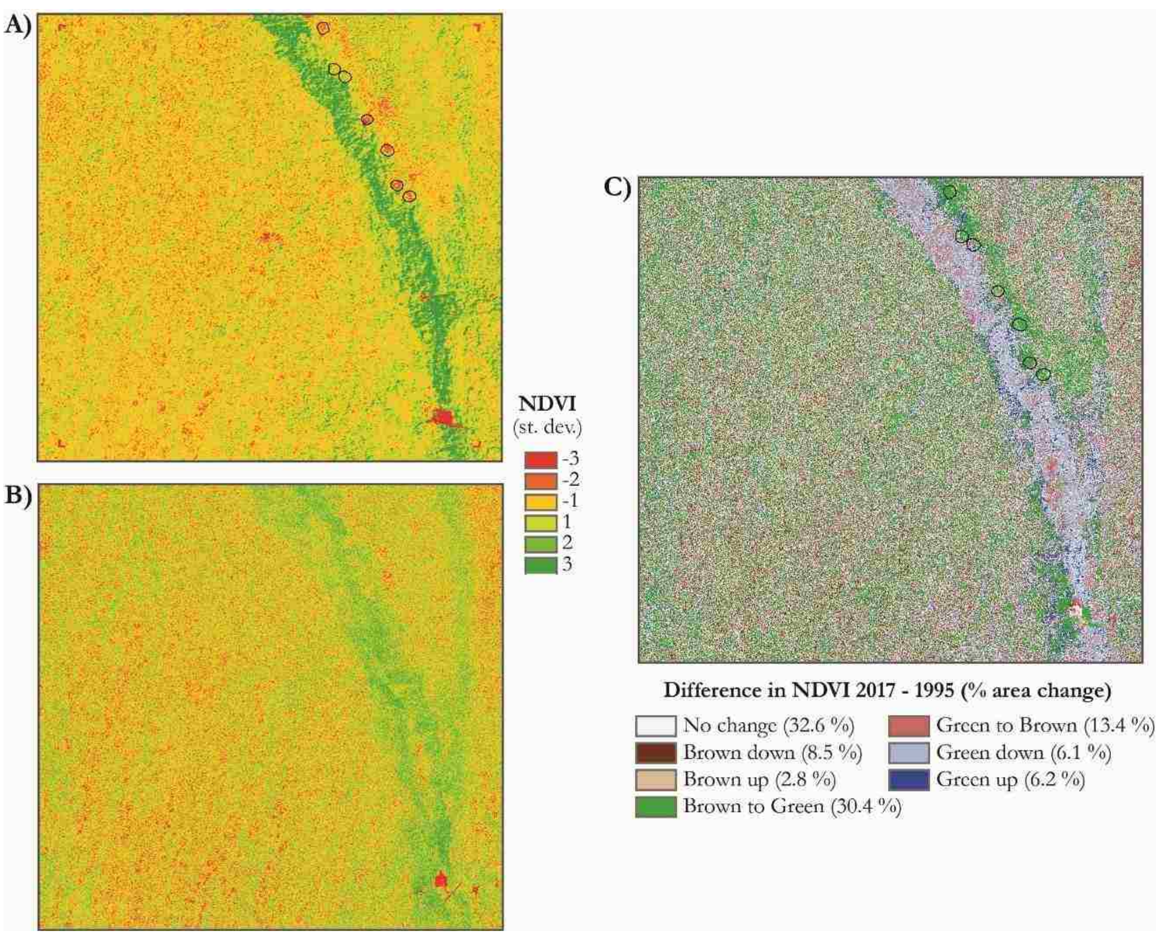

Figure 11. NDVI maps for A) 1995 and B) 2017 shown by standard deviation relative to the mean. Change from 1995 to 2017 is displayed in C), classified based upon change between the 1995 and 2017 standard deviation categories. ITEX open-top chambers are outlined in black next to the water track in A) and C). A weir is visible in the southeastern corner but was replaced with a different design between the images.

Differencing the point-cloud generated DEMs reveals a deepening of up to 50 cm on the east side within the water track and an increase in elevation up to 20 cm on the east edge of the plot (referring to changes greater than one standard deviation; Figure 12). The higher (green) values in the southwest corner of the plot are due to the presence of people and equipment on the plot while the images were acquired in 2017.

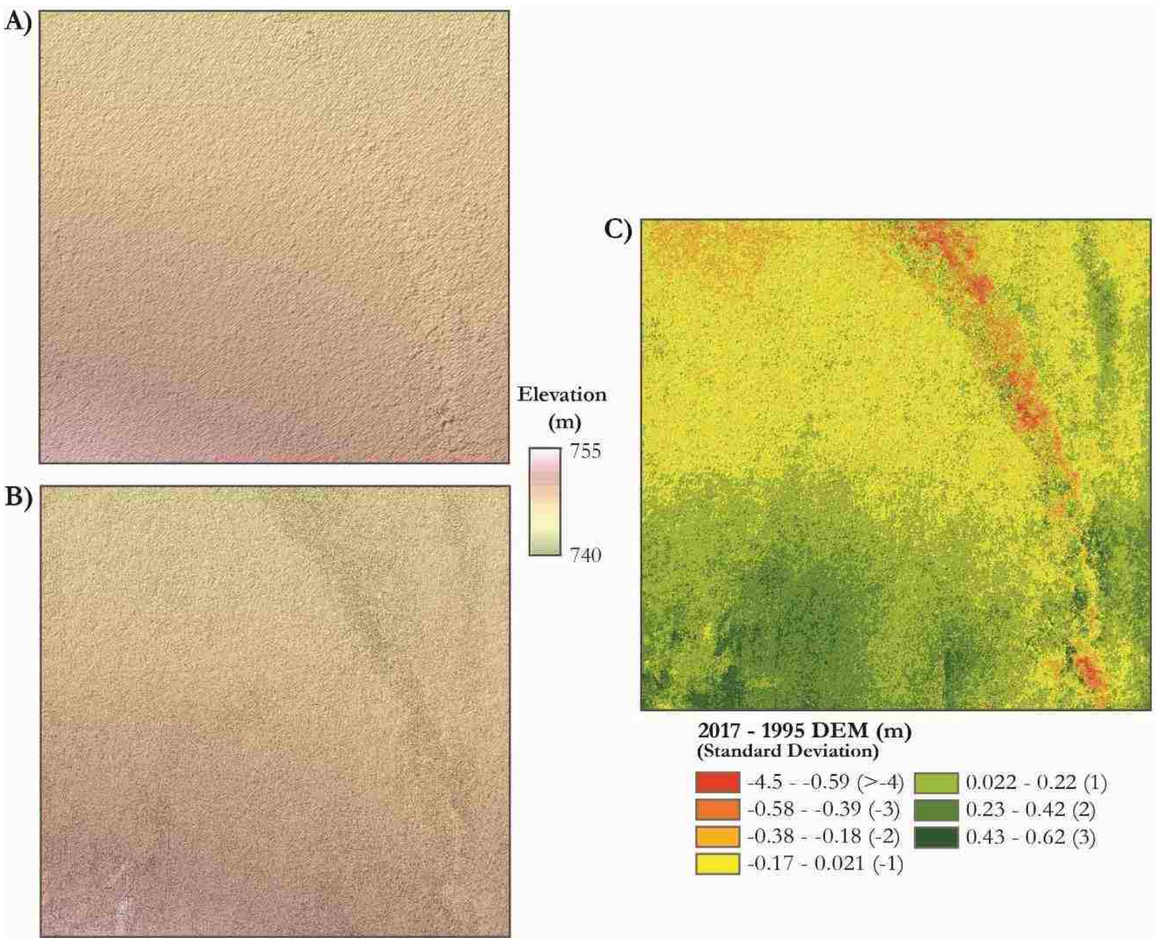

Figure 12. DEM generated from stereopairs for A) 1995 and B) 2017 with a hillshade underneath. C) displays the difference of these two DEMs showing surface change between 1995 and 2017, shown as standard deviation.

7 DISCUSSION

7.1 Temperatures, snow cover, and ALT

Air temperatures at Toolik Lake reflect the general trend of increasing temperatures found in most recent Arctic studies, with increases in both mean summer and winter temperatures. The increasing winter soil-surface temperature yet slight decrease in summer soil-surface temperature, as well as a decrease in both summer and winter n-factors, suggest that there is increased insulation between air and soil temperatures in both summer and winter.

Increases in mean active-layer thickness at CALM sites U12A and U12B reflect the overall increase in soil-surface temperature. As soil-surface temperatures increase, the depth of thaw also increases due to heat flow. The 1995 ALT measurements at 5 m intervals demonstrate that active layer is deepest along the water track, where low shrubs are the dominant species and surface water is exposed and flowing during summer. This set of measurements is scheduled to be resampled summer 2018 for a better understanding of how ALT is changing spatially within the plot. Mechanical measurements of ALT might not accurately capture the full impact of permafrost thaw as they are made relative to the ground surface. Studies in Barrow (Streletskiy et al., 2017), near Prudhoe Bay and in the Sagwon Hills (Shiklomanov et al., 2013), and elsewhere on the North Slope (Liu and Larson, 2018) have documented subsidence of the ground surface due to the volumetric loss when ice melts into water; however, no subsidence measurements have been taken at this plot.

The soil-surface temperatures of the 2-channel logger located adjacent to the water track (Units 7 and 8) reveal that mean winter soil-surface temperatures at this location are consistently higher than elsewhere (Figure 6), with a mean of -3.8 °C for units 7/8 and -7.8 °C for all other units over the period of observation. However, mean summer soil-surface temperatures are more similar to other logger units, with a mean of 3.7 °C for units 7/8 and 4.7 °C for all other units over the period of observation. This suggests that there is a difference in insulation between the water track and non-water track areas that influence winter soil-surface temperatures. Previous studies such as Sturm et al. (2001) have documented the role of vegetation in trapping snow to increase winter insulation, which will be addressed in Section 7.2. Sub-surface hydrology also plays a role, as flowing water in the water track would delay freezing in the winter.

Snowmelt calculated from daily soil-surface amplitude and mean daily air temperature at CALM site U12B reflects a later snowmelt over the period of observation, conflicting with the trend of an earlier start to the growing season found by Zeng et al. (2011) using satellite remote sensing. This difference is likely due to differences between coarse resolution remote sensing and plot level observations, demonstrating topographic and microclimatic spatial variability. Snow cover data between 2006 and 2017 from the Toolik Field Station Environmental Data Center also report a variable yet later snowmelt date (Toolik EDC, 2017). Analysis of both Toolik and nearby Imnavait (CALM sites U12B, U11B, and U11 C) reveal a later mean date of snowmelt by 0.21 days per year from 1996 to 2013 (Pyne, 2014). The method in which snowmelt and snow onset are calculated (Section 5.3) might provide some error, and the installation of snow cameras at the plot would increase the accuracy of snow duration data. Sturm et al. (2001) describe how an increase in vegetation thickness and height extends the snow-cover period since taller shrubs trap more snow, deepening the snow pack, and requiring more energy to thaw. However, shrubs also decrease albedo if they rise above the snow surface, and it can be difficult to predict the results of such competing processes.

7.2 Vegetation

In recent years, studies such as Beck and Goetz (2011), Epstein et al. (2012), and Ju and Masek (2016) have used satellite remote sensing to document a widespread increase in greenness across the Arctic. Using aerial photographs, this study was able to produce NDVI maps for both 1995 and 2017, mapping the variability in NDVI values within the 1 ha plot. The water track, dominated by low birch and willow shrubs, has the highest NDVI values while the surrounding tussock tundra has a mixture of higher and lower values. Comparison between NDVI in 1995 and 2017 reveal a relative lowering of greenness along the middle of the water track. This change in NDVI may be due to a larger amount of water visible at the ground surface in 2017 than 1995 (Figure 12). Figure 12 shows the changes within the ITEX plots (outlined in black), and an increase in greenness along the edges of the water track. This increase in greenness, as well as a visual comparison of the images, reveals a widening of the water track of approximately 4.5 m.

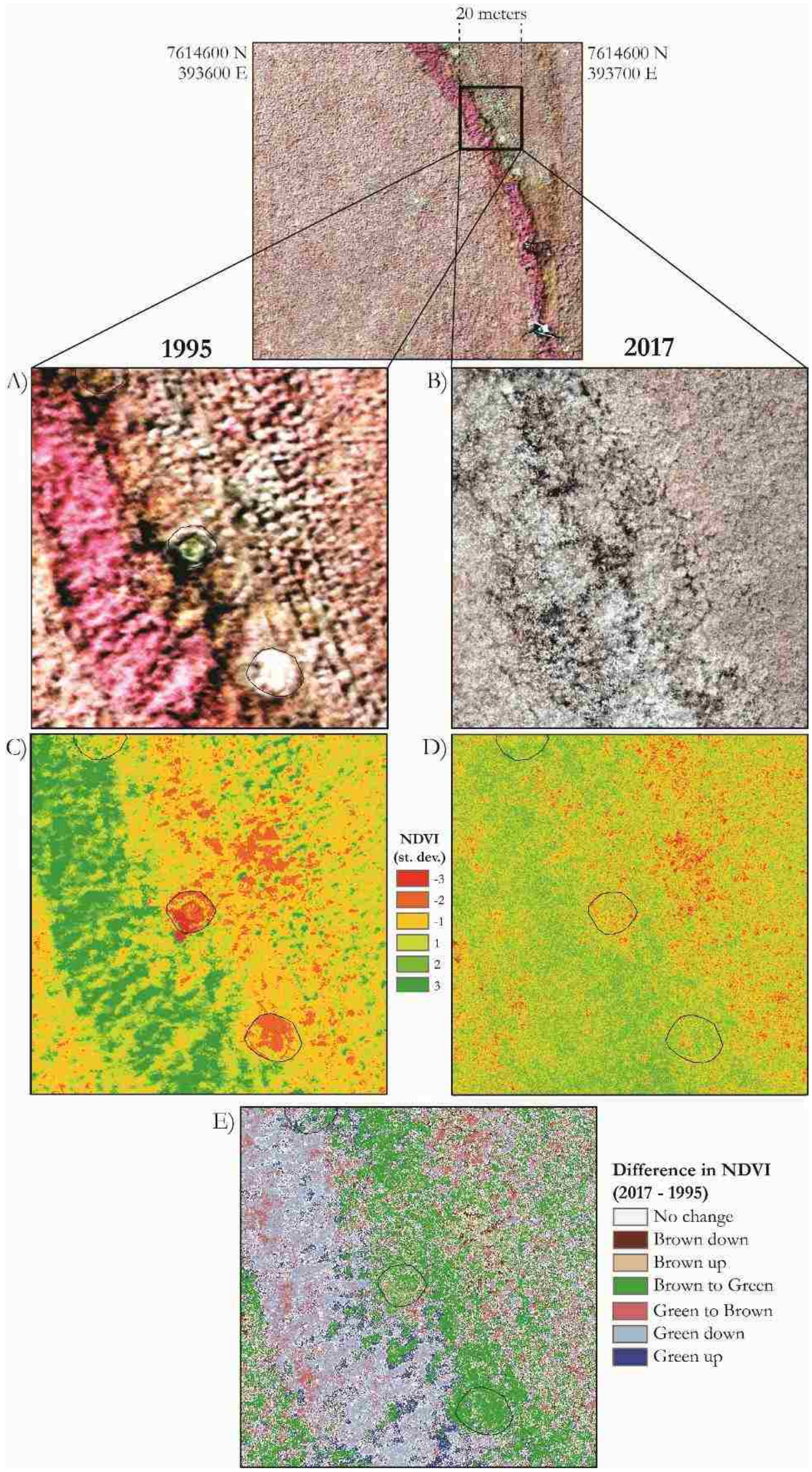

Figure 13. Images of the water track (A/B) and NDVI values (C/D) in 1995 and 2017, and difference in NDVI (E). Two ITEX open-top chambers and a control plot are visible in 1995, and their previous location is shown on the 2017 imagery for comparison.

Buchwal and Welker (2016) used tree ring analysis at Toolik Lake to explore the growth response of *Betula nana* (dwarf birch) and *Salix pulchra* (willow) to current and predicted temperature increases. They found that the warming in Alaska over the past 20 years is stimulating tree ring growth, however, impacting dwarf birch at a greater rate than willow. Using ground photos taken along the ALT transects, dominant vegetation type at the plot was determined within the water track, areas adjacent, and the strip of greening in the NE corner. Willow dominates the areas within the water track whereas dwarf birch is found adjacent to the water track. This may explain the more abundant greening adjacent to the water track than within it (Figure 11). The NE greening stripe is also dominated by dwarf birch and presumably growing at a faster rate than the willow (Buchwal and Welker, 2016), therefore "greening" faster than the rest of the plot.

Comparison between the DEMs produced by the 1995 photographs and the 2017 images reveal a lowering in elevation on the right side of the water track, where the NDVI reveals greening. This decrease could be a widening and deepening of the water track, incising as the flow of water shifts. The subsurface hydrology within the plot likely has a significant impact on vegetation dynamics, however, this has not been directly studied at the plot. The difference in resolution between the imagery**,** evident in Figure 12, may make surface water and the ground between plants more observable in the 2017 imagery than the 1995 imagery, leading to lower elevations. However, if more water was visible one would expect lower NDVI values.

7.3 **Synthesis**

Incorporating air and soil-surface temperature, ALT, snow cover characteristics, and vegetation dynamics into a time series demonstrates the complexity of feedbacks in a changing Arctic environment. As was documented by Sturm et al. (2001), shrub height and abundance have the largest impact on snow depth on tundra, trapping snow in and around the shrubs and breaking the wind to reduce drifting of snow. This blockage of the wind decreases wind-driven sublimation, reducing winter water loss and increasing soil moisture and runoff (Laycock and Shoop, 1986; Tabler, 1980, 1989; Peterson, 1982; Peterson and Schmidt, 1984; Pomeroy and Gray, 1995). The increased snow depth also increases subnivian temperatures, demonstrated by the higher winter soil-surface temperatures recorded at Units 7 and 8 along the water track than elsewhere at CALM site U12B. This enhances the deeper active layer (or thaw bulb) below the water track.

In the Arctic, soil respiration can occur at temperatures as low as -6°C (Clein and Schimel, 1995; Zimov et al., 1993a; Coxson and Parkison, 1987; Flanagan and Bunnell, 1980; Flanagan and Veum, 1974). For nearly all years of observation, mean winter soil-surface temperatures at Units 7 and 8 remained above -6°C, indicating that overwinter decomposition and nutrient mineralization was possible. Sturm et al. (2001) suggest that this greater release of nutrients during winter promotes the growth of shrubs as opposed to other tundra plants, where soil temperatures drop below the soil respiration threshold (such as Units 2- 6, 9, and 10), thus further promoting this positive feedback loop of shrub growth.

While this winter feedback appears to be occurring within the water track, summer effects may be counteracting some of the winter effects on soil-surface temperatures and decomposition. Increased shading by the shrub canopy likely decreases summer soil-surface temperatures, as seen in the slight decreasing trend at CALM U12B despite increasing summer air temperatures. However, Sturm et al. (2001) suggest that at low shrub densities the shrubs enhance the winter snowpack depth and the snow-shrub feedback loop can operate, and that the sparse canopy and low-angle summer sun minimizes summer shading effects.

7.4 Future studies

While this study introduces possible explanations for the changing temperature, snow, permafrost, and vegetation dynamics observed at CALM site U12B, further studies are necessary. Subsidence measurements would provide a better understanding of surface dynamics in relation to the active layer. The repeat measurement of ALT at 5 m intervals in August 2018 will aid in understanding the spatial distribution of changing ALT, particularly along the water track. Repeat UAS imagery in future years of equivalent resolution to the 2017 imagery (~ 0.5 cm/pixel) would aid in determining whether changes in the water track were due to differences in resolution or actual expansion and deepening, as well as the rate of this change. Surface and subsurface hydrological studies such as discharge, water temperature, nutrients, and freeze and thaw characteristics would also be beneficial for creating a more holistic understanding of this system.

8 CONCLUSION

Investigating air and soil-surface temperature, ALT, snow cover characteristics, and vegetation dynamics over a 22-year time series analysis demonstrates the complexity of feedbacks in a changing Arctic environment. Analysis at the 1 ha CALM site U12B near Toolik Lake revealed slightly increasing air temperatures in both summer and winter (Figure 5), increasing winter but decreasing summer soil-surface temperatures (Figure 5 and 6), increasing differences between air and soil-surface temperatures (Figure 7), decreasing summer and winter n-factors (Figure 7), increasing ALT (Figure 8), an increasingly later snowmelt date (Figure 10), and a deepening and widening of the water track (Figures 11, 12, and 13). These results are consistent with other studies (Raynolds et al., 2012; Tape et al., 2012; Bret-Harte et al., 2015) reporting an increase in vegetation and biomass in this region. Changes in vegetation, particularly shrubs within the water track, can increase snow trapping and warming winter soil-surface temperature conditions, possibly promoting overwinter decomposition and nutrient mineralization.

These results illustrate the importance of long-term research to quantify trends in a changing landscape, and the importance of spatial and spectral resolution in image analysis. This research aids in our understanding of the resulting biogeochemical feedbacks, ecosystem processes, and engineering implications of plot-level interactions on permafrost.

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