

Impacts of climate change and intensive lesser snow goose (*Chen caerulescens*
caerulescens) activity in high Arctic pond complexes - Banks Island, Northwest
Territories

by

Thomas Kiyoshi Fujiwara Campbell
Honours Bachelor of Science, University of Guelph, 2014

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE

in the School of Environmental Studies

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Supervisory Committee

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Abstract

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Rapid increases in air temperature in Arctic and subarctic regions are driving significant changes to surface water. These changes and their impacts are not well understood in sensitive high Arctic ecosystems. This thesis explores changes in surface water in the high Arctic pond complexes of western Banks Island, Northwest Territories, and examines the impacts of this change on vegetation communities. Landsat imagery (1985-2015) was used to detect trends in surface water, moisture, and vegetation productivity, aerial imagery change detection (1958 and 2014) quantified shifts in the size and distribution of waterbodies, and field sampling investigated factors contributing to observed changes. The impact of expanding lesser snow goose populations on observed changes in surface water was investigated using the aerial imagery change detection of 2409 waterbodies and an information theoretic model selection approach, while their impact on vegetation was assessed using data from field surveys. Our analyses show that the pond complexes of western Banks Island are drying, having lost 7.9% of the surface water that existed in 1985. This loss of surface water disproportionately occurred in smaller sized waterbodies, indicating that climate is the main driver. Model selection showed that intensive occupation of lesser snow geese was associated with more extensive drying and draining of waterbodies and suggests this intensive habitat use may reduce the resilience of pond complexes to climate warming. Evidence from field surveys suggests that snow goose foraging is also contributing to patches of declining vegetation productivity within drying wetland areas. Diminishing and degrading high Arctic pond complexes are likely to alter permafrost thaw and greenhouse gas emissions, as well as the habitat quality of these ecosystems. Additional studies focused the mechanisms of surface water loss, the direct impacts of wetland drying on vegetation, and the contributions of snow geese to these processes, are necessary to better understand the changes occurring on Banks Island.

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Chapter 1 – Introduction

Temperatures in Arctic and sub-Arctic regions have warmed twice as much as the global average (AMAP-SWIPA, 2012; Pithan & Mauritsen, 2014), which has triggered significant changes to hydrological systems (Lantz & Turner, 2015; Kaplan & New, 2006; Bintanja & Andry, 2017; Yoshikawa & Hinzman, 2003; Nitze *et al.*, 2017). Since lakes, ponds, and wetlands control a range of physical, geochemical, and biological processes in Arctic regions (Wolfe *et al.*, 2011; Negandhi *et al.*, 2013; Becker *et al.*, 2016; Slattery & Alisauskas, 2007), it is likely that changes in surface water will have extensive ecological impacts.

Recent changes in the number and extent of lakes and ponds in the Arctic have been attributed to: increasing evaporation (Smol & Douglas, 2007), fluctuations in precipitation (Plug *et al.*, 2008), permafrost degradation leading to lateral and subsurface drainage (Lantz & Turner, 2015; Smith *et al.*, 2005; Yoshikawa & Hinzman, 2003; Jones *et al.*, 2011), and thermokarst lake expansion (Olthof *et al.*, 2015; Roy-Leveillee & Burn, 2017). There has been considerable variation in surface water dynamics across the Arctic (Carroll *et al.*, 2011; Roach *et al.*, 2013; Nitze *et al.*, 2017; Jones *et al.*, 2011), however most broad-scale studies suggest that permafrost extent is a major determinant of change (Nitze *et al.*, 2017; Roach *et al.*, 2013). Studies in discontinuous permafrost zones have largely shown decreases in surface water, while studies in continuous permafrost zones have largely shown increases in surface water (Olthof *et al.*, 2015; Smith *et al.*, 2005; Roach *et al.*, 2013; Riordan *et al.*, 2006). Although, to date, these studies have been restricted to subarctic and low Arctic regions, and trends in the high Arctic remain largely unstudied.

High Arctic pond complexes may be particularly vulnerable to the effects of increasing air and ground temperatures (Woo & Young, 2006; Abnizova & Young, 2010). Shallow active layers common in the high Arctic, restrict groundwater storage capacity, reducing resilience during unusually dry periods (Woo *et al.*, 2006). High levels of ground-ice, typically found in regularly saturated soils (Woo *et al.*, 2006), make areas more susceptible to thermokarst induced changes to hydrology (Becker *et al.*, 2016; Steedman *et al.*, 2016; Fraser *et al.*, 2018). Furthermore, high Arctic pond complexes can

be little more than a series of shallow depressions infilled with water (Brown & Young, 2006; Abnizova & Young, 2010), which are disproportionately impacted by fluctuations in evaporation because of their high surface area to volume ratios (Smol & Douglas, 2007; Marsh & Bigras, 1988).

The impacts of changing surface water in high Arctic pond complexes are likely to be most obvious in the surrounding vegetation. Wetland vegetation has high moisture requirements, making it particularly sensitive to climate effects on water supply (van der Valk, 2005; Raulings *et al.*, 2010; Woo *et al.*, 2006). At evaporating high Arctic ponds on Ellesmere Island, Smol & Douglas (2007) found the surrounding wetlands were also drying and vegetation was sufficiently dry to be easily ignited. Changes in moisture may also alter vegetation community composition, as spatial variation in moisture can control the cover of dominant and subordinate species (Webber, 1978). In desiccated high Arctic wetlands near Resolute, Nunavut, Woo *et al.* (2006) described the replacement of hydrophytic vegetation by *Papaver radicum*, as well as various species of *Draba*, *Saxifraga*, and lichens.

In the largely arid polar deserts of the high Arctic, high primary productivity in pond complexes and wetlands makes them important breeding habitat for many herbivores, including the lesser snow goose (*Chen caerulescens caerulescens*). Interestingly, intensive and recurring lesser snow goose foraging could also be contributing to climate-driven changes to both surface water and vegetation. Intense snow goose foraging has been seen to reduce vegetation cover and alter community composition (Kotanen & Jefferies, 1997; Srivastava & Jefferies, 1996; Calvert, 2015; Hines *et al.*, 2010). It can also alter microtopography (Jefferies *et al.*, 1979) and increase near-surface ground temperatures and evaporation (Iacobelli & Jefferies, 1991; Srivastava & Jefferies, 1996), which likely decreases water retention in nearby waterbodies and may increase the risk of lateral drainage (Park, 2017). Lesser snow goose nesting colonies across the Arctic have seen rapid expansions in recent decades (Batt, 1997). The pond complexes of western Banks Island, Northwest Territories support over 95% of the western Arctic lesser snow goose population, which has almost tripled since 1976 (Kerbes *et al.*, 2014; Hines *et al.*, 2010). Field assessments (1999-2002) have

shown that geese disproportionately use wetland habitat areas on Banks Island during the breeding season (Hines *et al.*, 2010).

With limited historical data of ecological conditions in this remote region of the western Arctic, remote sensing data is an invaluable tool for understanding historical conditions and current ecological trajectories. However, field sampling is also necessary to ensure accurate interpretation of remote sensing data. The objectives of my MSc are to understand the nature of surface water change in the pond complexes of western Banks Island, Northwest Territories, and investigate how these changes may impact the local ecology. To complete these objectives, my research used 30-years of Landsat data, aerial imagery change detection, and field surveys of biotic and abiotic conditions. The results of this research are presented in chapters 2 and 3, as stand-alone manuscripts.

In chapter 2, my objective was to understand trends and patterns of surface water change in the pond complexes of Banks Island. I used Landsat imagery (1985-2015) to detect landscape trends in surface water. Higher resolution aerial imagery (1958 and 2014) and an information theoretic model selection approach were used to explore drivers of changes in size and distribution of waterbodies. Field sampling was used to investigate potential causes and contributing factors. In chapter 3, my objective was to investigate how recent changes in surface water have impacted vegetation productivity and community composition. I used Landsat imagery (1985-2015) to detect trends in surface moisture and vegetation productivity. Field sampling was used to document vegetation conditions and explore potential impacts of lesser snow goose grazing. The remaining sections of this chapter provide critical background information, omitted from chapters 2 and 3, regarding: the study area on Banks Island, ownership and importance of the area for the Inuvialuit people, hydrology and ecology on Banks Island, and the remote sensing methods used in chapters 2 and 3.

Study Area

Banks Island is located in the Northwest Territories and is the westernmost island in the Canadian Arctic Archipelago. The community of Sachs Harbour is the only permanent settlement on the Island and has a population of approximately 100 residents. This area has a harsh climate with a mean annual temperature of -12.8°C at Sachs Harbour. Summers are short with average daily temperatures rising above freezing for

only 3 months of the year, peaking at 6.6°C in July. Average annual precipitation is 151.5mm, with only 38% falling as rain (June to September). Recent warming in Canada has been unprecedented over the last millennium (Beltrami, *et al.*, 1992; Beltrami & Bourlon, 2004) and mean annual temperatures on Banks Island have shown a 3.5 °C increase since 1956 (Fraser *et al.*, 2018). Summer precipitation and maximum snow water equivalent before spring melt have changed minimally (Fraser *et al.*, 2018; Mudryk *et al.*, 2018).

The western side of Banks Island is characterized by gently rolling uplands, intersected by numerous west flowing rivers with wide floodplains. Alluvial terraces in these river valleys are dotted with thousands of shallow ponds and have nearly continuous vegetation cover, dominated by sedges, grasses, and mosses (Hines *et al.*, 2010; Ecosystem Classification Group, 2013). Ice-wedge polygons, non-sorted circles and stripes, and turf hummocks are widespread, indicating continuous permafrost (Ecosystem Classification Group, 2013). In this thesis, I focus on the alluvial terraces of the west flowing rivers valleys (Figure 1.1.).

These river valleys are important breeding habitat for many migratory bird species, including the lesser snow goose. The habitat on western Banks Island supports over 95% of the western Arctic lesser snow goose population. The main nesting colony of this population is located at the confluence of the Egg and Big rivers (Hines *et al.*, 2010; Ecosystem Classification Group, 2013) (Figure 1.1.). The Banks Island Migratory Bird Sanctuary No. 1 (BIMBS1) covers most of western Banks Island and was created to protect this colony (Hines *et al.*, 2010; Ecosystem Classification Group, 2013).

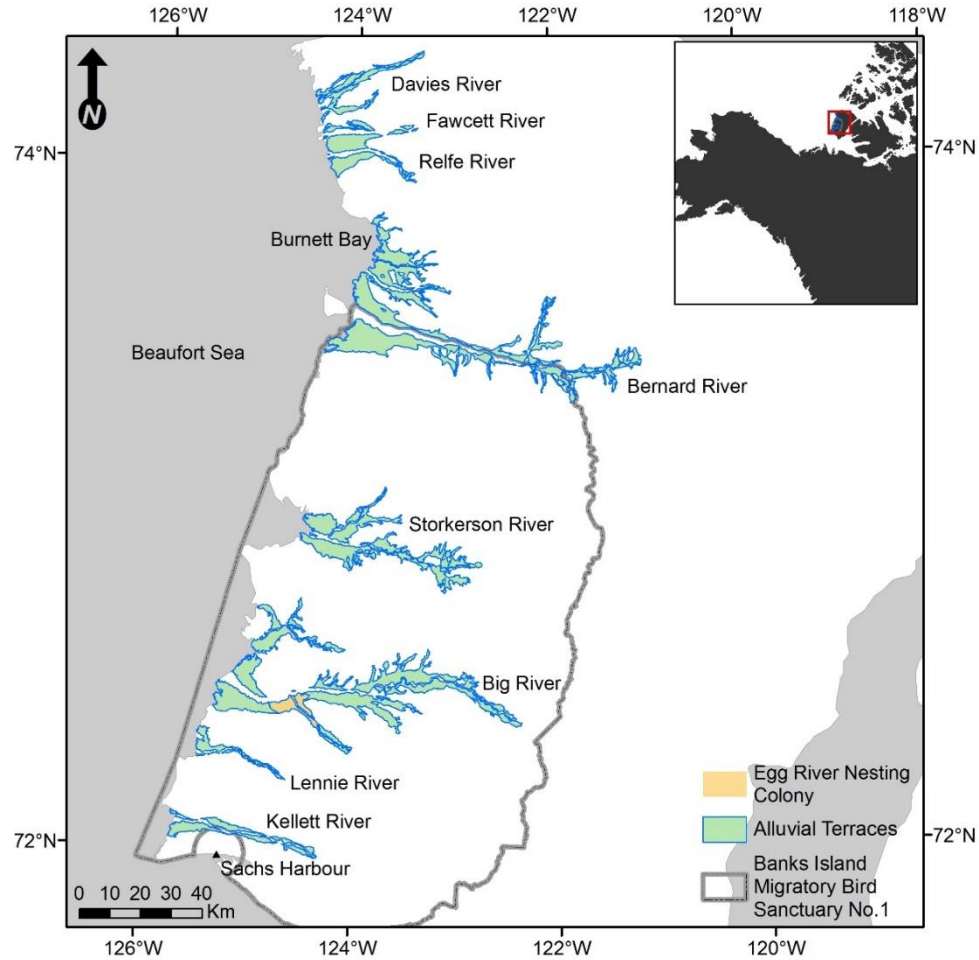


Figure 1.1. Map of the study area on Banks Island, Northwest Territories. Inset map at the upper right corner shows Banks Island as the westernmost island in the Canadian Arctic Archipelago.

Inuvialuit Land Claim

The Inuvialuit Final Agreement (IFA) was signed in 1984 (Indian and Northern Affairs Canada, 1984; Sachs Harbour Community Conservation Plan, 2008), granting ownership of approximately 90,650 km² of land to the Inuvialuit, in the Beaufort Sea-Mackenzie delta region (ILA, 2005), also known as the Inuvialuit Settlement Region (ISR). This area includes the Yukon north slope, the northern Mackenzie Delta, and the western Arctic islands, and contains six communities, Inuvik, Aklavik, Tuktoyaktuk, Paulatuk, Sachs Harbour, and Ulukhaktok (ILA, 2005; Sachs Harbour Community Conservation Plan, 2008).

Several co-management bodies also emerged from the IFA, including: two Wildlife Management Advisory Councils, the Fisheries Joint Management Committee,

the Inuvialuit Game Council, Hunters and Trappers Committees for each of the six communities, the Inuvialuit Land Administration, the Environmental Screening Committee, and the Environmental Impact Review Board (Sachs Harbour Community Conservation Plan, 2008). Within the ISR, land use planning is conducted through the Inuvialuit Land Administration and Community Conservation Plans, developed by the Inuvialuit Game Council and Inuvialuit Regional Corporation (Indian and Northern Affairs Canada, 1984). The 2008 Sachs Harbour Community Conservation Plan designated virtually all my study area as either category D or E importance; meaning they are of notable-to-extreme cultural importance or sensitivity and should be managed to eliminate as much damage as possible. These areas have been recognized as important for their past and present harvesting of fish, caribou, muskox, and geese. The BIMBS1, and more specifically the Egg River nesting colony, is also valued as nesting habitat for brant geese, snow geese, king eider, and long-tailed duck. Areas north of the BIMBS1 are important calving grounds for the Peary caribou. Furthermore, the whole western coast of Banks Island is valued as an important polar bear denning area.

High Arctic Wetland Hydrology

The wetland complexes that cover the alluvial terraces of the west-flowing rivers on Banks Island consist of ponds and lakes, surrounded by wetlands and wet sedge meadows. These areas receive relatively little precipitation throughout the year; Environment Canada climate normals for Sachs Harbour show average annual precipitation is 151.5 mm, with only 38% falling as rain. Although Banks Island receives relatively little precipitation, the underlying permafrost acts as an impermeable layer, preventing downward loss of rain, snowmelt, and flood waters (Woo & Young, 2006). Moisture collects in low-lying and low-gradient basins, producing these wetland areas. In most high Arctic wetlands, evaporation is the main cause of water loss, but lateral drainage is another common mechanism (Woo & Guan, 2006; Woo & Young, 2006).

Like most areas in the high Arctic, the largest influx of water on Banks Island occurs during spring snowmelt (Lewkowicz & French, 1982; Woo & Guan, 2006; Woo & Young, 2006). The snowmelt period is also one of the only times of the year where surface flow occurs. However, heavy summer rainfall events can occasionally generate surface flow, particularly in areas where the active layer remains saturated by summer

snowbanks (Lewkowicz & French, 1982). Despite the large influx of water during the snowmelt period, a slope runoff study near the Thomsen River on Banks Island showed that subsurface flow is the dominant form of water movement in the area (Lewkowicz & French, 1982). Subsurface flow occurs throughout the summer and can be critical in sustaining high Arctic wetlands (Lewkowicz & French, 1982; Woo & Young, 2006). In addition to subsurface flow, Woo & Young (2006) identified streamflow, inundation from lakes and seawater, and ground-ice thaw as major water sources sustaining high Arctic wetlands over the summer.

Habitat Impacts of Expanding Lesser Snow Goose Populations

In recent decades, lesser snow goose populations across the Canadian Arctic have seen dramatic increases, which have been linked to intensification of agricultural land-use in their southern wintering areas and a warming climate in Arctic nesting areas (Batt, 1997; Kotanen & Jefferies, 1997; Calvert, 2015). Agricultural fields have provided snow geese with surplus winter forage, while Arctic warming has provided more favourable nesting and brood rearing conditions (Batt, 1997; Calvert, 2015); this is evidenced by the observation that early snowmelt years yield more goslings than late snowmelt years (Samelius *et al.*, 2008). The largest nesting populations of lesser snow geese in Canada are all found in Nunavut, specifically the Queen Maud Gulf Migratory Bird Sanctuary, Baffin Island, and Southampton Island.

Lesser snow geese preferentially forage graminoid vegetation during nesting and brood rearing periods (Calvert, 2015) and moderate levels of snow goose grazing has been found to increase plant productivity in an ecosystem, due to the accelerated nutrient cycling from feces and urine (Ruess *et al.*, 1989; Calvert, 2015). Food can pass through the lesser snow goose digestive system in one or two hours, which can result in a defecation rate of up to once every 6 minutes (Ruess *et al.*, 1989). However, at higher population densities, intensive grazing and grubbing can cause lasting damages to ecosystems (Kotanen & Jefferies, 1997; Jefferies *et al.*, 1979). Grubbing is a form of snow goose foraging that involves the digging up of carbohydrate-rich roots and rhizomes of sedges, before above-ground biomass is available (Calvert, 2015). Grubbing can be particularly damaging because it diminishes plant's stored energy and exposes soils to the sun and wind.

The first and most severe observations of snow goose driven habitat degradation occurred in the salt marshes of the Hudson Bay lowlands. High levels of grubbing were seen to increase evaporation in the upper soil layers, which created a hydraulic gradient drawing up saline water from the underlying marine sediments (Iacobelli & Jefferies, 1991). Increased soil salinity damaged the remaining non-forage vegetation and inhibited general vegetation recovery (Iacobelli & Jefferies, 1991; Srivastava & Jefferies, 1995). Even in freshwater wetlands, intensive foraging can increase evaporation in soils, deplete vegetation biomass, and in extreme cases, create large barren areas of dried peat (Hines *et al.*, 2010; Iacobelli & Jefferies, 1991; Srivastava & Jefferies, 1996). At lower levels, foraging can also shift community composition to non-forage vegetation and species typically found in disturbed areas (Hik *et al.*, 1992; Hines *et al.*, 2010; Kotanen & Jefferies, 1997). Grubbing and trampling by snow geese has even been seen to alter microtopography, creating depressions and terraces; in some cases, shallow ponds can form within these depressions (Jefferies *et al.*, 1979).

To date, much of the research on snow goose overgrazing has been conducted in the salt marshes of the eastern Canadian Arctic and Hudson Bay region. However, the western Arctic lesser snow goose population has also grown rapidly in recent decades. The Banks Island nesting colony has almost tripled since 1976 (Figure 1.2.) and provides nesting grounds for over 95% of the western Arctic population (Kerbes *et al.*, 2014). In 2014, the western Arctic population was designated as overabundant (CWS, 2014; Calvert, 2015), meaning that it directly threatens the conservation of migratory birds, their habitats, agriculture, the environment, or other similar interests (CWS, 2013). However, despite the implementation of control measures, populations on Banks Island appear to still be increasing.

Compared to the Hudson Bay region, salt marshes are rare on Banks Island. They are restricted to small pockets along the coast, so geese typically breed far inland in freshwater areas (Calvert, 2015). Banks Island also has a vast amount of tundra and freshwater habitat, which allows for relatively low goose densities during brood rearing periods. Differences in climate, habitat, and geology between Banks Island and the Hudson Bay region suggest that snow goose overgrazing should have different impacts on vegetation and soils.

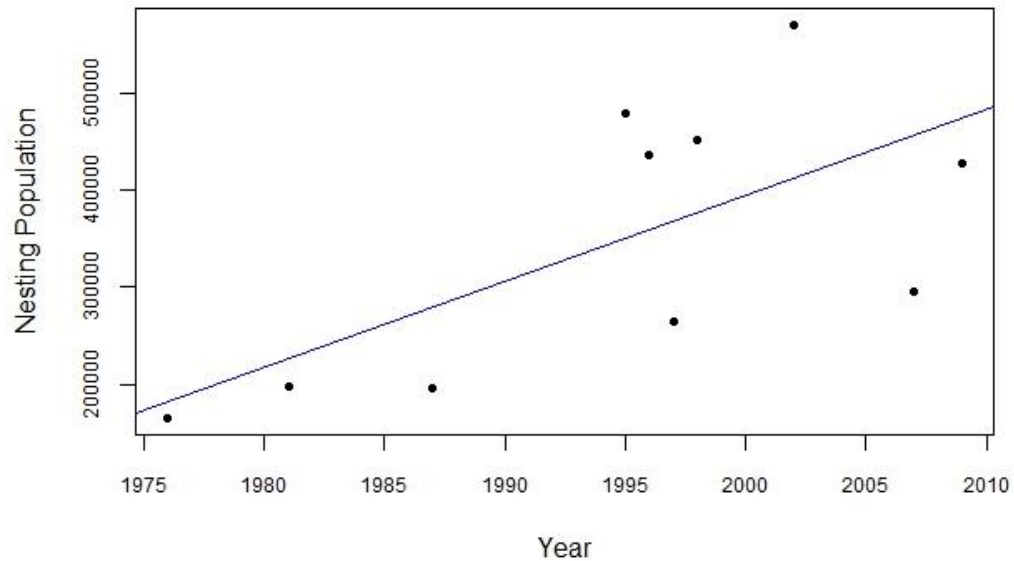


Figure 1.2. Estimated lesser snow goose nesting population on Banks Island, starting in 1976.
Data from Kerbes *et al.* (2014).

Remote Sensing and the Tasseled Cap Transformation

Remote sensing is a valuable tool that can be used to detect ecological changes over large areas (Fraser *et al.*, 2014). The use of multiple scales and data types in remote sensing studies can help to improve data interpretation and reduce detection errors, as well as provide unique information. Aerial photographs are useful in delineating prominent terrain features, while multispectral satellite images are useful in detecting land cover reflectance properties (Olthof *et al.*, 2015; Segal *et al.*, 2016; Nitze *et al.*, 2017).

The Landsat satellite program has a moderate 30 m spatial resolution and is the longest running satellite-based Earth imaging program; with multispectral data extending back to the early 1970s (Wulder *et al.*, 2008). Open access of the United States Geological Survey (USGS) Landsat archive in 2008 has resulted in the extensive use of the temporally consistent data for research purposes and the development of new change-detection techniques (Fraser *et al.*, 2014). Landsat data is commonly transformed into indices that measure specific groundcover properties. A commonly used series of indices comes from the Tasseled Cap (TC) transformation (Kauth & Thomas, 1976).

The Tasseled Cap (TC) transformation, derived from Landsat data, was originally developed by Kauth & Thomas (1976) to track the trajectories of surface reflectance in

agricultural fields. The original TC transformation used Landsat Multispectral Scanner (MSS) data and produced three indices, which included brightness, greenness, and yellowness. Since then, transformations for Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+), and Operational Land Imager (OLI) data have been developed, with the yellowness index being replaced by a wetness index (Table 1.1., 1.2., and 1.3.) (Crist & Cicone, 1984; Huang *et al.*, 2002; Baig *et al.*, 2014).

The TC is a valuable transformation of Landsat data because it provides a simple means of combining six Landsat bands to a more manageable three indices (Table 1.1., 1.2., and 1.3.), which is particularly useful when processing or analyzing data over large areas. The three TC indices provide important information on physical properties of the ground surface, which can be used for agricultural, resource management, and research purposes (Kauth & Thomas, 1976; Crist & Cicone, 1984; Fraser *et al.*, 2014).

The TC brightness index (TCB) measures total surface reflectance and is a weighted sum of Landsat bands 1-5, and 7 (or bands 2-7 for Landsat 8). The TC greenness index (TCG) is suitable for measuring green vegetation and uses the difference between near-infrared and visible bands. The cell structure of plants are strong reflectors of infrared wavelengths, while chlorophyll is a strong absorber of visible wavelengths (Crist & Cicone, 1984). The TC wetness index (TCW) is sensitive to water surfaces, soil moisture, and plant moisture (Crist & Cicone, 1984), contrasting shortwave infrared with visible and near infrared bands. Plotting these three indices against each other creates a three-dimensional space consisting of two planes that share the TCB axis. The “plane of vegetation” consists of the brightness and greenness indices and the “plane of soils” consists of the brightness and wetness indices (Kauth & Thomas, 1976; Crist & Cicone, 1984).

Table 1.1. TC Landsat 5 TM coefficients from Crist & Cicone (1984).

TC Index	Landsat TM Band					
	1	2	3	4	5	7
Brightness	0.3037	0.2793	0.4743	0.5585	0.5082	0.1863
Greenness	-0.2848	-0.2435	-0.5436	0.7243	0.0840	-0.1800
Wetness	0.1509	0.1973	0.3279	0.3406	-0.7112	-0.4572

Table 1.2. TC Landsat 7 ETM+ coefficients from Huang *et al.* (2002).

TC Index	Landsat ETM+ Band					
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	1	2	3	4	5	7
Brightness	0.3561	0.3972	0.3904	0.6966	0.2286	0.1596
Greenness	-0.3344	-0.3544	-0.4556	0.6966	-0.0242	-0.2630
Wetness	0.2626	0.2141	0.0926	0.0656	-0.7629	-0.5388

Table 1.3. TC Landsat 8 OLI coefficients from Baig *et al.* (2014).

TC Index	Landsat ETM+ Band					
	2	3	4	5	6	7
Brightness	0.3029	0.2786	0.4733	0.5599	0.5080	0.1872
Greenness	-0.2941	-0.2430	-0.5424	0.7276	0.0713	-0.1608
Wetness	0.1511	0.1973	0.3283	0.3407	-0.7117	-0.4559

Bibliography

- Abnizova, A. & Young, K.L. (2010). Sustainability of high Arctic ponds in a polar desert environment. *Arctic*. 63(1), 67-84.
- AMAP-SWIPA (2012). Arctic climate issues 2011: Changes in Arctic snow, water, ice and permafrost. *SWIPA 2011 Overview Report*. pp. 97.
- Baig, M.H.A., Zhang, L., Shuai, T., & Tong, Q. (2014). Derivation of a tasseled cap transformation based on Landsat 8 at-satellite reflectance. *Remote Sensing Letters*. 5(5), 423-431.
- Batt, B.D.J., editor. (1997). Arctic ecosystems in peril: Report of the Arctic Goose Habitat Working Group. *Arctic Goose Joint Venture Special Publication*. U.S. Fish and Wildlife Service, Washington, D.C. and Canadian Wildlife Service, Ottawa, Ontario. 1-120.
- Becker, M.S., Davies, T.J., & Pollard, W.H. (2016). Ground ice melt in the high Arctic leads to greater ecological heterogeneity. *Journal of Ecology*. 104, 114-124.
- Beltrami, H., Jessop, A.M., & Mareschal, J.-C. (1992). Ground temperature histories in eastern and central Canada from geothermal measurements: Evidence of climate change. *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section)*. 98, 167-184.
- Beltrami, H. & Bourlon, E. (2004). Ground warming patterns in the Northern Hemisphere during the last five centuries. *Earth and Planetary Science Letters*. 227(3-4), 169-177.
- Bintanja, R. & Andry, O. (2017). Towards a rain-dominated Arctic. *Nature Climate Change*. 7, 263-268.
- Brown, L. & Young, K.L. (2006). Assessment of three mapping techniques to delineate lakes and ponds in a Canadian high Arctic wetland complex. *Arctic*. 59(3), 283-293.
- Calvert, A.M. (2015). Interactions between light geese and northern flora and fauna: Synthesis and assessment of potential impacts. *Unpublished report to Environment Canada, Ottawa ON*. 1-37.
- Canadian Wildlife Service (CWS) Waterfowl Committee (2013). Population Status of Migratory Game Birds in Canada: November 2013. CWS Migratory Birds Regulatory Report Number 40.
- Canadian Wildlife Service (CWS) Waterfowl Committee (2014). Migratory Birds Regulations in Canada: July 2014. CWS Migratory Birds Regulatory Report Number 43.

- Carroll, M.L., Townshend, J.R.G., DiMiceli, C.M., Loboda, T., & Sohlberg, R.A. (2011). Shrinking lakes of the Arctic: Spatial relationships and trajectory of change. *Geophysical Research Letters*. 38(L20406), 1-5.
- Crist, E.P. & Cicone, R.C. (1984). A physically-based transformation of thematic mapper data – the TM tasseled cap. *IEEE Transactions on Geoscience and Remote Sensing*. GE-22(3), 256-263.
- Ecosystem Classification Group (2013). Ecological regions of the Northwest Territories – Northern Arctic. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada: 1-157.
- Fraser, R.H., Olthof, I., Kokelj, S.V., Lantz, T.C., Lacelle, D., Brooker, A., Wolfe, S. & Schwarz, S. (2014). Detecting landscape changes in high latitude environments using Landsat trend analysis: 1. Visualization. *Remote Sensing*. 6, 11533-11557.
- Fraser, R.H., Kokelj, S.V., Lantz, T.C., McFarlane-Winchester, M., Olthof, I., & Lacelle, D. (2018). Climate sensitivity of high Arctic permafrost terrain demonstrated by widespread ice-wedge thermokarst on Banks Island. *Remote Sensing*. 10(6), 954.
- Hik, D.S., Jefferies, R.L., & Sinclair, A.R.E. (1992). Foraging by geese, isostatic uplift and asymmetry in the development of salt-marsh plant communities. *Journal of Ecology*. 80(3), 395-406.
- Hines, J.E., Latour, P.B., Squires-Taylor, C. & Moore, S. (2010). The effects on lowland habitat in the Banks Island Bird Sanctuary Number 1, Northwest Territories, by the growing colony of lesser snow geese (*Chen caerulescens caerulescens*). *Environment Canada Occasional Paper*. 118, 8-26.
- Huang, C., Wylie, B., Yang, L., Homer, C., & Zylstra, G. (2002). Derivation of a tasseled cap transformation based on Landsat 7 at-satellite reflectance. *International Journal of Remote Sensing*. 23(8), 1741-1748.
- Iacobelli, A. & Jefferies, R.L. (1991). Inverse salinity gradients in coastal marshes and the death of stands of *Salix*: The effects of grubbing by geese. *Journal of Ecology*. 79, 61-73.
- Indian and Northern Affairs Canada (1984). The western Arctic claim: The Inuvialuit Final Agreement. Indian and Northern Affairs Canada.
- Jefferies, R.L., Jensen, A., & Abraham, K.F. (1979). Vegetational development and the effect of geese on vegetation at La Perouse Bay, Manitoba. *Canadian Journal of Botany*. 57, 1439-1450.
- Jones, B.M., Grosse, G., Arp, C.D., Jones, M.C., Anthony, K.M.W., & Romanovsky, V.E. (2011). Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *Journal of Geophysical Research*. 116, G00M03.

- Kaplan, J.O. & New, M. (2006). Arctic climate change with a 2°C global warming: Timing, climate patterns and vegetation change. *Climate Change*. 79, 213-241.
- Kauth, R.J. & Thomas, G.S. (1976). The tasseled cap -- A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. *LARS Symposia*. 159(4B), 41-51.
- Kerbes, R.H., Meeres, K.M., & Alisauskas, R.T. (2014). Surveys of nesting lesser snow geese and Ross's geese in Arctic Canada, 2002-2009. *Arctic Goose Joint Venture Special Publication, U.S. Fish and Wildlife Service, Washington, D.C. and Canadian Wildlife Service, Ottawa, Ontario*. 987-0-9881233-1-1.
- Kotanen, P.M. & Jefferies, R.L. (1997). Long-term destruction of sub-arctic wetland vegetation by lesser snow geese. *Ecoscience*. 4(2), 179-182.
- Lantz, T.C. & Turner, K.W. (2015). Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. *Journal of Geophysical Research: Biogeosciences*. 120(3), 513-524.
- Lewkowicz, A.G. & French, H.M. (1982). The hydrology of small runoff plots in an area of continuous permafrost, Banks Island, N.W.T.. *Hydrology in Permafrost Regions – Proc. 4th Can. Permafrost Conf.*. 151-162.
- Marsh, P. & Bigras, S.C. (1988). Evaporation from Mackenzie Delta lakes, N.W.T., Canada. *Arctic and Alpine Research*. 20(2), 220-229.
- Mudryk, L.R., Derksen, C., Howell, S., Laliberte, F., Thackeray, C., Sospedra-Alfonso, R., Vionnet, V., Kushner, P.J., & Brown, R. (2018). Canadian snow and sea ice: Historical trends and projections. *The Cryosphere*. 12, 1157-1176.
- Negandhi, K., Laurion, I., Whitticar, M.J., Galand, P.E., Xu, X., & Lovejoy, C. (2013). Small thaw ponds: An unaccounted source of methane in the Canadian high Arctic. *PLoS ONE*. 8(11), e78204.
- Nitze, I., Grosse, G., Jones, B.M., Arp, C.D., Ulrich, M., Fedorov, A., & Veremeeva, A. (2017). Landsat-based trend analysis of lake dynamics across northern permafrost regions. *Remote Sensing*. 9(7), Article 640.
- Olthof, I., Fraser, R.H., & Schmitt, C. (2015). Landsat-based mapping of thermokarst lake dynamics on the Tuktoyaktuk coastal plain: Northwest Territories, Canada since 1985. *Remote Sensing of Environment*. 168, 194-204.
- Park, J.S. (2017). A race against time: Habitat alteration by snow geese prunes the seasonal sequence of mosquito emergence in a subarctic brackish landscape. *Polar Biology*. 40, 553-561.
- Pithan, F. & Mauritsen, T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*. 7, 181-184.

- Plug, L.J., Walls, C., & Scott, B.M. (2008). Tundra lake changes from 1978 to 2001 on the Tuktoyaktuk Peninsula, western Canadian Arctic. *Geophysical Research Letters*. 35, L03502.
- Raulings, E.J., Morris, K., Roache, M.C., & Boon, P.I. (2010). The importance of water regimes operating at small spatial scales for the diversity and structure of wetland vegetation. *Freshwater Biology*. 55, 701-715.
- Riordan, B., Verbyla, D., & McGuire, A.D. (2006). Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. *Journal of Geophysical Research*. 111, G04002.
- Roach, J.K., Griffith, B., & Verbyla, D. (2013). Landscape influences on climate-related lake shrinkage at high latitudes. *Global Change Biology*. 19, 2276-2284.
- Roy-Leveillee, P. & Burn, C.R. (2017). Near-shore talik development beneath shallow water in expanding thermokarst lakes, Old Crow Flats, Yukon. *Journal of Geophysical Research: Earth Surface*. 122, 1070-1089.
- Ruess, R.W., Hik, D.S., & Jefferies, R.L. (1989). The role of lesser snow geese as nitrogen processors in a sub-Arctic salt marsh. *Oecologia*. 79(1), 23-29.
- Sachs Harbour, Wildlife Management Advisory Council (NWT) & Joint Secretariat (2008). Sachs Harbour Community Conservation Plan. 5-109.
- Samelius, G., Alisauskas, R.T., & Hines, J.E. (2008). Productivity of lesser snow geese on Banks Island, Northwest Territories, Canada, in 1995-1998. *Environment Canada Occasional Paper*. 115, 1-33.
- Segal, R.A., Lantz, T.C., & Kokelj, S.V. (2016). Acceleration of thaw slump activity in glaciated landscapes of the western Canadian Arctic. *Environmental Research Letters*. 11, 034025.
- Slattery, S.M. & Alisauskas, R.T. (2007). Distribution and habitat use of Ross' and lesser snow geese during late brood rearing. *The Journal of Wildlife Management*. 71(7), 2230-2237.
- Smith, L.C., Sheng, Y., MacDonald, G.M., & Hinzman, L.D. (2005). Disappearing Arctic lakes. *Science*. 308(5727), 1429.
- Smol, J.P. & Douglas, S.V. (2007). Crossing the final ecological threshold in high Arctic ponds. *PNAS*. 104(30), 12395-12397.
- Srivastava, D.S. & Jefferies, R.L. (1996). A positive feedback: Herbivory, plant growth, salinity, and the desertification of an Arctic salt-marsh. *Journal of Ecology*. 84(1), 31-42.

- Steedman, A.E., Lantz, T.C., & Kokelj, S.V. (2016). Spatio-temporal variation in high-centre polygons and ice-wedge melt ponds, Tuktoyaktuk Coastlands, Northwest Territories. *Permafrost and Periglacial Processes*. 28(1), 66-78. doi: 10.1002/ppp.1880.
- van der Valk, A.G. (2005). Water-level fluctuations in North American prairie wetlands. *Hydrobiologia*. 539, 171-188.
- Wolfe, B.B., Light, E.M., Macrae, M.L., Hall, R.I., Eichel, K., Jasechko, S., White, J., Fishback, L., & Edwards, T.W.D. (2011). Divergent hydrological responses to 20th century climate change in shallow tundra ponds, western Hudson Bay Lowlands. *Geophysical Research Letters*. 38 (L23402), 1-6.
- Woo, M.-K. & Guan, X.,J. (2006). Hydrological connectivity and seasonal storage change of tundra ponds in a polar oasis environment, Canadian high Arctic. *Permafrost and Periglacial Processes*. 17, 309-323.
- Woo, M.-K. & Young, K.L. (2006). High Arctic wetlands: Their occurrence, hydrological characteristics and sustainability. *Journal of Hydrology*. 320, 432-450.
- Woo, M.-K., Young, K.L., & Brown, L. (2006). High Arctic patchy wetlands: Hydrological variability and their sustainability. *Physical Geography*. 27(4), 297-307.
- Webber, P.J. (1978). Spatial and temporal variation of the vegetation and its productivity, Barrow Alaska. *Vegetation and Production Ecology of an Alaskan Arctic Tundra*. edited by L.L. Tieszen. Springer-Verlag, New York. 37-112.
- Wulder, M.A., White, J.C., Goward, S.N., Masek, J.G., Irons, J.R., Herold, M., Cohen, W.B., Loveland, T.R., & Woodcock, C.E. (2008). Landsat continuity: Issues and opportunities for land cover monitoring. *Remote Sensing of Environment*. 112, 955-969.
- Yoshikawa, K. & Hinzman, L.D. (2003). Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council Alaska. *Permafrost and Periglacial Processes*. 14, 151-160.

Chapter 2 – Impacts of climate change and intensive lesser snow goose (*Chen caerulescens caerulescens*) activity on surface water in high Arctic pond complexes

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Introduction

Recent temperature increases in Arctic regions have been twice the average global change (AMAP-SWIPA, 2012; Pithan & Mauritsen, 2014) and have triggered significant changes to regional hydrological systems, including surface water dynamics (Lantz & Turner, 2015; Kaplan & New, 2006; Bintanja & Andry, 2017; Yoshikawa & Hinzman, 2003; Nitze *et al.*, 2017). Changes in surface water are concerning, because lakes, ponds, and wetlands strongly influence a range of physical, geochemical, and biological processes (Wolfe *et al.*, 2011; Negandhi *et al.*, 2013; Becker *et al.*, 2016; Slattery & Alisauskas, 2007). Arctic freshwater systems are also tied to the global climate system, through their effects on permafrost thaw and greenhouse gas emissions from thawed ground (Anthony *et al.*, 2016; White *et al.*, 2007; Raymond *et al.*, 2013).

Changes in the abundance and surface area of lakes and ponds in the Arctic have been attributed to: increasing evaporation (Smol & Douglas, 2007), fluctuations in precipitation (Plug *et al.*, 2008), permafrost degradation leading to lateral and subsurface drainage (Lantz & Turner, 2015; Yoshikawa & Hinzman, 2003; Smith *et al.*, 2005; Jones *et al.*, 2011), and thermokarst lake expansion (Olthof *et al.*, 2015; Roy-Leveillee & Burn, 2017). The vulnerability of waterbodies to these processes depends on both waterbody dimensions (Arp *et al.*, 2011; Marsh & Bigras, 1988) and catchment characteristics (Nitze *et al.*, 2017; Turner *et al.*, 2014; Roach *et al.*, 2013). Regional differences in these factors has resulted in considerable variation in surface water dynamics across the Arctic (Nitze *et al.*, 2017; Jones *et al.*, 2011; Roach *et al.*, 2013; Carroll *et al.*, 2011). Several recent studies suggest that permafrost extent is a major determinant of change in surface water (Nitze *et al.*, 2017; Roach *et al.*, 2013). Most studies in discontinuous permafrost zones have reported decreases in surface water, while most studies in continuous permafrost zones have shown increases in surface water (Smith *et al.*, 2005; Olthof *et al.*, 2015; Roach *et al.*, 2013; Riordan *et al.*, 2006). However, these studies have been restricted to subarctic and low Arctic regions, and trends in the high Arctic remain largely unstudied.

High Arctic pond complexes may be particularly vulnerable to the effects of increasing air and ground temperatures (Woo & Young, 2006; Abnizova & Young, 2010). Small and shallow waterbodies, with high surface area to volume ratios, are

disproportionately impacted by fluctuations in evaporation (Smol & Douglas, 2007; Marsh & Bigras, 1988). In addition, a shallow active layer common in the high Arctic, restricts groundwater storage capacity, reducing resilience during unusually dry periods (Woo *et al.*, 2006). Furthermore, high ground-ice content typically found in regularly saturated soils (Woo *et al.*, 2006), makes areas more susceptible to thermokarst induced changes to hydrology (Becker *et al.*, 2016; Steedman *et al.*, 2017; Fraser *et al.*, 2018).

Changes in the extent of surface water in high Arctic pond complexes will likely impact surrounding vegetation and herbivore populations, particularly migratory bird species that use these areas as breeding habitat (Slattery & Alisauskas, 2007; Hines *et al.*, 2010). Pond complexes fill an important ecological niche in the otherwise arid polar deserts of the high Arctic. However, high grazing pressures from expanding herbivore populations could also be contributing to climate-driven changes in surface water. Lesser snow goose (*Chen caerulescens caerulescens*) nesting colonies across the Arctic have seen rapid expansions in recent decades; largely due to intensified agricultural land-use providing abundant forage in their southern wintering areas and a warming climate in Arctic nesting areas (Batt, 1997). These expanding nesting colonies have caused significant and lasting degradation to northern wetlands (Hines *et al.*, 2010; Kotanen & Jefferies, 1997; Srivastava & Jefferies, 1996; Calvert, 2015). Intensive and recurring foraging can alter microtopography (Jefferies *et al.*, 1979) and increase near-surface ground temperatures and evaporation (Srivastava & Jefferies, 1996; Iacobelli & Jefferies, 1991), which likely decreases water retention in nearby waterbodies and may increase the risk of lateral drainage (Park, 2017). Park (2017) found that ephemeral ponds surrounded by high levels of lesser snow goose grubbing had significantly shorter hydroperiods than ponds not associated with grubbing.

To improve our ability to predict the long-term impacts of climate change on high Arctic freshwater systems, additional case studies are required to understand the processes controlling surface water dynamics. The objectives of this study are to: (1) explore the extent of changing waterbodies within the pond complexes of western Banks Island, Northwest Territories, and (2) investigate the causes of this change. Landsat imagery (1985-2015) was used to detect long-term surface water trends, higher resolution aerial photographs (1958) and satellite imagery (2014) were used to explore changes in

the size and distribution of waterbodies, and field sampling investigated potential causes and contributing factors.

We tested three specific hypotheses: (1) the number and size of waterbodies on western Banks Island is decreasing, (2) the loss of small waterbodies is widespread, and (3) changes in the number and size of waterbodies are following different trajectories in heavily overgrazed snow goose nesting areas, compared to areas less impacted by overgrazing.

Study Area

Banks Island is the westernmost island in the Canadian Arctic Archipelago and part of the Inuvialuit Settlement Region in the Northwest Territories. The community of Sachs Harbour is the only permanent settlement on the Island and has a population of approximately 100 residents. Located within the northern or high Arctic ecozone, this area has a harsh climate with a mean annual temperature of -12.8 °C at Sachs Harbour. Summers are short with average daily temperatures rising above freezing for only 3 months of the year, peaking at 6.6 °C in July. Average annual precipitation is 151.5 mm, with only 38% falling as rain (June to September). Mean annual temperatures have shown a 3.5 °C increase since 1956, while summer precipitation and maximum snow water equivalent before spring melt have changed minimally (Fraser *et al.*, 2018; Mudryk *et al.*, 2018).

The western side of Banks Island is underlain by unconsolidated Miocene-Pliocene sands and gravels and characterized by gently rolling uplands, intersected by numerous west flowing rivers with wide floodplains (Lakeman & England, 2013; Ecosystem Classification Group, 2013). Alluvial terraces in these river valleys are dotted with thousands of shallow ponds and have nearly continuous vegetation cover, dominated by sedges, grasses, and mosses (Hines *et al.*, 2010; Ecosystem Classification Group, 2013). Decomposition of this vegetation has produced limited organic deposits, over predominantly Gleysolic Turbic Cryosols (Ecosystem Classification Group, 2013). Permafrost is continuous in this region and ice-wedge polygons, non-sorted circles and stripes, and turf hummocks are widespread (Ecosystem Classification Group, 2013). In this study, we focused on the alluvial terraces of the west flowing rivers valleys (Figure 2.1.).

The river valleys of western Banks Island are important breeding habitat for many migratory bird species, including the lesser snow goose. This habitat supports over 95% of the western Arctic lesser snow goose population. The main nesting colony of this population is located at the confluence of the Egg and Big rivers (Hines *et al.*, 2010; Ecosystem Classification Group, 2013) (Figure 2.1.). The Banks Island Migratory Bird Sanctuary No. 1 is the second largest bird sanctuary in Canada at 20,517 km², and was created to protect this colony (Hines *et al.*, 2010; Ecosystem Classification Group, 2013).

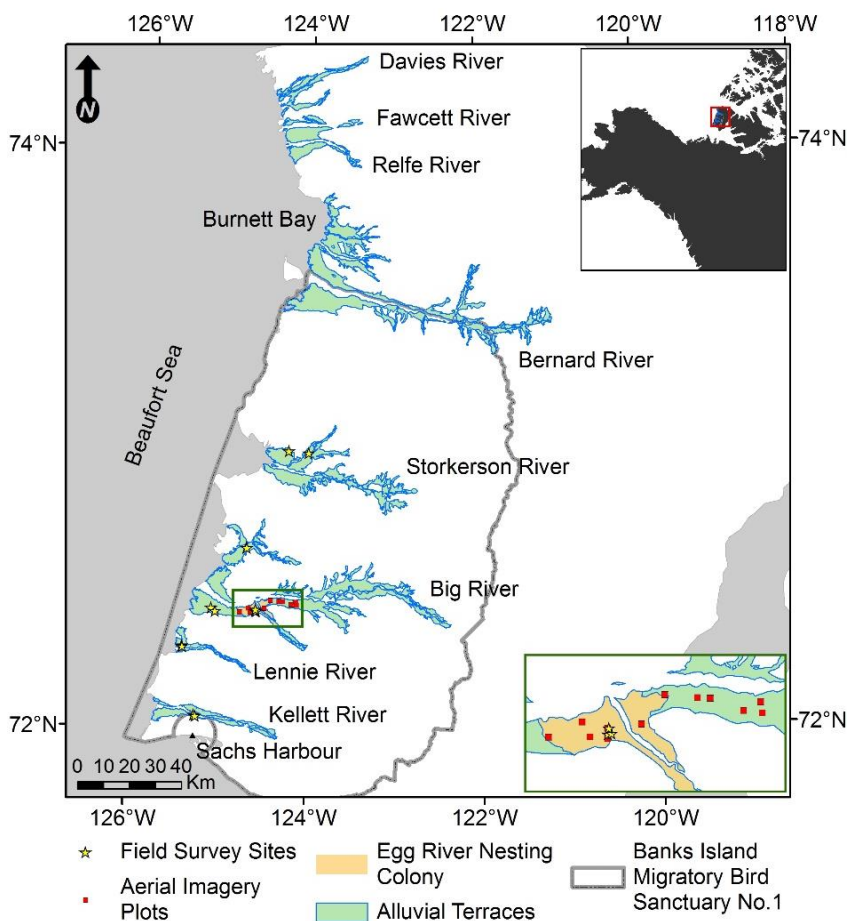


Figure 2.1. Map of the study area on Banks Island, Northwest Territories, showing field survey sites and areas where fine-scale imagery was analyzed. Inset map in the upper-right corner shows

Banks Island as the westernmost island in the Canadian Arctic Archipelago. Inset map in the bottom-right corner is an enlarged map of the nesting colony area, within the Big River valley.

Methods

a) Sub-pixel water fraction

To measure persistent changes in surface water, sub-pixel water fraction (SWF) was calculated for 94 30 m resolution images captured by the Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI sensors, between 1985 and 2015. Due to cloud cover, 1 to 7 images were used per year, which were adjusted over the time-series to optimize data coverage while ensuring that no significant relationship existed between year and the number of images per year. All images fell within the period of July 5th to August 10th, to minimize the influence of phenology and the spring freshet. Images were calibrated to top-of-atmosphere reflectance using USGS coefficients, and scan lines, clouds, and cloud shadows were masked out (Chander *et al.*, 2009).

SWF was calculated using the Tasseled Cap wetness (TCW) index, derived from each of the 94 Landsat images, and a histogram-breakpoint method (Olthof *et al.*, 2015). The TCW index is a transformation that contrasts shortwave infrared with visible and near infrared bands using established Tasseled Cap (TC) coefficients (Crist & Cicone, 1984; Huang *et al.*, 2002). The use of shortwave infrared bands in the TCW index makes it sensitive to water surfaces, soil moisture, and plant moisture (Crist & Cicone, 1984; Kauth & Thomas, 1976).

Following TCW transformation, breakpoint regression was applied to the frequency distribution of pixel values in each image to identify the land limit (LL), the threshold value separating pure land pixels from pixels of mixed land-water cover, and the water limit (WL), separating pure water pixels from pixels of mixed land-water cover. Breakpoint regression was applied to each image to reduce variabilities caused by different Landsat sensors, atmospheric conditions, and phenology states. Candidate breakpoints were determined using the ‘strucchange’ package (Zeileis *et al.*, 2002) in R software version 3.3.2 (R Core Team, 2016) and the breakpoint algorithm for estimating multiple possible breakpoints (Bai & Perron, 2003). Once range limits were obtained, the following equation was used to calculate the SWF of each mixed pixel in an image, where TCW is the Tasseled Cap Wetness value of the pixel being estimated. TCW values outside of the threshold LL and WL values were assigned 0% or 100% SWF, respectively.

$$SWF = \frac{(TCW - LL) \times 100\%}{(WL - LL)}$$

The accuracy of the histogram-breakpoint method in this terrain type was assessed by comparing SWF estimates to manually digitized estimates of surface water within 60 (0.25 km²) plots in the Big River valley. Manually digitized estimates of surface water were derived from WorldView-2 (WV02) satellite imagery (0.5 m resolution), acquired on July 9, 2014. Because of cloud cover and Landsat 7 scan line errors, the digitized surface water was compared against a multi-year SWF composite, calculated as the mean of SWF images from July 2013 and 2015.

To identify pixels that have exhibited persistent changes in surface water, we used Theil-Sen regression and the rank-based Mann-Kendall test to determine SWF trends and significance over time (1985-2015) (Olthof *et al.*, 2015; Fraser *et al.*, 2014). Theil-Sen regression is a nonparametric alternative to ordinary least squares regression that uses the median of all possible pairwise slopes instead of the mean. The rank-based Mann-Kendall test of significance is calculated through comparison to all possible pairwise slopes (Kendall & Stewart, 1967). The change in surface water for pixels with significant trends was estimated by multiplying the slope coefficient by the length of the time-series and the area of a single pixel (900 m²). These changes were then summed within each river valley to estimate regional surface water changes.

This analysis was restricted to the alluvial terraces of major river valleys (an area of ~2335 km²), which were manually delineated as areas of lowland terrain within 25 km of the main river channel (< 80 m above-sea-level) (Ecosystem Classification Group, 2013). Lowland terrain was visually identified using a 10 m resolution false-colour near-infrared Sentinel-2 satellite imagery acquired on July 19, 2017 and confirmed using a 5 m resolution digital elevation model (ArcticDEM) created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery (Noh & Howat, 2015).

b) Fine-scale surface water change detection

To explore and corroborate surface water dynamics at a finer scale, the historical and current extent of lakes and ponds was mapped within 12 (1 km²) plots using greyscale aerial photographs and WV02 satellite images in the Big River valley. Six (1 km²) plots were established in areas impacted by severe drying, and six (1 km²) plots

were established in stable areas that were minimally impacted by drying. Severe drying and stable plots were classified based on the composition of significant Local Indicators of Spatial Association (LISA) clusters (Anselin, 1995) of SWF trends within the Big River valley. Severe drying plots primarily consisted of negative SWF trend clusters (mean Δ of -271.5 m^2) and stable plots primarily consisted of low positive SWF trend clusters (mean Δ of $+55.6 \text{ m}^2$). Clusters of negative and positive SWF trends were present in opposing plots; however, they did not exceed 5% of the plot area. LISA clusters were generated using GeoDa software (1.8.16.4) and an order 2 Queen contiguity weights matrix, including lower orders (Anselin, 1995; Anselin, 2005).

Historical waterbodies greater than 50 m^2 were delineated using 1:60,000 scale aerial photographs acquired on July 14, 1958, with an effective pixel size of 1.5 m. Aerial photographs were georeferenced in ArcMap (10.4.1) using a first order polynomial transformation and 6-11 control points. The current extent of the waterbodies in these plots was delineated using WV02 satellite imagery (0.5 m resolution) acquired on July 9, 2014. Summer precipitation was similar in 1958 and 2014, reducing the likelihood that interannual variation in precipitation could influence differences in surface water extent. All waterbodies were digitized on-screen while viewing images, at a 1:500 scale. If new waterbodies appeared in the 2014 imagery, their historical areas were recorded as zero. A chi-square test was used to determine if the size class distribution of waterbodies in 1958 in severe drying and stable plot types deviated from their expected distribution. Expected values were calculated by multiplying the total number of waterbodies in each size class with the total number in each plot type and dividing by the sample size. Waterbodies were tallied within eight size classes, which progressively doubled in size to account for the lower frequencies of larger waterbodies.

To explore potential drivers of surface water change in the Big River valley, we used an information-theoretic approach to compare models based on four *a priori* hypotheses regarding the cause of change in the area of individual waterbodies from 1958-2014 (Burnham & Anderson, 2002). Hypotheses were informed by the literature (Table 2.1.) and models were constructed using the linear models procedure in R software (3.3.2) (R Core Team, 2016). To account for the greater potential change in surface area of larger sized waterbodies, an interaction term for pond size was also added

to several models. The 2015 Tasseled Cap Greenness (TCG) parameter used in models 2 and 3 (Table 2.1.) was calculated using the same methods as for the TCW index (Crist & Cicone, 1984; Huang *et al.*, 2002). The distance from the colony parameter used in models 4 and 5 was log transformed because visual inspection of the data suggested the relationship was non-linear. The flow accumulation parameter used in models 6 and 7 was calculated using the ArcticDEM (Noh & Howat, 2015) and the Fill, Flow Direction, and Flow Accumulation tools on ArcMap (10.4.1). Prior to model selection, all model parameters were examined for outliers using Cleveland dotplots (Zuur *et al.*, 2010) and collinearity using Pearson correlation coefficient matrices. To keep variance inflation factors below 3.0, variable pairs with correlation values greater than 0.7 were not included in the same model (Zuur *et al.*, 2010; Graham, 2003).

Following model selection, we performed an additional analysis using categorical intervals of waterbody size and distance from the nesting colony, to better understand how snow goose occupation may be influencing change proportional to waterbody area. This was conducted using the GLIMMIX procedure in SAS (9.3) to construct a linear mixed effects model of proportional area change versus categorical groupings of waterbody size and distance from the colony (Littell, *et al.*, 2006). Pairwise comparisons among categories were made using the least-squares procedure, estimated using the restricted-maximum likelihood method. The model included the aerial imagery plots as a random effect. Degrees of freedom were determined using the Kenward-Roger method (Littell, *et al.*, 2006).

Table 2.1. Descriptions of the four *a priori* hypotheses, parameters included, and model statements. The impact column describes the hypothesized direction of the relationship between the listed parameter and waterbody area change.

Hypothesis	Parameter	Description	Impact (+/-)	Model Number and Statement	Citation
Size: Smaller ponds are more vulnerable to change and climatic variability, compared to larger ponds.	Pond size	Waterbody extent from the 1958 aerial photographs.	+	1) Area change ~ Pond size	(Smol & Douglas, 2007; Arp <i>et al.</i> , 2011; Marsh & Bigras, 1988)
Vegetation: Vegetation cover insulates near-	2015 TCG	Average TCG value within 0-25 m of the	+	2) Area change ~ 2015 TCG	(Woo <i>et al.</i> , 2006; Price, 1971;

surface ground temperatures and increases soil water retention, sustaining subsurface hydrological connectivity and reducing system water loss through evaporation.		waterbody, taken from a July 18, 2015 Landsat scene.		3) Area change ~ 2015 TCG + Pond size	Fisher <i>et al.</i> , 2016; Gornall <i>et al.</i> , 2007; Woo & Guan, 2006)
				4) Area change ~ 2015 TCG + Pond size + 2015 TCG * Pond size	
				5) Area change ~ log(Colony distance)	
Herbivore intensity: Intensive and recurring goose foraging can alter microtopography, and increase soil temperature and evaporation levels, which may reduce hydroperiod in nearby waterbodies or increase risk of drainage.	Colony distance	Distance from the nesting colony, which was delineated as areas of high snow goose density, using data from Samelius <i>et al.</i> (2008).	+	6) Area change ~ log(Colony distance) + Pond size	(Srivastava & Jefferies, 1996; Jefferies <i>et al.</i> , 1979; Iacobelli & Jefferies, 1991; Park, 2017)
				7) Area change ~ log(Colony distance) + Pond size + log(Colony distance) * Pond size	
				8) Area change ~ Flow accumulation	
Surface water connectivity: Drainage areas will have higher levels of thermal erosion gullying and are more likely to experience lateral drainage.	Flow accumulation	Maximum flow level within 25 m of the waterbody, based on the number of upslope pixels.	-	9) Area change ~ Flow accumulation + Pond size	(Kokelj & Jorgenson, 2013)
				10) Area change ~ Flow accumulation + Pond size + Flow accumulation * Pond size	

c) Field surveys

To characterize field conditions in areas that showed declines in SWF and explore potential causes of these changes, surveys were conducted at 13 sites within five river valleys in July, 2017 (Figure 2.1.). Field sites were selected using LISA clusters of SWF trends and included **drying sites**, within clusters of negative SWF trends, and **control sites**, within clusters of low positive SWF trends and areas outside of significant clusters. We also visited several **colony sites** that were located within clusters of negative SWF trends, within 1 km of the densest parts of the nesting colony (Samelius *et al.*, 2008). Colony sites were sampled to differentiate drying patterns in highly used snow goose habitat areas, from areas not intensively used by snow geese. All sampling locations were selected within the alluvial terraces, between 0-20 m in elevation.

At each site, 11 measurement points were established at 10 m intervals along a north-south oriented 100 m transect. At each point, measurements were made of thaw depth, soil moisture, vegetation cover, and goose grubbing. Thaw depth was measured using an active layer probe, which was pushed into the ground until the depth of refusal. Soil moisture was measured using a handheld moisture probe (HH2 Moisture Meter with a Theta Probe soil moisture sensor-ML2x, from Delta-T Devices Ltd., Cambridge, England). Vegetation cover was measured by visually estimating the percent cover of vascular plants within a 50 cm² quadrat, aligned with the bottom-left corner at the measurement point. Goose grubbing was measured by counting the number of grub holes within the same 50 cm² quadrat. Grubbing is a particularly destructive form of foraging which targets below-ground roots and rhizomes before above ground vegetation is available. Along each transect, we also noted if points were located within a former pond basin. Former pond basins were identified based on the absence of organic material within a pond-shaped topographic depression.

To test for significant differences in thaw depth, soil moisture, vegetation cover, and goose grubbing among drying, control, and colony site types we constructed linear mixed effects models using the GLIMMIX procedure in SAS (9.3) (Littell, *et al.*, 2006). Pairwise comparisons among site types were made using the least-squares procedure, estimated using the restricted-maximum likelihood method. All models included site and river valley as random effects. Degrees of freedom were determined using the Kenward-Roger method (Littell, *et al.*, 2006). Measurements that landed within former pond basins were excluded from statistical comparisons of these variables, as they represented landcover with a different origin and substrate.

Results

a) Sub-pixel water fraction

Between 1985 and 2015, the alluvial terraces of western Banks Island lost 33.3 km² of surface water and gained 3.9 km² of surface water, resulting in a net loss of 29.3 km² or 7.9% of the original surface water (Figure A1.1., A1.2., and A1.3.). Regional SWF trends indicate that surface water has declined in all river valleys except the Kellett (Figure 2.2.). The Bernard River valley lost the largest absolute area of surface water

(8.83 km²) and the Relfe-Fawcett River valley lost the highest proportion of original surface water (17.1%).

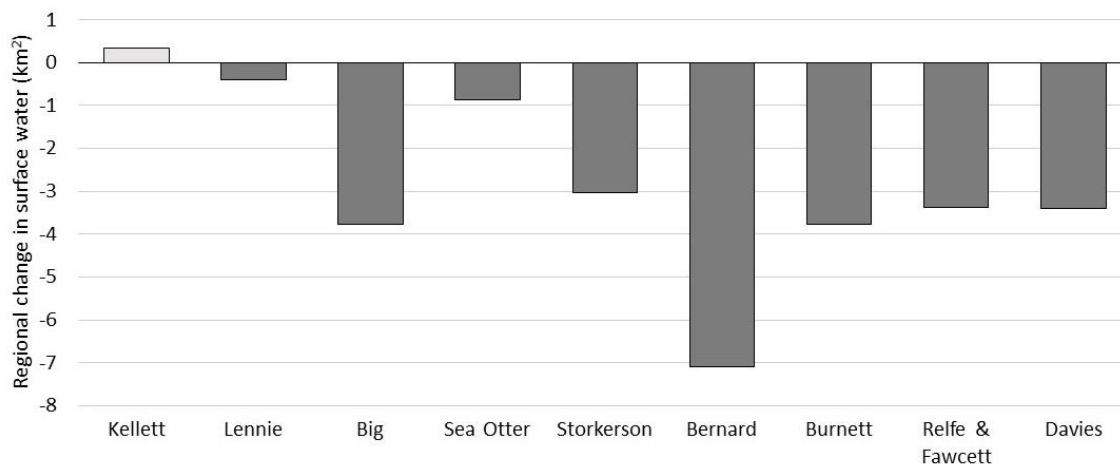


Figure 2.2. Net change in surface water from 1985-2015 in the 9 major river valleys of western Banks Island. River valleys are ordered by latitude, with the Kellett (at left) being the most southern and the Davies (at right) being the most northern. SWF trends ($p < 0.05$) were determined using 94 Landsat images between 1985-2015.

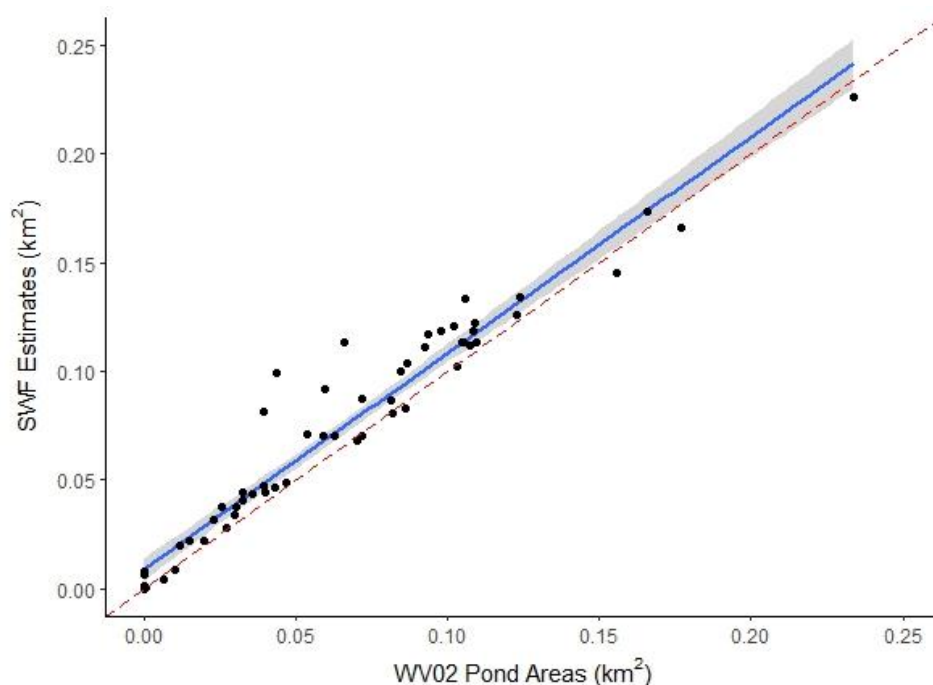


Figure 2.3. Sum of sub-pixel water fraction pixel values plotted against the sum of the area of manually delineated waterbodies within 500 m² plots. The blue line represents the model predictions (SWF estimates ~ WV02 Pond Areas), the grey bar represents the 95% confidence interval, and the dotted red line shows a 1:1 relationship.

Estimates of SWF made using the histogram-breakpoint method were strongly correlated with waterbody areas delineated manually. An ordinary least-squares regression model of the sum of SWF pixel values and the sum of manually delineated waterbody areas within the 60 accuracy assessment plots produced an r^2 value of 0.942 and a residual standard error of 0.0124 (Figure 2.3.). In our study, the histogram-breakpoint SWF method typically overestimated surface water (Figure 2.3.). On average, SWF estimations diverged from manually delineated waterbody areas by 0.00863 km² (~3.5% of the plot area). This small overestimation is likely linked to the sensitivity of TCW to plant moisture (Crist & Cicone, 1984; Kauth & Thomas, 1976) and the occurrence of saturated sedge meadows on the landscape, which would not have been delineated as waterbodies using the aerial imagery. However, consistency of overestimation across a range of surface water proportions indicates it is not likely to impact the slopes of SWF trends across the time-series (1985-2015).

b) Fine-scale surface water change detection

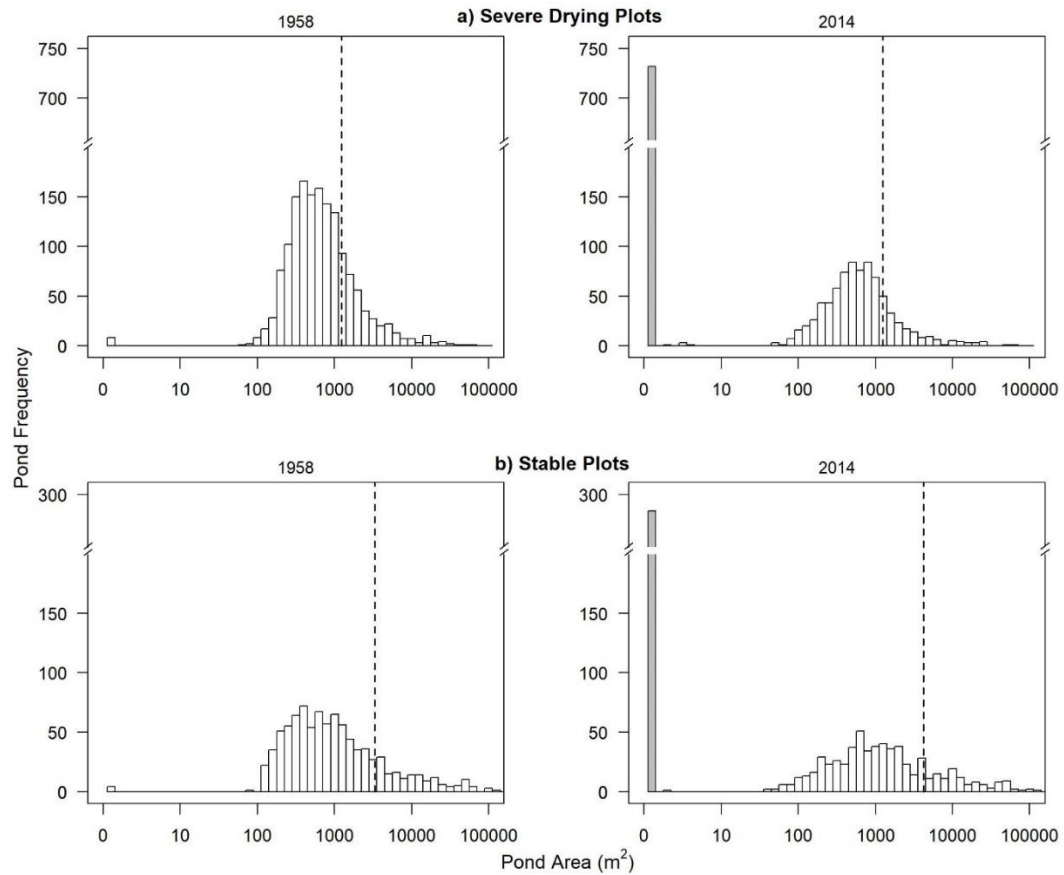


Figure 2.4. Size distributions of waterbodies mapped using aerial imagery, split by plot type and year. The dashed black lines show the average waterbody size within that year and plot, excluding waterbodies with a size of 0 m². The grey bars in 2014 show the number of waterbodies that experienced complete drainage.

There were large reductions in the number of waterbodies between 1958 and 2014, in both severe drying and stable plots (Figure 2.4.). Severe drying plots exhibited a complete loss of 732 (48.1%) waterbodies, while stable plots lost 286 (38.1%) waterbodies. Lost waterbodies ranged in their original size, from 58.5 m² to 17,708.5 m². Only 12 new waterbodies were recorded in the 2014 imagery and only 19.9% of all waterbodies either increased in surface area or remained stable (-10% to +10% change).

Severe drying and stable plots exhibited differences in waterbody density and average size. In 1958, severe drying plots had a mean density of 253 waterbodies per km² and a mean waterbody size of 1,228.2 m². Stable plots had a mean density of 149 waterbodies per km² and a much larger mean waterbody size of 3,319.2 m². The chi-

square test ($p < 0.001$) confirmed that areas exhibiting severe drying had more small waterbodies ($50\text{-}900\text{ m}^2$) and fewer large waterbodies ($> 900\text{ m}^2$) than expected. Conversely, stable areas had fewer small waterbodies ($50\text{-}900\text{ m}^2$) and more large waterbodies ($> 900\text{ m}^2$) than expected (Table 2.2.).

Table 2.2. Observed and expected chi-square size class distributions of waterbodies in severe drying and stable plots. Bold numbers indicate the number of observed waterbodies exceeds the number of expected waterbodies. Numbers with an asterisk indicate a significant difference from the expected value, using a Bonferroni correction ($p < 0.0063$).

	Severe drying		Stable	
	Observed	Expected	Observed	Expected
50-450 m ²	625	597	324	352
450-900 m ²	455*	402	184*	237
900-1,800 m ²	249	255	156	150
1,800-3,600 m ²	100*	121	93*	72
3,600-7,200 m ²	53	64	49	38
7,200-14,400 m ²	15*	35	41*	21
14,400-28,800 m ²	14*	23	22*	13
28,800-120,000 m ²	4*	18	25*	11
Column totals	1515	1515	894	894

Across all plots, 47.8% of the total surface water loss occurred in waterbodies smaller than $1,800\text{ m}^2$, despite the fact that these waterbodies only accounted for 20.5% of the total surface area in 1958 (Table 2.3.). Smaller waterbodies lost a higher proportion of their total area, compared to larger waterbodies (Table 2.3.). The smallest size class ($50\text{-}450\text{ m}^2$) lost 90.6% of the total area, compared to the 5% lost by the largest size class ($28,800\text{-}120,000\text{ m}^2$).

In stable and severe drying plots, there was an increase in the mean size of waterbodies present in 2014 (Figure 2.4.), which is indicative of a disproportionate loss of small waterbodies. The change in mean waterbody size between 1958-2014 was considerably smaller in severe drying plots ($\Delta 9.4\text{ m}^2$), compared to stable plots ($\Delta 876.9\text{ m}^2$), which showed a more balanced loss of waterbodies of varying sizes.

Table 2.3. Summary statistics including the total number, area, change, and proportion of change for waterbodies in different size classes.

Waterbody size in 1958 (m ²)	50-450	450-900	900-1,800	1,800-3,600	3,600-7,200	7,200-14,400	14,400-28,800	28,800-120,000
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Count	949	639	405	193	102	56	36	29
Total area (m²)	213,525	431,325	546,750	521,100	550,800	604,800	777,600	2,157,600
Change in total area (m²)	-193,437	-212,536	-204,329	-153,752	-151,374	-119,682	-142,308	-107,254
Proportion of total area lost	90.59%	49.28%	37.37%	29.51%	27.48%	19.79%	18.30%	4.97%

The model selection procedure showed that large reductions in waterbody area were most strongly associated with waterbody size and proximity to the nesting colony. The best model included an interaction between distance from the colony and pond size (Table 2.4.).

Table 2.4. Candidate models for change in waterbody area, with goodness-of-fit metrics. The table is ordered by model fit and the best model is shown in bold.

Model number	Explanatory variables	R ²	AICc	ΔAICc	AICc weight	Rank
7	log(Colony Distance) + Pond Size + log(Colony Distance) * Pond Size	0.429	39960.4	0	1.0	1
6	log(Colony Distance) + Pond Size	0.291	40482.6	522.2	4.0*10 ⁻¹¹⁴	2
4	2015 TCG + Pond Size + 2015 TCG * Pond Size	0.276	40532.4	572.0	6.2*10 ⁻¹²⁵	3
3	2015 TCG + Pond Size	0.220	40710.3	749.9	1.4*10 ⁻¹⁶³	4
1	Pond Size	0.211	40739.5	779.1	6.6*10 ⁻¹⁷⁰	5
9	Flow Accumulation + Pond Size	0.210	40741.0	780.6	3.1*10 ⁻¹⁷⁰	6
10	Flow Accumulation + Pond Size + Flow Accumulation * Pond Size	0.210	40742.5	782.1	1.4*10 ⁻¹⁷⁰	7
5	log(Colony Distance)	0.0995	41056.4	1096.0	9.8*10 ⁻²³⁹	8
2	2015 TCG	0.00926	41286.4	1326.0	1.1*10 ⁻²⁸⁸	9
8	Flow Accumulation	0.00264	41302.5	1342.1	3.6*10 ⁻²⁹²	10

Waterbody area losses were larger near the colony regardless of waterbody size, but the impact of the colony was most obvious in larger waterbodies. This was evidenced by an increase in the slope, of the relationship between distance from the colony and area loss, in larger waterbodies (Figure 2.5.).

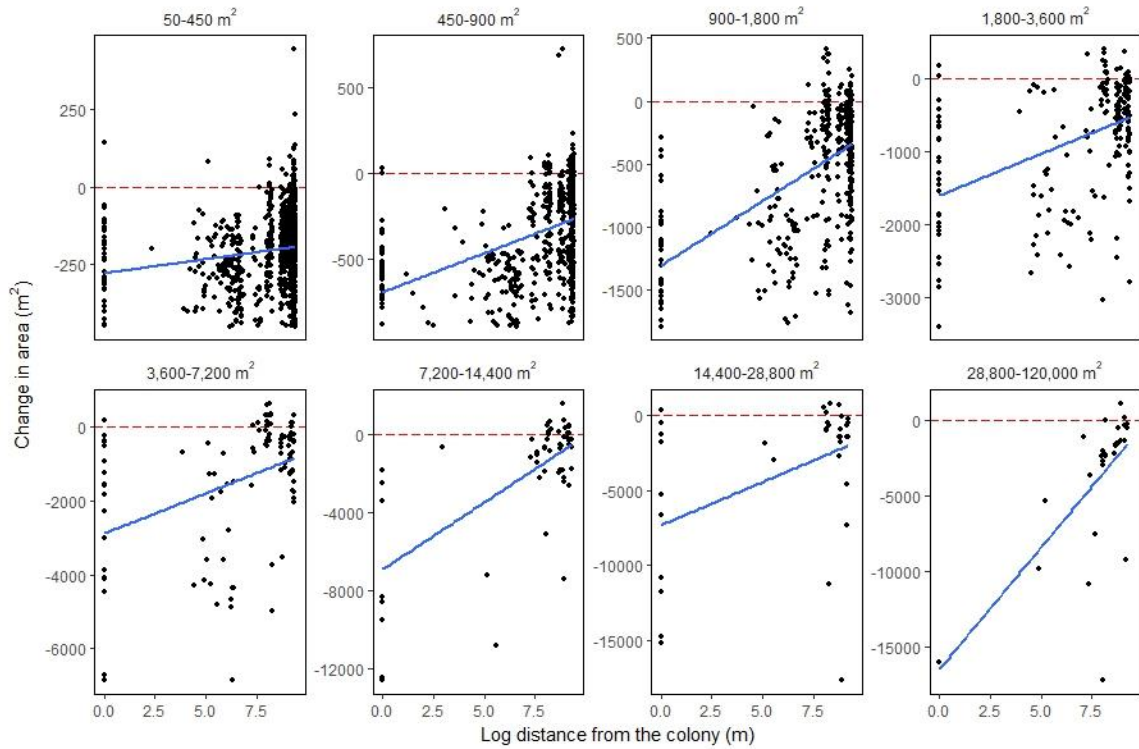


Figure 2.5. Visualization of interaction effect (distance from the colony and waterbody size) in the best model (Table 2.4.). Data were divided based on the waterbody size classes indicated above each panel. Each point represents the change in area of a single waterbody. The blue lines show model predictions for waterbody area change within that size class. The dotted red reference lines show no change in waterbody area.

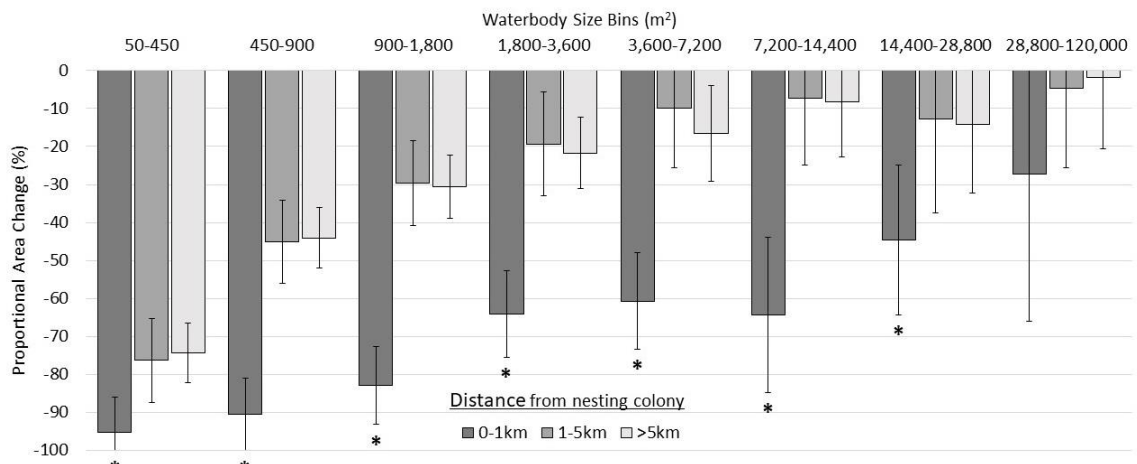


Figure 2.6. Bar plots showing the proportional area change at distance from the nesting colony intervals, within each waterbody size class. Error bars represent 95% confidence intervals. Asterisks are present when the 0-1 km distance group is significantly different from the other distance groups, based on the least-squares means estimates.

All waterbody size classes, except the largest ($> 28,800 \text{ m}^2$), had significantly greater proportional area loss ($p < 0.05$) within 1 km of the nesting colony, compared to waterbodies between 1-5 km, and further than 5 km from the nesting colony (Figure 2.6.). At distances greater than 1 km from the nesting colony, waterbodies showed similar proportional changes in all size classes. Regardless of distance from the colony, the smallest waterbody size class had the largest proportional area loss at 95.3% \pm 9.2 for 0-1 km from the nesting colony, 76.3% \pm 11.1 for 1-5 km, and 74.4% \pm 7.8 for greater than 5 km.

c) Field surveys

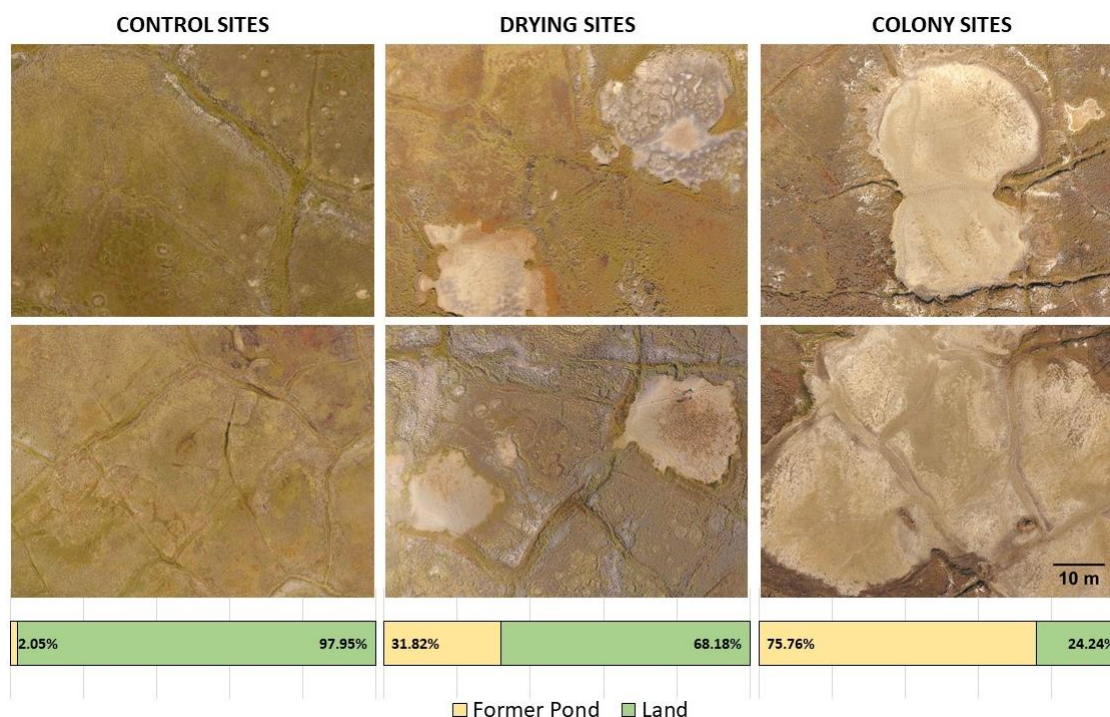


Figure 2.7. Aerial photographs captured using a UAV during July, 2017 field surveys. The bars below the images show the proportion of field transects classified as former pond basins and regular land.

Field surveys showed evidence of widespread drying, as all site types intersected former pond basins to some extent. Colony sites had the highest proportion of former pond basins (75.76%), then drying sites (31.82%), and then control sites (2.05%) (Figure

2.7.). Regardless of site type, former pond basins intersected transect lines exclusively within pixels that experienced negative SWF trends.

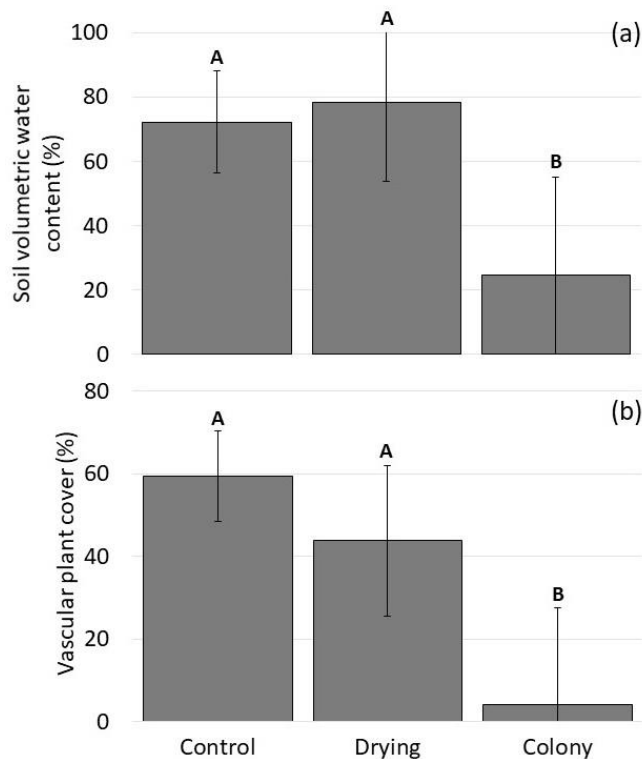


Figure 2.8. Least-squares means estimates of (a) soil volumetric water content and (b) vegetation cover from the linear mixed effects models. Error bars represent 95% confidence intervals and bars with different letters are significantly different.

Soils were significantly drier at colony sites ($p < 0.05$) compared to the control and drying site types, which were not significantly different from each other (Figure 2.8.). Mean soil volumetric water content was three times lower at colony sites ($24.6\% \pm 30.4\%$), compared to drying ($78.4\% \pm 24.6\%$) and control sites ($72.2\% \pm 15.8\%$). Thaw depth was not significantly different among site types. Vegetation cover was also significantly lower at the colony sites ($p < 0.01$) (Figure 2.8.), where groundcover was dominated by exposed peat. Mean vascular plant cover was ten to 15 times lower at colony sites ($4.1\% \pm 23.6\%$), compared to drying ($43.8\% \pm 18.2\%$) and control sites ($59.5\% \pm 10.9\%$). Goose grubbing was not significantly different among site types.

Discussion

The results of our analyses confirm our hypothesis that the number and size of waterbodies in the pond complexes of western Banks Island are decreasing. This observation differs from most surface water studies in the low Arctic (Smith *et al.*, 2005; Olthof *et al.*, 2015), which have reported increases in surface water. In the pond complexes of western Banks Island, only a small portion of existing waterbodies expanded and few new waterbodies emerged. This indicates that surface water responses to climate change in high Arctic regions are distinct and require additional research, as the high Arctic is one of Canada's largest ecozones, covering about 15% of the country. Estimates of change in surface water based on the SWF analysis and manual aerial imagery digitization span different time periods, but results from both sources of information showed similar patterns of substantial surface water loss.

Smaller waterbodies are more vulnerable

Our observation that small waterbodies are being disproportionately affected is aligned with our second hypothesis and suggests that climate is the main driver of drying in the study area. Almost half of the loss in surface water occurred in small waterbodies (50-1,800 m²), despite only making-up 20.5% of the total surface water in 1958. There are several climate-driven processes that may be contributing to the loss of surface water on Banks Island. Warming summer temperatures and extended ice-free seasons increase annual evaporative losses and can lead to the complete desiccation of waterbodies (Smol & Douglas, 2007; Woo & Guan, 2006). The effects of this would be most evident in small and shallow waterbodies because of their high surface area to volume ratios (Smol & Douglas, 2007; Arp *et al.*, 2011; Marsh & Bigras, 1988). Declines in terrestrial water storage in large river basins across the Arctic have also been linked to increases in evapotranspiration (Suzuki *et al.*, 2018). Warmer and longer summers would also reduce summer snow pack, which might be sustaining wet areas with meltwater throughout the ice-free season (Woo & Young, 2006; Woo *et al.*, 2006; Brown & Young, 2006). Most of the summer snow pack observed in the 1958 aerial photographs was not visible in the 2014 aerial imagery, despite having acquisition dates only five days apart. Warming air and ground temperatures can also increase thaw depth and groundwater storage capacities, which might lower the water table (Woo *et al.*, 2006). This would reduce

hydrological connectivity (Woo *et al.*, 2006) and could potentially desiccate shallow waterbodies perched above the lowered water table. Degradation of low-centred polygonal terrain, from increasing ground temperatures, would also result in a large loss of small waterbodies (Liljedahl *et al.*, 2016). As low-centred polygons degrade into high-centred polygons, their capacity to hold water decreases. Our data suggests this is not occurring because it would also result in an increase in waterbodies in the trough areas of the polygons (Liljedahl *et al.*, 2016), which we did not observe. Furthermore, areas visited in the field, which experienced concentrated losses of small waterbodies, have remained low-centred polygonal terrain. Further investigation is needed to evaluate the potential contributions of these processes and understand how similar terrain types in other regions of the Arctic are being impacted. The knowledge of hunters and land-users can also provide significant insight into these processes (Riedlinger & Berkes, 2001; Ashford & Castleden, 2001; Ferguson & Messier, 1997).

Our finding that small ponds are the most vulnerable to change highlights the importance of using fine-scale data or sub-pixel/spectral un-mixing techniques for surface water change detection in areas with small waterbody size distributions. It is important to use data at appropriate scales or remote sensing techniques that are matched with the biophysical variation in the area of interest. In our study area, most waterbodies were smaller than 900 m², the size of the Landsat pixel footprint. Previous broad-scale analyses, not considering sub-pixel information (Pekel *et al.*, 2016), were only sensitive to changes impacting the majority of a pixel and therefore did not detect the magnitude of change we observed.

Intensified drying in the nesting colony

Our results also confirm our hypothesis that surface water changes are following different trajectories in the nesting colony area and indicate that the intensive occupation of lesser snow geese may be reducing the resilience of waterbodies to climate warming, by facilitating drying or draining processes. Reductions in waterbody area were larger and more consistent closer to the nesting colony, regardless of original waterbody size. Colony sites were shown to have reduced vegetation cover and soil moisture, which are common impacts of overgrazing in expanding snow goose nesting colonies (Srivastava & Jefferies, 1996; Calvert, 2015). Vegetation provides a strong insulating layer that

stabilizes near-surface ground temperatures and increases soil moisture retention (Iacobelli & Jefferies, 1991; Srivastava & Jefferies, 1996). Reductions in the vegetation layer associated with intense goose activity have been found to increase evaporation in soils (Srivastava & Jefferies, 1996), which may reduce subsurface hydrological connectivity. Waterbodies isolated from subsurface inputs are more vulnerable to desiccation over the ice-free season (Woo & Young, 2006; Abnizova & Young, 2010; Woo & Guan, 2006).

Trampling by lesser snow geese, which can create depressions and terraces (Jefferies *et al.*, 1979), likely contributes to reduced vegetation cover to increase the risk of lateral drainage through accelerated degradation of ice-wedge polygons. Ice-wedge polygons are one of the most common forms of ground ice in the Arctic (French, 2007; Lachenbruch, 1962) and were ubiquitous at our field sites. These features have been suggested to be more vulnerable to degradation in higher latitude areas because wedge ice is located closer to the ground surface and is less insulated from changing air temperatures (Steedman *et al.*, 2017; Fraser *et al.*, 2018).

Since lesser snow goose breeding areas are synonymous with wet Arctic habitats, a better understanding of the impacts of these animals on permafrost and surface water dynamics is important. Similar patterns of surface water loss can be seen in the lowland areas of Southampton Island, Nunavut (Pekel *et al.*, 2016), which hosts the third largest lesser snow goose population in the Canadian Arctic (Calvert, 2015). As populations continue to expand, impacts to freshwater systems in the Canadian Arctic are likely to intensify. Further research on snow goose habitat impacts to permafrost and surface water dynamics are necessary, as this topic is largely unstudied to date.

Implications

Drying of high Arctic wetlands will impact lesser snow geese and other herbivore populations, as these areas provide important breeding habitat in largely arid polar deserts (Calvert, 2015). A recent study projected 30-80% reductions in lake extent within areas of five Alaskan National Wildlife Refuges over the next 50-years, and anticipated these areas would not persist as important waterfowl production areas if rates of change continue (Roach *et al.*, 2013). Changes in waterbody area can also affect permafrost thaw (Anthony *et al.*, 2016; White *et al.*, 2007; Raymond *et al.*, 2013) and increase methane

and carbon dioxide emissions with shoreline expansion (Anthony *et al.*, 2016; Martin *et al.*, 2018). Understanding surface water change in high Arctic environments is therefore critical in making accurate evaluations of greenhouse gas emissions across the Arctic.

Conclusion

Based on the data analyzed here, we draw the following conclusions:

- The pond complexes on western Banks Island are drying.
- Wetland drying is being caused by warming climate, but is exacerbated in areas with intensive snow goose habitat use.
- Future studies should explore the mechanisms causing pond desiccation, the impacts of snow geese on these processes, and the impacts of drying on vegetation and permafrost conditions.
- Remote sensing studies must use data and methods that consider the biophysical variation in the area of interest, to adequately assess environmental changes.

Bibliography

- Abnizova, A. & Young, K.L. (2010). Sustainability of high Arctic ponds in a polar desert environment. *Arctic*. 63(1), 67-84.
- AMAP-SWIPA (2012). Arctic climate issues 2011: Changes in Arctic snow, water, ice and permafrost. *SWIPA 2011 Overview Report*. pp. 97.
- Anselin, L. (1995). Local indicators of spatial association – LISA. *Geographical Analysis*. 27(2), 93-115.
- Anselin, L. (2005). GeoDa: An introduction to spatial data analysis. *Geographical Analysis*. 38(1), 5-22.
- Anthony, K.W., Daanen, R., Anthony, P., Schneider von Deimling, T., Ping, C.-L., Chanton, J.P., & Grosse, G. (2016). Methane emissions proportional to permafrost carbon thawed in Arctic lakes since the 1950s. *Nature Geoscience*. 9, 679-685.
- Arp, C.D., Jones, B.M., Urban, F.E., & Grosse, G. (2011). Hydrogeomorphic processes of thermokarst lakes with grounded-ice and floating-ice regimes on the Arctic coastal plain, Alaska. *Hydrological Processes*. 25, 2422-2438.
- Ashford, G. & Castleden, J. (2001). Inuit observations on climate change: Final report. *International Institute for Sustainable Development*. 1-31.
- Bai, J. & Perron, P. (2003). Computation and analysis of multiple structural change models. *Journal of Applied Econometrics*. 18, 1-22.
- Batt, B.D.J., editor. (1997). Arctic ecosystems in peril: Report of the Arctic Goose Habitat Working Group. *Arctic Goose Joint Venture Special Publication*. U.S. Fish and Wildlife Service, Washington, D.C. and Canadian Wildlife Service, Ottawa, Ontario. 1-120.
- Becker, M.S., Davies, T.J., & Pollard, W.H. (2016). Ground ice melt in the high Arctic leads to greater ecological heterogeneity. *Journal of Ecology*. 104, 114-124.
- Bintanja, R. & Andry, O. (2017). Towards a rain-dominated Arctic. *Nature Climate Change*. 7, 263-268.
- Brown, L. & Young, K.L. (2006). Assessment of three mapping techniques to delineate lakes and ponds in a Canadian high Arctic wetland complex. *Arctic*. 59(3), 283-293.
- Burnham, K.P. & Anderson, D.R. (2002). Model selection and multimodel inference: A practical information-theoretic approach (2nd edition). *New York, Springer*.
- Calvert, A.M. (2015). Interactions between light geese and northern flora and fauna: Synthesis and assessment of potential impacts. *Unpublished report to Environment Canada, Ottawa ON*. 1-37.

- Carroll, M.L., Townshend, J.R.G., DiMiceli, C.M., Loboda, T., & Sohlberg, R.A. (2011). Shrinking lakes of the Arctic: Spatial relationships and trajectory of change. *Geophysical Research Letters*. 38(L20406), 1-5.
- Chander, G., Markham, B.L., & Helder, D.L. (2009). Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment*. 113, 893-903.
- Crist, E.P. & Cicone, R.C. (1984). A physically-based transformation of thematic mapper data – the TM tasseled cap. *IEEE Transactions on Geoscience and Remote Sensing*. GE-22(3), 256-263.
- Ecosystem Classification Group (2013). Ecological regions of the Northwest Territories – Northern Arctic. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada: 1-157.
- Ferguson, M.A.D. & Messier, F. (1997). Collection and analysis of traditional ecological knowledge about a population of Arctic tundra caribou. *Arctic*. 50(1), 17-28.
- Fisher, J.P., Estop-Aragones, C., Thierry, A., Charman, D.J., Wolfe, S.A., Hartley, I.P., Murton, J.B., Williams, M. & Phoenix, G.K. (2016). The influence of vegetation and soil characteristics on active-layer thickness of permafrost soils in boreal forest. *Global Change Biology*. 22, 3127-3140.
- Fraser, R.H., Olthof, I., Kokelj, S.V., Lantz, T.C., Lacelle, D., Brooker, A., Wolfe, S. & Schwarz, S. (2014). Detecting landscape changes in high latitude environments using Landsat trend analysis: 1. Visualization. *Remote Sensing*. 6, 11533-11557.
- Fraser, R.H., Kokelj, S.V., Lantz, T.C., McFarlane-Winchester, M., Olthof, I., & Lacelle, D. (2018). Climate sensitivity of high Arctic permafrost terrain demonstrated by widespread ice-wedge thermokarst on Banks Island. *Remote Sensing*. 10(6), 954.
- French, H.M. (2007). The periglacial environment (3rd edition). *John Wiley & Sons: Chichester*.
- Gornall, J.L., Jonsdottir, I.S., Woodin, S.J., Van der Wal, R. (2007). Arctic mosses govern below-ground environment and ecosystem processes. *Oecologia*. 153, 931-941.
- Graham, M.H. (2003). Confronting multicollinearity in ecological multiple regression. *Ecology*. 84(11), 2809-2815.
- Hines, J.E., Latour, P.B., Squires-Taylor, C. & Moore, S. (2010). The effects on lowland habitat in the Banks Island Bird Sanctuary Number 1, Northwest Territories, by the growing colony of lesser snow geese (*Chen caerulescens caerulescens*). *Environment Canada Occasional Paper*. 118, 8-26.

- Huang, C., Wylie, B., Yang, L., Homer, C., & Zylstra, G. (2002). Derivation of a tasseled cap transformation based on Landsat 7 at-satellite reflectance. *International Journal of Remote Sensing*. 23(8), 1741-1748.
- Iacobelli, A. & Jefferies, R.L. (1991). Inverse salinity gradients in coastal marshes and the death of stands of *Salix*: The effects of grubbing by geese. *Journal of Ecology*. 79, 61-73.
- Jefferies, R.L., Jensen, A., & Abraham, K.F. (1979). Vegetational development and the effect of geese on vegetation at La Perouse Bay, Manitoba. *Canadian Journal of Botany*. 57, 1439-1450.
- Jones, B.M., Grosse, G., Arp, C.D., Jones, M.C., Anthony, K.M.W., & Romanovsky, V.E. (2011). Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *Journal of Geophysical Research*. 116, G00M03.
- Kaplan, J.O. & New, M. (2006). Arctic climate change with a 2°C global warming: Timing, climate patterns and vegetation change. *Climate Change*. 79, 213-241.
- Kauth, R.J. & Thomas, G.S. (1976). The tasseled cap -- A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. *LARS Symposia*. 159(4B), 41-51.
- Kendall, M.G. & Stuart, A.S. (1967). Advanced Theory of Statistics. *Charles Griffin and Company, London, UK*. 2.
- Kokelj, S.V. & Jorgenson, M.T. (2013). Advances in thermokarst research. *Permafrost and Periglacial Processes*. 24, 108-119.
- Kotanen, P.M. & Jefferies, R.L. (1997). Long-term destruction of sub-arctic wetland vegetation by lesser snow geese. *Ecoscience*. 4(2), 179-182.
- Lakeman, T.R. & England, J.H. (2013). Late Wisconsinan glaciation and postglacial relative sea-level change on western Banks Island, Canadian Arctic Archipelago. *Quaternary Research*. 80(1), 99-112.
- Lantz, T.C. & Turner, K.W. (2015). Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. *Journal of Geophysical Research: Biogeosciences*. 120(3), 513-524.
- Lachenbruch, A.H. (1962). Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. *Geological Society of America Special Papers*. 70, 1-66.
- Liljedahl, A.K., Boike, J., Daanen, R.P., Fedorov, A.N., Frost, G.V., Grosse, G., Hinzman, L.D., Iijima, Y., Jorgenson, J.C., Matveyeva, N., Necsoiu, M., Reynolds, M.K., Romanovsky, V.E., Schulla, J., Tape, K.D., Walker, D.A., Wilson, C.J.,

- Yabuki, H., & Zona, D. (2016). Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience*. 9, 312-319.
- Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., & Schabenberger, O. (2006). SAS for mixed models (2nd edition). *Carry, NC. SAS Institute Inc.*
- Marsh, P. & Bigras, S.C. (1988). Evaporation from Mackenzie Delta lakes, N.W.T., Canada. *Arctic and Alpine Research*. 20(2), 220-229.
- Martin, A.F., Lantz, T.C., & Humphreys, E.R. (2018). Ice wedge degradation and CO₂ and CH₄ emissions in the Tuktoyaktuk coastlands, Northwest Territories. *Arctic Science*. 4(1), 130-145.
- Mudryk, L.R., Derksen, C., Howell, S., Laliberte, F., Thackeray, C., Sospedra-Alfonso, R., Vionnet, V., Kushner, P.J., & Brown, R. (2018). Canadian snow and sea ice: Historical trends and projections. *The Cryosphere*. 12, 1157-1176.
- Negandhi, K., Laurion, I., Whiticar, M.J., Galand, P.E., Xu, X., & Lovejoy, C. (2013). Small thaw ponds: An unaccounted source of methane in the Canadian high Arctic. *PLoS ONE*. 8(11), e78204.
- Nitze, I., Grosse, G., Jones, B.M., Arp, C.D., Ulrich, M., Fedorov, A., & Veremeeva, A. (2017). Landsat-based trend analysis of lake dynamics across northern permafrost regions. *Remote Sensing*. 9(7), Article 640.
- Noh, M.-J. & Howat, I.M. (2015). Automated stereo-photogrammetric DEM generation at high latitudes: Surface extraction with TIN-based search-space minimization (SETSM) validation and demonstration over glaciated regions. *GIScience & Remote Sensing*. 52(2), 198-217.
- Olthof, I., Fraser, R.H., & Schmitt, C. (2015). Landsat-based mapping of thermokarst lake dynamics on the Tuktoyaktuk coastal plain: Northwest Territories, Canada since 1985. *Remote Sensing of Environment*. 168, 194-204.
- Park, J.S. (2017). A race against time: Habitat alteration by snow geese prunes the seasonal sequence of mosquito emergence in a subarctic brackish landscape. *Polar Biology*. 40, 553-561.
- Pekel, J.-F., Cottam, A., Gorelick, N., & Belward, A.S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*. 540, 418-422.
- Pithan, F. & Mauritsen, T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*. 7, 181-184.
- Plug, L.J., Walls, C., & Scott, B.M. (2008). Tundra lake changes from 1978 to 2001 on the Tuktoyaktuk Peninsula, western Canadian Arctic. *Geophysical Research Letters*. 35, L03502.

- Price, L.W. (1971). Vegetation, microtopography, and depth of active layer on different exposures in subarctic alpine tundra. *Ecology*. 52(4), 638-647.
- R Core Team (2016). R: A language and environment for statistical computing. *R Foundation for Statistical Computing, Vienna, Austria*. URL <https://www.R-project.org/>.
- Raymond, P.A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Durr, H., Meybeck, M., Ciais, P., & Guth, P. (2013). Global carbon dioxide emissions from inland waters. *Nature*. 503, 355-387.
- Riedlinger, D. & Berkes, F. (2001). Contributions of traditional knowledge to understanding climate change in the Canadian Arctic. *Polar Record*. 37(203), 315-328.
- Riordan, B., Verbyla, D., & McGuire, A.D. (2006). Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. *Journal of Geophysical Research*. 111, G04002.
- Roach, J.K., Griffith, B., & Verbyla, D. (2013). Landscape influences on climate-related lake shrinkage at high latitudes. *Global Change Biology*. 19, 2276-2284.
- Roy-Leveillee, P. & Burn, C.R. (2017). Near-shore talik development beneath shallow water in expanding thermokarst lakes, Old Crow Flats, Yukon. *Journal of Geophysical Research: Earth Surface*. 122, 1070-1089.
- Samelius, G., Alisauskas, R.T., & Hines, J.E. (2008). Productivity of lesser snow geese on Banks Island, Northwest Territories, Canada, in 1995-1998. *Environment Canada Occasional Paper*. 115, 3-33.
- Slattery, S.M. & Alisauskas, R.T. (2007). Distribution and habitat use of Ross' and lesser snow geese during late brood rearing. *The Journal of Wildlife Management*. 71(7), 2230-2237.
- Smith, L.C., Sheng, Y., MacDonald, G.M., & Hinzman, L.D. (2005). Disappearing Arctic lakes. *Science*. 308(5727), 1429.
- Smol, J.P. & Douglas, S.V. (2007). Crossing the final ecological threshold in high Arctic ponds. *PNAS*. 104(30), 12395-12397.
- Srivastava, D.S. & Jefferies, R.L. (1996). A positive feedback: Herbivory, plant growth, salinity, and the desertification of an Arctic salt-marsh. *Journal of Ecology*. 84(1), 31-42.
- Steedman, A.E., Lantz, T.C., & Kokelj, S.V. (2016). Spatio-temporal variation in high-centre polygons and ice-wedge melt ponds, Tuktoyaktuk Coastlands, Northwest

- Territories. *Permafrost and Periglacial Processes*. 28(1), 66-78. doi: 10.1002/ppp.1880.
- Suzuki, K., Matsuo, K., Yamazaki, D., Ichii, K., Iijima, Y., Papa, F., Yanagi, Y., & Hiyama, T. (2018). Hydrological variability and changes in the Arctic circumpolar tundra and the three largest pan-Arctic river basins from 2002-2016. *Remote Sensing*. 10, 402.
- Turner, K.W., Wolfe, B.B., Edwards, T.E., Lantz, T.C., Hall, R.I., & La Rocque, G. (2014). Controls on water balance of shallow thermokarst lakes and their relations with catchment characteristics: A multi-year, landscape-scale assessment based on water isotope tracers and remote sensing in Old Crow Flats, Yukon (Canada). *Global Change Biology*. 20, 1585-1603.
- White, D., Hinzman, L., Alessa, L., Cassano, J., Chambers, M., Falkner, K., Francis, J., Gutowski Jr., W.J., Holland, M., Holmes, R.M., Huntington, H., Kane, D., Kliskey, A., Lee, C., McClelland, J., Peterson, B., Rupp, T.S., Straneo, F., Steele, M., Woodgate, R., Yang, D., Yoshikawa, K., & Zhang, T. (2007). The arctic freshwater system: Changes and impacts. *Journal of Geophysical Research*. 112, G04S54.
- Wolfe, B.B., Light, E.M., Macrae, M.L., Hall, R.I., Eichel, K., Jasechko, S., White, J., Fishback, L., & Edwards, T.W.D. (2011). Divergent hydrological responses to 20th century climate change in shallow tundra ponds, western Hudson Bay Lowlands. *Geophysical Research Letters*. 38 (L23402), 1-6.
- Woo, M.-K. & Guan, X.,J. (2006). Hydrological connectivity and seasonal storage change of tundra ponds in a polar oasis environment, Canadian high Arctic. *Permafrost and Periglacial Processes*. 17, 309-323.
- Woo, M.-K. & Young, K.L. (2006). High Arctic wetlands: Their occurrence, hydrological characteristics and sustainability. *Journal of Hydrology*. 320, 432-450.
- Woo, M.-K., Young, K.L., & Brown, L. (2006). High Arctic patchy wetlands: Hydrological variability and their sustainability. *Physical Geography*. 27(4), 297-307.
- Yoshikawa, K. & Hinzman, L.D. (2003). Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council Alaska. *Permafrost and Periglacial Processes*. 14, 151-160.
- Zeileis, A., Leisch, F., Hornik, K., & Kleiber, C. (2002). Strucchange: An R package for testing for structural change in linear regression models. *Journal of Statistical Software*. 7(2), 1-38.
- Zuur, A.F., Ieno, E.N., & Elphick, C.S. (2010). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution*. 1, 3-14.

Appendix A - Sub-pixel water fraction trend surfaces

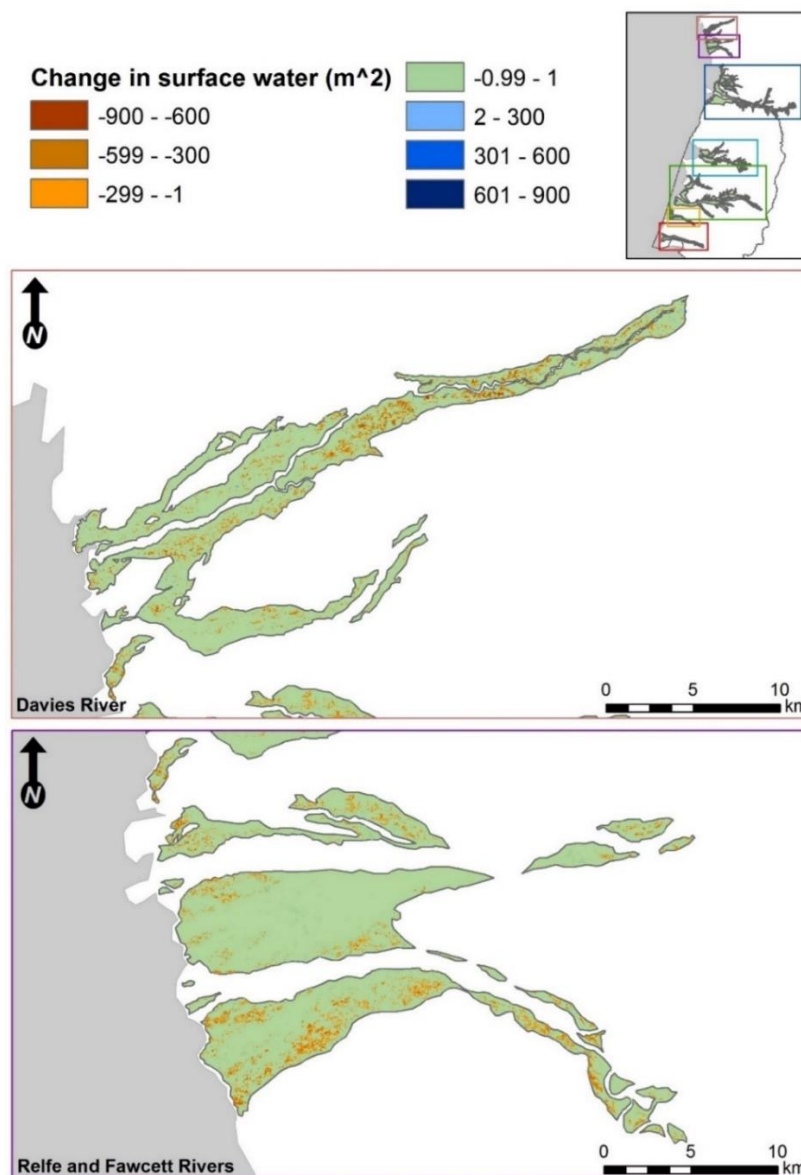


Figure A1.1. Sub-pixel water fraction trend surfaces of the Davies, Relfe, and Fawcett river valleys of western Banks Island, between 1985-2015.

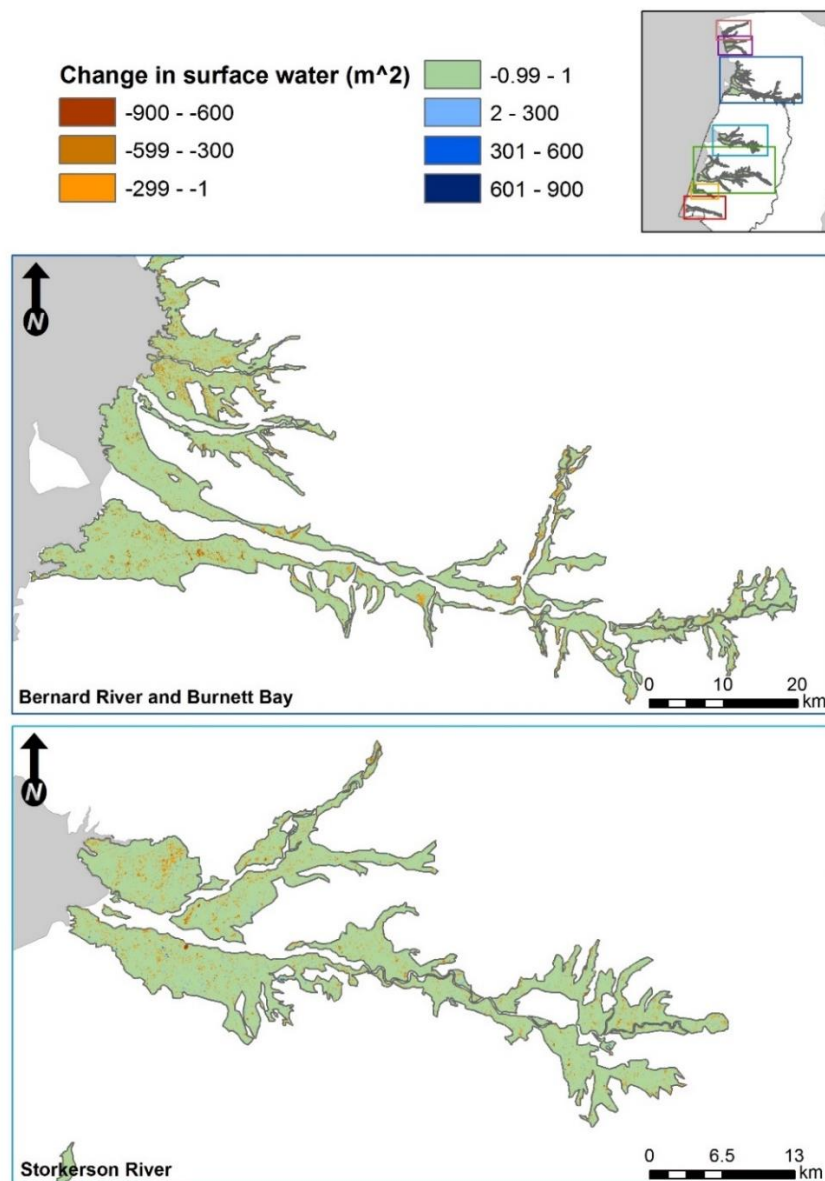


Figure A1.2. Sub-pixel water fraction trend surfaces of the Burnett Bay area, and the Bernard and Storkerson river valleys of western Banks Island, between 1985-2015.

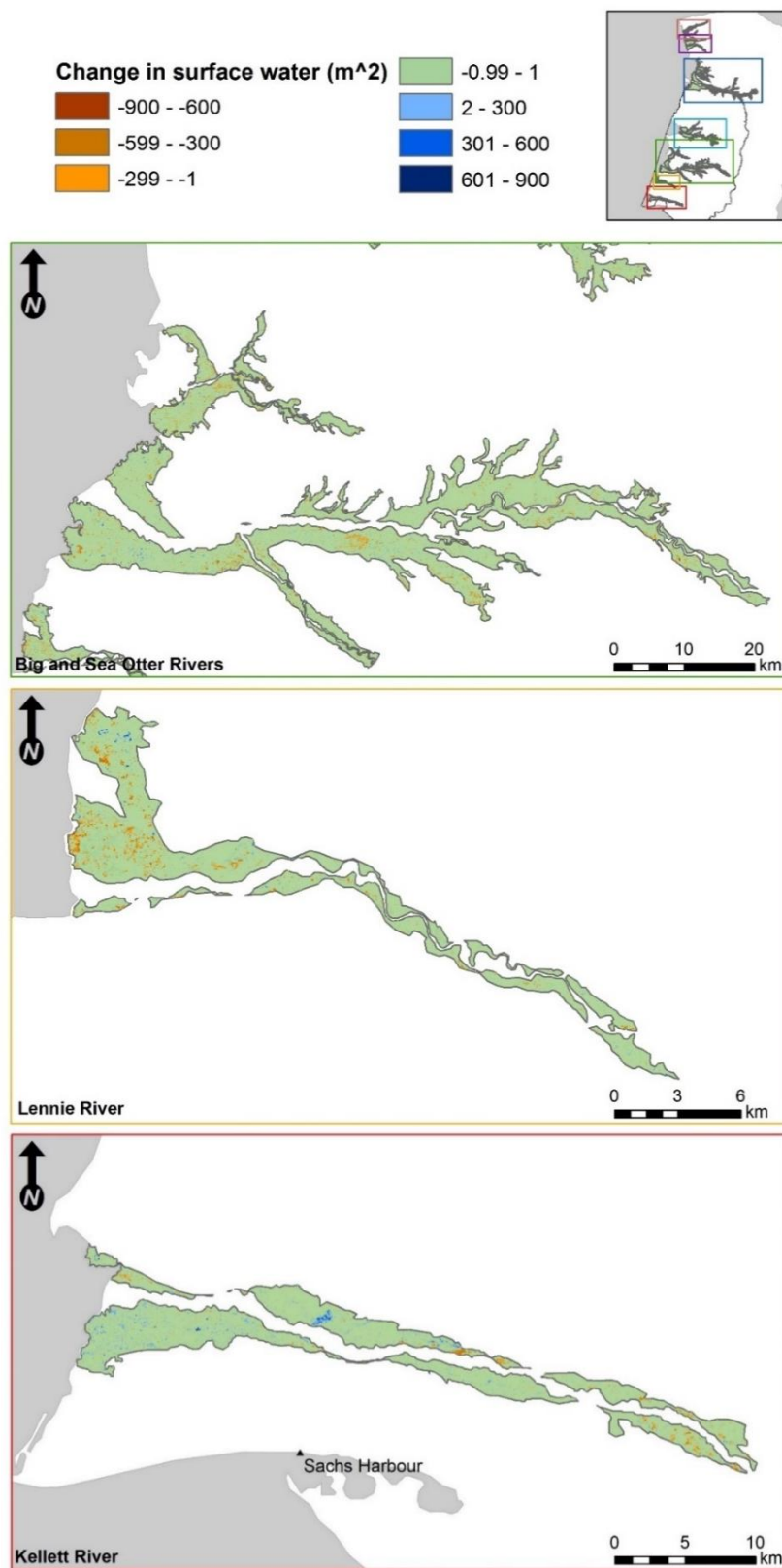


Figure A1.3. Sub-pixel water fraction trend surfaces of the Sea Otter, Big, Lennie, and Kellett river valleys of western Banks Island, between 1985-2015.

Chapter 3 – Vegetation change in drying high Arctic pond complexes on Banks Island, Northwest Territories (1985-2015)

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Authorship Statement: TKFC, TCL, RHF conceived the study; TKFC conducted the research; CKT, TCL, RHF analyzed data; TKFC, TCL, RHF wrote manuscript

Introduction

Rapidly warming temperatures in Arctic regions have caused widespread changes to vegetation (Fraser *et al.*, 2014a; Lantz *et al.*, 2010; Myers-Smith *et al.*, 2011; Kaplan & New, 2006; Ju & Masek, 2016). Most research on this vegetation change has focused on increases in vegetation productivity (greening). Greening in many low Arctic regions has been linked to the expansion of upright and dwarf shrubs (Myers-Smith *et al.*, 2011; Ropars & Boudreau, 2012; Tremblay *et al.*, 2012), accompanied by declines in moss and lichen cover (Fraser *et al.*, 2014a; Moffat *et al.*, 2016). Hill & Henry (2011) observed greening in high Arctic wet sedge tundra, associated with increased biomass of graminoids, dwarf shrubs, and forbs. Yet broad-scale remote sensing shows considerable heterogeneity in recent productivity trends, with extensive greening and browning (decreases in vegetation productivity) evident across the Arctic (Guay *et al.*, 2014; Ju & Masek, 2016). To explore factors contributing to the spatial heterogeneity of vegetation change, additional case studies are needed, particularly in areas experiencing vegetation browning and in less studied high Arctic regions.

Changing moisture availability may be linked to the observed variability in vegetation productivity trends, as spatial variation in moisture levels is considered the primary determinant of functional group dominance in tundra ecosystems (Billings & Mooney, 1968; Becker *et al.*, 2016; Webber, 1978; Atkinson & Treitz, 2013). In addition, vegetation responses to warming temperatures have been found to vary, depending on moisture conditions (Elmendorf *et al.*, 2012). Several recent studies in the Canadian high Arctic have documented drying or desiccation of wetland areas (Smol & Douglas, 2007; Woo *et al.*, 2006; Campbell *et al.*, 2018). Change in surface water and moisture availability in these areas is likely altering or damaging vegetation communities, as wetland vegetation is particularly sensitive to changes in available moisture (van der Valk, 2005; Raulings *et al.*, 2010; Woo *et al.*, 2006). In desiccated high Arctic wetlands near Resolute, Nunavut, Woo *et al.* (2006) described the replacement of hydrophytic vegetation by *Papaver radicum*, as well as various species of *Draba*, *Saxifraga*, and lichens. At evaporating high Arctic ponds on Ellesmere Island, Smol & Douglas (2007) found the surrounding wetlands were also drying and vegetation was sufficiently dry to be easily ignited.

Bryophytes make-up a significant proportion of the vegetation cover in high Arctic wetland habitats (Ecosystem Classification Group, 2013; CAVM Team, 2003). Many bryophytes are adapted for desiccation because they cannot regulate leaf transpiration in the way that vascular plants do (Proctor & Tuba, 2002; Proctor, 2000; Proctor *et al.*, 2007). As a result, their productivity and colouration are subject to external moisture conditions (Proctor & Tuba, 2002; Proctor, 2000). May *et al.* (2018) found that while not totally synchronized, both primary productivity and normalized difference vegetation index (NDVI) declined in *Sphagnum* and *Pleurocarpus* bryophyte communities, with declining moisture content. This reduction in NDVI was mostly caused by increased red wavelength reflectance, which is greater in brown vegetation compared to green vegetation (May *et al.*, 2018). These characteristics make bryophytes likely to persist through long-term reductions in moisture, while significantly changing reflectance measurements to those associated with desiccated vegetation.

In the arid and polar desert regions of the high Arctic, the high primary productivity of wetland areas makes them important breeding habitat for many herbivores. Lesser snow geese (*Chen caerulescens caerulescens*) disproportionately use wetland habitat areas during the breeding season (Hines *et al.*, 2010; Slattery & Alisauskas, 2007) and could be exacerbating climate driven changes to vegetation in drying wetlands. Breeding populations of lesser snow geese have grown rapidly across the Arctic in recent decades, negatively impacting vegetation cover, community composition, and soil moisture (Kotanen & Jefferies, 1997; Srivastava & Jefferies, 1996; Calvert, 2015; Jefferies *et al.*, 2006).

To improve our ability to predict the long-term impacts of climate change on high Arctic wetlands, additional case studies are required to investigate the drivers of regional and local variations in vegetation change. In this study we combined the analysis of multispectral Landsat satellite imagery (1985-2015) and regional spatial data, with field sampling, to examine the relationships among wetland drying, vegetation productivity, and snow goose habitat use on Banks Island, Northwest Territories.

We hypothesized that drying alluvial terraces in western Banks Island are experiencing (1) declines in vegetation productivity, associated with increasing cover of desiccated bryophytes and subordinate forbs, shrubs, and lichens. We also hypothesized

that (2) vegetation change in drying wetland areas is most severe in areas intensely used by lesser snow geese.

Study Area

Banks Island is the westernmost island in the Canadian Arctic Archipelago and part of the Inuvialuit Settlement Region in the Northwest Territories. The community of Sachs Harbour is the only permanent settlement on the Island and has a population of approximately 100 residents. Located within the northern or high Arctic ecozone, this area has a harsh climate with a mean annual temperature of -12.8 °C at Sachs Harbour. Summers are short with average daily temperatures rising above freezing for three months of the year, peaking at 6.6 °C in July. Average annual precipitation is 151.5 mm, with only 38% falling as rain between June and September. Recent warming in Canada has been unprecedented over the last millennium (Beltrami, *et al.*, 1992; Beltrami & Bourlon, 2004) and mean annual temperatures on Banks Island have shown a 3.5 °C increase since 1956 (Fraser *et al.*, 2018). Summer precipitation and maximum snow water equivalent before spring melt have changed minimally (Fraser *et al.*, 2018; Mudryk *et al.*, 2018).

The western side of Banks Island is characterized by gently rolling uplands, intersected by numerous west flowing rivers with wide floodplains. Alluvial terraces in these river valleys are dotted with thousands of shallow ponds and have nearly continuous vegetation cover, dominated by sedges, grasses, and mosses (Hines *et al.*, 2010; Ecosystem Classification Group, 2013). Moss communities are dominated by species from the desiccation tolerant *Bryopsida* class (Ecosystem Classification Group, 2013; CAVM Team, 2003; Proctor *et al.*, 2007). The island is underlain by continuous permafrost (French, 2016) and ice-wedge polygons, non-sorted circles and stripes, and turf hummocks are widespread (Ecosystem Classification Group, 2013). In this study, we focused on the alluvial terraces of the west flowing rivers valleys (Figure 3.1.). Between 1985-2015, these areas experienced a 7.9% decline in surface water, likely associated with increasing evaporation levels (Campbell *et al.*, 2018).

These areas are important breeding habitat for many migratory bird species, including the lesser snow goose. The habitat on western Banks Island supports over 95% of the western Arctic lesser snow goose population, which has almost tripled since 1976

(Kerbes *et al.*, 2014; Hines *et al.*, 2010). The main nesting colony for this population is located at the confluence of the Egg and Big rivers (Hines *et al.*, 2010; Ecosystem Classification Group, 2013) (Figure 3.1.). The Banks Island Migratory Bird Sanctuary No. 1 (BIMBS1) was created to protect this colony and is the second largest bird sanctuary in Canada at 20,517 km² (Hines *et al.*, 2010; Ecosystem Classification Group, 2013).

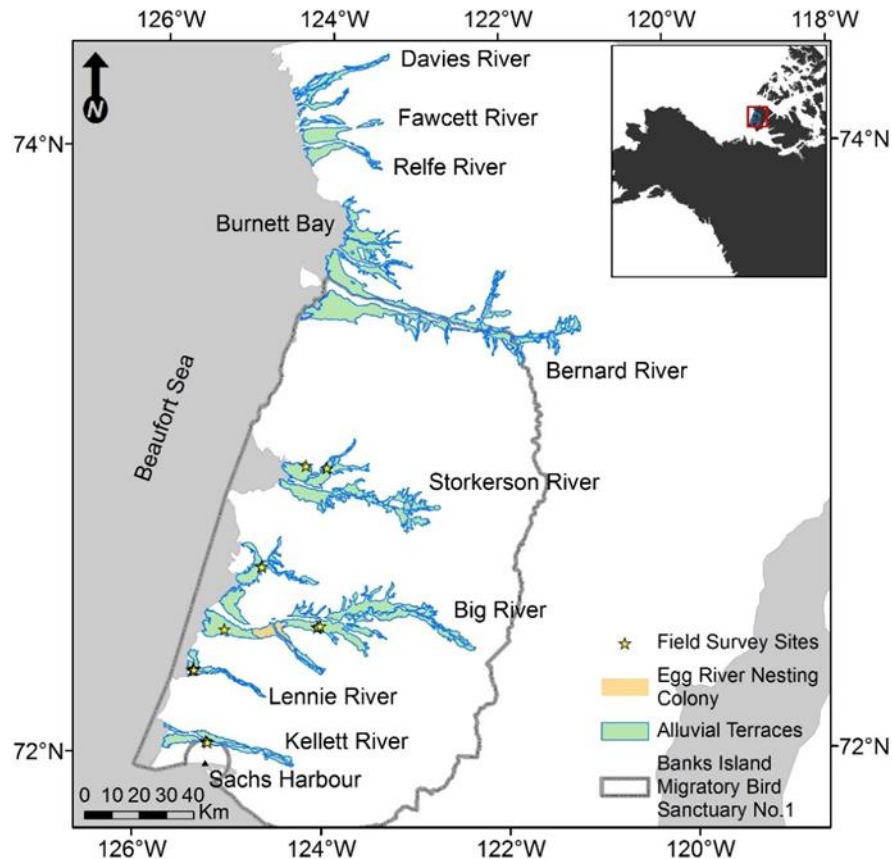


Figure 3.1. Map of the study area on Banks Island, Northwest Territories, including field survey sites and the Egg River nesting colony. Inset map at the bottom right shows Banks Island as the westernmost island in the Canadian Arctic Archipelago.

Methods

a) Remote sensing & broad-scale analysis

To explore landcover changes between 1985 and 2015, we analyzed a time-series of near-annual Tasseled Cap (TC) transformed Landsat images. Time-series were assembled for TC greenness (TCG) and wetness (TCW) indices, using 720 30 m resolution images captured by the Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI

sensors, between 1985 and 2015. All images were acquired between June 29 and August 31, to minimize phenological differences between years. Images were calibrated to top-of-atmosphere reflectance using USGS coefficients, and scan lines, clouds, and cloud shadows were masked out (Chander *et al.*, 2009).

TC images were created using linear combinations of Landsat bands (bands 1-5 and 7 for Landsat 5 TM and Landsat 7 ETM+ images, and bands 2-7 for Landsat OLI images) and established TC coefficients (Crist & Cicone, 1984; Huang *et al.*, 2002). Tasseled Cap greenness (TCG) uses the difference between near-infrared and visible bands, making it suitable for measuring green vegetation. Tasseled Cap wetness (TCW) contrasts shortwave infrared with visible and near infrared bands which makes it sensitive to water surfaces, soil moisture, and plant moisture (Crist & Cicone, 1984).

To identify areas that have exhibited persistent changes in reflectance over time, a trend surface (1985-2015) was generated for both TCG and TCW, using Theil-Sen regression and the rank-based Mann-Kendall test (Fraser *et al.*, 2014b; Olthof *et al.*, 2015). Theil-Sen regression is a nonparametric alternative to ordinary least squares regression that uses the median of all possible pairwise slopes instead of the mean. The rank-based Mann-Kendall test of significance is calculated through comparison to all possible pairwise slopes (Kendall & Stuart, 1967). The pixel values in the resultant trend surfaces represent the change in TCG and TCW indices, which were estimated by multiplying the slope coefficient by the length of the time-series. Regional changes in TCW were also determined using the focal statistics tool in ArcMap (10.4.1), as the mean TCW change within a three-pixel radius.

Analysis of the resultant trend surfaces was restricted to the alluvial terraces of major river valleys (an area of $\sim 2335 \text{ km}^2$), which were manually delineated as areas of lowland terrain within 25 km of the main river channel ($< 80 \text{ m}$ above-sea-level) (Ecosystem Classification Group, 2013). Lowland terrain was visually identified using a 10 m resolution false-colour near-infrared Sentinel-2 satellite imagery acquired on July 19, 2017, and confirmed using a 5 m resolution digital elevation model (ArcticDEM) created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery (Noh & Howat, 2015).

To investigate the relationship between vegetation productivity and varying changes in moisture, a generalized additive model (GAM) was constructed using the TCG trend pixel values and their corresponding regional TCW trends (the mean TCW trend within a three-pixel radius). A GAM is a generalized linear model, where the linear predictor is replaced by a set of non-linear smooth functions and a parametric component of the linear predictor. This method allows for consideration of non-linear portions of the data and changing relationships (Wood, 2011). The data consisted of 200,000 values extracted from the TCG and regional TCW trend surfaces, excluding pixels where the y-intercept of the TCW trend was greater than 130, which were determined to be entirely water in 1985 using a histogram-breakpoint method (Olthof *et al.*, 2015). The GAM was constructed using the restricted-maximum likelihood smoothing parameter estimation method from the ‘mgcv’ package (Wood, 2011), in R software version 3.3.2 (R Core Team, 2016). Field survey data was used to confirm that declines in TCW were true declines in moisture, as TCW can be sensitive to plant moisture (Crist & Cicone, 1984).

To investigate the drivers of spatial variation in vegetation productivity trends within drying areas, we used random forest decision tree regression with change in TCG as the response variable. This analysis was conducted on a balanced sample of 5,000 greening data points and 5,000 browning data points, all with declining regional TCW trends. The model was constructed using the ‘randomForest’ package (Liaw & Wiener, 2002) in R software version 3.3.2 (R Core Team, 2016). The following explanatory variables were included in the analysis: TCG in 1985, TCW in 1985, habitat type, latitude, elevation, relative elevation, and flow accumulation. TCG and TCW in 1985 were calculated as the y-intercepts of their respective Theil-Sen trends from 1985 to 2015. Habitat type was assigned using a landcover classification of the BIMBS1, derived from Landsat 5 TM data with 94% overall accuracy (Hines *et al.*, 2010). Elevation was taken from the 5 m resolution ArcticDEM, referenced to the WGS84 ellipsoid (Noh & Howat, 2015). Relative elevation was calculated by subtracting the mean elevation within a 5 km radius from the 30 m ArcticDEM elevation. Flow accumulation was calculated using the ArcticDEM and the fill, flow direction, and flow accumulation tools from the ArcMap (10.4.1) hydrology toolset (Jenson & Domingue, 1988). Spatial data that did not

match the 30 m Landsat spatial resolution was aggregated using the mean value within a 30 m by 30 m area.

b) Field surveys

To characterize vegetation communities in the study area and explore factors potentially contributing to reductions in productivity, field sampling was conducted in July 2017, at 19 sites. All sites were located between 0-35m in elevation, within 5 river valleys (Figure 3.1.). Sampling was also necessary to determine whether declines in TCW are true declines in moisture. Since TCW is sensitive to plant moisture (Crist & Cicone, 1984), declines in vegetation productivity could plausibly cause declines in both TCG and TCW to some extent, potentially creating a false correlation between variables. Field sites were selected and classified based on TCG and regional TCW trends. Site types included: (1) browning-drying areas (pixels with negative regional TCW and TCG trends), (2) stable-drying areas (pixels with negative regional TCW and low positive TCG trends), and (3) control areas (pixels with low positive regional TCW and TCG trends). At two field sites, transects were split into two site categories, based on pixel values. Field surveys were not conducted in the nesting colony area, where vegetation has been uniquely degraded by snow geese to mounds of exposed peat and soil (Hines *et al.*, 2010; Campbell *et al.*, 2018).

At each site, 11 plots were established at 10 m intervals, along a north-south oriented 100 m transect. In each plot, measurements were made of vegetation cover, the proportion of desiccated bryophytes, thaw depth, near-surface soil moisture, goose grazing, and goose grubbing. Vegetation cover was measured by visually estimating the percent cover of dominant genera (*Carex* spp., *Eriophorum* spp., *Saxifraga* spp., *Dryas* spp., *Senecio* spp., *Petasites* spp., and *Salix* spp.), bryophytes, and lichens within a 50 cm² quadrat. Percent cover of bare soil, exposed peat, and standing water were also estimated. The proportion of desiccated bryophytes was measured by visually estimating the percent cover of bryophytes with matte brown to dark discolouration up to the shoot tip, using photographs taken directly above each quadrat, then dividing that by the total bryophyte cover in the plot. Thaw depth was measured using an active layer probe, which was pushed into the ground until the depth of refusal and soil moisture was measured using a handheld moisture probe (HH2 Moisture Meter with a Theta Probe soil moisture

sensor-ML2x, from Delta-T Devices Ltd., Cambridge, England). Goose grazing was measured by calculating the percentage of graminoid stems with grazed tips within the 50 cm² quadrat. Goose grubbing was measured by counting the number of grub holes within the 50 cm² quadrat. Grubbing is a particularly destructive form of foraging which targets below-ground roots and rhizomes before above ground vegetation is available.

To evaluate the impacts of wetland drying on vegetation community composition in browning-drying, stable-drying, and control areas, we used a non-metric multidimensional scaling (NMDS) analysis. This analysis used a $\log(x+1)$ matrix of the percent cover of dominant genera and functional groups, as well as the cover of bare soil and exposed peat. The NMDS analysis was conducted using the ‘Vegan’ package (Oksanen *et al.*, 2017) in R version 3.3.2 (R Core Team, 2016). An analysis of similarities (ANOSIM) test was used to test if site types showed differences in community composition. At many sites, a number of plots fell within desiccated pond basins (Figure 3.2.). Since these plots represented land cover with a different origin and substrate, they were excluded from this analysis.

Linear mixed effects models constructed using the GLIMMIX procedure in SAS (9.3) (Littell *et al.*, 2006), were used to test for significant differences in functional group cover, the proportion of desiccated bryophyte cover, thaw depth, soil moisture, goose grazing, and goose grubbing among browning-drying, stable-drying, and control site types. Pairwise comparisons among site types were made using the least-squares means procedure, which relies on the restricted-maximum likelihood method. Degrees of freedom were determined using the Kenward-Roger method (Littell *et al.*, 2006). All models included site and river valley as random effects. Models for proportional desiccated bryophyte cover and goose grazing used a binomial distribution and the probit link function to optimize model strength (Hahn & Soyer, 2005). All measurements that landed within former pond basins were also excluded from these analyses.

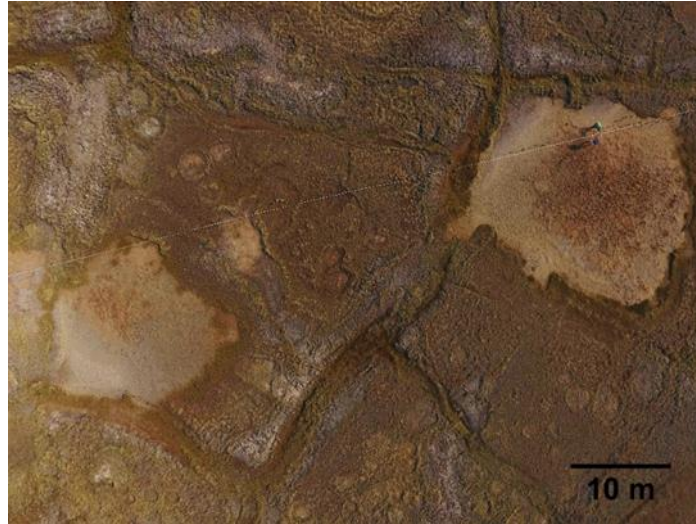


Figure 3.2. Photograph, taken from an unmanned aerial vehicle (UAV), showing desiccated pond basins along a field survey transect in the Storkerson River valley.

Results

a) Remote sensing & broad-scale analysis

Between 1985 and 2015, TCG measured vegetation productivity increased across 96.2% (2143.4 km²) of the alluvial terraces studied and decreased across 3.6% of this area (81.3 km²) (Figure 3.3.). Among these river valleys, the Bernard River had the largest total area of browning pixels (38.0 km²) and the highest proportion of browning pixels (7.1%) (Figure 3.3. & 3.4.). The Big River valley, which contains the Egg River snow goose nesting colony, had the second highest total area of browning pixels (12.6 km²), but a much lower proportion of browning pixels (2.1%). Browning was typically seen surrounding waterbodies and in the areas between clusters of small waterbodies.

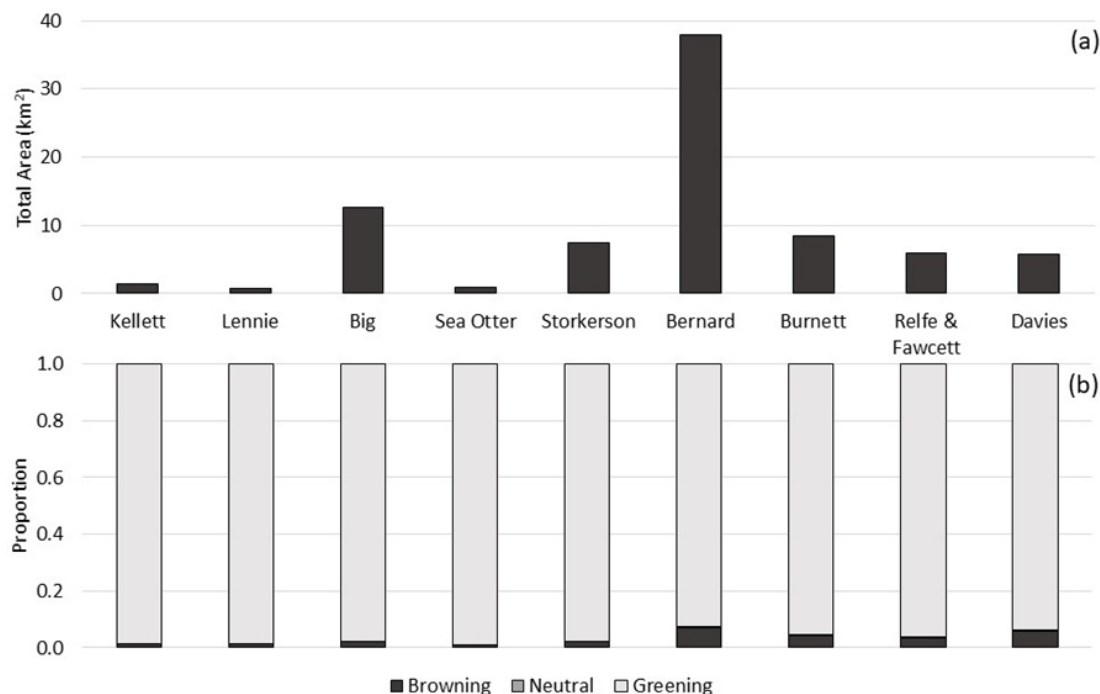


Figure 3.3. Vegetation browning in the major river valleys of western Banks Island: (a) the total area of browning within each river valley and (b) the proportions of increasing, decreasing, and neutral TCG trends, within each river valley.



Figure 3.4. TCG trends in the most degraded river valley, the Bernard River, and Burnett Bay to the north of the Bernard River valley.

Vegetation browning was associated with areas showing declines in TCW (Figures 3.5. & 3.6.). The GAM confirmed a positive relationship between TCG change and regional TCW change ($p < 0.0001$), which plateaued at high and low changes in

regional TCW (Figure 3.5.). GAM predictions of TCG change were negative when regional TCW reductions were greater than ~500 (Figure 3.5.). The model produced an R-squared value of 0.299, indicating there is considerable variance not explained by the model.

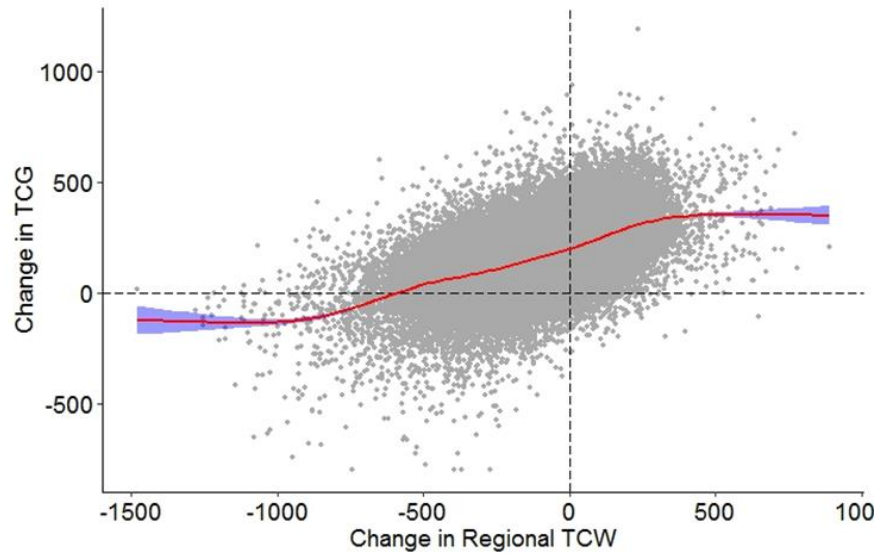


Figure 3.5. Change in TCG plotted against the change in regional TCW. The solid red line shows the GAM predictions between TCG and regional TCW trends, with 95% confidence intervals represented by the adjacent blue bars. The dashed black lines show zero change in TCG and regional TCW.

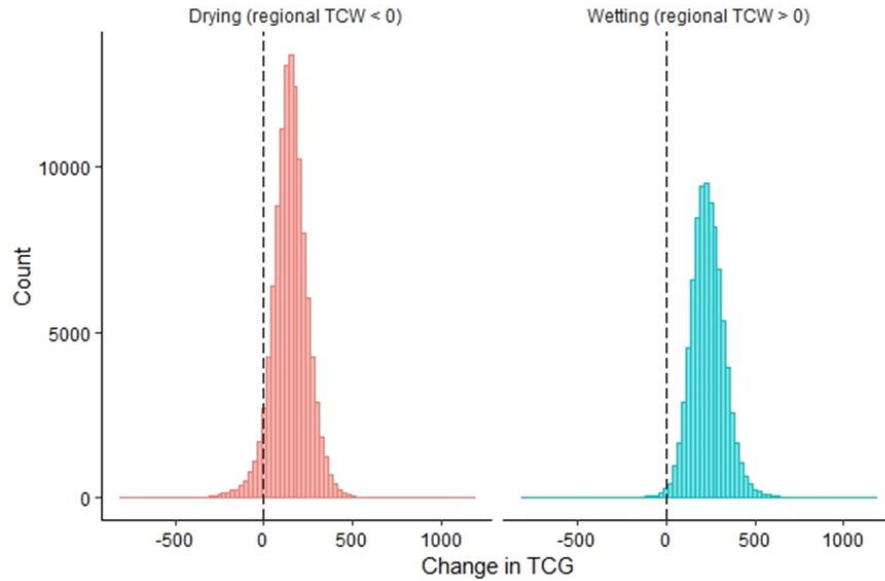


Figure 3.6. Frequency distributions of TCG trends, classified as having negative or positive change in regional TCW. 0.53% of pixels with significantly positive change in regional TCW had negative TCG trends, while 5.9% of pixels with significantly negative change in regional TCW had negative TCG trends.

The random forest regression of TCG trends in drying areas explained 65.6% of the variance and had a relatively low root-mean-square error of 89.8. TCG in 1985 was the explanatory variable with the largest impact on model accuracy, but latitude, elevation, and TCW in 1985 all improved model accuracy by more than 90% when included in the model (Figure 3.7.). Partial dependence plots showed that predicted declines in TCG were associated with areas of higher vegetation productivity in 1985. Predicted changes in TCG were also lower in northern latitudes, low elevation areas (between ~0 m and ~40 m above sea level), and areas that had high moisture levels in 1985 (Figure 3.8.).

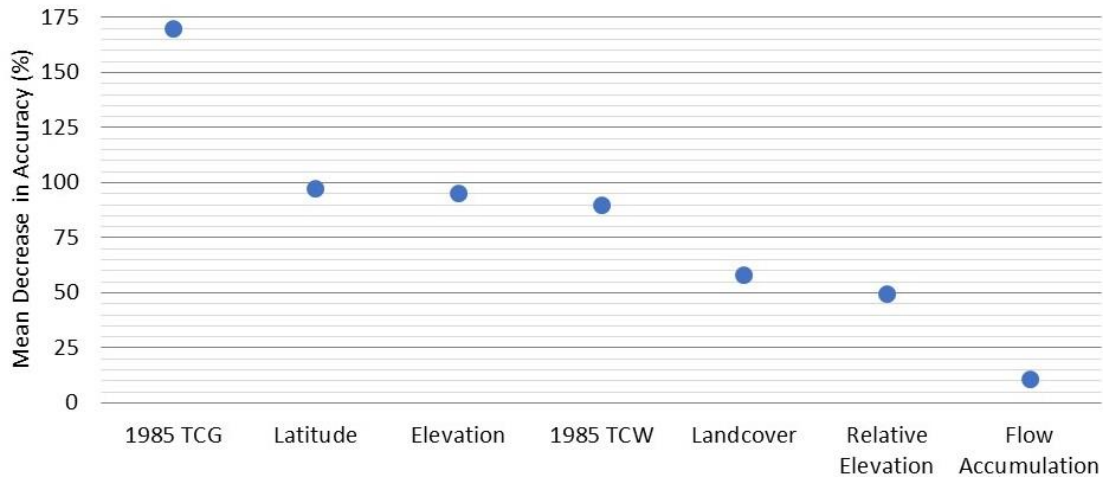


Figure 3.7. The percentage decrease in accuracy when each explanatory variable is removed from the model; calculated using the mean difference between the prediction errors of the out-of-bag data and the prediction errors after permuting each explanatory variable, normalized by the standard deviation of the differences (Liaw & Wiener, 2002).

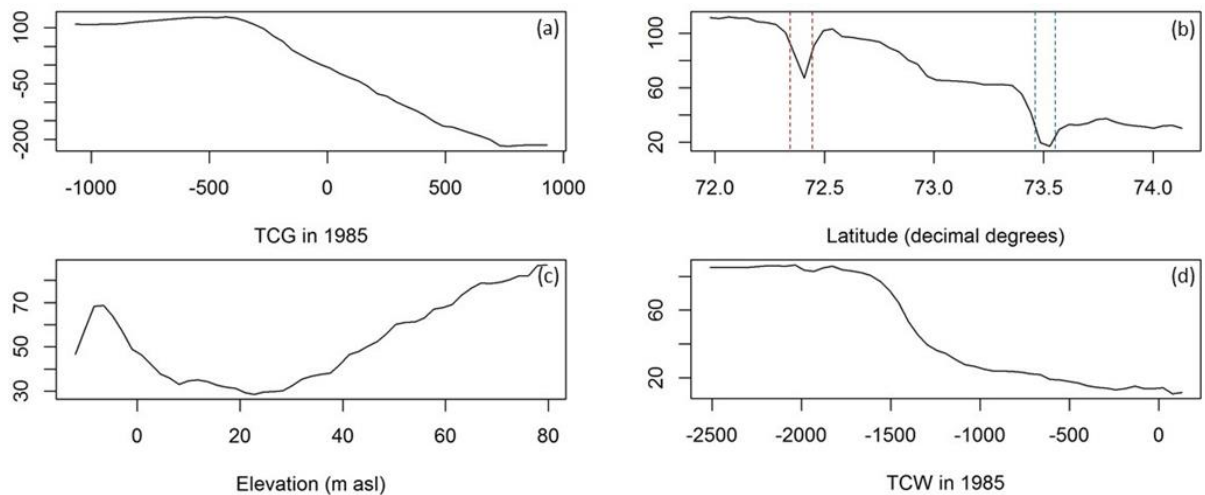


Figure 3.8. Partial dependence plots of the most important explanatory variables in the random forest regression, (a) TCG in 1985, (b) latitude, (c) elevation, and (d) TCW in 1985. The y-axis shows the mean predicted TCG trend, at different levels of the given explanatory variable, with the influence of the other explanatory variables averaged (Friedman, 2001). The dashed red lines in the latitude partial dependence plot indicate the location of the nesting colony in the Big River valley and the dashed blue lines indicate the location of the Bernard River valley.

b) Field surveys

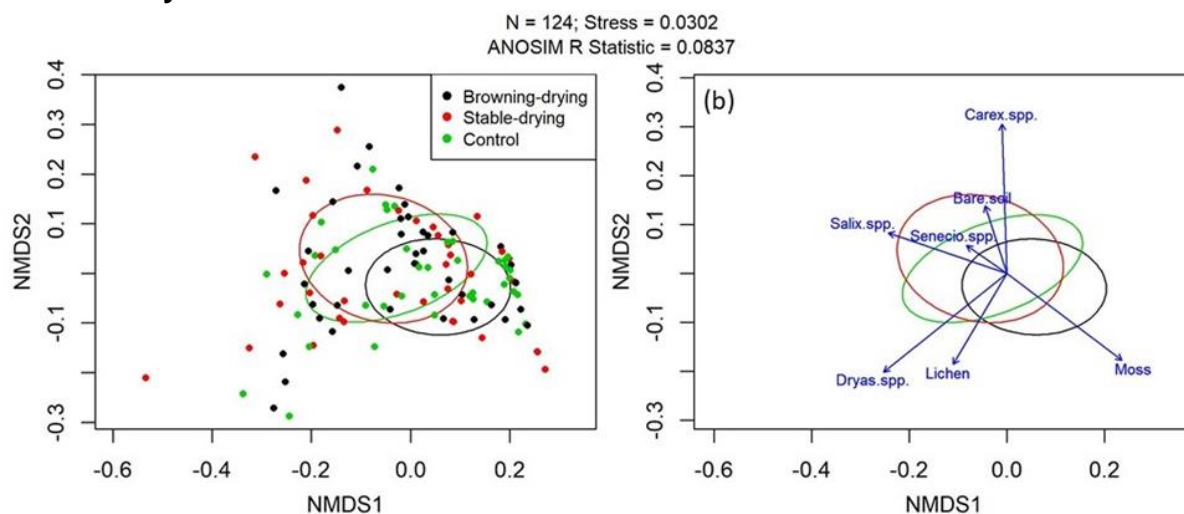


Figure 3.9. NMDS ordination plots showing similarity of vegetation community composition among sites. (a) Points on the ordination are individual field plots, which are close together when they have similar composition. Ellipses represent the standard deviation of NMDS1 and NMDS2 for each site type. (b) The blue arrows on this ordination plot show the significant associations between the genera/functional groups and the point scores for each field plot.

The NMDS ordination of field plots (Figure 3.9.) shows that community composition has considerable overlap among site types. This is reflected in the ANOSIM R statistic of 0.0837 ($p < 0.001$), which indicates statistical similarity among site types, as they resemble random groupings. The NMDS solution had a stress of 0.0302, indicating the two-dimensional plot is representative of vegetation composition differences and similarities.

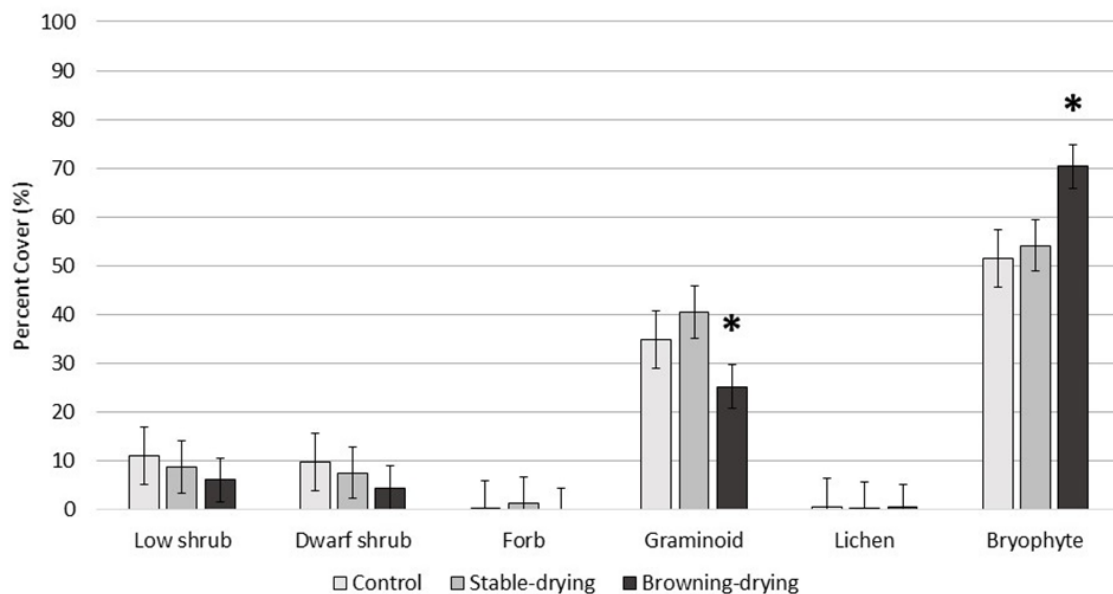


Figure 3.10. Mean functional group percent cover in each site type, estimated based on the linear mixed effects model. Error bars represent the 95% confidence intervals of the mean and asterisks are present when a site type has significantly different functional group cover from the other site types ($p < 0.05$).

Bryophytes were the dominant functional group and had the highest percent cover in all site types ($p < 0.001$), followed by graminoids ($p < 0.0001$) (Figure 3.10.). Within functional groups, there were significant differences among site types. Browning-drying sites had lower graminoid cover ($p < 0.05$) and higher bryophyte cover ($p < 0.0001$), than stable-drying and control sites (Figure 3.10.). The cover of low shrubs, dwarf shrubs, forbs, and lichens did not differ among site types.

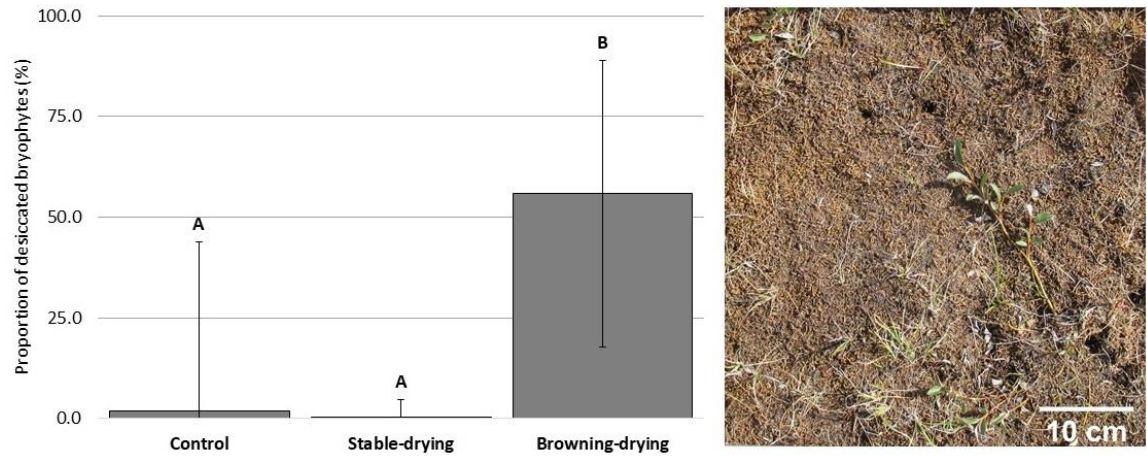


Figure 3.11. Mean proportion of desiccated bryophytes (desiccated bryophyte cover divided by total bryophyte cover) among site types, based on the linear mixed effects model. Error bars represent the 95% confidence interval of the mean and bars with different letters are significantly different. The photograph on the right shows a plot with high cover of desiccated bryophytes.

Desiccated bryophytes were present in all site types, but their proportional cover, was significantly higher at browning-drying sites ($p < 0.05$), compared to control and stable-drying sites, which were not different from each other (Figure 3.11.).

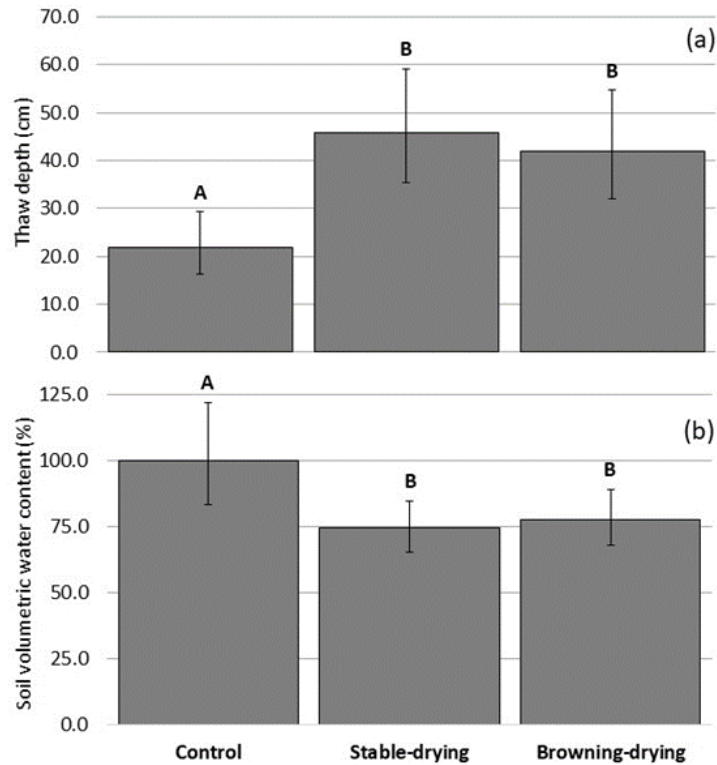


Figure 3.12. Mean thaw depth (a) and soil volumetric water content (b), based on the linear mixed effects models. Error bars represent the 95% confidence interval of the mean and bars with different letters are significantly different.

Soil volumetric water content was significantly lower in browning-drying and stable-drying site types, compared to the control site type ($p < 0.05$) (Figure 3.12.). Soil moisture was not different between the browning-drying and stable-drying site types. Similarly, thaw depth was statistically greater in browning-drying and stable-drying site types, compared to the control site type ($p < 0.0001$) (Figure 3.12.). Thaw depth was not different between the browning-drying and stable-drying site types.

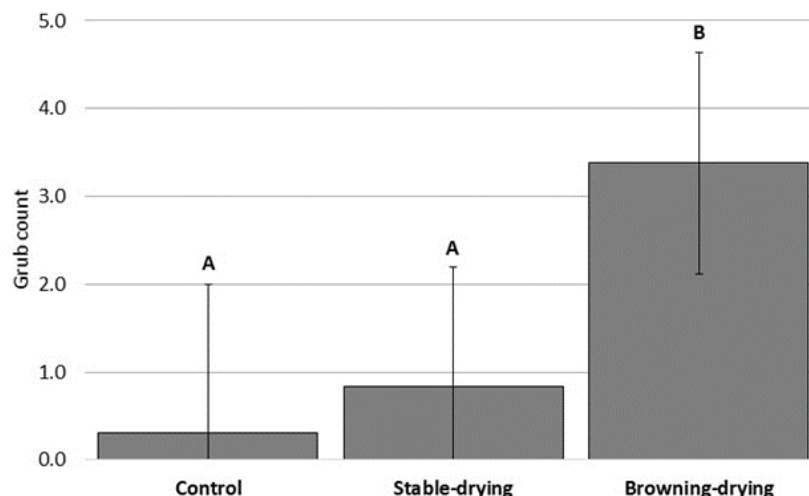


Figure 3.13. Mean counts of goose grubbing, based on the linear mixed effects model. Error bars represent the 95% confidence interval of the mean and bars with different letters are significantly different.

Goose grubbing was higher in browning-drying plots compared to control and stable-drying plots ($p < 0.05$), which were statistically similar to each other (Figure 3.13.). Mean grub counts were four to 11 times higher in browning-drying plots (3.38 ± 1.26), compared to stable-drying (0.83 ± 1.36) or control plots (0.30 ± 1.70). There were no statistical differences in goose grazing among site types.

Discussion

Association between drying patterns and declining vegetation productivity

The positive association between changes in moisture and vegetation conditions in both Landsat data and field surveys suggests that declining productivity in areas of the alluvial terraces of western Banks Island, have been caused by reduced moisture. Declines in TCG were not as dominant as the drying described by Campbell *et al.* (2018), but were near-exclusively associated with declines in TCW. Regardless of change in TCG, field sampling confirmed lower near-surface soil moisture levels in field site types with drying TCW trends, indicating that change in TCW is a good indicator of changes in moisture. In total, localized browning affected an area of 81.3 km^2 , which was associated with high initial productivity and moisture (1985) and low-elevations. On Banks Island these conditions are somewhat concurrent with each other (Hines *et al.*, 2010; Ecosystem

Classification Group, 2013) and the high moisture requirements of vegetation in these low-lying areas makes them more vulnerable to impacts from wetland drying (Woo *et al.*, 2006; van der Valk, 2005; Raulings *et al.*, 2010). Furthermore, as Banks Island is largely a polar desert, high productivity areas have greater potential for negative changes in productivity. Predicted changes in productivity were also lower in high latitude areas, which is likely because the northern river valleys had relatively large extents and high proportions of browning pixels. These river valleys also experienced the most severe surface water losses between 1985 and 2015 (Campbell *et al.*, 2018), further supporting the connection between drying conditions and productivity declines.

Our analyses also suggest that declines in productivity are the result of changes in bryophyte physiology and small reductions in graminoid vegetation. Since bryophytes were the dominant functional group across all site types, it is likely that changes in their physiology made the largest contribution to changes in reflectance. Browning-drying areas had higher cover of bryophytes and higher proportions of desiccated bryophytes, compared to stable-drying and control areas. Since desiccated bryophytes reflect more visible red light than saturated bryophytes (May *et al.*, 2018), this change would result in lower TCG index values (Crist & Cicone, 1984; Huang *et al.*, 2002). Reduced graminoid cover could also lower TCG index values, as bryophytes can have a lower ratio of near-infrared to visible red light reflectance, compared to vascular vegetation (Huemmrich *et al.*, 2013). Furthermore, a reduction in the graminoid canopy would expose more of the bryophyte carpet, which is more susceptible to desiccation and discolouration in a drying environment (Proctor & Tuba, 2002; Proctor, 2000; Proctor *et al.*, 2007). Our field data show that differences in vegetation community structure were unrelated to TCG trends. Additional field sampling at a broader range of sites is required to better characterize changes in reflectance associated with specific vegetation change. With increasingly widespread changes to Arctic vegetation communities (Myers-Smith *et al.*, 2011; Raynolds & Walker, 2016; Hill & Henry, 2011), a better understanding of spectral profiles associated with these vegetation changes would allow for more efficient assessments of change in remote Arctic regions. Furthermore, due to the varying productivity capacities among bryophyte species, bryophyte desiccation in other areas of

the Arctic could be affecting carbon balance estimates by inflating remotely sensed vegetation productivity declines (Street *et al.*, 2012; May *et al.*, 2018).

Snow goose impacts

Our findings suggest that lesser snow geese are also contributing to the observed declines in vegetation productivity. Browning-drying areas had higher levels of goose grubbing, compared to stable-drying and control areas. Grubbing can expose the upper soil layers to the sun and wind, increasing evaporation (Iacobelli & Jefferies, 1991; Srivastava & Jefferies, 1996), which may have contributed to bryophyte desiccation. Intensive grubbing is also known to reduce the stored biomass and canopy of graminoid vegetation (Iacobelli & Jefferies, 1991; Srivastava & Jefferies, 1996; Calvert, 2015), which has a considerable influence on evaporation levels in understory vegetation (Stoner *et al.*, 1978). The fact that the highest levels of browning occurred in the Bernard and Big River valleys, the areas with the highest known densities of snow geese during nesting and brood rearing (Hines *et al.*, 2010), also suggests that snow geese are playing a role. Lesser snow geese are known to be capable of changing vegetation at scales easily observable by satellite (Jefferies *et al.*, 2006). However, it is also possible that snow goose activity was connected to declining vegetation productivity because preferred snow goose foraging habitat is more vulnerable to browning. Although Tasseled Cap trends and field measurements of soil moisture indicate that declining moisture alone may not be sufficient to cause declines in productivity, additional studies using exclosures could help determine if browning would occur independently of snow goose foraging. Additional research on snow goose distributions north of the Bernard River would also provide valuable insight, as these river valleys had relatively high levels of browning, but unknown levels of goose activity.

Implications

Vegetation change in high Arctic wetlands is likely to impact ecosystems in several ways. Changes in vegetation conditions can affect permafrost thaw, with the potential to increase methane and carbon dioxide emissions (Fisher *et al.*, 2016; Gornall *et al.*, 2007). Shading from the vascular canopy and a thick bryophyte layer have a particularly strong influence on active layer thickness and can maintain a shallow thaw

throughout summer months (Gornall *et al.*, 2007; Fisher *et al.*, 2016). At our sites, thaw depth was thicker at both drying site types, compared to the control site type, indicating that ground temperatures are already increasing in connection with the drying processes. Understanding vegetation responses in drying wetlands is also critical for evaluating impacts on a range of species (lesser snow geese, brant geese, king eider, Arctic Islands caribou, Peary caribou, and muskox) that rely on these habitats for forage and protection during nesting and calving periods (Sachs Harbour & Joint Secretariat, 2008; Slattery & Alisauskas, 2007). These animals and the study area also hold significant cultural importance for the Inuvialuit of Sachs Harbour (Sachs Harbour & Joint Secretariat, 2008).

Conclusion

Wetland drying in the alluvial terraces of western Banks Island is causing localized declines in vegetation productivity, nested within a predominantly greening landscape. The overall extent of change was small and was linked to the magnitude of drying, initial vegetation and moisture conditions, and lesser snow goose foraging pressures. Declines in productivity are likely a reflection of changes in bryophyte physiology, caused by increased moisture loss. Vegetation change associated with drying wetland habitats are likely to impact permafrost active layer depth and greenhouse gas emissions, as well as local wildlife and land users.

Bibliography

- Abnizova, A. & Young, K.L. (2010). Sustainability of high Arctic ponds in a polar desert environment. *Arctic*. 63(1), 67-84.
- Anselin, L. (1995). Local indicators of spatial association – LISA. *Geographical Analysis*. 27(2), 93-115.
- Ashford, G. & Castleden, J. (2001). Inuit observations on climate change: Final report. *International Institute for Sustainable Development*. 1-31.
- Atkinson D.M. & Treitz, P. (2013). Modeling biophysical variables across an Arctic latitudinal gradient using high spatial resolution remote sensing data. *Arctic, Antarctic, and Alpine Research*. 45(2), 161-178.
- Becker, M.S., Davies, T.J., & Pollard, W.H. (2016). Ground ice melt in the high Arctic leads to greater ecological heterogeneity. *Journal of Ecology*. 104, 114-124.
- Beltrami, H., Jessop, A.M., & Mareschal, J.-C. (1992). Ground temperature histories in eastern and central Canada from geothermal measurements: Evidence of climate change. *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section)*. 98, 167-184.
- Beltrami, H. & Bourlon, E. (2004). Ground warming patterns in the Northern Hemisphere during the last five centuries. *Earth and Planetary Science Letters*. 227(3-4), 169-177.
- Billings, W.D. & Mooney, H.A. (1968). The ecology of Arctic and alpine plants. *Biological reviews of the Cambridge Philosophical Society*. 43(4), 481-529.
- Calvert, A.M. (2015). Interactions between light geese and northern flora and fauna: Synthesis and assessment of potential impacts. *Unpublished report to Environment Canada, Ottawa ON*. 1-37.
- Campbell, T.K.F., Lantz, T.C., & Fraser, R.H. (2018). Impacts of climate change and intensive lesser snow goose (*Chen caerulescens caerulescens*) activity on surface water in high Arctic pond complexes. *Remote Sensing*. 10(12), 1892.
- CAVM Team (2003). Circumpolar Arctic vegetation map. *Conservation of Arctic Flora and Fauna (CAFF) Map No. 1, U.S. Fish and Wildlife Service, Anchorage Alaska*.
- Chander, G., Markham, B.L., & Helder, D.L. (2009). Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment*. 113, 893-903.
- Crist, E.P. & Cicone, R.C. (1984). A physically-based transformation of thematic mapper data – the TM tasseled cap. *IEEE Transactions on Geoscience and Remote Sensing*. GE-22(3), 256-263.

- Ecosystem Classification Group (2013). Ecological regions of the Northwest Territories – Northern Arctic. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada: 1-157.
- Elmendorf, S.C., Henry, G.H.R., Hollister, R.D., Bjork, R.G., Boulanger-Lapointe, N., Cooper, E.J., Cornelissen, J.H.C., Day, T.A., Dorrepaal, E., Elumeeva, T.G., Gill, M., Gould, W.A., Harte, J., Hik, D.S., Hofgaard, A., Johnson, D.R., Johnstone, J.F., Jonsdottir, I.S., Jorgenson, J.C., Klanderud, K., Klein, J.A., Koh, S., Kudo, G., Lara, M., Levesque, E., Magnusson, B., May, J.L., Mercado-Diaz, J.A., Michelsen, A., Molau, U., Myers-Smith, I.H., Oberbauer, S.F., Onipchenko, V.G., Rixen, C., Schmidt, N.M., Shaver, G.R., Spasojevic, M.J., Porhallsdottir, P.E., Tolvanen, A., Troxler, T., Tweedie, C.E., Villareal, S., Wahren, C.-H., Walker, X., Webber, P.J., Welker, J.M., & Wipf, S. Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Climate Change*. 2, 453-457.
- Ferguson, M.A.D. & Messier, F. (1997). Collection and analysis of traditional ecological knowledge about a population of Arctic tundra caribou. *Arctic*. 50(1), 17-28.
- Fisher, J.P., Estop-Aragones, C., Thierry, A., Charman, D.J., Wolfe, S.A., Hartley, I.P., Murton, J.B., Williams, M. & Phoenix, G.K. (2016). The influence of vegetation and soil characteristics on active-layer thickness of permafrost soils in boreal forest. *Global Change Biology*. 22, 3127-3140.
- Fraser, R.H., Lantz, T.C., Olthof, I., Kokelj, S.V., & Sims, R.A. (2014a). Warming-induced shrub expansion and lichen decline in the western Canadian Arctic. *Ecosystems*. 17, 1151-1168.
- Fraser, R.H., Olthof, I., Kokelj, S.V., Lantz, T.C., Lacelle, D., Brooker, A., Wolfe, S., & Schwarz, S. (2014b). Detecting landscape changes in high latitude environments using Landsat trend analysis: 1. Visualization. *Remote Sensing*. 6, 11533-11557.
- Fraser, R.H., Kokelj, S.V., Lantz, T.C., McFarlane-Winchester, M., Olthof, I., & Lacelle, D. (2018). Climate sensitivity of high Arctic permafrost terrain demonstrated by widespread ice-wedge thermokarst on Banks Island. *Remote Sensing*. 10(6), 954.
- French, H.M. (2016). The tundra and polar semi-desert landscapes of Banks Island and Prince Patrick Island, western Canadian Arctic. Cuadernos de *Investigacion Geografica*. 42(2), 321-340.
- Friedman, J. (2001). Greedy function approximation: The gradient boosting machine. *Annals of Statistics*. 29(5), 1189-1232.
- Gornall, J.L., Jonsdottir, I.S., Woodin, S.J., Van der Wal, R. (2007). Arctic mosses govern below-ground environment and ecosystem processes. *Oecologia*. 153, 931-941.

- Guay, K.C., Beck, P.A., Berner, L.T., Goetz, S.J., Baccini, A., & Buermann, W. (2014). Vegetation productivity patterns at high northern latitudes: A multi-sensor satellite data assessment. *Global Change Biology*. 20, 3147-3158.
- Hahn, E.D. & Soyer, R. (2005). Probit and logit models: Differences in the multivariate realm. *The Journal of the Royal Statistical Society, Series B*. 1-12.
- Hill, G.B. & Henry, G.H.R. (2011). Responses of high Arctic wet sedge tundra to climate warming since 1980. *Global Change Biology*. 17, 276-287.
- Hines, J.E., Latour, P.B., Squires-Taylor, C. & Moore, S. (2010). The effects on lowland habitat in the Banks Island Bird Sanctuary Number 1, Northwest Territories, by the growing colony of lesser snow geese (*Chen caerulescens caerulescens*). *Environment Canada Occasional Paper*. 118, 8-26.
- Huang, C., Wylie, B., Yang, L., Homer, C., & Zylstra, G. (2002). Derivation of a tasseled cap transformation based on Landsat 7 at-satellite reflectance. *International Journal of Remote Sensing*. 23(8), 1741-1748.
- Huemmrich, K.F., Gamon, J.A., Tweedie, C.E., Campbell, P.K.E., Landis, D.R., & Middleton, E.M. (2013). Arctic tundra vegetation functional types based on photosynthetic physiology and optical properties. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. 6(2), 265-275.
- Iacobelli, A. & Jefferies, R.L. (1991). Inverse salinity gradients in coastal marshes and the death of stands of *Salix*: The effects of grubbing by geese. *Journal of Ecology*. 79, 61-73.
- Jefferies, R.L., Jano, A.P., & Abraham, K.F. (2006). A biotic agent promotes large-scale catastrophic change in the coastal marshes of Hudson Bay. *Journal of Ecology*. 94(1), 234-242.
- Jenson, S.K. & Domingue, J.O. (1988). Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering and Remote Sensing*. 54(11), 1593-1600.
- Ju, J. & Masek, J.G. (2016). The vegetation greenness trend in Canada and US Alaska from 1984-2012 Landsat data. *Remote Sensing of Environment*. 176, 1-16.
- Kaplan, J.O. & New, M. (2006). Arctic climate change with a 2°C global warming: Timing, climate patterns and vegetation change. *Climate Change*. 79, 213-241.
- Kendall, M.G. & Stuart, A.S. (1967). Advanced Theory of Statistics. *Charles Griffin and Company, London, UK*. 2.
- Kerbes, R.H., Meeres, K.M., & Alisauskas, R.T. (2014). Surveys of nesting lesser snow geese and Ross's geese in Arctic Canada, 2002-2009. *Arctic Goose Joint Venture*

Special Publication, U.S. Fish and Wildlife Service, Washington, D.C. and Canadian Wildlife Service, Ottawa, Ontario. 987-0-9881233-1-1.

- Kotanen, P.M. & Jefferies, R.L. (1997). Long-term destruction of sub-arctic wetland vegetation by lesser snow geese. *Ecoscience*. 4(2), 179-182.
- Lantz, T.C., Gergel, S.E., & Kokelj, S.V. (2010). Spatial heterogeneity in the shrub tundra ecotone in the Mackenzie Delta region, Northwest Territories: Implications for Arctic environmental change. *Ecosystems*. 13, 194-204.
- Liaw, A. & Wiener, M. (2002). Classification and regression by randomForest. *R News*. 2(3), 18-22.
- Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., & Schabenberger, O. (2006). SAS for mixed models (2nd edition). *Carry, NC. SAS Institute Inc.*
- May, J.L., Parker, T., Unger, S., & Oberbauer, S.F. (2018). Short term changes in moisture content drive strong changes in Normalized Difference Vegetation Index and gross primary productivity in four Arctic moss communities. *Remote Sensing of Environment*. 212, 114-120.
- Moffat, N.D., Lantz, T.C., Fraser, R.H., & Olthof, I. (2016). Recent vegetation change (1980-2013) in the tundra ecosystems of the Tuktoyaktuk Coastlands, NWT, Canada. *Arctic, Antarctic and Alpine Research*. 48, 581-597.
- Mudryk, L.R., Derksen, C., Howell, S., Laliberte, F., Thackeray, C., Sospedra-Alfonso, R., Vionnet, V., Kushner, P.J., & Brown, R. (2018). Canadian snow and sea ice: Historical trends and projections. *The Cryosphere*. 12, 1157-1176.
- Myers-Smith, I.H., Hik, D.S., Kennedy, C., Cooley, D., Johnstone, J.F., Kenney, A.J., & Krebs, C.J. (2011). Expansion of canopy-forming willows over the twentieth century on Herschel Island, Yukon Territory, Canada. *AMBIO*. 40(6), 610-623.
- Negandhi, K., Laurion, I., Whiticar, M.J., Galand, P.E., Xu, X., & Lovejoy, C. (2013). Small thaw ponds: An unaccounted source of methane in the Canadian high Arctic. *PLoS ONE*. 8(11), e78204.
- Noh, M.-J. & Howat, I.M. (2015). Automated stereo-photogrammetric DEM generation at high latitudes: Surface extraction with TIN-based search-space minimization (SETSM) validation and demonstration over glaciated regions. *GIScience & Remote Sensing*. 52(2), 198-217.
- Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., & Wagner, H. (2017). Vegan: Community ecology package. *R package version 2.4-4*. <https://CRAN.R-project.org/package=vegan>.

- Olthof, I., Fraser, R.H., & Schmitt, C. (2015). Landsat-based mapping of thermokarst lake dynamics on the Tuktoyaktuk coastal plain: Northwest Territories, Canada since 1985. *Remote Sensing of Environment*. 168, 194-204.
- Proctor, M.C.F. (2000). The bryophyte paradox: Tolerance of desiccation, evasion of drought. *Plant Ecology*. 151(1), 41-49.
- Proctor, M.C.F. & Tuba, Z. (2002). Poikilohydry and homoihydry: Antithesis or spectrum of possibilities?. *New Phytologist*. 156, 327-349.
- Proctor, M.C.F., Oliver, M.J., Wood, A.J., Alpert, P., Stark, L.R., Cleavitt, N.L., & Mishler, B.D. (2007). Desiccation-tolerance in bryophytes: A review. *The Bryologist*. 110(4), 595-621.
- R Core Team (2016). R: A language and environment for statistical computing. *R Foundation for Statistical Computing, Vienna, Austria*. URL <https://www.R-project.org/>.
- Raulings, E.J., Morris, K., Roache, M.C., & Boon, P.I. (2010). The importance of water regimes operating at small spatial scales for the diversity and structure of wetland vegetation. *Freshwater Biology*. 55, 701-715.
- Raynolds, M.K. & Walker, D.A. (2016). Increased wetness confounds Landsat-derived NDVI trends in the central Alaska North Slope region, 1985-2011. *Environmental Research Letters*. 11(8), 085004.
- Riedlinger, D. & Berkes, F. (2001). Contributions of traditional knowledge to understanding climate change in the Canadian Arctic. *Polar Record*. 37(203), 315-328.
- Ropars, P. & Boudreau, S. (2012). Shrub expansion at the forest-tundra ecotone: Spatial heterogeneity linked to local topography. *Environmental Research Letters*. 7, 015501.
- Sachs Harbour, Wildlife Management Advisory Council (NWT) & Joint Secretariat (2008). Sachs Harbour Community Conservation Plan. 5-109.
- Samelius, G., Alisauskas, R.T., & Hines, J.E. (2008). Productivity of lesser snow geese on Banks Island, Northwest Territories, Canada, in 1995-1998. *Environment Canada Occasional Paper*. 115, 1-33.
- Slattery, S.M. & Alisauskas, R.T. (2007). Distribution and habitat use of Ross' and lesser snow geese during late brood rearing. *The Journal of Wildlife Management*. 71(7), 2230-2237.
- Smol, J.P. & Douglas, S.V. (2007). Crossing the final ecological threshold in high Arctic ponds. *PNAS*. 104(30), 12395-12397.

- Srivastava, D.S. & Jefferies, R.L. (1996). A positive feedback: Herbivory, plant growth, salinity, and the desertification of an Arctic salt-marsh. *Journal of Ecology*. 84(1), 31-42.
- Stoner, W.A., Miller, P.C., & Oechel, W.C. (1978). Simulation of the effect of the tundra vascular plant canopy on the productivity of four plant species. In Tieszen, L.L., *Vegetation and Production Ecology of an Alaskan Arctic Tundra* (pp. 371-387). New York, NY, Springer.
- Street, L.E., Stoy, P.C., Sommerkorn, M., Fletcher, B.J., Sloan, V.L., Hill, T.C., & Williams, M. (2012). Seasonal bryophyte productivity in the sub-Arctic: A comparison with vascular plants. *Functional Ecology*. 26, 365-378.
- Tremblay, B., Levesque, E., & Boudreau, S. (2012). Recent expansion of erect shrubs in the low Arctic: Evidence from eastern Nunavik. *Environmental Research Letters*. 7, 035501.
- Ulrich, M., Grosse, G., Chabrillat, S., & Schirrmeister, L. (2009). Spectral characterization of periglacial surfaces and geomorphological units in the Arctic Lena Delta using field spectrometry and remote sensing. *Remote Sensing of Environment*. 113, 1220-1235.
- van der Valk, A.G. (2005). Water-level fluctuations in North American prairie wetlands. *Hydrobiologia*. 539, 171-188.
- Webber, P.J. (1978). Spatial and temporal variation of the vegetation and its productivity, Barrow Alaska. *Vegetation and Production Ecology of an Alaskan Arctic Tundra*. edited by L.L. Tieszen. Springer-Verlag, New York. 37-112.
- Wolfe, B.B., Light, E.M., Macrae, M.L., Hall, R.I., Eichel, K., Jasechko, S., White, J., Fishback, L., & Edwards, T.W.D. (2011). Divergent hydrological responses to 20th century climate change in shallow tundra ponds, western Hudson Bay Lowlands. *Geophysical Research Letters*. 38 (L23402), 1-6.
- Woo, M.-K., Young, K.L., & Brown, L. (2006). High Arctic patchy wetlands: Hydrological variability and their sustainability. *Physical Geography*. 27(4), 297-307.
- Wood, S.N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society*. 73(1), 3-36.

Chapter 4 - Conclusion

Summary

Temperatures in Arctic and sub-Arctic regions have warmed twice as much as the average global increase (AMAP-SWIPA, 2011; Pithan & Mauritsen, 2014), triggering rapid shifts in high latitude ecosystems (Lantz & Turner, 2015; Kaplan & New, 2006; Bintanja & Andry, 2017; Yoshikawa & Hinzman, 2003; Nitze *et al.*, 2017; Fraser *et al.*, 2014; Lantz *et al.*, 2010; Myers-Smith *et al.*, 2011). Surface water is changing across the Arctic, which is concerning because it strongly influences a range of physical, geochemical, and biological processes (Wolfe *et al.*, 2011; Negandhi *et al.*, 2013; Becker *et al.*, 2016; Slattery & Alisauskas, 2007). Regional variation in surface water trends has been substantial (Carroll *et al.*, 2011; Roach *et al.*, 2013; Nitze *et al.*, 2017; Jones *et al.*, 2011) and remains largely unstudied in the high Arctic. High Arctic pond complexes and wetlands fill an important ecological niche, having high moisture levels, primary productivity, and nearly continuous vegetation cover, in contrast to the arid and sparsely vegetated polar deserts that surround them (Woo & Young, 1997; Hines *et al.*, 2010; Ecosystem Classification Group, 2013). High Arctic pond complexes and wetlands are however potentially very vulnerable to changes in surface water because of the regional permafrost conditions and typical waterbody basin physiography (Woo & Young, 2006; Smol & Douglas, 2007; Woo *et al.*, 2006; Steedman *et al.*, 2016; Fraser *et al.*, 2018), which can be little more than a series of shallow depressions infilled with water (Brown & Young, 2006; Abnizova & Young, 2010). Declining surface water in these high Arctic habitats would have resounding impacts on the nearby vegetation communities (Becker *et al.*, 2016; Webber, 1978) and animals that depend on them (Hines *et al.*, 2010; Slattery & Alisauskas, 2007).

The objectives of my MSc were to understand the nature of surface water change in the pond complexes of western Banks Island, Northwest Territories, and investigate how these changes impact the local vegetation. Presented in chapters 2 and 3, these objectives were undertaken using a combination of remote sensing data and field surveys of biotic and abiotic conditions.

In chapter 2, I found that the pond complexes on western Banks Island are drying, having lost 7.9% of the surface water that existed since 1985. This loss of surface water

disproportionately occurred in smaller waterbodies, suggesting that climate warming is the main driver of this change. The results of this investigation also suggest that expanding lesser snow goose populations are exacerbating this loss of surface water in areas with intensive habitat use, such as the Egg River nesting colony. In chapter 3, I showed that vegetation change, in the form of declining productivity, occurred sporadically in drying wetland areas. Productivity declines were most prominent in areas with higher initial productivity and moisture, low-elevation areas, and in high latitude river valleys. Observed declines in productivity were likely caused by a combination of wetland drying and lesser snow goose foraging pressures, which may be facilitating increased moisture loss in an already drying ecosystem. Ultimately, chapters 2 and 3 provide a more complete basis for understanding the recent changes occurring in the pond complexes of western Banks Island, a largely unstudied ecosystem. However, further study is needed to adequately understand the relative contributions of these factors.

Multi-component understanding of ecosystem change

Results from this thesis indicate that vegetation communities in high Arctic pond complexes are more resilient than waterbodies to climate change. Vegetation community composition and cover were found to be similar across levels of changing moisture conditions, with the small differences observed potentially attributable to higher levels of snow goose foraging. Furthermore, declines in vegetation productivity were not nearly as dominant or consistent as declines in surface water. This could be related to the affect of warming temperatures on increasing biomass in high Arctic wet sedge communities (Hill & Henry, 2011). More favorable temperatures could be compensating for the reduced moisture conditions.

Field data from chapter 3 suggest that the surface water loss observed in chapter 2 is related to a deepening permafrost active layer. Chapter 3 field sites classified as drying, had deeper thaw depths and lower near-surface soil moisture levels than control field sites. This provides evidence for one of the possible explanations mentioned in chapter 2, that a deepening active layer may be increasing groundwater storage capacities, lowering the water table (Woo *et al.*, 2006), and desiccating shallow waterbodies perched above the lowered water table. The effects of recent warming summer temperatures on

permafrost have been apparent in nearby upland terrain on Banks Island, through widespread thawing of ground-ice (Fraser *et al.*, 2018). Additional investigations to understand water table dynamics in this area, would shed light on the likelihood of this explanation. Thaw depth and soil moisture differences were not found between drying and control sites when sub-pixel water fraction (SWF) was used to classify field sites in chapter 2. This may be because SWF specifically measures surface water, while Tasseled Cap Wetness (TCW) is more sensitive to general moisture, including the moisture of soils and vegetation. Thus, it is likely the control areas in chapter 2 may also be experiencing declines in moisture but were classified as controls because of the strict requirement of surface water loss. Additional analyses aimed at understanding the spatial relationships between declining surface water and general moisture would help to clear-up differences in the results of chapters 2 and 3.

Limitations and future research priorities

A fundamental limitation of this thesis is the relatively short-term record provided by the Landsat archive. While it is the longest running satellite-based Earth imaging program, the Landsat record only extends back to the early 1970s (Wulder *et al.*, 2008). This is not long enough to understand the range of natural variability prior to the influence of recent climate change and expanding snow goose populations. In the absence of a longer-term record, it is difficult to know if the declines in surface water and vegetation productivity observed between 1985 and 2015, have occurred throughout history. Paleolimnological methods can be used to determine hydrological regimes on a geological time-scale, by analyzing differences in diatom assemblages (Smol & Douglas, 2007). The expertise of local hunters and land-users can also produce valuable information (Riedlinger & Berkes, 2001; Ashford & Castleden, 2001; Ferguson & Messier, 1997). Discussions and personal accounts can shed light on historical conditions and ecosystem cycles (Riedlinger & Berkes, 2001). It is however unlikely that the changes observed in this thesis have occurred regularly throughout history, as the recent warming in Canada has been unprecedented over the last millennium (Beltrami, *et al.*, 1992; Beltrami & Bourlon, 2004).

Another major limitation of this thesis lies in the lack of historical field data. Because of this, I had to substitute space for time, by comparing areas that have changed

with areas that have not changed according to the remote sensing data. However, unchanged areas may have remained that way because of factors that were not considered in the site selection process, but which may affect the measurements taken in the field. If controls fail to consider all pre-disturbance conditions, results can seriously underestimate the affect of a disturbance (Franca *et al.*, 2016). Thus, results from the field data should be interpreted conservatively. Furthermore, my space for time substitution relies on remote sensing data, which has its own limitations.

The Tasseled Cap (TC) transformation is a useful configuration of Landsat data, which is easy to interpret because it translates six Landsat bands into a more manageable three indices (Crist & Cicone, 1984; Huang *et al.*, 2002). However, this reduction of six bands to three indices also results in a loss of information and variability (Crist & Cicone, 1984), which may be useful for distinguishing pixels based on spectral properties. It should also be noted that even with more detailed information, there are limitations to the subtleties that 30 m resolution can detect. Due to the limited satellite data available, a decision needs to be made regarding the type of data used in a study, based on the goals of the study. The Landsat program has the longest running time-series of data but may be limited by the moderate 30 m resolution. Alternative satellite programs may have higher resolutions, but lack the temporally extensive data required to determine historical trends. In this thesis, the use of Landsat data was determined to be the optimal choice and a sub-pixel water fraction technique was employed to reduce the loss of information created by the moderate resolution. Future studies should make use of spectral unmixing techniques to better quantify changes in vegetation (Sonnentag *et al.*, 2007). Spectral unmixing techniques use known reflectance values of vegetation types across the electromagnetic spectrum to estimate the proportion of each vegetation type in a pixel. This would require extensive field data from homogeneous vegetation stands and multiple habitat types, to adequately determine the spectral profiles of each vegetation type, but would provide much more detailed information on how vegetation has changed from 1985-2015.

Further research should also focus on confirming the processes leading to drying or draining of waterbodies in the study area, as trends indicate they are continuing. Isotope analysis (Wolfe *et al.*, 2011; Lamhonwah *et al.*, 2017), hydrological and ground temperature instrumentation (Woo & Young, 1997; Lewkowicz & French, 1982), as well

as further remote sensing analyses, could provide valuable information on these processes. Monitoring of evaporation, subsurface flow, water table depth, and thaw depth, at ponds of various sizes would provide insight on water balances over the ice-free season and the relative impact of these factors on water balances in ponds of different sizes (Narancic *et al.*, 2017). This information would also be valuable in understanding hydrological connectivity in the study area. Remote sensing change detection of the summer snow pack, as well as measurements of subsurface flow near existing and former summer snowbanks, would also help to clarify if residual snowbanks are irreplaceable sources of water on Banks Island over the ice-free season.

Conclusion

The goal of this thesis was to understand the nature of surface water change and resultant impacts to vegetation in the pond complexes of western Banks Island, Northwest Territories. I found that surface water was declining, particularly in smaller waterbodies, which suggests that warming climate is the main driver. Many climate driven processes could be causing this surface water loss, but field data from chapter 3 raises the possibility that it is related to a deepening permafrost active layer. Intensive snow goose activity is likely contributing to higher than normal declines in surface water in highly used habitat areas, like the Egg River nesting colony. Evidence also suggests that snow goose foraging is contributing to patches of declining vegetation productivity in drying wetlands. However, much uncertainty remains regarding the interactions between wetland drying, primary productivity, and snow goose activity, which need to be studied further to better understand the changes occurring on Banks Island. To fill key gaps in knowledge, future studies could make use of diatom paleolimnological methods (Smol & Douglas, 2007), local and traditional knowledge (Riedlinger & Berkes, 2001; Ashford & Castleden, 2001; Ferguson & Messier, 1997), spectral unmixing remote sensing techniques (Sonnentag *et al.*, 2007), and hydrological and ground temperature instrumentation (Woo & Young, 1997; Lewkowicz & French, 1982).

Bibliography

- Abnizova, A. & Young, K.L. (2010). Sustainability of high Arctic ponds in a polar desert environment. *Arctic*. 63(1), 67-84.
- AMAP-SWIPA (2012). Arctic climate issues 2011: Changes in Arctic snow, water, ice and permafrost. *SWIPA 2011 Overview Report*. pp. 97.
- Ashford, G. & Castleden, J. (2001). Inuit observations on climate change: Final report. *International Institute for Sustainable Development*. 1-31.
- Becker, M.S., Davies, T.J., & Pollard, W.H. (2016). Ground ice melt in the high Arctic leads to greater ecological heterogeneity. *Journal of Ecology*. 104, 114-124.
- Beltrami, H., Jessop, A.M., & Mareschal, J.-C. (1992). Ground temperature histories in eastern and central Canada from geothermal measurements: Evidence of climate change. *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section)*. 98, 167-184.
- Beltrami, H. & Bourlon, E. (2004). Ground warming patterns in the Northern Hemisphere during the last five centuries. *Earth and Planetary Science Letters*. 227(3-4), 169-177.
- Bintanja, R. & Andry, O. (2017). Towards a rain-dominated Arctic. *Nature Climate Change*. 7, 263-268.
- Brown, L. & Young, K.L. (2006). Assessment of three mapping techniques to delineate lakes and ponds in a Canadian high Arctic wetland complex. *Arctic*. 59(3), 283-293.
- Carroll, M.L., Townshend, J.R.G., DiMiceli, C.M., Loboda, T., & Sohlberg, R.A. (2011). Shrinking lakes of the Arctic: Spatial relationships and trajectory of change. *Geophysical Research Letters*. 38(L20406), 1-5.
- Crist, E.P. & Cicone, R.C. (1984). A physically-based transformation of thematic mapper data – the TM tasseled cap. *IEEE Transactions on Geoscience and Remote Sensing*. GE-22(3), 256-263.
- Ecosystem Classification Group (2013). Ecological regions of the Northwest Territories – Northern Arctic. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada: 1-157.
- Ferguson, M.A.D. & Messier, F. (1997). Collection and analysis of traditional ecological knowledge about a population of Arctic tundra caribou. *Arctic*. 50(1), 17-28.
- Franca, F., Louzada, J., Korasaki, V., Griffiths, H., Silveira, J.M., & Barlow, J. (2016). Do space-for-time assessments underestimate the impacts of logging on tropical biodiversity? An Amazonian case study using dung beetles. *Journal of Applied Ecology*. 53, 1098-1105.

- Fraser, R.H., Olthof, I., Kokelj, S.V., Lantz, T.C., Lacelle, D., Brooker, A., Wolfe, S. & Schwarz, S. (2014). Detecting landscape changes in high latitude environments using Landsat trend analysis: 1. Visualization. *Remote Sensing*. 6, 11533-11557.
- Fraser, R.H., Kokelj, S.V., Lantz, T.C., McFarlane-Winchester, M., Olthof, I., & Lacelle, D. (2018). Climate sensitivity of high Arctic permafrost terrain demonstrated by widespread ice-wedge thermokarst on Banks Island. *Remote Sensing*. 10(6), 954.
- Hill, G.B. & Henry, G.H.R. (2011). Responses of high Arctic wet sedge tundra to climate warming since 1980. *Global Change Biology*. 17, 276-287.
- Hines, J.E., Latour, P.B., Squires-Taylor, C. & Moore, S. (2010). The effects on lowland habitat in the Banks Island Bird Sanctuary Number 1, Northwest Territories, by the growing colony of lesser snow geese (*Chen caerulescens caerulescens*). *Environment Canada Occasional Paper*. 118, 8-26.
- Huang, C., Wylie, B., Yang, L., Homer, C., & Zylstra, G. (2002). Derivation of a tasseled cap transformation based on Landsat 7 at-satellite reflectance. *International Journal of Remote Sensing*. 23(8), 1741-1748.
- Jones, B.M., Grosse, G., Arp, C.D., Jones, M.C., Anthony, K.M.W., & Romanovsky, V.E. (2011). Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *Journal of Geophysical Research*. 116, G00M03.
- Kaplan, J.O. & New, M. (2006). Arctic climate change with a 2°C global warming: Timing, climate patterns and vegetation change. *Climate Change*. 79, 213-241.
- Lamhonwah, D., Lafreniere, M.J., Lamoureux, S.F., & Wolfe, B.B. (2017). Evaluating the hydrological and hydrochemical responses of a high Arctic catchment during an exceptionally warm summer. *Hydrological Processes*. 31, 2296-2313.
- Lantz, T.C., Gergel, S.E., & Kokelj, S.V. (2010). Spatial heterogeneity in the shrub tundra ecotone in the Mackenzie Delta region, Northwest Territories: Implications for Arctic environmental change. *Ecosystems*. 13, 194-204.
- Lantz, T.C. & Turner, K.W. (2015). Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. *Journal of Geophysical Research: Biogeosciences*. 120(3), 513-524.
- Lewkowicz, A.G. & French, H.M. (1982). The hydrology of small runoff plots in an area of continuous permafrost, Banks Island, N.W.T.. *Hydrology in Permafrost Regions – Proc. 4th Can. Permafrost Conf.*. 151-162.
- Myers-Smith, I.H., Hik, D.S., Kennedy, C., Cooley, D., Johnstone, J.F., Kenney, A.J., & Krebs, C.J. (2011). Expansion of canopy-forming willows over the twentieth century on Herschel Island, Yukon Territory, Canada. *AMBIO*. 40(6), 610-623.

- Narancic, B., Wolfe, B.B., Pienitz, R., Meyer, H., & Lamhonwah, D. (2017). Landscape-gradient assessment of thermokarst lake hydrology using water isotope tracers. *Journal of Hydrology*. 545, 327-338.
- Negandhi, K., Laurion, I., Whitticar, M.J., Galand, P.E., Xu, X., & Lovejoy, C. (2013). Small thaw ponds: An unaccounted source of methane in the Canadian high Arctic. *PLoS ONE*. 8(11), e78204.
- Nitze, I., Grosse, G., Jones, B.M., Arp, C.D., Ulrich, M., Fedorov, A., & Veremeeva, A. (2017). Landsat-based trend analysis of lake dynamics across northern permafrost regions. *Remote Sensing*. 9(7), Article 640.
- Pithan, F. & Mauritsen, T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*. 7, 181-184.
- Riedlinger, D. & Berkes, F. (2001). Contributions of traditional knowledge to understanding climate change in the Canadian Arctic. *Polar Record*. 37(203), 315-328.
- Roach, J.K., Griffith, B., & Verbyla, D. (2013). Landscape influences on climate-related lake shrinkage at high latitudes. *Global Change Biology*. 19, 2276-2284.
- Slattery, S.M. & Alisauskas, R.T. (2007). Distribution and habitat use of Ross' and lesser snow geese during late brood rearing. *The Journal of Wildlife Management*. 71(7), 2230-2237.
- Smol, J.P. & Douglas, S.V. (2007). Crossing the final ecological threshold in high Arctic ponds. *PNAS*. 104(30), 12395-12397.
- Sonnentag, O., Chen, J.M., Roberts, D.A., Talbot, J., Halligan, K.Q., & Govind, A. (2007). Mapping tree and shrub leaf area indices in an ombrotrophic peatland through multiple endmember spectral unmixing. *Remote Sensing of Environment*. 109, 342-360.
- Steedman, A.E., Lantz, T.C., & Kokelj, S.V. (2016). Spatio-temporal variation in high-centre polygons and ice-wedge melt ponds, Tuktoyaktuk Coastlands, Northwest Territories. *Permafrost and Periglacial Processes*. 28(1), 66-78. doi: 10.1002/ppp.1880.
- Webber, P.J. (1978). Spatial and temporal variation of the vegetation and its productivity, Barrow Alaska. *Vegetation and Production Ecology of an Alaskan Arctic Tundra*. edited by L.L. Tieszen. Springer-Verlag, New York. 37-112.
- Wolfe, B.B., Light, E.M., Macrae, M.L., Hall, R.I., Eichel, K., Jasechko, S., White, J., Fishback, L., & Edwards, T.W.D. (2011). Divergent hydrological responses to 20th century climate change in shallow tundra ponds, western Hudson Bay Lowlands. *Geophysical Research Letters*. 38 (L23402), 1-6.

- Woo, M.-K. & Young, K.L. (1997). Hydrology of a small drainage basin with polar oasis environment, Fosheim Peninsula, Ellesmere Island, Canada. *Permafrost and Periglacial Processes*. 8, 257-277.
- Woo, M.-K. & Young, K.L. (2006). High Arctic wetlands: Their occurrence, hydrological characteristics and sustainability. *Journal of Hydrology*. 320, 432-450.
- Woo, M.-K., Young, K.L., & Brown, L. (2006). High Arctic patchy wetlands: Hydrological variability and their sustainability. *Physical Geography*. 27(4), 297-307.
- Wulder, M.A., White, J.C., Goward, S.N., Masek, J.G., Irons, J.R., Herold, M., Cohen, W.B., Loveland, T.R., & Woodcock, C.E. (2008). Landsat continuity: Issues and opportunities for land cover monitoring. *Remote Sensing of Environment*. 112, 955-969.
- Yoshikawa, K. & Hinzman, L.D. (2003). Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council Alaska. *Permafrost and Periglacial Processes*. 14, 151-160.