A MULTISCALE ANALYSIS OF FACTORS ASSOCIATED WITH SHRUB COVER AND SHRUB EXPANSION ON THE NORTH SLOPE OF ALASKA.

A Dissertation

by

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ABSTRACT

Species distributions are expected to shift with changes in climate at a global scale. The northern latitudes are warming at a rate three times greater than the global mean, which has resulted in the Arctic tundra undergoing many environmental changes in addition to increasing temperatures. One of the most notable changes is that of shrub expansion. Shrub expansion is an important process to understand since it impacts local thermal regimes, and carbon sequestration or release. The aim of the research was to determine where key areas of shrub cover and shrub expansion are to aid in understanding how much of the North Slope of Alaska is likely to support increased shrub growth. This was achieved by addressing the following three questions: 1) How is shrub cover distributed at the regional scale and what regional environmental variables is it associated with? 2) How is shrub cover distributed, and where are the key areas of expansion at the landscape scale? 3) How do shrubs respond to a local disturbance?

I used a combination of historical and contemporary imagery to analyze the patterns of shrub cover and shrub expansion at regional, landscape, and local scales on the North Slope of Alaska. The images were classified using a maximum likelihood classification process in ENVI, and then analyzed in ArcGIS. The relationships between shrub cover and shrub expansion, and selected environmental variables were determined statistically using R. The findings of this research suggest that: 1) shrub cover on the North Slope exhibits a latitudinal gradient, with greatest coverages in the southern areas; 2) shrub cover is greatest in river floodplains, but the greatest rates of expansion are on floodplain slopes, and within the first ten meters of streams; and 3) shrub colonization has been facilitated by processes linked to the disturbance of the Trans-Alaska Pipeline System. The combination of these findings provide better understanding of where key areas of shrub expansion are on the North Slope of Alaska, which will aid in improving Arctic vegetation models.

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CHAPTER I

INTRODUCTION

1.1 General introduction

1.1.1 Climate change and the Arctic

Northern latitudes experience warming at a rate three times greater than the global mean, and therefore some of the most notable environmental changes have been in the Arctic (Eastman and Warren 2010, Serreze and Barry 2011). Arctic amplification has many known and potential causes, with changes in albedo being cited as one of the key drivers, but that in itself is a complex process that has multiple feedbacks (Eastman and Warren 2010, Serreze and Barry 2011). The Arctic plays an important role in the global climate through interactions and feedback couplings with the atmosphere, land surfaces, and the ocean (Dong et al. 2010). It is important to improve the understanding of these complex interactions to allow for better predictions of changes. One of the processes that has been shown to modify climate in the high latitudes through impacts on the energy budget by influencing changes in albedo is that of shifts in vegetation cover (Swann et al. 2010). The Arctic regions are expected to experience an increase in plant species richness, which will cause ecological consequences at population, community, and ecosystem scales (Post et al. 2009, Sommer et al. 2010).

While Arctic warming is resulting in a greening trend, the magnitude and direction of such changes at the local scale are, however, very context dependent (Vellend et al. 2017). More recently there have been reports of decreasing productivity and a “browning” trend in parts of the Arctic. While there is ample evidence for continued shrubification, which is said to be driving greening in the tundra, there is also browning occurring in the tundra regions, although, the mechanism driving browning in the tundra is uncertain (Bieniek et al. 2015, Epstein et al. 2015, Phoenix and Bjerke 2016). Browning trends of the boreal forests regions of southwestern Alaska can be explained by increased drought stress and insect infestation (Bieniek et al. 2015). There is also evidence showing weakening of the correlation between temperature and vegetation productivity in Arctic ecosystems (Piao et al. 2014). This weakening, however, is spatially dependent as the relationship between NDVI and temperature remains unchanged over northern Eurasia (Bi et al. 2013). The overall greening of the Arctic is likely impacting other climatic feedbacks, however with this uncertainty, the exact consequences are not yet known (Pearson et al. 2013).

1.1.2 Shrub expansion as an Arctic change

Shrub expansion is occurring globally across several biomes; this phenomenon is being increasingly documented in Arctic tundra areas (Naito and Cairns 2011a, Sturm, Racine and Tape 2001b, Tape, Sturm and Racine 2006a, Hallinger, Manthey and Wilmking 2010, Myers-Smith et al. 2011b, Elmendorf et al. 2012b, Frost et al. 2013, Naito and Cairns 2015, Ackerman et al. 2017, Martin et al. 2017, Myers-Smith and Hik 2017). It is important to understand this process as it is one of the primary mechanisms of Arctic change due to the impacts it has on thermal regimes, and carbon sequestration or release (Naito and Cairns 2011a). The functional traits of plants in the tundra are changing in response to increased temperatures and changes in soil moisture; generally in areas of warming, plant communities are increasing in height (Bjorkman et al. 2018). Above-ground biomass in the Arctic is predicted to increase by 15-68%, which will result in decreases in albedo, and increases in evapotranspiration (Pearson et al. 2013); which, when combined, are likely to result in a positive feedback, and even more warming (Blok et al. 2011). While shrub expansion in the Low Arctic tundra ecosystem as a response to climate warming has been widely reported, it is not only as a result of the warming trend (Frost et al. 2013). Summer temperature is the primary controlling factor with regards to shrub expansion at large spatial and temporal scales, but at the landscape scale, shrub expansion is influenced by complex interactions between climate and local environmental conditions (Frost et al. 2013).

Increases in regional temperatures are also expected to result in widespread permafrost degradation, especially in areas where ground temperatures are close to freezing, (Lloyd et al. 2003). Disturbances in the tundra, such as permafrost degradation, have the potential to create sites that are favorable for tall shrub establishment (Myers-Smith et al. 2011a). However, there is still little known regarding the relationship between shrub expansion and permafrost thaw (Frost et al. 2018). Shading by vegetation cover can have a stabilizing effect and reduce permafrost degradation (Yi, Woo and Arain 2007). Contrary to this, increases in shrub cover also encourages further productivity as the canopy traps snow, which insulates the soil in winter and allows for extended microbial activity, and thus acts as a positive feedback for more growth (Sturm et al. 2001a, Sturm et al. 2005b). However, Myers-Smith and Hik (2013) found no evidence for increased soil decomposition under shrub cover, but there was a measured winter insulating and summer cooling effect under shrub canopy cover.

1.1.3 Arctic shrub expansion studies to date

Shrub expansion is one of the most notable changes in the pan-Arctic region (Naito and Cairns 2011b). Sturm et al. (2001b) reported evidence for an increase in shrub abundance based on aerial photography over a period of 50 years. This study proved instrumental in setting the platform for subsequent shrub expansion studies, such as, Tape et al. (2006a), Blok et al. (2010), Hallinger et al. (2010), Myers-Smith et al. (2011a), Naito and Cairns (2011b), Loranty and Goetz (2012), Frost et al. (2013), and Naito and Cairns (2015). The most comprehensive study on shrub expansion in the Arctic to date is by Tape et al. (2006a) which used repeat aerial photography, plot studies, and satellite remote sensing over a pan-Arctic extent. Expansion is reported to be occurring by increases in the size of individuals, number of patches, the in-filling of patches, and by expansion into areas which once were shrub-free (Sturm et al. 2001b, Tape et al. 2006a).

Martin et al. (2017) identified 23 proximal controls relating to shrub growth and expansion, and while temperature and precipitation are the most important controls, there is a decoupling with these two controls. Contrary to this, Myers-Smith and Hik (2017) studied willow shrublines in the Kluane Region of the southwest Yukon Territory, Canada, and concluded that advancing shrubline is determined by a regional factor, such as climate, as opposed to a more local factor. Their analyses indicate that if growing conditions improve or even remain the same over the next 50 years, tall willow cover will increase by at least 20% (Myers-Smith and Hik 2017).

Permafrost conditions and shrub expansion operate as coupled systems. Myers-Smith et al. (2011a) observed a dieback in *Betula nana* patches in northeast Siberia, and linked this to permafrost degradation. A study by Blok et al. (2010) found that active layer thickness was greater in areas where the deciduous shrub *Betula nana* was removed, which suggests that shrub establishment offset the amount of permafrost thaw expected from increasing temperatures. When combining these results it can be suggested that shrub expansion could serve as a negative feedback to increasing temperatures as lower soil temperatures will result in lower rates of soil decomposition, and therefore reduced amounts of carbon released to the atmosphere (Blok et al. 2010).

1.1.4 Knowledge gaps

Changes in tundra vegetation potentially have far-reaching consequences due to them playing important roles in ecosystem processes, services, and climate regulation at local and global scales (Elmendorf et al. 2012a). Considering the broad impacts of Arctic environmental change and the relatively low number of studies in tundra environments, there is a need for further research on the potential type and extent of changes in tundra regions (Callaghan et al. 2011). The process of shrub expansion is likely to have a disproportionate impact on further warming, however, the rate at which this will take place is unknown (Chapin et al. 2005). Model improvements are required to make better predictions of future shifts in vegetation distributions in order to quantify possible feedbacks (Pearson et al. 2013).

Methods and analyses concerned with the growth of shrubs have improved the ability to investigate shrub growth and recruitment in tundra ecosystems at the scale of individuals, however, there is still a need to understand changes at the landscape or biome scale (Myers-Smith et al. 2015c). While shrub expansion is largely suggested to be occurring as a result of increased summer air temperatures, observed patterns of expansion are heterogeneous in nature, which suggests that there are processes other than air temperature influencing shrub expansion (Martin et al. 2017). Therefore, a better understanding of the heterogeneity of shrub expansion at the landscape scale is required to connect plot-level results to regional greening trends (Ackerman et al. 2017). There is also the need to investigate the response of shrubs to disturbance, as disturbances are likely to become more frequent under changing climate conditions.

This research contributes to knowledge gaps by determining where the shrubs currently are on the landscape, and where key areas of expansion are. Rapid shrub expansion has been observed in the floodplains of Arctic environments, and thus the riparian regions have received much attention; however, few studies have focused on expansion rates outside of riparian areas. Few studies have focused on the advances of shrublines up hillslopes and northward in the Arctic, but instead focus on changes in abundance or cover (Myers-Smith and Hik 2017). Shrub expansion is likely to persist with climate warming, but will be limited to certain habitats (Swanson 2015), thus, it is important to obtain better estimates of how much of the North Slope of Alaska is likely to see shrub expansion. This highlights the need to investigate shrub expansion in the interfluves (i.e. the areas outside of riparian regions) as, owing to their great expanse, they have the greatest influence on what happens in the Arctic. Links with climate, and possible feedbacks cannot be confidently established without a full understanding of change across all topographic regions (Tape et al. 2006a), and the patterns thereof (Ropars and Boudreau 2012). This research analyzed the associations between shrub cover and regional scale variables, and analyzed shrub cover and expansion in relation to landscape position, and in response to disturbance.

Overall, this research provides better understanding of where key areas of shrub expansion are on the North Slope of Alaska. Shrub expansion has major implications in both the environmental and economic spheres; thus, rigorous research is required to inform land management policies, as well as contribute to the understanding of one of the many effects of climate change (Myers-Smith et al. 2011a). Arctic vegetation models assume that vegetation changes are homogenous across the entire tundra biome (Myers-Smith et al. 2015b), however, this is not the case due to local influencing factors that control shrub cover and expansion. By obtaining a better idea of the rates observed in the more representative areas of the Arctic (the interfluvial areas), better estimates of total shrub expansion rates in the Arctic can be made.

1.2 Research aim

The aim of this research is to determine where key areas of shrub cover and shrub expansion are to aid in understanding how much of the North Slope of Alaska is likely to support increased shrub growth. This was addressed by three main lines of inquiry, namely:

1. How is shrub cover distributed at the regional scale and what regional environmental variables is it associated with?
2. How is shrub cover distributed, and where are the key areas of expansion at the landscape scale?
3. How do shrubs respond to a local disturbance?

1.3 Study area

This research focused on shrub expansion on the North Slope of Alaska, which contains three main ecoregions; the Arctic Coastal Plain, Arctic Foothills, and the Brooks Range (Tape et al. 2006a). The North Slope is characterized by tundra vegetation, mainly sedge tussocks, or shrubs (*Alnus* spp., *Betula glandulosa*, *B. nana*, and *Salix* spp.) (Tape et al. 2006a, Naito and Cairns 2011b), and is under snow cover for 7 to 9 months (Walker et al. 1989). The region is divided by meandering and braided streams, most of which flow north from their headwaters in the Brooks Range (Frohn, Hinkel and Eisner 2005, Tape et al. 2006a). The valley systems are separated by flat benches (interfluves) (Tape et al. 2006a), and is underlain by continuous permafrost. While these attributes are similar across the North Slope, the climate, vegetation, landscape ages, and topography does vary for each of the ecoregions (Walker et al. 1989).

The Arctic Coastal Plain is a relatively low-relief surface that gently rises from the Arctic Ocean to roughly 200 meters above sea level at the Arctic Foothills to the south (Hinkel et al. 2007). This region receives relatively little precipitation, of which most falls as snow, has cool summers, but a relatively warm winter due to the low continentality brought about its proximity to the ocean and sea ice (Zhang, Osterkamp and Stamnes 1996). The Arctic Foothills, the area north of the Brooks Range, has a more variable and continental climate than the of the coastal areas (Walker et al. 1989), with a mean January temperature of -22°C and mean July temperature of 11°C (Zhang et al. 1996, Oswald et al. 2003). The broad, east-west trending, Brooks Range is the southernmost ecoregion of the North Slope; it also has a continental climate, with similar winter temperatures to that of the Arctic Foothills, but a higher mean June temperature of 20.8°C (Higuera et al. 2009). Studies by Tape et al. (2006a), Beck et al. (2011), Naito and Cairns (2011b), and others, have focused on shrub expansion on the North Slope of Alaska, but specific to the riparian areas, so this research will be a valuable contribution to the existing body of literature.

1.4 Dissertation organization

This dissertation is comprised of six main chapters. This introduction, Chapter I, is a general overview of the dissertation. Chapter II provides a broad background to vegetation in riparian areas. It examines the connection between the terrestrial and aquatic zones, ecological interactions, the impact on riparian zones under changing climatic conditions, and finally provides an overview of Arctic riparian systems. Chapters III – V focused on determining controls of shrub cover and expansion, each at a different scale. Chapter III examines the distribution of shrub cover at the regional scale to determine what environmental variables are important in controlling shrub presence on the North Slope of Alaska. Chapter IV seeks to determine the importance landscape position has on shrub cover and shrub expansion. This is achieved by examining patterns of shrub cover and shrub expansion in relation to topographic region and proximity to rivers. The relationships between shrub cover and shrub expansion are also explored in floodplains, as well as outside of floodplains to determine whether these patterns differ. Chapter V assesses the status of shrub presence along the Trans-Alaska Pipeline System to determine shrub responses to a local disturbance. This was achieved by recording shrub presence or absence intersecting transects along the pipeline in its aboveground and buried situations in historical and contemporary imagery, and compared these results to those of adjacent control transects. Finally, Chapter VI concludes the dissertation with a summary of the findings of this dissertation.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Riparian ecosystems, defined by the corridor between the low-water mark and the terrestrial landscape that can be affected by elevated water tables or extreme flooding, are complex, diverse, and dynamic high-value habitats (Naiman, Decamps and Pollock 1993, Nilsson and Berggren 2000, Tockner et al. 2010). This makes these ecosystems unique areas as they serve as the ecotone between the terrestrial and aquatic zones, as well as connecting corridors between regions (Malanson 1993). Riparian areas are under threat due to both anthropogenic and other natural impacts, which creates a need to better understand them to allow for their conservation (Naiman et al. 1993, Nilsson and Berggren 2000, Tockner et al. 2010, Bendix 2013).

The dependence of plants on water to survive means that the distribution, composition, and structure of plant communities are shaped by the spatiotemporal patterns of water availability (Asbjornsen et al. 2011) This creates a strong coupling between vegetation, water and nutrients (Newman et al. 2006). The relationships between riparian vegetation and channel process has gained increasing attention with an average of 116 papers published on the topic in the decade of 2000 to 2009, a marked increase from less than one paper per year on the topic in the 1980s (Merritt 2013).

A number of emerging disciplines highlight the importance of research into the linkages between vegetation and water resources. A relatively new interdisciplinary hybrid discipline, known as ecohydrology, combines principles of ecology and hydrology (Newman et al. 2006, Asbjornsen et al. 2011). The premise of this discipline is to understand the role of hydrologic processes in shaping the biological communities, as well as understand how the feedbacks from biological communities influence the water cycle (Nuttle 2002, Newman et al. 2006). Another related emerging subdiscipline is biogeomorphology, which when focused on fluvial geomorphology, allows for a better understanding of the nonlinear relationships between the forces that influence succession and rejuvenation in fluvial corridors (Corenblit et al. 2007). Fluvial landscape ecology combines ecology, geography and hydrology to better address issues relating to the combination of patch dynamics and hierarchy theory, which is often a challenge in fluvial landscapes (Poole 2002). These interdisciplinary approaches are key to helping scientists forecast the nature, magnitude, and rate of environmental changes, something which is imperative to allow for decision-makers to best manage the impacts on natural and socioeconomic systems (Clark et al. 2001, Newman et al. 2006). Understanding environmental responses to a changing climate and how to best adapt to and potentially mitigate these changes is a fundamental challenge for ecohydologists as we enter the Anthropocene (Wilcox, Sorice and Young 2011).

2.2 The nature of the riparian landscape

Traditionally, the term ‘riparian’ relates ecologically to that which is affected by rivers (Malanson 1993), however, riparian vegetation is influenced by both fluvial and upland geomorphic processes (Auble, Friedman and Scott 1994). This makes riparian areas heterogeneous landscapes, which act as transitions between terrestrial and aquatic ecosystems (Nilsson and Svedmark 2002). Riparian landscapes vary widely in structure and function, according to the environment they are found in, but they all are shaped by and also shape the aquatic environment (Malanson 1993). The patterns of riparian vegetation are strongly linked to the physical transverse and longitudinal gradients caused by rivers (Friedman et al. 2006).

River corridors create linear features on the landscape, which from a landscape ecology perspective, makes them interesting features to study the heterogeneity of interactions between spatial pattern and ecological processes at multiple scales (Ward et al. 2002). A number of unique characteristics make riparian areas unique ecosystems; these include them being the lowest point of any given landscape, their high boundary-to-area rations, the high rates of ecological succession, as well as their tight coupling with adjacent surface and subsurface habitats (Tockner et al. 2010).

There is a reciprocal relationship between riparian vegetation and fluvial processes. Vegetation presence, form, structure, distribution, and abundance all serve to influence valley form and associated fluvial processes (Merritt 2013). Stream size, its position within the drainage network, the hydrological regime, and local geomorphology play a role in controlling the width of the riparian corridor and how much vegetation impacts on the steam (Naiman et al. 1993). This relationship between riparian vegetation and fluvial processes has been the focus of many studies in recent decades (Merritt 2013), however, there has been a greater concentration on the role of streams on vegetation at the local scale, and few have considered the important avenue of the broader scale of the impact of riparian vegetation on upland systems (Tabacchi et al. 1998). Large-scale research on the connections between upland vegetation and hydrologic flows is an important avenue to pursue as this will aid in determining how to best manage these habitats to conserve their integrity and protect downstream water supplies (Asbjornsen et al. 2011).

The patterns of species in riparian areas is governed by combination of environmental gradients, disturbance, and competition (Malanson 1993), whereas scale plays a role in governing the influence that environmental factors have on diversity (Gould and Walker 1997). Riparian environments vary in terms of scale according to direction of axis (Bendix 1994). The longitudinal axis runs along the length of the valley is evident at small map scales, typically on the order of a few kilometers, and the transverse axis runs across the valley is typically examined at the scale of meters (Malanson 1993, Bendix 1994).

2.2.1 The structure of riparian systems

2.2.1.1 The longitudinal profile

One of the earliest classifications of river zonation is that by Davis (1890) which divides the longitudinal profile of a channel according to slope gradient. Since slope gradient determined the stage of the river, the classification by Davis (1890) moves from youthful high potential energy (eroding) zones in the headwaters, to the mature areas that have the potential to reach an equilibrium between erosion and deposition in the middle reaches, to the old age, low velocity flows near the mouth where deposition occurs. This classification has received criticism since velocity of the river is not necessarily determined by the stage of the river, however, Davis' approach of downstream change in characteristics still has use for the zonal geomorphological classification of rivers (Rowntree, Wadeson and O'Keefe 2000).

Rivers often flow through multiple ecoregions, which makes the landscape structure of riparian areas unique (Malanson 1993). Longitudinal vegetation patterns shaped by the riparian environment are usually evident at small map scales, and typically display a down-valley arrangement of relatively homogenous sections of vegetation (Bendix 1994). However, the longitudinal pattern of landforms can change along the course of the river, which can influence species composition due to changes in isolation and connectivity (Malanson 1993). Potential influencing variables on the longitudinal pattern of riparian vegetation include elevation, valley orientation, valley width, fire history, and lithology (Bendix 1994). While the longitudinal gradient is important, local site characteristics and regional trends can be more important in shaping community structure in riparian systems (Wyant and Ellis 1990).

A study by Tabacchi and Tabacchi (2001) found that along the longitudinal profile of the Adour River in southwest France, exotic and native ruderals were responsible for significant intermediate term changes in community composition. The patterns of functional type along the longitudinal gradient of the river were the same for natives and exotics, which means that monitoring changes in functional type can inform on the underlying dynamics of biodiversity in the context of climate and land use changes (Tabacchi and Tabacchi 2001). Renofalt, Nilsson and Jansson (2005) found that species richness is highest in the middle reaches of the river during periods of intermediate disturbances by floods, which favors high diversity, whereas following high disturbance events, diversity decreased on a downstream gradient as the magnitude and duration of floods increases downstream.

Downstream dispersal is an important process that influences species composition (Renofalt et al. 2005). Riparian systems typically have a hump-shaped pattern of maximum diversity in the middle reaches, since beyond that the sediments are frequently disturbed, which inhibits the ability of species to establish (Nilsson et al. 1994). This pattern does not necessarily translate for tributaries. Nilsson et al. (1994) found that tributaries generally had the lowest species diversity at intermediate altitudes. Woody vegetation was also found to be more prevalent along tributaries than main channels, whereas the main channels were dominated by smaller, faster growing species (Nilsson et al. 1994).

2.2.1.2 The transverse profile

The flows governed by the longitudinal structure of the river and the geomorphological setting play a role in shaping the transverse structure of the river (Malanson 1993). The transverse structure of a riparian area is key in governing the pattern of vegetation. The nature of river flow, and thus geomorphology, means that vegetation changes with distance from the river’s edge (Reinecke et al. 2015). The magnitude and timing of flow, the area it overflows, and the velocity, depth and duration of inundation all contribute to shaping the geomorphology of the riparian environment (Reinecke et al. 2015).

Additionally, variables that could influence the transverse patterns of riparian vegetation include water table height, flow regimes (including flooding), and the texture of the substrate (Bendix 1994, Reinecke et al. 2015). While valley-side processes have long been acknowledged as having an influence on riparian vegetation, their role is often seen as unimportant compared to the main channel (Friedman et al. 2006). However, in the case of the upper San Miguel and South Fork San Miguel Rivers, valley-side processes were found to be the main influence on riparian vegetation along some reaches of the rivers (Friedman et al. 2006).

2.2.2 Succession in riparian systems

Succession in fluvial corridors is dependent on the interactions between resisting forces, such as sediment cohesiveness, bed and vegetation roughness, and destructive forces, such as floods (Corenblit et al. 2007). These forces mainly play a role in succession along cross sections of rivers, however, at the river reach scale, these factors do not vary as much, so any changes in vegetation pattern could be attributed to time since last disturbance (Baker and Walford 1995). Succession in riparian systems is difficult to predict though, since the aforementioned factors relating to both the biota and environment can change the path of succession (Baker and Walford 1995). Primary succession is common in riparian areas due to new plant communities developing on newly deposited sites, or on abandoned channels (Malanson 1993). The spatio-temporal aspect of succession in fluvial corridors is reliant on bioclimatic, hydrogeomorphic, anthropogenic influences and system history, making it a succession in fluvial landscapes a complex process (Corenblit et al. 2007).

2.3 Ecohydrological interactions

Patterns and structure of riparian vegetation are influenced by fluvial and geomorphological processes and forms (Bendix and Hupp 2000). The mutual interactions between biota and hydrological processes can potentially yield positive feedbacks that create complex echoydrological dynamics (D'Odorico et al. 2010). Influencing mechanisms include flow dynamics, sedimentation, and propagule dispersal (Bendix and Hupp 2000, Bendix 2013). However, there is still more to be known about which factors control species richness in river corridors (Nilsson et al. 1991).

While the focus of the interactions between fluvial landforms and vegetation dynamics in river corridors has traditionally been on the role that landforms play in shaping biological communities, it is now acknowledged that organisms or communities also have the potential to act as controls on geomorphic processes (Corenblit et al. 2007, Bendix 2013). The extent of modification in fluvial corridors by flooding events is mainly a function of the vegetation dynamics in the system, which means vegetation plays a major role in post disturbance recovery in these systems (Corenblit et al. 2007). Vegetation impacts on the fluvial system through its relatively quick ability to colonize on base channel substrate after floods, which allows for the trapping of sediment due to its ability to resist total destruction from flow, and then allows an increase in sediment cohesiveness (Corenblit et al. 2007).

2.3.1 Fluvial systems as an influencing variable on vegetation

Riparian zones are high-value habitats; in order to conserve them, it is necessary to gain a better theoretical understanding of them as a biogeomorphic unit in the landscape (Bendix 2013). Early works relating vegetation to fluvial processes were mostly descriptive and specific to local places and taxa (Bendix 2013). Vegetation patterns and structure in valley bottoms are strongly influenced by fluvial geomorphological processes and forms, which impact flow regimes, and in turn shapes plant demography and controls resource availability (Bendix 2013, Bendix and Hupp 2000). The impact of flood regimes on the composition, distribution, and structure of riparian vegetation was first recognized in the 1930s. One particular example of this recognition is the work of (Illichevsky 1933), he noted that the vegetation in areas that are flooded annually is substantially different to the vegetation in the valley bottom and plateau which is not inundated with water. Mechanisms that influence the patterns and structure of riparian vegetation include flood energy, sedimentation, prolonged inundation, water table depth and dynamics, soil chemistry, and propagule dispersal (Bendix 2013).

While the focus of the interactions between fluvial landforms and vegetation dynamics in river corridors has traditionally been on the role that landforms play in shaping biological communities, it is now acknowledged that organisms or communities also have the potential to act as controls on geomorphic processes (Corenblit et al. 2007). Thus, in order to fully understand both the fluvial processes and ecology of the riparian zone, a biogeomorphic approach is necessary (Bendix 2013). There is, however, the danger of generalizing theories across unlike environments, which calls for close examination of the fluvial-vegetation interactions for each type of environment (Bendix 2013).

2.3.2 Factors influencing ecohydrological interactions

Streamflow variability influences most processes in the fluvial landscape (Dixon 2003, Doulatyari et al. 2014). Streamflow varies spatially along the longitudinal and transverse gradients, which also vary temporally (Lite, Bagstad and Stromberg 2005). Channel dynamics shape the local topography in the riparian zone, which feeds back to control the channel dynamics (Malanson 1993).

River flow dynamics limit riparian vegetation through means of physical disturbance, or serve to encourage plant growth by creating a suitable resource environment (Bendix 2013). Floods also play an important role in the colonization of riparian plants; new deposits create sites for colonization, high energy floods could destroy existing vegetation and limit competition, and a lack of flood following germination will determine whether a seedling persists to maturity (Bendix and Hupp 2000). Since plants are adapted to particular hydrologic conditions, changes in flow regimes can have dramatic effects on plant community composition in riparian ecosystems (D'Odorico et al. 2010). Changes have generally been found to have negative impacts on biodiversity and ecosystem services, however, there has been little success in determining a general relationship between flow alteration and ecological responses (Warfe et al. 2014).

Erosion and deposition, processes central to fluvial geomorphology, are both time- and place-dependent (Malanson 1993). Vegetation plays an important role in controlling flow, and thus impacts on sediment erosion or deposition (Malanson 1993). Sedimentation can either support the establishment of riparian vegetation through the creation of suitable landforms for colonization, or act against it by causing mortality by burial (Bendix 2013). The texture of the sediment also plays an important role in the amount of water available (Bendix 2013), and therefore what species are able to persist in an area.

Vegetation in and along riverbeds modify the energy flows, water and sediment of riparian corridors (D'Odorico et al. 2010). Depending on the nature and location of the vegetation, sites of deposition or erosion are likely to occur, thus playing a role in shaping channel morphology (McKenney, Jacobson and Wertheimer 1995). Malanson and Butler (1990) hypothesized that woody debris creates and stabilizes sedimentary bar deposits, which then intercept more sediment and debris. This sediment and soil then allows for the establishment and development of plant communities, which encourages further deposition of fine sediment, thus increasing the size and height of these bars, and forming a positive feedback (Malanson and Butler 1990). River corridors are also important pathways for dispersal through seeds transported by fluvial processes, animal dispersal, and by the channeling of wind (Malanson 1993, Johansson, Nilsson and Nilsson 1996).

2.4 The riparian landscape under changing conditions

Alterations in flow regimes from natural and anthropogenic related causes reduce the natural ability of river response to disturbances, which calls for proactive management strategies in light of changing climate conditions (Palmer et al. 2008). Combinations of disturbance factors affect the rates and direction of succession, thus, if these processes change, the direction and rate in species composition will too (Malanson 1993, Johnson 1994). Because riparian systems in their natural state are able to adapt to environmental change, their reorganization can also act as early warning systems (Nilsson et al. 2012). Due to the geographically variable nature of riparian systems and climate change impacts, a place-based understanding of spatiotemporal heterogeneity of these systems is required (Seavy et al. 2009). The response of hydrologic systems to changes depends largely on the geographic and anthropogenic contexts (Asbjornsen et al. 2011). Knowledge of rivers in their unaltered state will set the benchmark for successful protection and restoration under changing conditions (Ward et al. 2002), however, this is not always possible.

2.4.1 Climate related impacts on riparian systems

Changes in global climate conditions will have significant impacts on riparian systems. Atmospheric circulation changes impact moisture fluxes and surface energy, which will have immediate and long-term impacts on river systems (Nijssen et al. 2001). Increases in global temperature can affect the amount of precipitation (Palmer et al. 2009), as well as the amount of evapotranspiration in watersheds (Nijssen et al. 2001). Increases in the amount of precipitation, and thus, the likelihood of flooding too will also impact the natural flow regime of rivers and can result in a change in the diversity and functioning of riparian vegetation assemblages (Palmer et al. 2009, D'Odorico et al. 2010, Lawson et al. 2015). This can result in changes to surface hydrology, which will likely have significant impacts on society, as well as regional physical and ecological processes (Nijssen et al. 2001).

Due to the tight linkage between rivers and their terrestrial landscapes, changes to the inputs associated with climate change, will potentially affect river food web productivity and composition (Wrona et al. 2016). It has been predicted that there will be an increase in hydrologic fluctuations under climate change conditions, however, there is still a lack of understanding regarding how ecosystems may respond to the combination of hydrologic extremes and climate change (D'Odorico et al. 2010). It is difficult to forecast potential changes to flow regimes as seasonal timing and variability of flow due to a changing climate will vary between rivers and regions (Woo et al. 2008). A study along the San Pedro River in Arizona found that an increase in stream intermittency would likely lead to a shift from a hydric to mesic plant community, which could then lead to hydrologic and geomorphic feedbacks (Stromberg, Lite and Dixon 2010). To ensure the correct management of fluvial ecosystems, it is imperative to improve understanding of how plant community structures are likely to respond to climate change (McShane et al. 2015, Rocha et al. 2015).

2.4.2 Human altered riparian systems

Riparian areas are some of the most threatened ecosystems due to human constructs and the spread of non-native species (Tockner et al. 2010). These areas have high human occupancy and dominance due to the goods and services they provide society, which makes them easily exploited (Palmer et al. 2009, Tockner et al. 2010). Floodplains maintain their highest levels of heterogeneity in their natural state, however, many floodplain reaches have been altered, leading to an inaccurate understanding of the patterns and processes in riverine landscapes (Ward et al. 2002). The natural regime hypothesis states that riparian species are adapted to a particular temporal and spatial flow regime, which needs to be maintained in order to support that community (Stromberg 2001). The main causes of riparian vegetation loss and degradation are due to changes in herbivory regimes, alteration in hydrologic regimes, and conversion of land use to irrigated cropland or urban areas (Stromberg 2001). Human impacts on riparian systems are far-reaching owing to their operation at multiple spatial and temporal scales (Steiger et al. 2005). Since floodplain ecosystems are highly sensitive to anthropogenic impacts (Nilsson and Berggren 2000, Mosner et al. 2015), the ability of river systems to continue to provide existing goods and services is largely dependent on successful management schemes (Palmer et al. 2009). Alterations to the water and sediment regimes of riverine systems by means of various activities, can modify the structure of the riparian habitat and ultimately damage the ecological integrity of the system (Steiger et al. 2005). The manner in which these ecosystems can be protected is one of the most important current questions (Nilsson and Berggren 2000).

The natural flow regime of a river includes the quantity, timing and variability of flow, controlled by river size, climate, geology, topography, and vegetative cover (Poff et al. 1997). Natural flow regimes can be altered through damming (Nilsson and Berggren 2000), land use change (Allan 2004), and extraction, stream diversion, and canalization (Poff and Zimmerman 2010). Stream diversion has many potential impacts on riparian communities that threaten the system (Smith et al. 1991). Areas below reservoirs are impacted by a reduction of flow variation and flood peaks (Malanson 1993). Exact responses of vegetation to an alteration of flow are difficult to predict due to rivers being complex and dynamic ecosystems with interactions between hydrological, geomorphological, and biological variables (Jansson et al. 2000). The greatest impacts on riparian vegetation from changes in streamflow result from changes in disturbance and stress regimes (Shafroth, Stromberg and Patten 2002). Terraces are allowed to build up in areas where flooding is eliminated due to flow regulation, which then results in a shift of forces to those that are autogenic (Decamps et al. 1988). Smith et al. (1991) found that stream diversion had the greatest impact on plants on hot days when the lessened water supplies were not sufficient to maintain the evaporative demands of the plants. To prevent dieback of vegetation and encourage recruitment in riparian corridors, watershed managers need to determine what the minimum flow and seasonal variation of the systems are (Smith et al. 1991).

Large amounts of water are consumed by the agricultural sector to sustain croplands and rangelands (D'Odorico et al. 2010). While water is a necessary component of agriculture, if not managed correctly, it can have a very damaging effect on riparian systems. Irrigation and dams can result in major reductions in river flow, and hence have far reaching implications for ecohydrologic connectivity (D'Odorico et al. 2010). Apart from high amounts of water extraction, overgrazing can also negatively impact a hydrological regime. Overgrazing can result in compacted soils and lowered water tables; to revert these impacts, stocking rates could need to be reduced or grazing completely eliminated from the system (Stromberg 2001). Areas not bordered by riparian forest due to agricultural conversion have also been found to have higher rates of erosion (Micheli, Kirchner and Larsen 2004).

Deforestation in riparian corridors impacts on wildlife through the removal of suitable habitats, and also impacts the actual stream through lowering water levels and quality of habitat (Sweeney et al. 2004). Channel width tends to increase and bank erosion becomes more prominent at sites which have been logged (Boothroyd et al. 2004). Erosion can also increase following the construction of a dam. A study on the Sacramento River, California, found that channel migration and erodibility increased by up to 50% following the construction of an upstream dam (Micheli et al. 2004).

The most effective way to restore riparian ecosystems affected by changes in fluvial processes is to revert back to the natural hydrologic regime (Stromberg 2001). In order to do this effectively, a landscape approach is required (Tockner, Malard and Ward 2000).

2.5 Overview of Arctic riparian systems

The majority of the Arctic lands are low-lying, with some mountains and high plateaus (Serreze and Barry 2005). The High Arctic is mostly comprised of tundra, which at its northernmost limits is cold and lacks moisture, classifying it as a polar desert (Serreze and Barry 2005). The Low Arctic is highly vegetated, with 80-100% surface coverage, dominated mostly by shrubs, sedges and grasses (Serreze and Barry 2005). Arctic hydrology allows for the connection of landscapes and environmental gradients through rivers, lakes, ponds, and wetlands (Wrona et al. 2016). Most runoff from snowmelt occurs in the spring months, followed by increases in runoff from glacial melt in the summer months (Marsh and Woo 1981). River discharge generally appears to be increasing across the Arctic in recent decades (Bring et al. 2016), with an approximately 7% increase to the Arctic Ocean for records from 1936 to 1999 (Peterson et al. 2002).

2.5.1 Arctic rivers and climate change

Hydro-ecological processes are impacted by even slight changes in climate (Prowse et al. 2006). Due to temperature variability being higher in the Arctic than the rest of the globe (Serreze and Barry 2011), Arctic freshwater systems are particularly sensitive to climate change (Prowse et al. 2006). Snow-dominated drainage basins in the mid to high latitudes are likely to experience the greatest changes in hydrological cycles due to a combination of these regions experiencing greater warming than the rest of the globe, and because of reductions in the amount of water stored in the snow pack (Nijssen et al.

2001). The cold season in the terrestrial regions of the northern latitudes has the highest projected temperature increases, which will have a significant impact on the timing and severity of hydrologic events such as spring freshet and ice breakup (Prowse et al. 2006). Changes to patterns of Arctic precipitation will also impact on Arctic riparian systems (Serreze and Barry 2011).

Discharge into the Arctic Ocean is dominated by a few large rivers, with 68% of all discharge coming from the four largest drainage basins, namely the Ob, Yenisey, Lena and Mackenzie (Serreze and Barry 2005). Annual discharge for the six largest Eurasian rivers that flow into the Arctic Ocean increased by 7% between 1936 and 1999 (Peterson et al. 2002). Increases correlate with the North Atlantic Oscillation, as well as increases in global mean surface air temperatures (Peterson et al. 2002). While changes in temperature and precipitation are the main drivers of increased river discharge (Lique et al. 2016, Vihma et al. 2016), there is still uncertainty regarding mechanisms of such increases. In some basins, permafrost thaw has been the dominant mechanism behind a change in the hydrological regime (Bring et al. 2016). The sensitivity of Arctic freshwater systems to small changes in climate means that multiple hydro-ecological processes are affected by a changing climate, making these systems very vulnerable (Prowse et al. 2006).

Owing to the heterogeneity of Arctic landscapes and sensitivity of Arctic landscapes to climate change, streamflow changes will not impact all systems in the same manner (Botter et al. 2013). For example, regional conditions such as elevation and vegetation cover type will influence the amount of snow storage and runoff, which means that hydrology changes will differ from basin to basin (Essery and Pomeroy 2004). Seasonal differences in flow regimes are often great for most catchments, which means that the type of water availability and sensitivity to climate change will also likely be different according to the time of year (Botter et al. 2013). Increases in winter temperatures reduce snow cover, which can lead to increases in rainfall events, and extended spring snowmelt lead to increases in winter runoff (Lammers et al. 2001). Such increases in winter flow rates have been observed in the Ob, Yenisey, and Lena basins, which could have a wide range of impacts including stream and river chemistry, habitat, icing, and erosion and sediment fluxes (Hinzman et al. 2005).

It is expected that as warming persists in the cold season of the Arctic regions, ice breakups and flooding are likely to be less severe as they will be initiated in periods of lower insolation (Prowse et al. 2006). Long-term analyses of the hydrologic regime of the Lena River in Siberia show that there is a strong link between changes in climate and stream flow and river ice thickness, leading to an alteration of the river's hydrologic regime (Yang et al. 2002). Such changes include the advance of spring melt leading to higher daily discharge in May and lower amounts in June (Yang et al. 2002). These shifts are important for rivers which form in permafrost rich areas as the majority of geomorphic processes occur over a relatively short period of time (Walker and Hudson 2003).

Warming temperatures could lead to more time for geomorphic processes to act, and thus, also initiate changes in the riparian environment. Almost all of the Arctic land areas are underlain by permafrost, which makes it the primary control of hydrologic processes (Serreze and Barry 2005). Arctic lakes, rivers and ponds are significantly influenced by cryospheric components, which then influences the habitats of these systems and the biota that occupy them (Prowse et al. 2006). Therefore, changes in permafrost occurrence and distribution due to warming climate effects will lead to changes in geomorphological and hydrological processes (Hinzman et al. 2005). Thermokarst erosion will likely alter the fluvial geomorphology of Arctic systems due to increases in suspended sediment loads, however, new fluvial-morphological adjustments will likely take place over hundreds of years due to the extended amount of time it takes for new vegetation to establish and stabilize the landforms (Prowse et al. 2006). Deepening active layers increases the potential of runoff storage, which will lower spring peak flows, however, summer thaw will increase the amount of base flow from groundwater flow, causing a flattening of annual hydrographs (Prowse et al. 2006). River water properties will also be affected by increased permafrost thaw. An increase in groundwater and decrease in surface runoff contributions will lead to an alteration in river temperatures and chemical properties (Hinzman et al. 2005). A modeling study by Hinzman and Kane (1992) found that increases in storage capabilities of the permafrost soils will lead to variable responses in runoff, depending on whether rainfall was received in the form of a many light events, or a few major ones. While permafrost thaw has led to increases river discharge, it is unlikely that it is the main driving mechanism behind the observed increases in Arctic river discharge (McClelland et al. 2004). McClelland et al. (2004) also state that even when coupled with increases in fires, and dam regulation, discharge increases are still too high to be from those mechanisms, and are likely due to increased atmospheric moisture transport under climate change conditions.

In Alaska, river basins with glaciers have exhibited increases in runoff, likely due to glacial melt, whereas river basins lacking large glaciers have shown decreases in runoff, presumably due to increases in evapotranspiration rates exceeding those of increasing precipitation (Hinzman et al. 2005). Discharge data from the Kurapak River in Alaska indicates that a seasonal shift in the hydrologic regime in response to regional warming on the North Slope of Alaska is taking place (Hobbie and Kling 2014). Overall changes in the amount of runoff in the Toolik Lake region have not been observed, however, the timing of peak runoff has, and it is expected that it will continue to shift (Hobbie and Kling 2014). When coupling increased temperatures with no increases in total annual runoff, rivers are more susceptible to drought, which has been observed for the Kurapak River in recent years (Hobbie and Kling 2014). Droughts have negative impacts on biota due to the drying of river channels, reduction in amount of habitable areas and by impeding annual immigrations (Hobbie and Kling 2014).

Changes to the hydrologic regimes in the Arctic through adjustments to precipitation, evapotranspiration (ET), and runoff, combined with changes related to runoff from snow, ice, and permafrost will have major impacts on related physical, geochemical, biological, and ecological processes in terrestrial, freshwater, and marine ecosystems (Wrona et al. 2016). However, given the regional variability of the Arctic, there is still great uncertainty regarding the direction and magnitude of such impacts (Wrona et al. 2016). While these changes are expected, it is difficult to forecast exactly how they will develop as they will be different according to environmental gradients related to stream order, latitude, and topography (Wrona et al. 2016).

2.5.2 Implications for Arctic tundra vegetation

The Arctic is species poor and uniform region, making it a relatively simple system (Malanson 1993). Species diversity in the Arctic is generally highest in the riparian areas, making them areas of interest from a landscape ecology perspective (Malanson 1993). Vegetation on the North Slope of Alaska predominantly consists of perennial forbs, grasses, sedges, dwarf shrubs, mosses and lichens, however, it is common for rivers and streams to have shrublands adjacent to their margins (Schickhoff, Walker and Walker 2002). In the Toolik Lake area, local abiotic conditions, largely influenced by topographic position, are key in limiting or facilitating the presence of species, and thus, affect community diversity (Shaver et al. 2014). Riparian vegetation has a key influence on Arctic rivers as it can alter water and light regimes, as well as increase the amount of organic matter in surface waters (Wrona et al. 2016). Therefore, the combination of hydrologic and climatic related changes can have a major impact on terrestrial and freshwater ecosystem services (Wrona et al. 2016).

Changes in flow regimes could result in either increases or decreases in habitat availability or quality throughout the Arctic (Prowse et al. 2006, Wrona et al. 2016). Thawing permafrost and increased glacial melt water will increase input to streams and rivers, thus creating more unstable hydrologic conditions and result in both lateral and longitudinal shifts in vegetation (Nilsson et al. 2012). Increased temperatures, changes in hydrology, and increased ice dynamics are potential ways that climate change can affect riverine ecosystems in boreal environments (Nilsson et al. 2012). Ice break-up is a major disturbance that shapes the geomorphology of the riparian zone in such systems (Scrimgeour et al. 1994); changes in the timing and magnitude of ice break-up events can lead to changes in vegetation structure due to changes in geomorphological structures.

The downslope movement of water and materials in the Arctic results in a linkage between the hydrological, biogeochemical, and plant-community processes that shape the zonation of vegetation from the dry heaths on high-lying areas to the tall shrubs in the low-lying riparian areas (Kling et al. 2014). This results in distinct spatial differences in vegetation composition and productivity (Kling et al. 2014), which when affected by changing conditions, will lead to changes in community diversity (Shaver et al. 2014). In the Imnavait Creek watershed Walker and Walker (1996) found that well-developed water tracks contained willow and dwarf-birch communities, which are distinctly different to the surrounding tussock tundra. As permafrost thaws, it is likely that these water tracks will become more developed, and therefore, there will be a shift in the vegetative communities. High elevation tundra streams tend to lack well-developed willow shrublands, however, they become more established in the lower elevations (Walker and Walker 1996).

Shrub expansion is a well-documented change occurring in the Arctic tundra regions (Sturm et al. 2001b, Tape et al. 2006a, Hallinger et al. 2010, Myers-Smith et al. 2011b, Naito and Cairns 2011a, Elmendorf et al. 2012b, Frost et al. 2013, Naito and Cairns 2015, Ackerman et al. 2017, Martin et al. 2017, Myers-Smith and Hik 2017).

While shrub expansion is mostly thought to be due to increases in temperature and precipitation, changes in local hydrological processes can also contribute to increased shrub growth (Wrona et al. 2016). It has been shown that shrub expansion rates are greatest in high resource environments where there is greater moisture availability (Naito and Cairns 2011b, Tape et al. 2012). Therefore, changes to local hydrology can encourage further shrub growth.

With increases in the distribution and height of shrubs, less snow is redistributed by wind and lost to sublimation (Liston et al. 2002), which will impact on local river hydrology. Evapotranspiration is likely to increase as longer growing seasons and more favorable conditions, which could encourage further shrub expansion. A shift in the plant communities in the tundra environment from non-transpiring mosses and lichens to shrublands could lead to drier surface conditions (Prowse et al. 2006, Wrona et al. 2016). However, the complexity of the interactions between factors such as land surface heterogeneity, soil properties, vegetation characteristics, and moisture availability makes modeling evapotranspiration difficult and uncertain (Bring et al. 2016).

Changes in the distribution of shrubs will lead to shifts in the distribution of Arctic wildlife that browse them (Tape et al. 2016b). A northward expansion of moose (Alces alces) (Tape et al. 2016b), snowshoe hare (Lepus americanus) (Tape et al. 2016a), and ptarmigan (Lagopus lagopus, L. muta) (Christie et al. 2014a) has been observed in tundra regions of Alaska (Zhou et al. 2017). Since these species prefer the *Salix alaxensis* as forage, it is likely that the expansion of shrubs is causing the changes to their distribution patterns (Zhou et al. 2017). The moose and hares will likely continue to increase in concentrations in the riparian corridors in the Brooks Range and on the North Slope of Alaska where tall shrub expansion is prevalent (Zhou et al. 2017). Browsing can alter the architecture, growth and reproduction of shrubs (Christie et al. 2015), which can influence stream banks that are stabilized by shrubs. Herbivory, therefore, will also play a role in shaping vegetation composition, and could moderate the rates of expansion of the preferred willow species (Christie et al. 2015). Shifts in the distribution of these herbivores will also impact on local communities who rely on subsistence hunting and trapping (Vargas-Moreno et al. 2016).

Riparian shrublands are key for providing streambank stability, have relatively high species diversity, provide organic matter for aquatic biota, provide resources and services for wildlife, and cover a significant spatial extent, which makes them an important aspect of Arctic landscape ecosystems (Schickhoff et al. 2002). A study comparing a constructed Arctic stream to natural reference streams in the Barrenlands region of the Canadian Arctic found that the riparian zone of the constructed stream was lacking vegetation, and as a result had lower amounts of woody debris, coarse particulate organic matter (CPOM), and epilithon, which supported lower amounts of macrophytes and bryophytes (Jones, Scrimgeour and Tonn 2008). This suggests that with increases in riparian vegetation, Artic streams could have more productive environments, and ultimately a shift in community structure. Multidisciplinary studies at the basin scale will be key to understanding the connections between hydrology, the atmosphere, oceans, ecology and resources in the Arctic (Bring et al. 2016).

2.6 Conclusion

Riparian areas are unique habitats that serve as the connection between terrestrial and aquatic zones. These areas are, however, sensitive to both natural and anthropogenic related changes. As a result, the linkages between vegetation and water resources is now gaining much attention in the form of specialist fields, such as, ecohydrology, biogeomorphology, and fluvial landscape ecology. Such interdisciplinary research is crucial in order to best conserve riparian systems under changing conditions.

The reciprocal relationship between vegetation and fluvial processes, and varied scales of influence makes understanding these complex systems challenging. The connections between upland vegetation, and fluvial systems is an important relationship that needs to be established in order to best manage the integrity of these systems and downstream water supplies. An understanding of these systems is imperative for effective management through anthropogenic and natural drivers of change. Monitoring of riparian systems is important to determine the benchmark for protection and restoration, and since these systems can act as good early warning systems in response to changes.

Due to the tight linkages to climate, hydro-ecological processes are even impacted by minor changes in climatic conditions. One system that is particularly sensitive is the Arctic, which is warming at a rate higher than the rest of the globe. This will have significant impacts on hydrologic regimes, and can ultimately lead to shifts in the riparian ecological communities.

CHAPTER III

REGIONAL SCALE PATTERNS OF SHRUB COVER AND RELATED ENVIRONMENTAL VARIABLES ON THE NORTH SLOPE OF ALASKA.

3.1 Introduction

Species distributions are expected to shift with changes in climate at a global scale (Walther et al. 2002, Parmesan and Yohe 2003, Gaston 2009, Chen et al. 2011), however, in the case of shrub expansion, climate is not the only driving factor. Processes influencing shrub expansion operate at different scales. The “greening” of the Arctic has been documented at multiple scales. Myneni et al. (1997) used the normalized difference vegetation index (NDVI) created from satellite imagery to investigate changes in plant productivity at the global scale. The greatest increases in photosynthetic activity from 1981 to 1991 were found between 45° and 70° N, which tracked with increases in the amplitude of the seasonal cycle of atmospheric CO_2 at Point Barrow, Alaska (Myneni et al. 1997). The authors conclude that at the regional scale, there is highly significant evidence for changes in photosynthetic activity and CO_2 in response to changes in surface air temperature (Myneni et al. 1997). A similar study that focused on the Arctic tundra photosynthetic activity north of 70°N between 1982 and 1999 also found significant increases in productivity in Russia, the Alaska North Slope, parts of northern Canada and Scandinavia (Stow et al. 2004). A more regional study, specific to northern Alaska, found a 16.9% increase in greenness (Jia, Epstein and Walker 2003). Finer scale (1-km resolution) analyses were conducted for four vegetation types over an 11 year period; it was found that the greatest increases in greenness were in the areas of moist acidic tundra (Jia et al. 2003). A study based on the seasonally integrated normalized difference vegetation index (SINDVI) for the north slope of Alaska found increasing SINDVI values for the whole region, however, the increases in the foothills were higher than those in the coastal plain (Stow et al. 2003).

A conversion of arctic tundra to shrubland will have ramifications for sensible heat flux (Sturm et al. 2005a, Sturm et al. 2005b). Dark shrubs protruding through snow also leads to a reduction in albedo, and more regional warming, leading to accelerated snow melt (Sturm et al. 2005a, Sturm et al. 2005b). Additionally, increased shrubs can be a carbon sink due to the allocation of carbon to the woody stems of shrubs, however, the potential warming of soils by the insulation of shrubs can lead to a change in the thermal regime of permafrost, and result in the loss of large carbon stocks (Oechel et al. 2000, Sturm et al. 2005a, Sturm et al. 2005b). Increases in shrub habitat has also facilitated the northward expansion of species such as moose (*Alces alces*) (Tape et al. 2016b), snowshoe hare (*Lepus americanus*) (Tape et al. 2016a), and ptarmigan (*Lagopus lagopus, L. muta*) (Christie et al. 2014a) in the tundra regions of Alaska (Zhou et al. 2017). Shrub height was found to be a controlling factor for the occurrence of those species, which means that as shrubs continue to expand, there will be more available habitat for them (Zhou et al. 2017).

Species distribution changes will impact subsistence hunting and trapping abilities for local communities. Further, herbivory also has the ability to shape vegetation distribution and composition. The fast-growing willow (*Salix* spp.) are preferred by the main herbivores over the well-defended alder (*Alnus viridis*) and resinous dwarf birch (*Betula nana exilis*) (Christie et al. 2015). This means herbivory could slow down the rates of expansion of the willow species (Christie et al. 2014b). When considering potential feedbacks and the impact on local communities, it highlights the need for ecosystem-based habitat status and trends monitoring (Vargas-Moreno et al. 2016).

There is still uncertainty regarding the factors that facilitate shrub growth and expansion. Since the rates of shrub cover increase vary at the regional and landscape scales, there is a need for more studies that focus on the northward expansion of shrubs, to help determine the associated environmental variables (Frost and Epstein 2014, Myers-Smith and Hik 2017).

Temperature and precipitation have long been regarded to be the dominant drivers of increases in Arctic productivity, however, recently a decoupling of these drivers from Arctic productivity has been noted (Martin et al. 2017). While it has been assumed that vegetation productivity will track with temperature increases, there is evidence that vegetation productivity is not increasing northward at the same rate as temperature (Huang et al. 2017). To test whether temperature and precipitation are still the driving factors of increases in Arctic productivity, or whether they have decoupled, multiple temperature and precipitation variables are tested here.

Since the base of the active layer acts as a barrier to roots, permafrost can act as a controlling factor regarding shrub establishment (National Research Council 2003). However, since the Arctic is warming, there is an expectation that widespread permafrost degradation will occur (Jorgenson, Shur and Pullman 2006, Shur and Jorgenson 2007, Grosse et al. 2011). Under these conditions, shrubs may be establishing in areas of lesser permafrost extent. Therefore, here the relationship between shrub cover and permafrost zonation index is tested.

Interactions between climate and local biophysical factors affect artic and boreal ecosystems, with environmental gradients and disturbance regimes encouraging different responses to climate warming at the ecosystem scale (Jorgenson et al. 2015). Edaphic factors, such as soil pH and soil moisture, as well as factors related to topography and disturbance are key to determining the spatial patterns and floristic compositions of riparian plant communities on the Arctic Slope of Alaska (Schickhoff et al. 2002). Understanding the diverse responses of ecosystems to climate change is a notable challenge (Jorgenson et al. 2015). There is not yet consensus regarding the rate at which vegetation will change to a different class; Pearson et al. (2013) projected that 48-69% of Arctic vegetation will change class by the 2050s, whereas Jorgenson et al. (2015) project a much slower rate of 13%. Here community, functional group, and floristic province data are used to assess where the greatest shrub cover is in relation to dominant vegetation type classifications.

One of the most important factors that determines vegetation composition in the Arctic tundra is substrate pH (Walker 2000). Swanson (2015) found along with July temperatures above 10.5°C, soil acidity to be a limiting factor of the presence of tall shrubs in five National Parks in northern Alaska, with the highest shrub canopy volumes on weakly acidic to neutral soils (pH 6 – 7). The different shrub species tolerate specific environmental conditions. *Alnus viridis* is more tolerant of more acidic soils, however, it also required higher summer temperatures for favorable growing conditions (Swanson 2015). The *Salix* species varied, with *S. pulchra* proving to be tolerant of wetter, and moderately acidic soils, whereas *S. alaxensis* was found on well-drained soils with a more neutral pH (Swanson 2015). Shrub cover in relation to soil pH (Acidic, Circumneutral, and Carbonate) is tested here.

Another potentially important driver of shrub growth is that of soil moisture (Ackerman et al. 2017). Some tall shrub species prefer well-drained microsites. Lloyd et al. (2003) found that the dry thaw-pond banks were colonized preferentially over the surrounding tundra. Since shrubs may be limited to such microsites even if climatic conditions are favorable, the association between shrub cover and lake coverage is examined here. In areas where there are a higher proportion of lake coverage, there may be a higher amount of shrub cover due to the chance for favorable microsites.

Topography could also play a role in the amount of shrub cover on a landscape. Temperatures are lower at higher elevations; thus, shrub establishment could be limited at higher elevations in mountainous terrain. Contrary to the temperature control, it has also been found that shrubs are expanding at higher rates on shallow hillslopes (Myers-Smith and Hik 2017). For these reasons, the relationship between topography and shrub cover is also tested here.

This chapter assesses the distribution of shrub cover at the regional scale, and its association with selected environmental variables. This was addressed by the following two objectives:

1. Assess whether there is a relationship between shrub cover and latitude and/or longitude.
2. Determine whether there is an association between shrub cover and temperature, precipitation, permafrost, vegetation functional group, community type, substrate pH, lake cover, topography, floristic province and bioclimate subzone.

The results of this objective will aid in understanding whether the entire North Slope is likely to undergo shrub expansion at the same rate, or whether certain areas are still limited regionally by environmental variables.

3.2 Methods

To analyze the distribution of shrub cover and its environmental associations, 50 areas of interest on the North Slope of Alaska were selected based on image availability, with the goal to obtain a representative sample of the different land cover types on the North Slope. The areas of interest were delineated in a manner which incorporated all the topographic variability present in that area, and thus ranged between 36 km^2 and 404 km^2. High resolution satellite images from WorldView-2, WorldView-3 and GeoEye-1 satellites were sourced from DigitalGlobe, Inc. Archives. The resolution of the images is 46 cm, 31 cm, and 41 cm respectively. The images, acquired in June to September of 2010 and 2016, were selected based on the lack of snow and cloud cover.

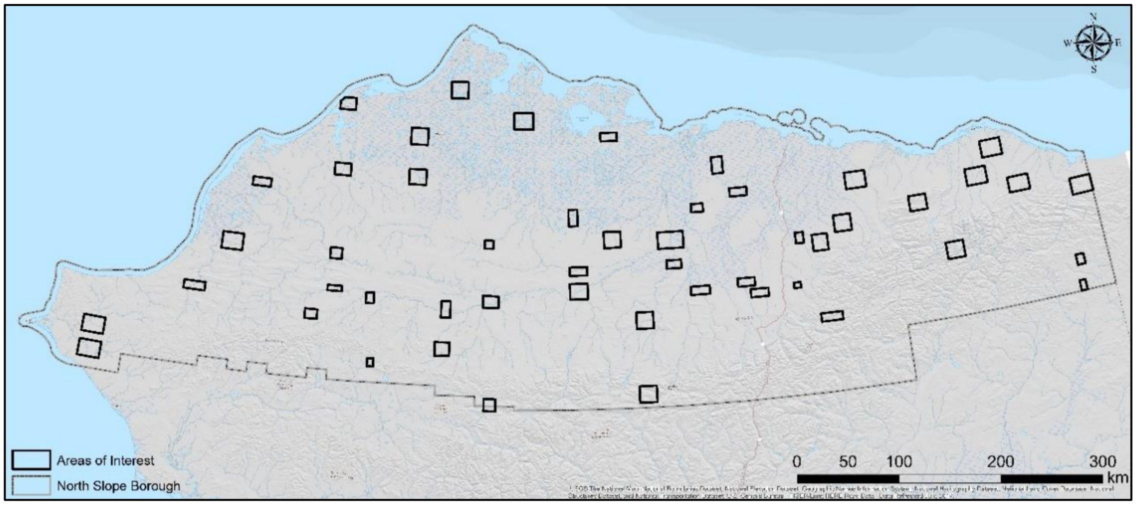

Figure 1: The 50 areas of interest on the North Slope of Alaska.

The image tiles were mosaicked using ArcMap 10.5, and then resampled to a resolution of 0.5 m to ensure all images were in a common resolution before analysis. Each image was then classified independently using the supervised Maximum Likelihood classifier in ENVI 5.4. Each image was then reclassified in ArcMap 10.5 to classes of “non-shrub’ (0) and “shrub” (1), which allowed for a calculation of percent shrub cover.

To test whether there is a relationship between percent shrub cover and latitude and longitude, the central point of each image was assigned using ArcMap 10.5, and then statistically tested using linear regression. The relationship between temperature, precipitation, and permafrost was also testing using linear regression, based on the value at each of those central points. Spatially interpolated temperature and precipitation climate data, averaged from 1970-2000, were sourced at the 30 second (~1km^2) scale from WorldClim 2, Global Climate Data (Fick and Hijmans 2017). The following temperature variables were selected for analyses: Annual Mean Temperature (Figure 2), Max Temperature of the Warmest Month (Figure 3), and Min Temperature of the Coldest Month (Figure 4). Precipitation was analyzed by Annual Precipitation (Figure 5), Precipitation of Wettest Month (Figure 6), and Precipitation of Driest Month (Figure 7) Permafrost coverage data (Figure 8) were sourced from Gruber (2012). This high resolution (< 1km) permafrost zonation index (PZI) is sensitive to local spatial heterogeneity, and ranges from 0.01 for areas of isolated patches of permafrost to 1 for areas of continuous permafrost (Gruber 2012).

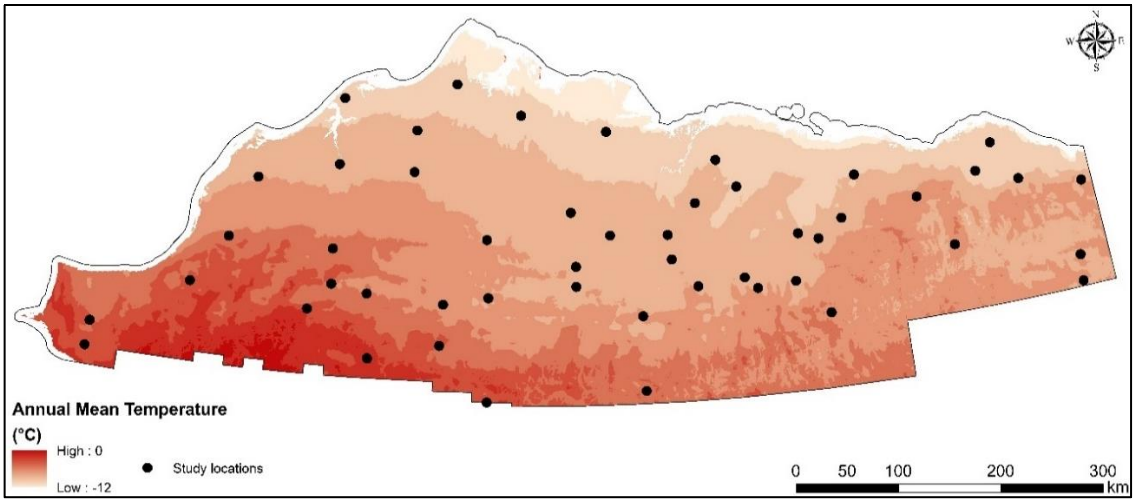

Figure 2: Mean annual mean temperature (1970-2000) on the North Slope of Alaska (Fick and Hijmans 2017).

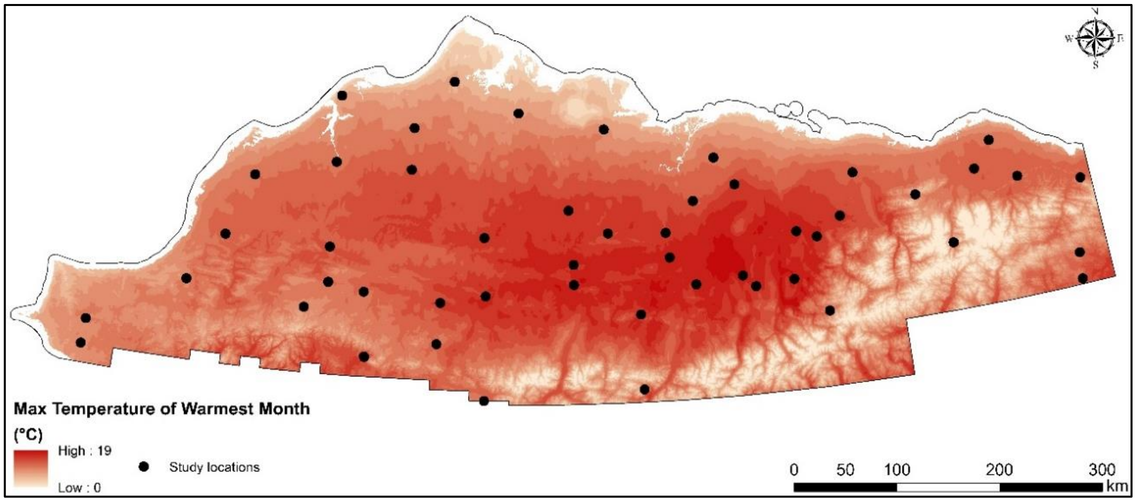

Figure 3: Mean maximum temperature (1970-2000) of the warmest month on the North Slope of Alaska (Fick and Hijmans 2017).

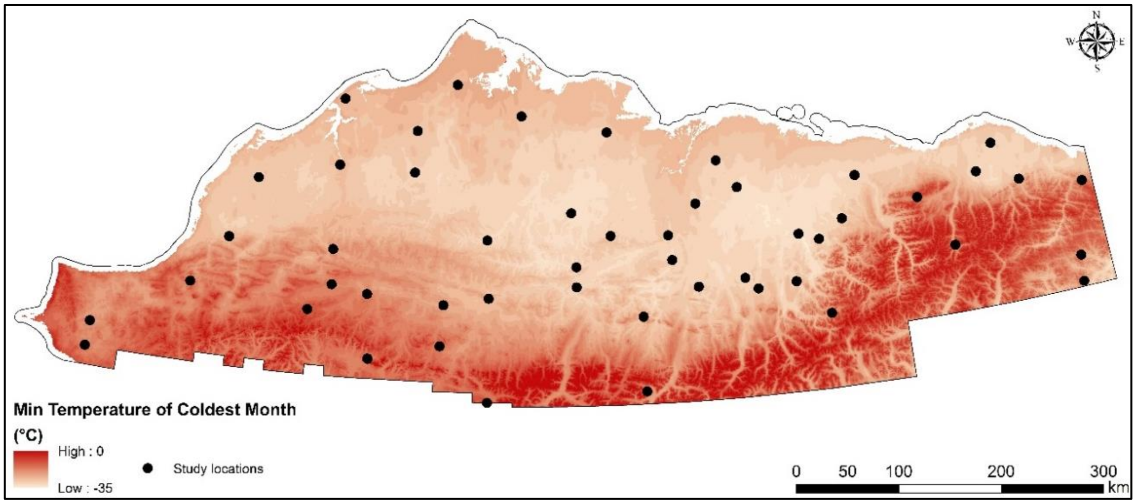

Figure 4: Mean minimum temperature (1970-2000) of the coldest month on the North Slope of Alaska (Fick and Hijmans 2017).

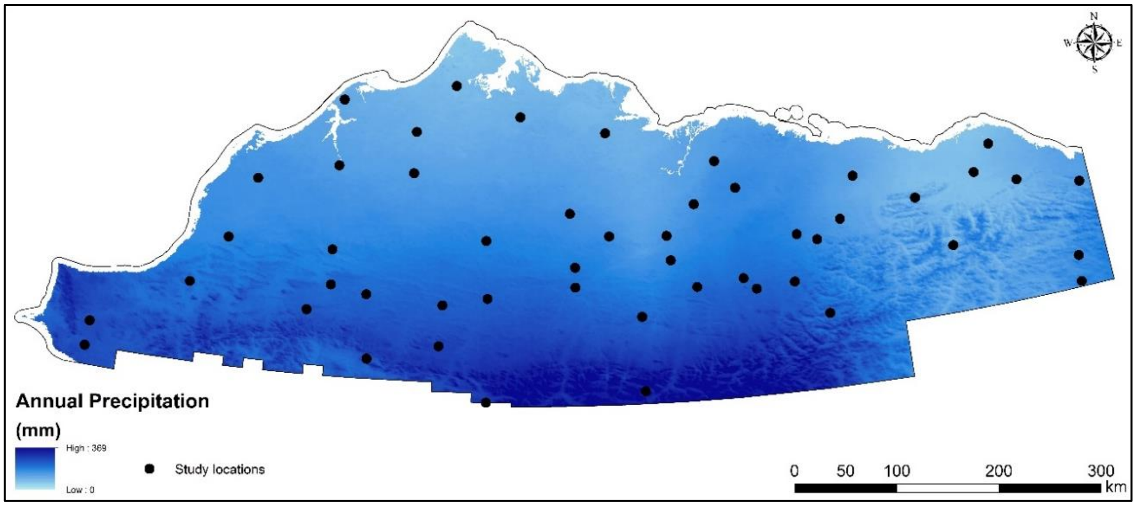

Figure 5: Mean annual precipitation (1970-2000) on the North Slope of Alaska (Fick and Hijmans 2017).

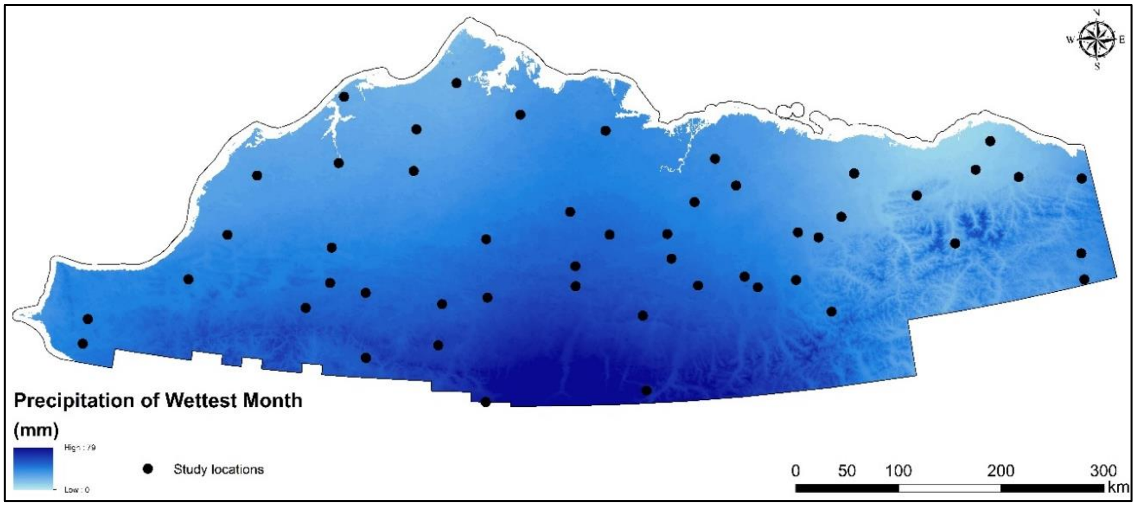

Figure 6: Mean precipitation of the wettest month (1970-2000) on the North Slope of Alaska (Fick and Hijmans 2017).

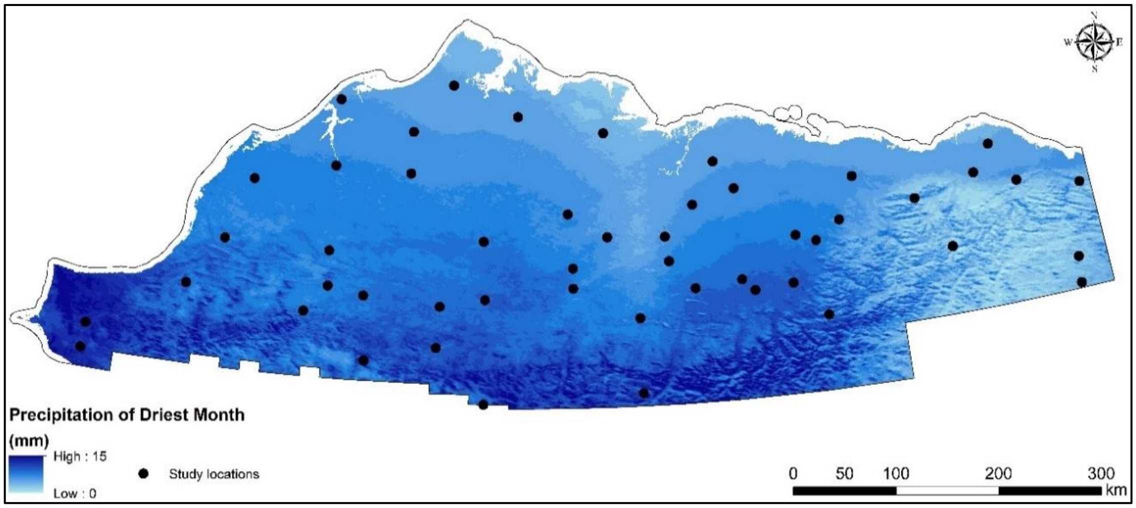

Figure 7: Mean precipitation of the driest month (1970-2000) on the North Slope of Alaska (Fick and Hijmans 2017).

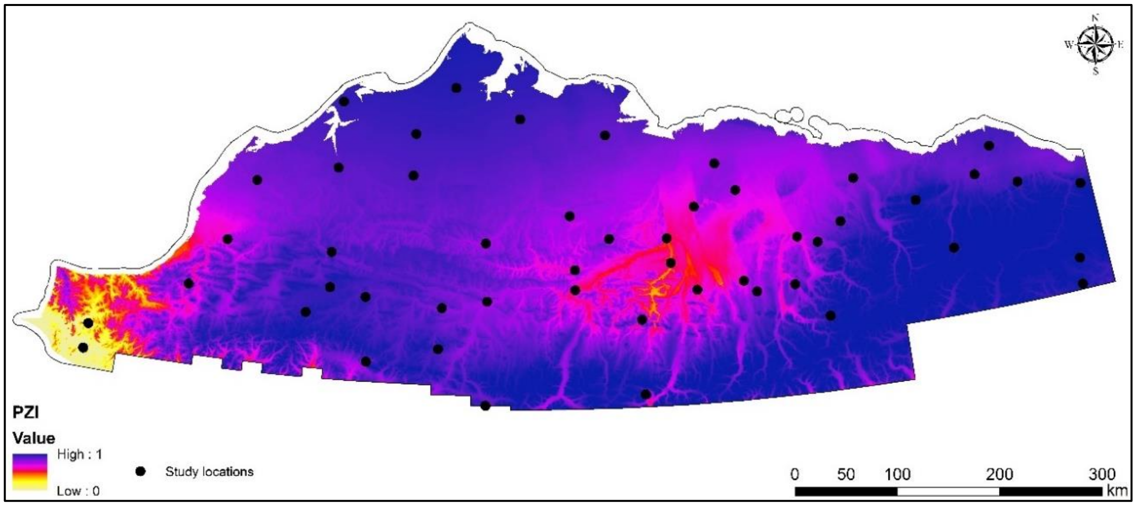

Figure 8: Permafrost zonation index on the North Slope of Alaska (Gruber 2012).

A dataset from NASA's Pre-Above project was used to test whether other regional environmental variables have an influence on shrub cover at the regional scale (Raynolds & Cooper, 2016). This dataset includes the spatial distributions of vegetation types, geobotanical characteristics, and physiographic features for the Alaskan Arctic tundra region (Raynolds & Cooper, 2016). These variables include vegetation cover, substrate pH, lake cover, topography, floristic province, and bioclimate subzone (Table 1). The vegetation cover consists of 33 units (15 were intersected by these data), mapped according to dominant plant functional type, on specific substrates or in different geographic regions (Figure 9, Table 1) (Raynolds & Cooper, 2016). For the analysis of this study, this layer was also reclassified by physiognomic unit, namely barrens, graminoid tundras, erect-shrub tundras, and wetlands (Figure 10, Table 1). The substrate pH has just three classes, acidic, circumneutral, and carbonate (Figure 11, Table 1). The lakes layer consists of data of percent coverage by lakes in four categories, namely <2%, 2-10%, 10-25%, and 25-50% (Figure 12, Table 1). Topography is split into areas of plains, hills, mountains, lagoons, glaciers, and lakes (Figure 13, Table 1). Two floristic provinces are present on the North Slope of Alaska, namely Beringian Alaska, and Northern Alaska (Figure 14, Table 1). There are five bioclimate subzones in the Arctic, however only three are present in Alaska, subzone C, D, and E, with subzone C being the furthest north (Figure 15, Table 1).

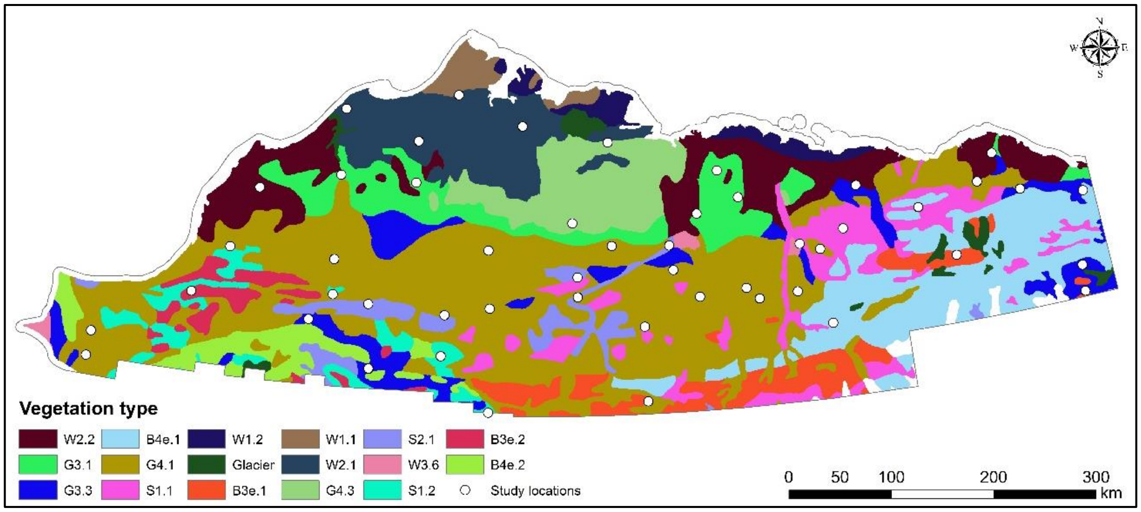

Figure 9: Vegetation type on the North Slope of Alaska (Raynolds & Cooper, 2016).

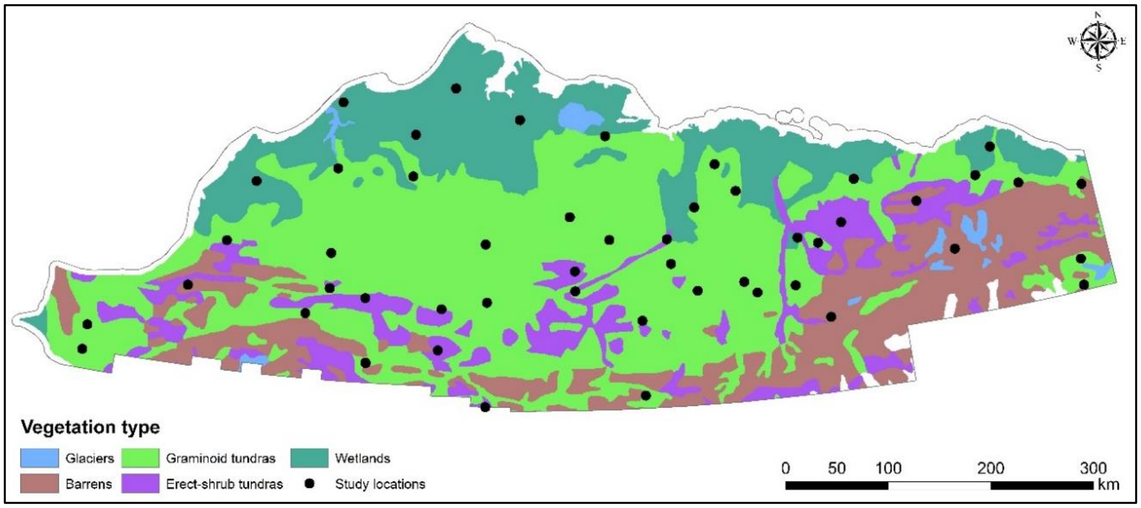

Figure 10: Distribution of plant physiognomic units on the North Slope of Alaska (Raynolds & Cooper, 2016).

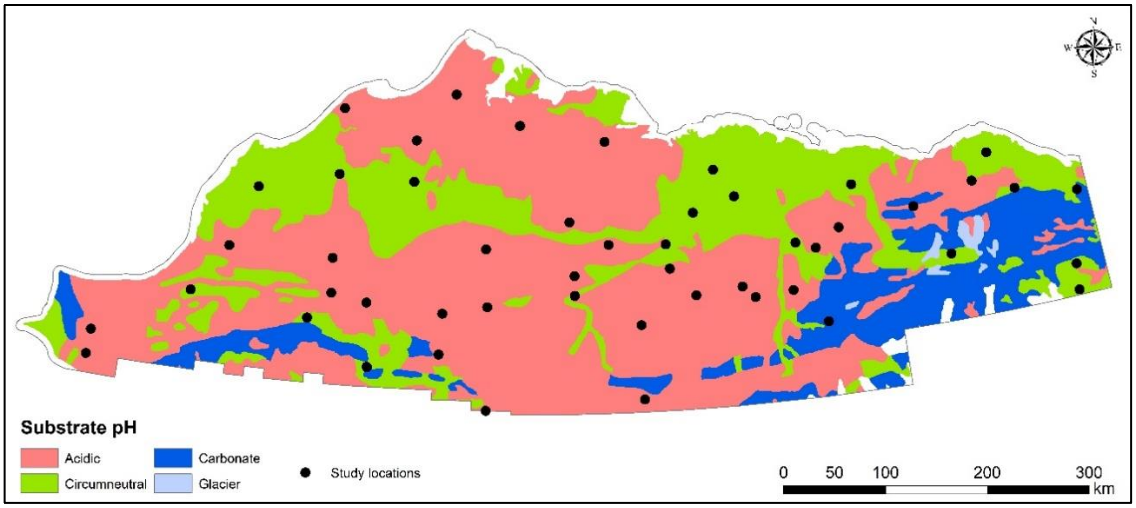

Figure 11: Substrate pH on the North Slope of Alaska (Raynolds & Cooper, 2016).

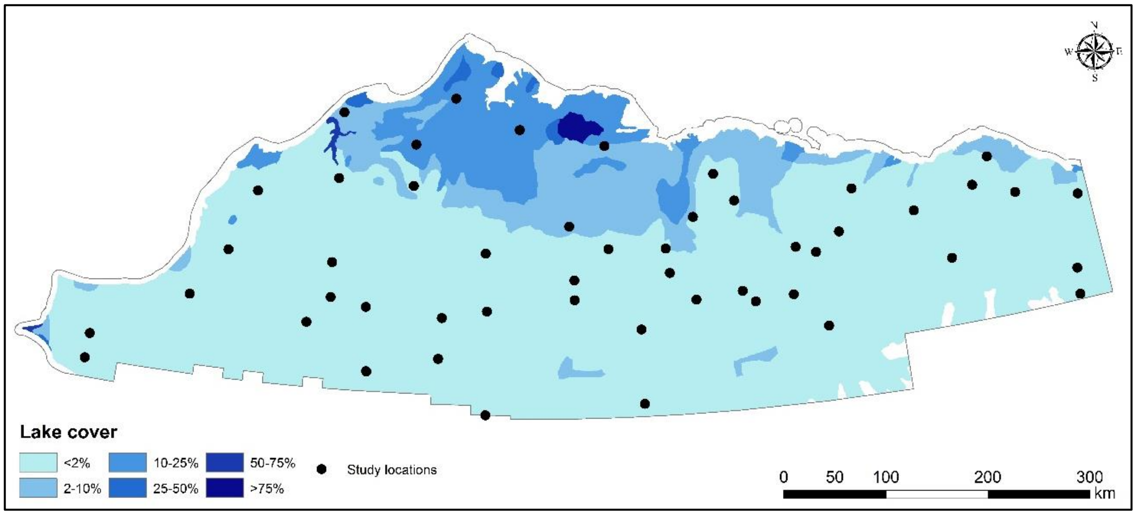

Figure 12: Percent lake cover across the North Slope of Alaska (Raynolds & Cooper, 2016).

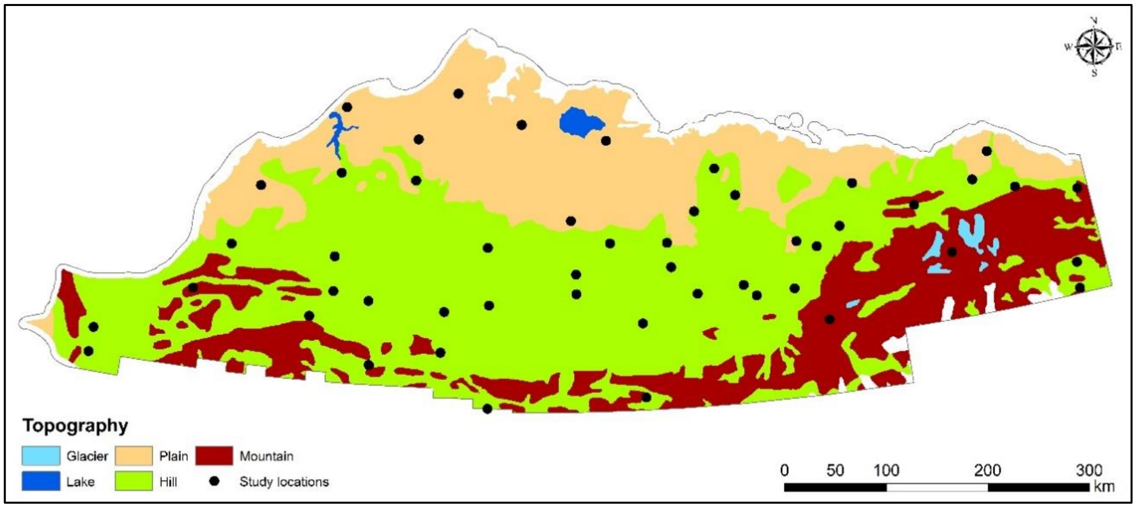

Figure 13: Topography of the North Slope of Alaska (Raynolds & Cooper, 2016).

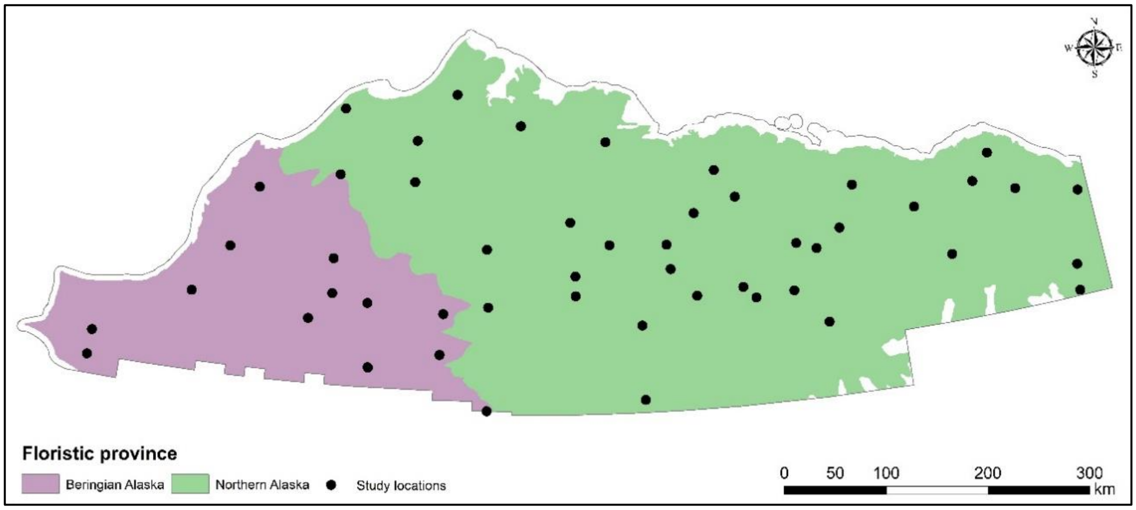

Figure 14: Floristic provinces of the North Slope of Alaska (Raynolds & Cooper, 2016).

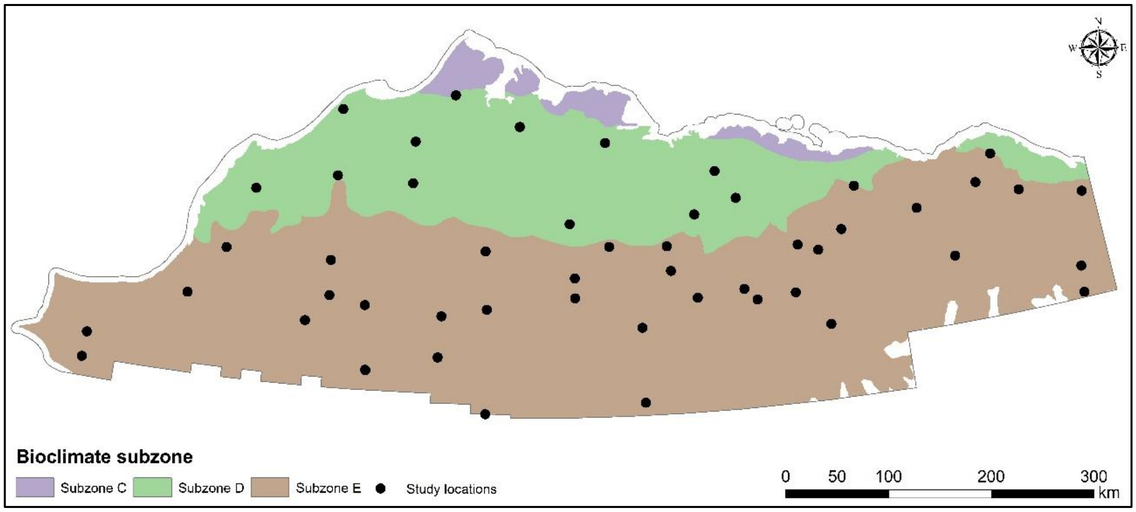

Figure 15: Bioclimate subzones of the North Slope of Alaska (Raynolds & Cooper, 2016).

If one of the areas of interest was intersected by more than one value of each of the variables, the shrub classification maps where split in ArcMap 10.5 according to the spatial extent of that variable, and a new percent coverage was calculated for each of the new sections. The associations between shrub cover and vegetation cover, substrate pH, lake cover, topography, and bioclimate subzone were tested using one-way Analysis of Variance (ANOVA). Post-hoc analysis was conducted using Tukey's HSD test to determine whether there is a significant difference between each pair of means for each variable. Since floristic province only has two groups, the difference between the means of these groups was tested using a two-tailed Student's t-test. All statistical tests were conducted at the 95% level of confidence.

Table 1: Sample size and mean percent shrub cover for all variables studied and each of their classes.

Variable & *Class*	**n**	**Mean**
Functional group	100	8.83
Barrens	15	9.81
Graminoid tundras	48	8.71
Erect-shrub tundras	19	11.41
Wetlands	18	5.61
Community type	101	8.84
B3e.1. Acidic mountain complexes (Brooks Range)	4	12.28
B3e.2. Acidic mountain complexes (NW Alaska)	1	29.00
B4e.1. Nonacidic mountain complexes (Brooks Range)	7	2.57
B4e.2. Nonacidic mountain complexes (NW Alaska)	3	17.03
G3.1. Moist nonacidic tundra (N. Arctic Coastal Plain)	9	4.16
G3.3. Moist nonacidic tundra (Arctic Foothills, Seward P.)	13	13.13
G4.1. Tussock tundra (entire map)	25	8.52
G4.3. Tussock tundra on sands (Arctic Coastal Plain)	2	3.30
S1.1. Shrubby tussock tundra (NE Alaska)	9	9.37
S1.2. Dwarf-shrub, lichen tundra (NW Alaska)	5	7.56
S2.1. Willow-birch tundra (entire map)	5	18.94
W1.1. Wet acidic coastal complex (N. Alaska)	1	0.10
W2.1. Wet acidic complex (N. Alaska, Seward, P.)	5	0.47
W2.2. Wet nonacidic coastal complex (N. Alaska)	10	8.65
W3.6. Wet nonacidic complex (warmer parts of NW Alaska)	2	5.95
Substrate pH	72	8.67
Acidic	35	7.33
Circumneutral	27	11.07
Carbonate	10	6.91
Lake coverage	59	7.87
<2%	45	9.28
2-10%	9	4.96
10-25%	4	0.58
25-50%	1	0.00
Topography	72	8.68
Plain	17	5.90
Hill	42	9.19
Mountain	13	10.68
Floristic province	52	8.32
Beringian Alaska	11	11.75
Northern Alaska	41	7.40
Bioclimate subzone	57	8.18
Subzone C	1	0.10
Subzone D	17	4.50
Subzone E	39	9.99

3.3 Results

Percent shrub cover ranged between 0% and 24.6%. There is a relationship between shrub cover (%) and latitude, however, this relationship was not present with longitude (p = 0.45). The general decrease in shrub cover with an increase in latitude can be seen in Figure 16 below.

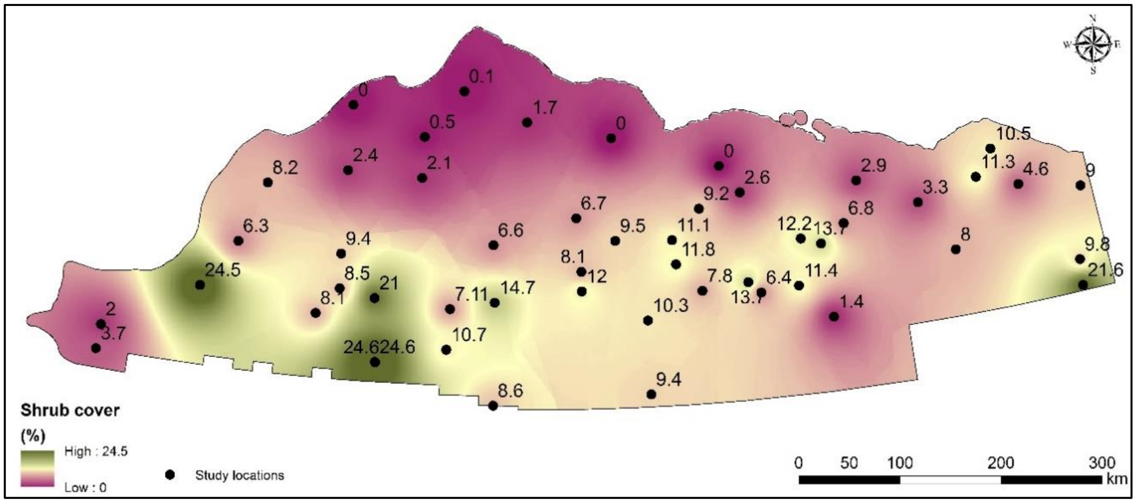

Figure 16: Interpolated shrub cover for the entire North Slope of Alaska.

There is a statistically significant relationship between annual mean temperature and shrub cover, as well as the maximum temperature of the warmest month, however, there is no relationship with minimum temperature of the coldest month (Table 2). There is a significant relationship with all the precipitation variables tested (Table 2).

The distribution of shrub cover for each of the remaining environmental variables is visualized in Figure 17. There is no significant relationship between shrub cover and functional group, community type, substrate pH, and topography (Table 2). Those which are significantly related to percent shrub cover are percent lake coverage, and bioclimate subzone. Within lake coverage, the greatest significant difference was between areas with <2% coverage and 10-25% coverage (p = 0.015). The most significant difference in means for bioclimate subzones was between subzone D and subzone E (p = 0.004).

Table 2: *P*-values and significance for each of the regional scale variables analyzed.

Variable	**p-value**
Annual Mean Temperature	0.00062
Max Temperature of Warmest Month	0.00843
Min Temperature of Coldest Month	0.133
Annual Precipitation	0.00096
Precipitation of Wettest Month	0.0044
Precipitation of Driest Month	0.00373
Permafrost	0.851
Functional group	0.211
Community type	0.073
Substrate pH	0.14
Lake coverage	0.003
Topography	0.175
Floristic province	0.1046
Bioclimate subzone	0.002

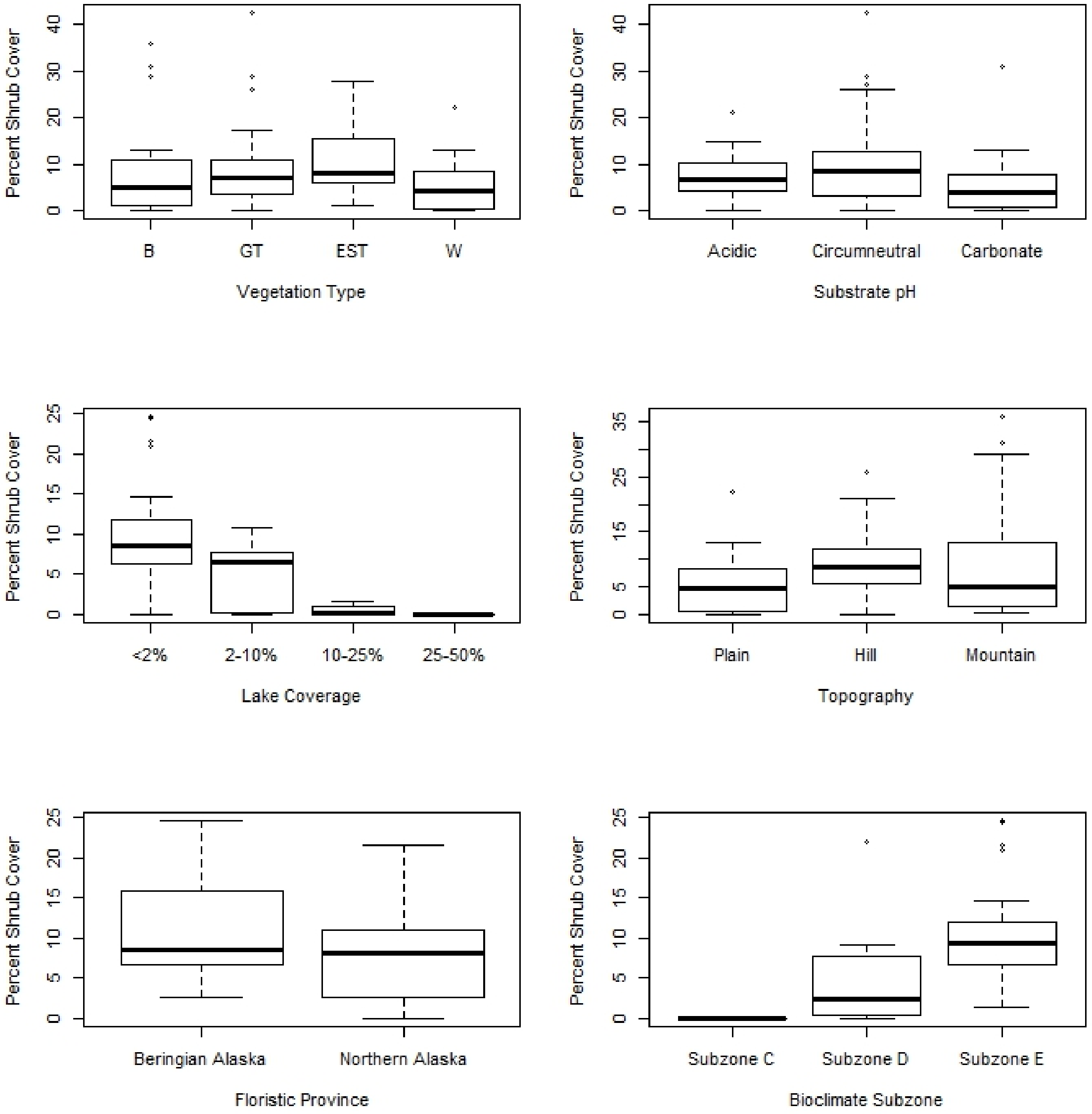

Figure 17: Boxplots of percent shrub cover and various environmental variables. For vegetation type, "B" is Barrens, "GT" is Graminoid Tundras, "EST" is Erect Shrub Tundras, and "W" is Wetlands.

3.4 Discussion

These results show that percent shrub cover is related to latitude, with the more southern areas having higher amounts of shrub cover on the landscape. There is, however, no relationship with longitude. This strong latitudinal relationship is due to one or a combination of environmental variables that change along a latitudinal gradient. Shrub cover was found to have a significant relationship with annual mean temperature, maximum temperature of the warmest month, annual precipitation, precipitation of the driest month, lake coverage, and climatic subzone, all of which also have latitudinal patterns (Figure 2, Figure 3, Figure 5, Figure 6, Figure 7, Figure 12, Figure 15, Table 2).

Since annual mean temperature and maximum temperature of warmest month were significantly related to shrub cover, but minimum temperature of the coldest month was not, it can be suggested that a limiting factor to shrub expansion is temperature in the growing season. This relationship between an increase in reproductive response and summer growing season temperature was observed for *Cassiope tetragona* in the Canadian High Arctic (Rayback and Henry 2005). Of interest here is that there is a significant difference in mean shrub cover in bioclimate subzone D and subzone E, which suggests that if it is a temperature control, conditions in subzone D are not yet as favorable as those in subzone E. Therefore, this study uses remote sensed evidence to support what plot scale experimental (Elmendorf et al. 2012a, Elmendorf et al. 2012b, Natali, Schuur and Rubin 2012) and dendrochronological studies (Forbes, Fauria and Zetterberg 2010, Hallinger et al. 2010, Myers-Smith et al. 2015b) have shown with shrub increases linked to warming air and soil temperatures.

As air and soil temperatures warm, so will the amount of soil moisture increase due to the thawing of permafrost. Another factor that contributes to increased soil moisture is that of precipitation, which was found here to have a significant relationship with shrub cover. Ackerman et al. (2017) found that while *Salix pulchra* has responded positively to an increase in July temperatures, their model was a better fit at the riparian sites when compared to those at dry upland sites. Similarly, Elmendorf et al. (2012b) found that the association between summer warming and increased vascular plant abundance was dependent on other factors including climate zone, moisture regime and permafrost. This shows that while temperature is suggested to be the dominant control on shrub growth and expansion, there are still other mechanisms that serve to facilitate or limit shrubification.

Percent lake cover was also found to be significantly related to shrub cover. While local topography related lakes has been shown to influence shrub cover (Lloyd et al. 2003), at the regional scale this is likely a significant factor due to its latitudinal pattern, with higher lake coverage at the higher latitudes due to them being flatter and having greater permafrost coverage.

It has been suggested that there is a decoupling with temperature and precipitation and Pan-Arctic shrub change (Martin et al. 2017). Based on a study of 23 proximal controls, Martin et al. (2017) found that there is insufficient evidence to answer questions regarding Pan-Arctic shrub change, and suggest that there could be more than one mechanism facilitating increased shrub growth and expansion. Permafrost and soil characteristics have been found to have an influence on plant response to climate change on the northern foothills of the Alaska Range (Natali et al. 2012). These variables were not found to have a relationship with shrub cover, however, this is likely due to the regional scale not being able to capture landscape level heterogeneity. At the regional scale, the entire North Slope of Alaska is underlain by continuous permafrost, however, there will still be landscape scale variation that will allow for shrub establishment.

It is likely that as temperature warms, shrubs are then able to colonize in areas where the environmental conditions are suitable but were previously not colonized due to temperature limitations. This emphasizes the need to conduct shrub cover and expansion studies at the landscape scale, to determine which factors beyond temperature and precipitation facilitate shrub growth and expansion.

3.5 Conclusions

As temperatures warm, it is expected that shrubs will expand northward, which will impact on the local energy balance (Sturm et al. 2005b, Sturm et al. 2005a), carbon balance (Oechel et al. 2000, Sturm et al. 2005b, Sturm et al. 2005a), and result in the shift in species that utilize shrubs (Tape et al. 2016b, Zhou et al. 2017). Shrub cover on the North Slope of Alaska follows a latitudinal pattern with greater coverages in the southern parts of the North Slope. This is likely due to controlling factors such as temperature and precipitation also exhibiting this latitudinal gradient. Therefore, the extensive regional scale analyses of this remote sensed study support plot scale studies that show that shrub cover is associated with temperature and precipitation. However, it has also been shown that these factors are not the only to influence shrub cover. While regional drivers, such as increases in summer temperature, are important, there is still a high degree of heterogeneity in shrub responses (Martin et al. 2017). Therefore, to obtain a better understanding of factors that influence shrub growth and expansion, and how much of the North Slope will likely undergo a conversion from tundra to shrubland, similar studies need to be conducted, but at the landscape scale. However, while there will still be heterogeneity in shrub cover at the landscape scale, these regional scale findings are important for forecasting responses system responses in the Arctic to continued warming.

CHAPTER IV

A LANDSCAPE SCALE ANALYSIS OF THE RELATIONSHIPS BETWEEN TALL SHRUB ESTABLISHMENT, AND TOPOGRAPHIC REGIONS AND HYDROLOGIC FEATURES.

4.1 Introduction

Shrub expansion has been widely documented in the Arctic, however, there are still questions regarding how this process will progress. Regional scale studies show that there is a northward expansion of shrubs, however, owing to local heterogeneity, shrub expansion is not likely to occur at the same rates across all landscapes and regions (Jia, Epstein and Walker 2006). Landscape scale factors such as topography, disturbance, and biotic interactions play important roles in regulating shrub expansion (Ackerman et al., 2017). Based on plot studies in Alaskan national parks, Swanson (2015) concluded that tall shrub expansion is likely to be limited to favorable areas covering at most one quarter of the 80 000 km^2 area of study. Such conditions include areas where the July mean temperatures are higher than 10.5ºC, soil is weakly acidic to neutral, summer thaw depths greater than 80cm, and that have good drainage (Swanson 2015).

Shrubification is most evident on hill slopes and in valley bottoms (Tape et al. 2006a). Studies by (Naito and Cairns 2011b, Naito and Cairns 2015) focused on the rates of shrub expansion in floodplains at multiple sites on the northern Brooks Range and North Slope uplands of Alaska. Their findings indicate that rates of shrub expansion are greatest in high resource environments (Naito and Cairns 2015), particularly in areas where there is high water throughflow and accumulation (Naito and Cairns 2011b). Ackerman et al. (2017) compared shrub growth trajectories across different soil moisture levels; this study found that while *Salix pulchra* is likely to respond in a similar way in dry upland and mesic riparian sites to moderate temperature increases, shrubs in the mesic riparian areas will most likely respond more favorably to sustained increases of more than 2°C. Since high rates of shrub expansion have been found in the floodplains of Arctic environments, most studies have focused on them, with areas outside of the floodplains receiving little attention.

The most common deciduous tall shrubs (>0.5m) on the North Slope are birch (*Betula nana* and *B. glandulosa*), willow (*Salix alaxsensis*, *S. pulchra*, *S. glauca*) and alder (*Alnus crispa*) (Tape et al. 2006a). Dwarf shrubs are also common on the North Slope, however, they are not detectable in the imagery, and are therefore not studied here. Owing to the morphology of tall shrubs, they have a greater potential to alter local environmental conditions. Tall shrub species typically trap snow and increase snow depth in their vicinity (Sturm et al. 2005b). Tall shrubs also typically remain above the snow year round, which results in lower albedo where they are exposed (Sturm et al. 2005a, Pomeroy et al. 2006, Bonfils et al. 2012). Increased snow depth encourages winter biological activity, and lower albedo can lead to local warming, both of which create favorable conditions for increased shrub growth (Sturm et al. 2005a, Sturm et al. 2005b).

One of the research needs identified by Myers-Smith et al. (2011a) is “to what extent is the potential expansion of shrubs across Arctic landscapes constrained by landscape position?" Not all of the Arctic will respond to changes in climate in the same manner, as demonstrated by large areas of the Arctic that exhibit little or no change (Post et al., 2009b, Post et al., 2009a), which highlights the need for further studies to quantify the rate of expansion across all geomorphic units (Naito and Cairns, 2011b, Myers-Smith et al., 2015a). A better understanding of the heterogeneity of shrub expansion at the landscape scale is vital to allow for an accurate incorporation into global vegetation and climate models (Ackerman et al. 2017). The establishment of tall shrub species is likely to be limited by the availability of well-drained microsites (Lloyd et al., 2003). This is evidenced by Wolter et al. (2016) who found a difference in vegetative communities between polygon ridges and high-centered polygons, and the troughs and the low-lying centers of polygons. Such results stress the need to include geomorphological setting when conducting shrub expansion studies at the landscape scale. This can be done by quantifying expansion patterns by topographic region, as well as in relation to hydrological features.

This chapter aimed to determine the importance of landscape position has on shrub cover and expansion and has the following objectives:

1. Compare patterns of shrub cover and expansion across major topographic regions to determine which areas of the landscape are experiencing the greatest changes.
2. Quantify the impact of proximity to rivers and streams on shrub cover and shrub expansion.
3. Determine whether shrub cover and shrub expansion patterns differ in proximity to rivers and streams in the floodplain versus outside of the floodplain.

4.2 Methods

To analyze the relationship between shrub cover and topographic region, as well as the relationship between shrub cover and distance from rivers and streams, eight areas of interest on the North Slope of Alaska were selected based on the locations of already available historical imagery (Figure 18). Since the sites were limited to already acquired historical imagery, there was no option to select sites between the Nimiuktuk and Ayiyak sites. The areas of interest range between 4.3 km^2 and 106.5 km^2 (Table 3). Historical color infrared vertical aerial photographs were sources from the United States Geological Survey Earth Resources Observation Science (USGS EROS) (Figure 19). The historical images were captured between 1978 and 1985, at resolution of ~ 91 cm (Table 3). These images were co-registered to contemporary imagery using 80-100 ground control points and the Delaunay triangulation transformation (Naito and Cairns 2011b). High resolution contemporary satellite images from WorldView-2, WorldView-3 and GeoEye-1 satellites were sourced from DigitalGlobe inc. Archives (Figure 19). The resolution of the contemporary images is 46 cm, 31 cm, and 41 cm respectively. The images were captured between 2010 and 2016 (Table 3), and were selected based on time of year, and the lack of snow and cloud cover.

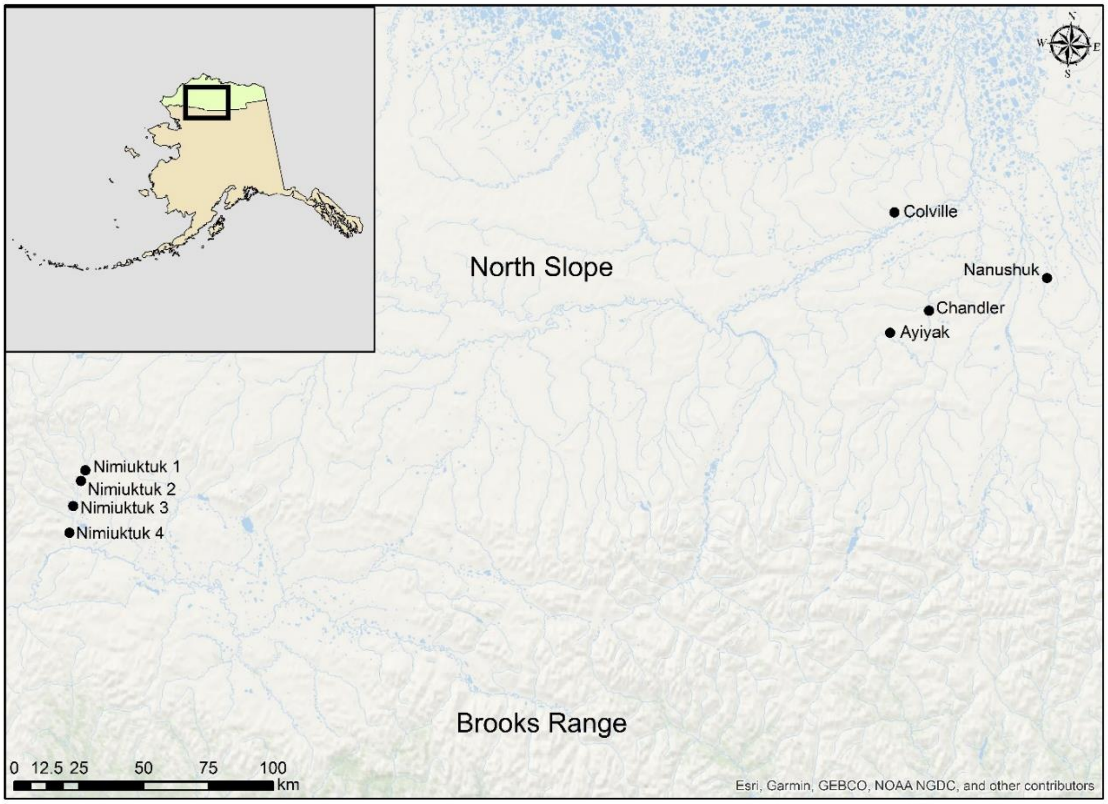

Figure 18: The eight study sites located on the North Slope of Alaska.

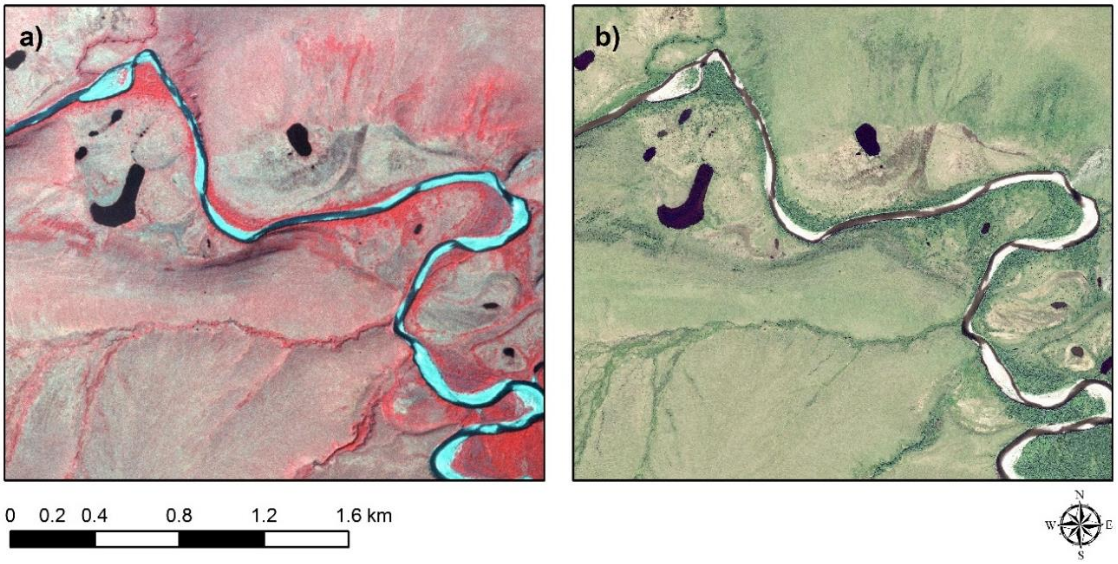

Figure 19: a) Historical EROS color infrared aerial image from 1985 of part of the Ayiyak area of interest. b) The corresponding Worldview Satellite image from 2010.

Table 3: Size of each study area, image dates, and number of years between images for each site.

Study Sites	Area (km2)	Historical Image Year	Contemporary Image Year	Study Years
Ayiyak	45.8	1985	2010	25
Chandler	13.6	1978	2010	32
Colville	106.5	1980	2011	31
Nanushuk	21.6	1978	2016	38
Nimiuktuk 1	8.2	1977	2013	36
Nimiuktuk 2	13.1	1985	2013	28
Nimiuktuk 3	22.4	1985	2013	28
Nimiuktuk 4	4.3	1980	2013	33

Since the historical imagery is ~ 91 cm resolution, all of the images were resampled to a common resolution of 1 m, which limited this study to the detection of tall shrub expansion. Each image was then classified independently using the supervised Maximum Likelihood classifier in ENVI 5.4. The classifications were then reclassified in ArcMap 10.5 to classes of “non-shrub’ (0) and “shrub” (1), which allowed for a calculation of percent shrub cover (Figure 20, Figure 21, Figure 22, Figure 23, Figure 24, Figure 25, Figure 26, Figure 27). Surface water was manually digitized and removed from the classifications to allow for a more accurate calculation of percent cover of land available to shrub colonization (Figure 20, Figure 21, Figure 22, Figure 23, Figure 24, Figure 25, Figure 26, Figure 27).

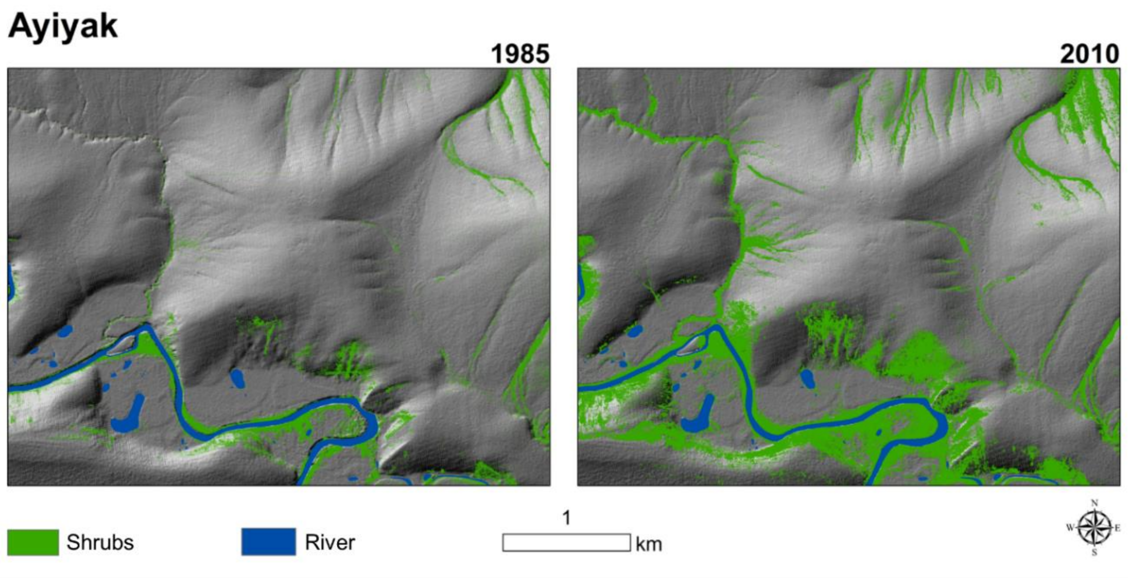

Figure 20: Historical and contemporary hydrology and shrub cover for part of the Ayiyak River site.

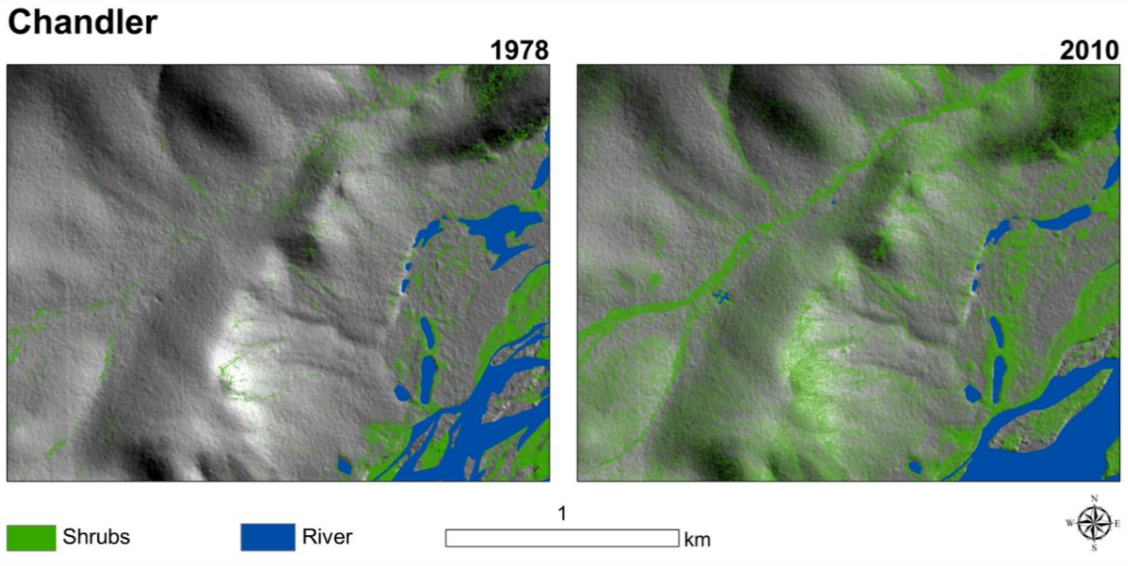

Figure 21: Historical and contemporary hydrology and shrub cover for part of the Chandler River site.

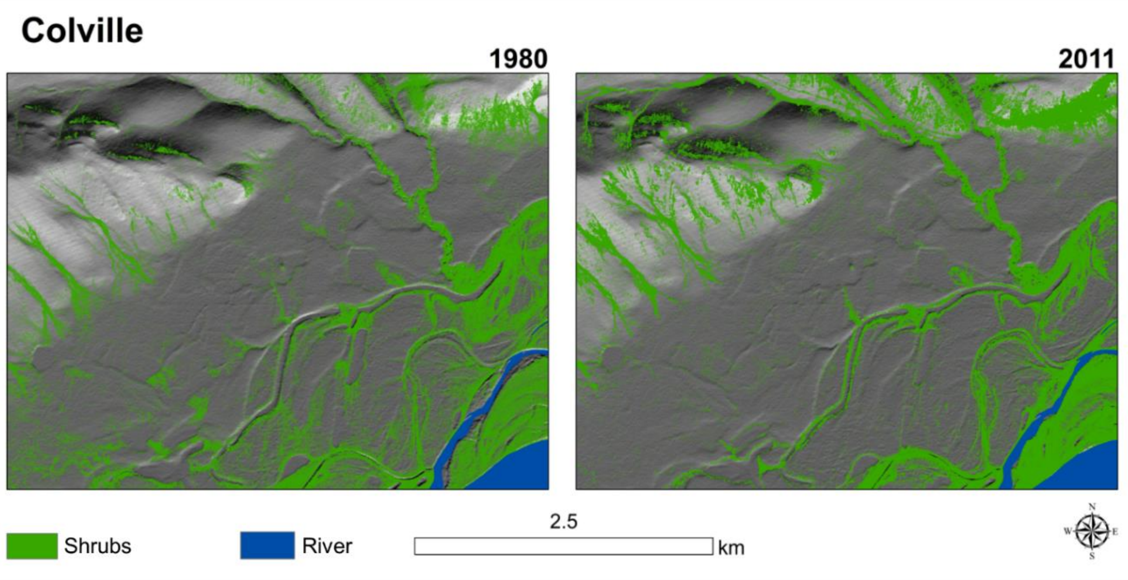

Figure 22: Historical and contemporary hydrology and shrub cover for part of the Colville River site.

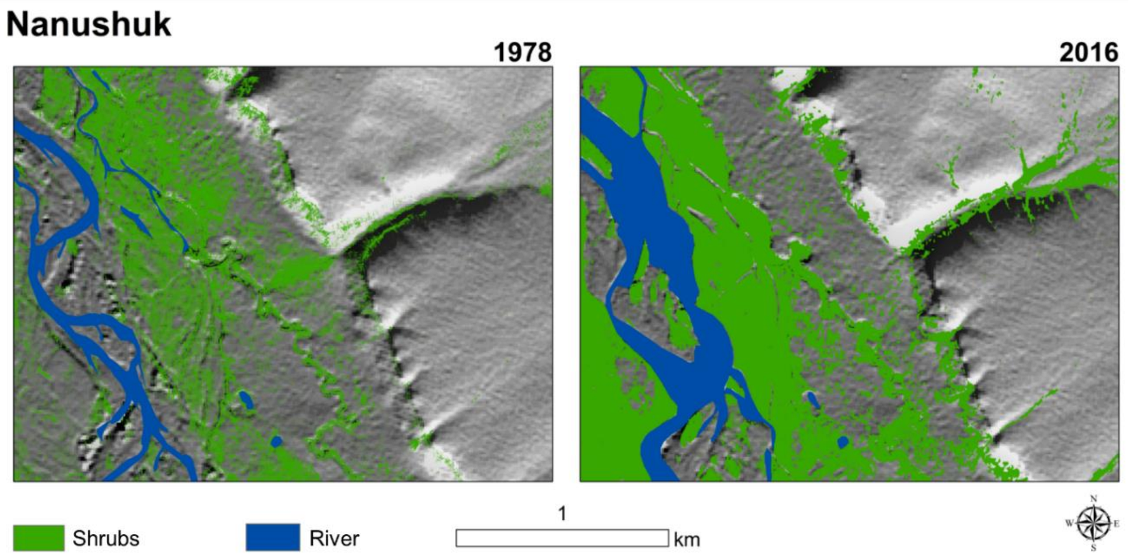

Figure 23: Historical and contemporary hydrology and shrub cover for part of the Nanushuk River site.

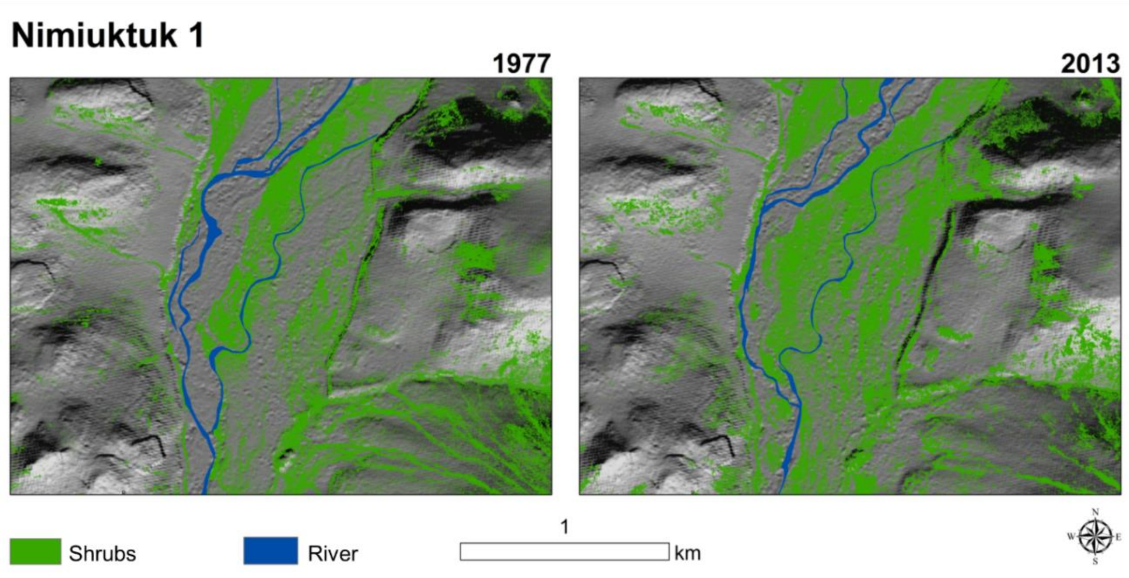

Figure 24: Historical and contemporary hydrology and shrub cover for part of the Nimiuktuk River site 1.

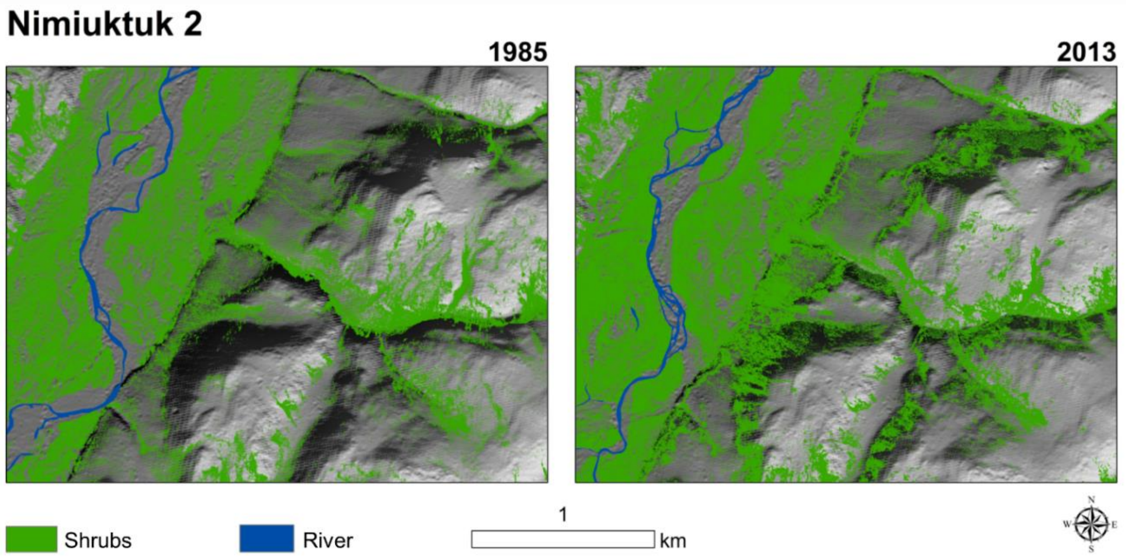

Figure 25: Historical and contemporary hydrology and shrub cover for part of the Nimiuktuk River site 2.

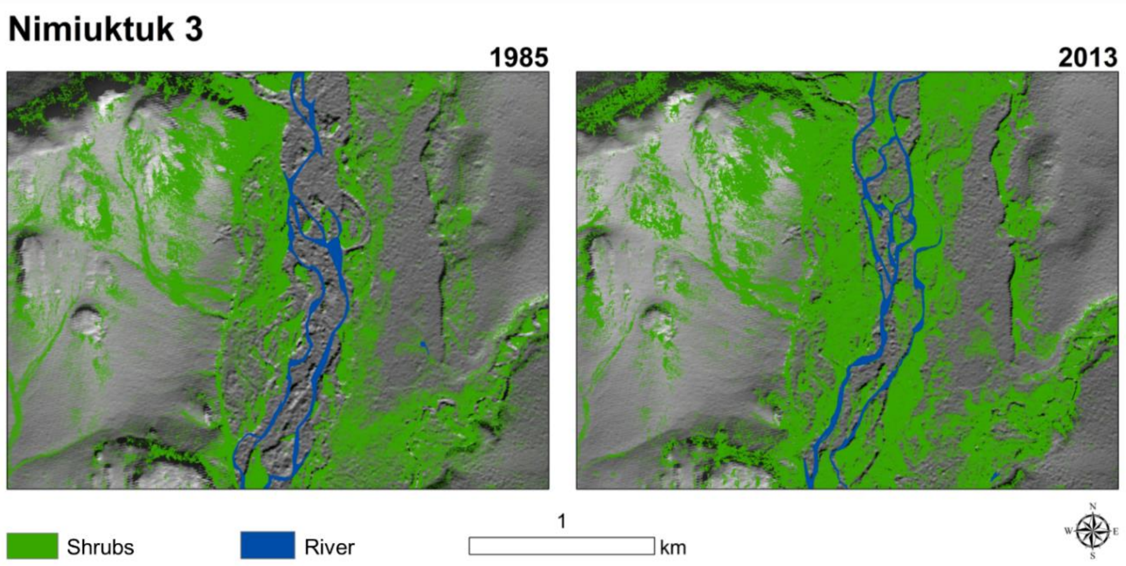

Figure 26: Historical and contemporary hydrology and shrub cover for part of the Nimiuktuk River site 3.

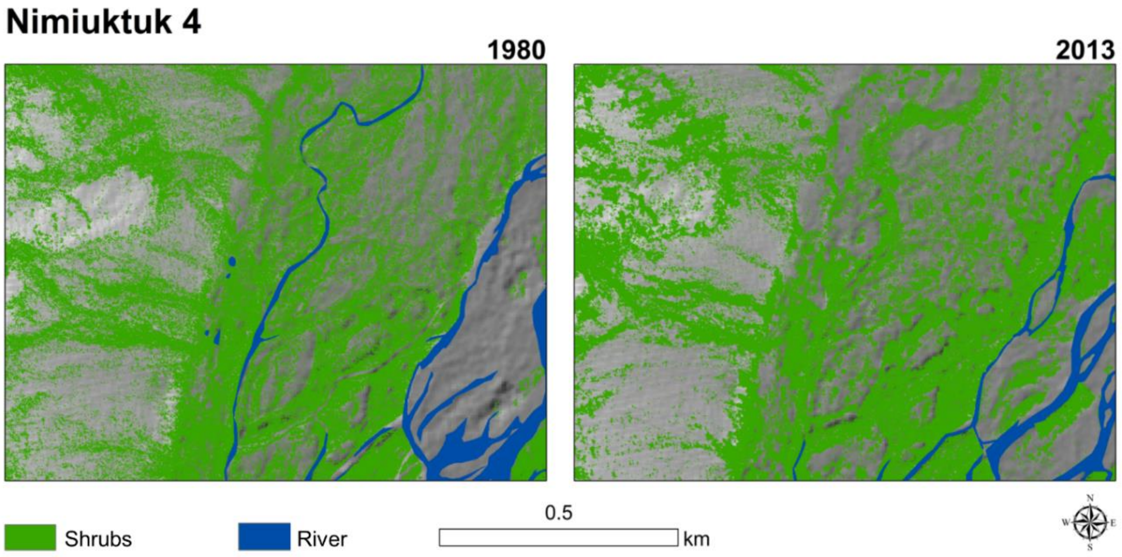

Figure 27: Historical and contemporary hydrology and shrub cover for part of the Nimiuktuk River site 4.

4.2.1 Topographic analysis

The topographic regions were manually digitized by interpretation of the satellite images, as well as the associated slope layers and Digital Elevation Models (DEMs) (Figure 28). The topographic regions include floodplains (FP), river terraces (T), floodplain slopes (FPS), valley slopes (VS), and interfluves (I). Floodplains were delineated to the point where there was a sharp increase in slope. The slopes immediately adjacent to the floodplains were classified as the floodplain slopes. Areas of the landscape flattened out again after a slight elevational gain were classified as river terraces. The elevation and slope layers were then used to delineate the valley slopes, with the flatter areas separating them being classified as interfluvial areas. The results of the manual classification was inspected using a combination of hillshade and DEM layers; any delineations that did not match the topography of the landscape were corrected manually. Percent shrub cover per topographic region was then calculated using ArcMap 10.5 “Zonal Statistics as Table” tool. The results were exported to Microsoft Excel for summary, and then analyzed in RStudio. All statistical tests were conducted at the 95% level of confidence.

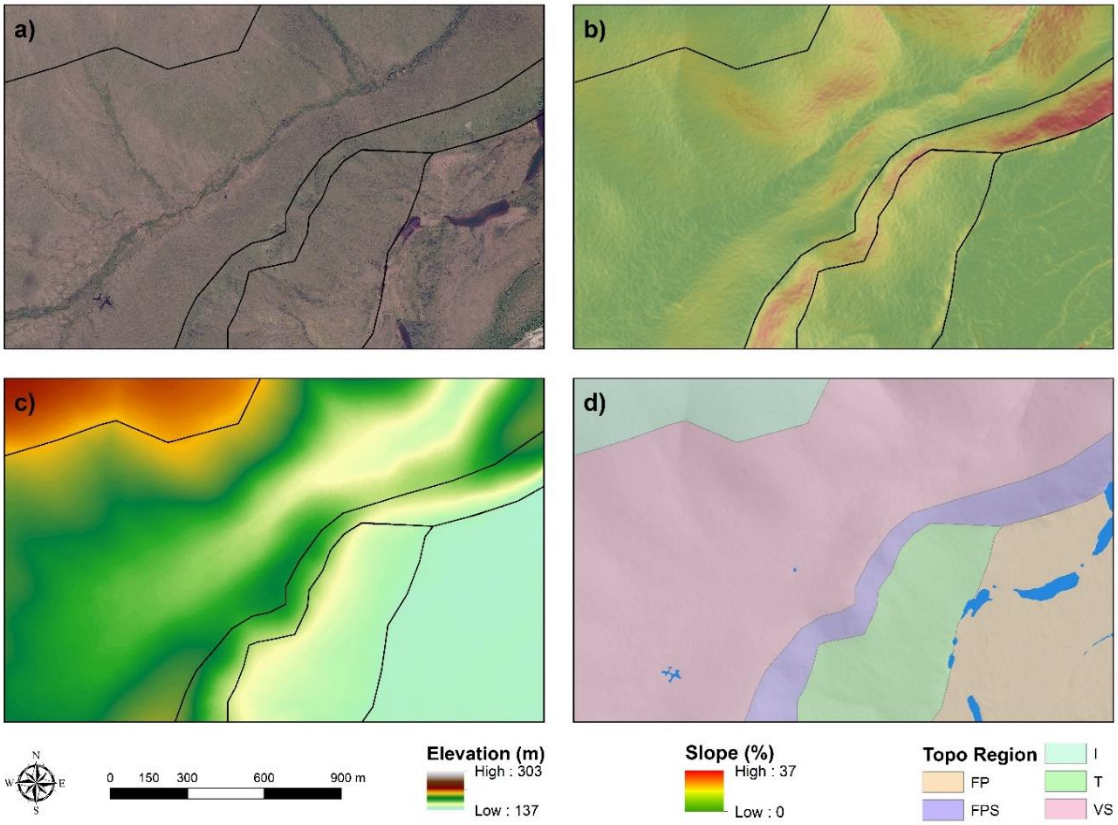

Figure 28: Example of a a) satellite image, b) slope layer, and c) digital elevation model used to delineate d) topographic regions.

To test whether there is a significant increase in shrub cover in the contemporary imagery, compared to the historical imagery, one-way Analysis of Variance (ANOVA) was conducted in RStudio. This process was repeated to test for a significant difference between shrub cover and topographic region for the historical, and contemporary imagery. To determine which topographic regions are significantly different from each other, post-hoc analysis was conducted using Tukey's HSD test in RStudio.

4.2.2 Hydrologic analysis

Streams were delineated in ArcMap 10.5 using the Hydrology toolset, and then combined with the river and surface water data that were manually delineated to create a complete layer of surface hydrology for each area of interest (Figure 29). Multiple buffers were created around the hydrological features at 0-10m, 11-20m, 21-30m, 31-40m, 41-50m, 51-100m, 101-150m, 151-200m, 201-300m, and 301-400m intervals. Shrub cover was then extracted for each of these intervals using ArcMap 10.5's "Zonal Statistics as Table" function. This was done for the whole area of interest, and then repeated for the floodplain only, and all areas outside of the floodplain. These data were then consolidated in Microsoft Excel and prepared for analysis.

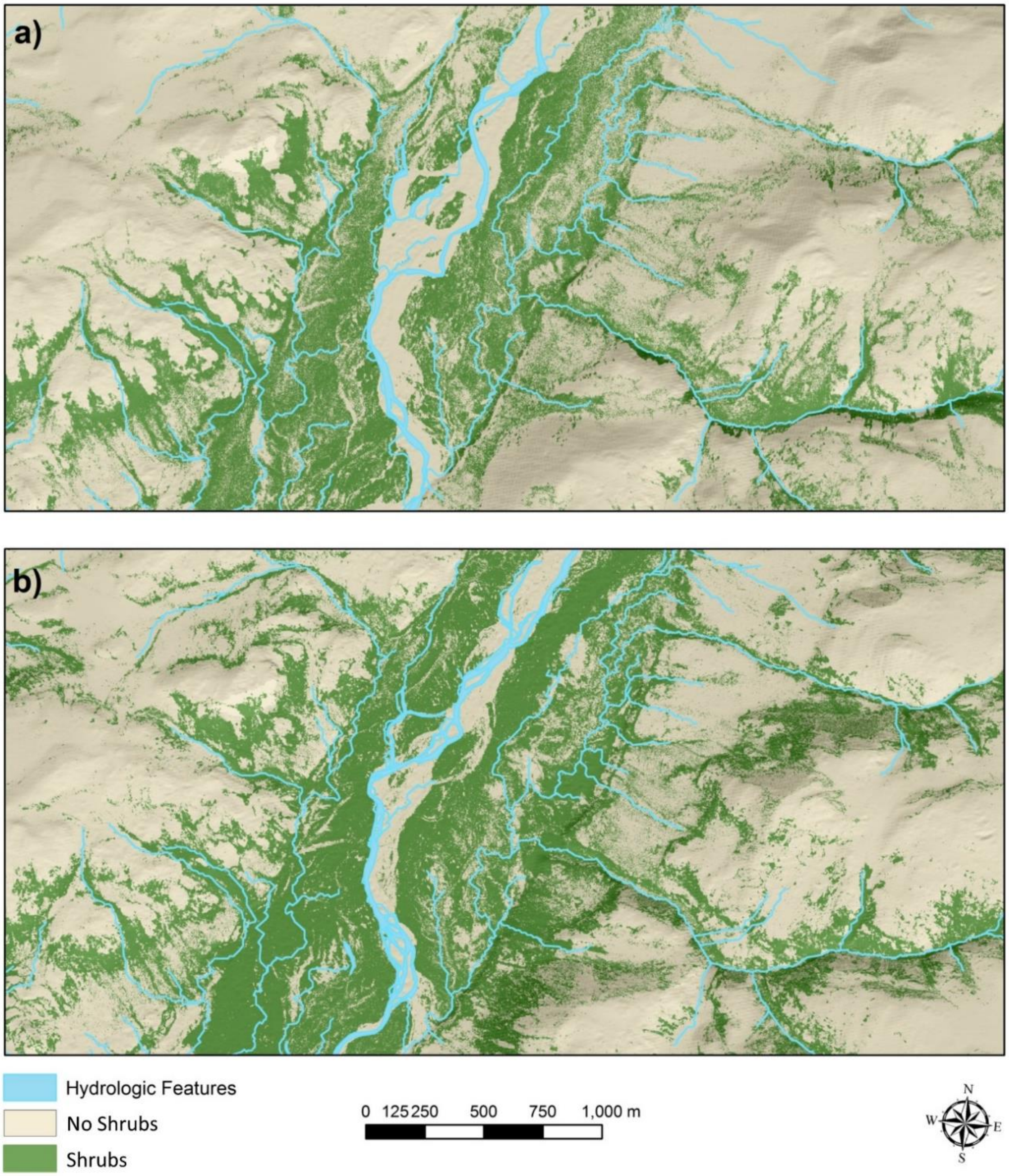

Figure 29: Portion of Nimiuktuk River site 2 showing an example of the delineated hydrologic features and shrub cover.

Two-way Analysis of Variance (ANOVA) in RStudio was conducted to test for a difference between shrub cover and distance from hydrological features, as well as the difference between shrub cover and the historical and contemporary images. The association between shrub cover and distance from hydrological features was further investigated by one-way Analysis of Variance (ANOVA) in RStudio. ANOVA was used to test for significant differences in mean shrub cover for the larger distance intervals (0-100m, 101-200m, 201-300m, and 301-400m) and at smaller distance intervals (0-10m, 11-20m, 21-30m, 31-40m, 41-50m) for both the historical and contemporary imagery. These analyses were conducted for the entire area of interest ("all data"), within the floodplain, and outside of the floodplain. Tukey's HSD using RStudio was conducted to determine which distance intervals had shrub cover significantly different from each other.

4.3 Results

4.3.1 Topographic analysis

Generally all topographic regions experienced an increase in shrub cover over time (Figure 30). Historically, the floodplains had the highest percent shrub cover. This is still true at most sites in the contemporary imagery, although there are some sites with the highest shrub cover recorded on the floodplain slopes (Figure 30). Typically, the interfluvial areas and valley slopes had the lowest percent shrub cover (Figure 30).

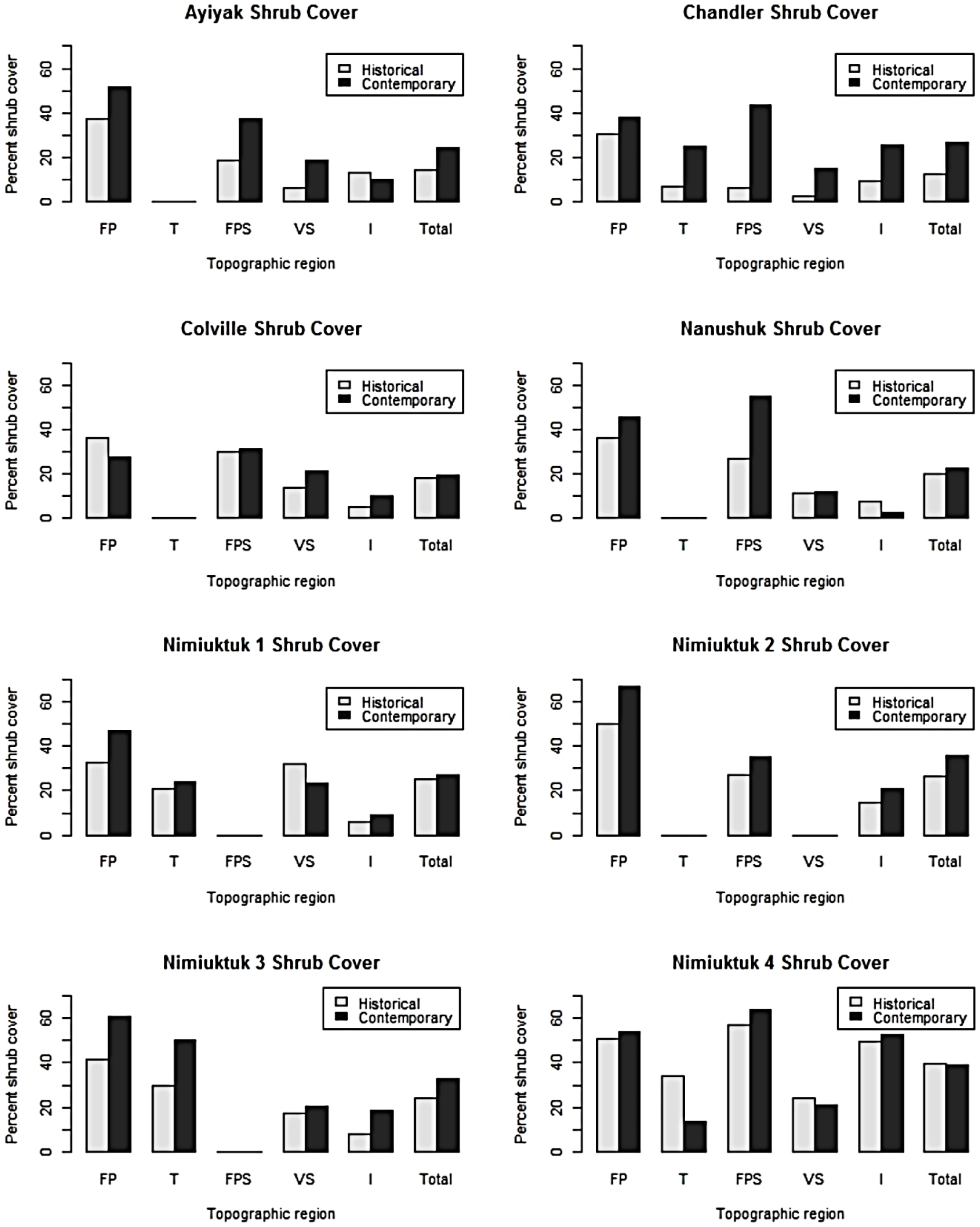

Figure 30: Historical and contemporary percent shrub cover for each topographic region for each of the study sites. FP = floodplains, T = river terraces, FPS = floodplain slopes, VS = valley slopes, I = interfluves.

Seven of the eight sites experienced an overall gain in shrub cover; the lowest gain (1.41%) was recorded at the Colville site, and the greatest gain (14.07%) was recorded at the Chandler site (Table 4). Nimiuktuk 4 experienced an overall loss, however, this can mostly be attributed to a major loss (20.96%) on the river terrace, as the floodplain, floodplain slopes, and interfluvial areas all experienced an overall gain (Table 4). All sites had less than 0.5% annual increase in shrub cover (Table 5). The Colville, Nanushuk, Nimiuktuk 1, Nimiuktuk 2, and Nimiuktuk 4 sites experienced negligible change with annual rates of 0.05%, 0.06%, 0.06%, and -0.01% respectively (Table 5).

Table 4: Overall percent change of each topographic region for each of the eight study sites.

	Percent Change					
	FP	**T**	**FPS**	**VS**	**I**	**Total Change**
Ayiyak	14.48		18.94	12.05	-3.46	**9.58**
Chandler	7.29	18.14	37.17	11.96	16.50	**14.07**
Colville	-8.33		0.85	7.38	4.96	**1.41**
Nanushuk	9.32		27.43	0.35	-4.47	**2.42**
Nimiuktuk 1	13.96	2.71		-9.06	3.22	**2.07**
Nimiuktuk 2	16.66		7.87		6.75	**9.56**
Nimiuktuk 3	19.35	20.29		3.33	10.15	**8.83**
Nimiuktuk 4	2.96	-20.96	7.00	-3.25	2.68	**-0.42**
Mean	9.46	5.04	16.54	3.25	4.54	**5.94**

Table 5: Annual rates of change for each of the topographic regions for each site.

	Annual Rate of Change					
	FP	**T**	**FPS**	**VS**	**I**	**Total**
Ayiyak	0.58		0.76	0.48	-0.14	**0.38**
Chandler	0.23	0.57	1.16	0.37	0.52	**0.44**
Colville	-0.27		0.03	0.24	0.16	**0.05**
Nanushuk	0.25		0.72	0.01	-0.12	**0.06**
Nimiuktuk 1	0.39	0.08		-0.25	0.09	**0.06**
Nimiuktuk 2	0.59		0.28		0.24	**0.34**
Nimiuktuk 3	0.69	0.72		0.12	0.36	**0.32**
Nimiuktuk 4	0.09	-0.64	0.21	-0.10	0.08	**-0.01**
Mean	0.32	0.18	0.53	0.12	0.15	**0.20**

On average the topographic region that experienced the greatest change in shrub cover is the floodplain slopes, with an increase of 16.5% (Figure 31). The next greatest change was experienced in the floodplains with a mean increase of 9.5% (Figure 31). The river terraces, valley slopes, and interfluves experienced smaller changes (< 5%) (Figure 31).

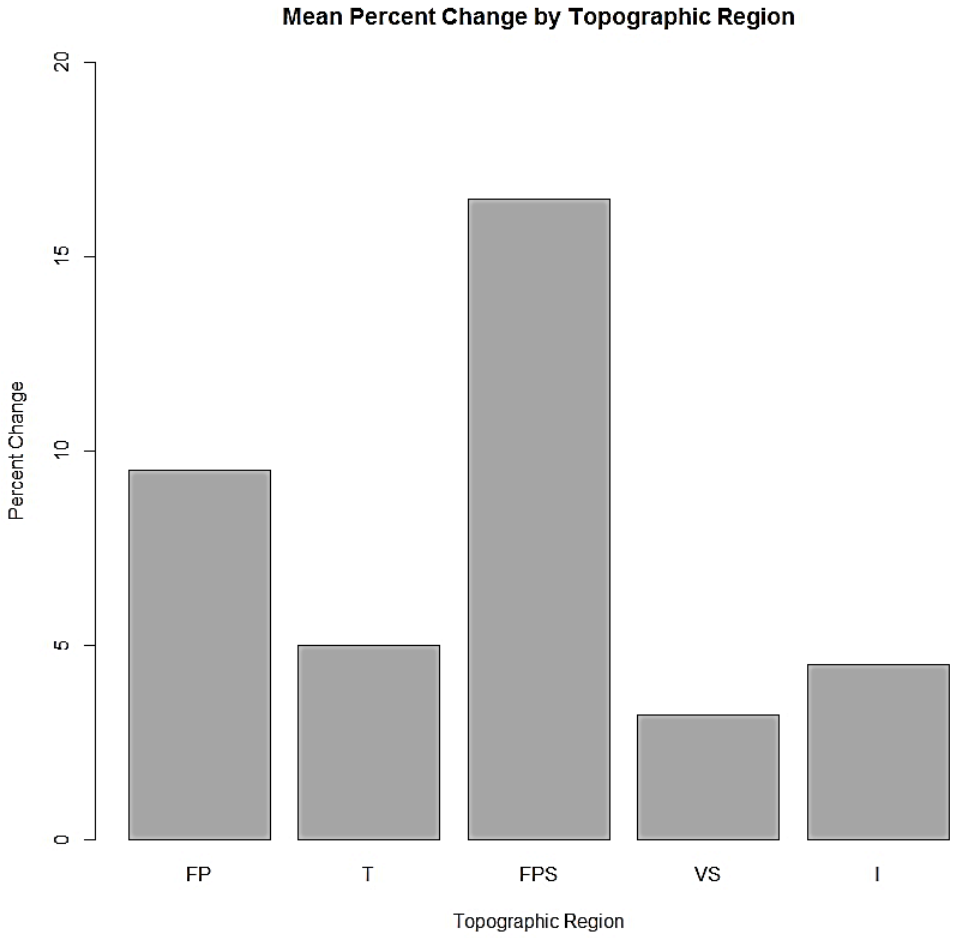

Figure 31: Mean percent change in shrub cover for each topographic region. FP = floodplains, T = river terraces, FPS = floodplain slopes, VS = valley slopes, I = interfluves.

One-way ANOVA revealed that, on average, there is a significant difference between shrub cover between the historical and contemporary periods (Figure 32). There is also a significant difference between shrub cover and the topographic regions in the historical and contemporary imagery (Figure 33).

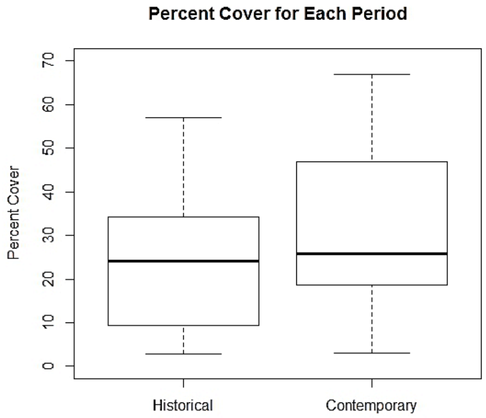

Figure 32: Boxplot showing the mean percent shrub cover for the historical and contemporary imagery.

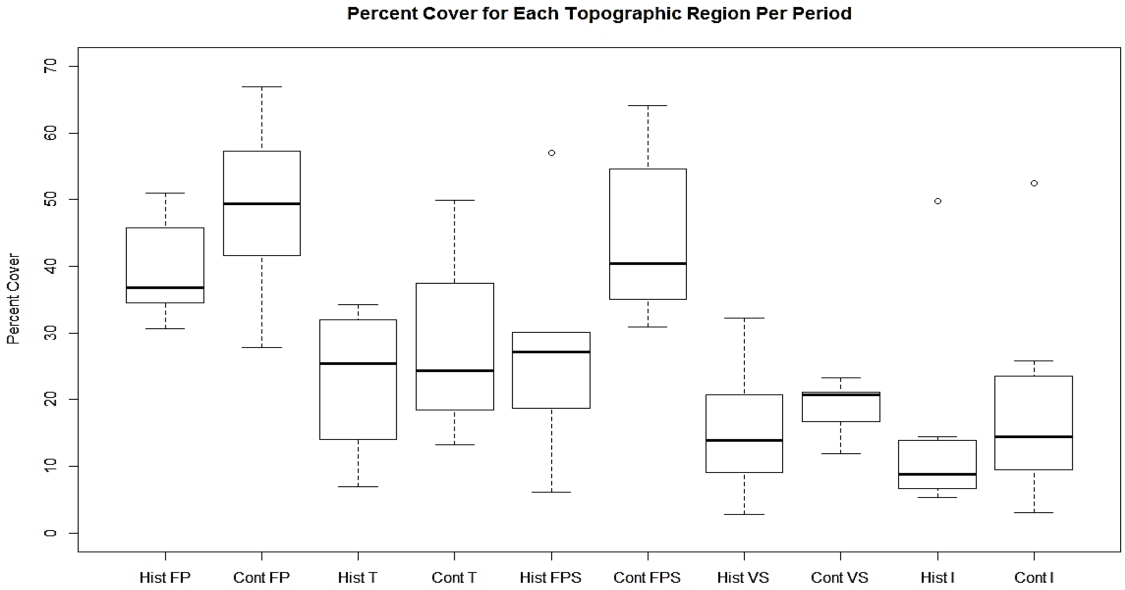

Figure 33: Boxplot showing mean percent shrub cover for each topographic region for the historical and contemporary imagery. Hist = historical imagery, Cont = contemporary imagery. FP = floodplains, T = river terraces, FPS = floodplain slopes, VS = valley slopes, I = interfluves.

Post-hoc analysis showed that in the historical imagery there is a significantly greater amount of shrub cover in the floodplains than valley slopes, as well as in the floodplains than interfluves (Figure 34). These same relationships exist in the contemporary imagery, however, with the addition a significantly higher percentage shrub cover on the floodplain slopes than valley slopes, as well as on the floodplain slopes than the interfluves (Figure 35).

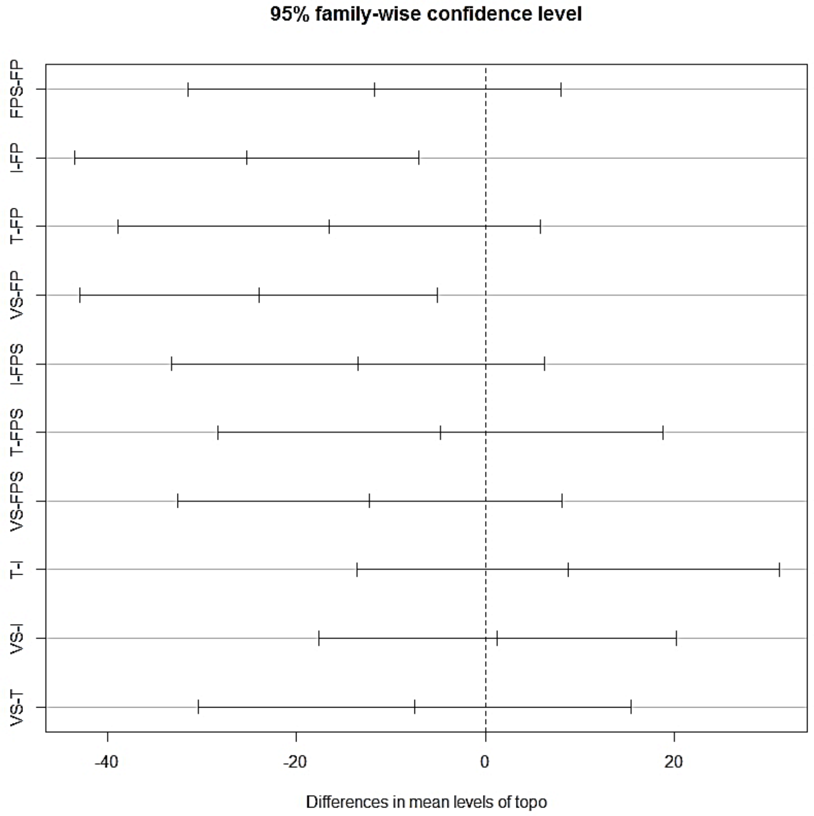

Figure 34: Summary of Tukey HSD for shrub cover by region for historical imagery.

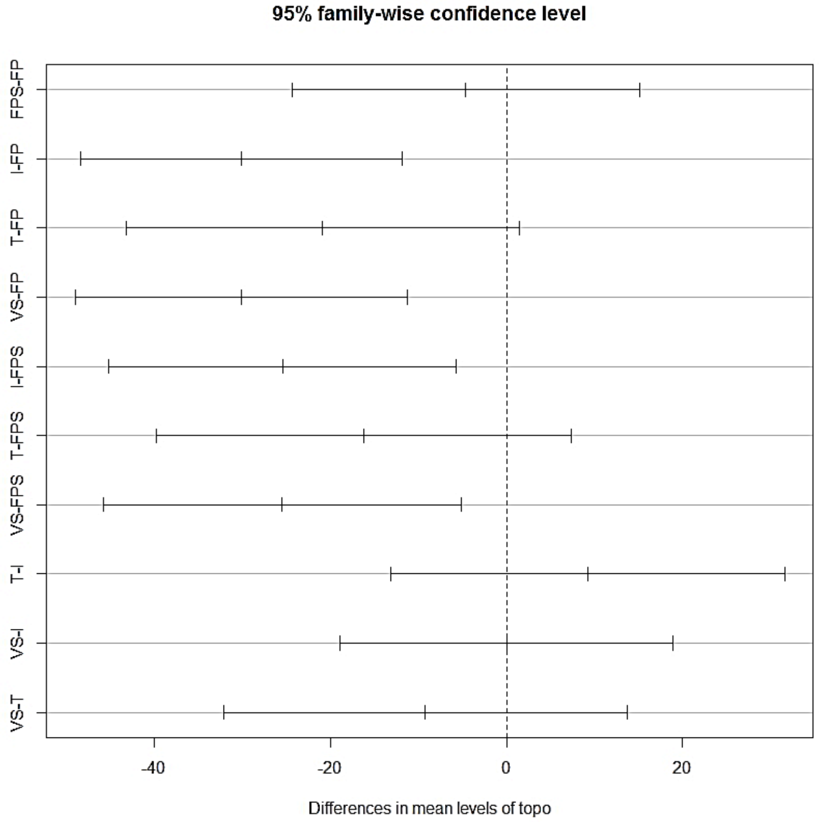

Figure 35: Summary of Tukey HSD for shrub cover by region for contemporary imagery.

4.3.2 Hydrologic analysis

An increase in mean shrub cover was found across all distance intervals (Figure 36 & Figure 37). In general across the whole study area and outside of the floodplains, mean shrub cover decreases with increasing distance from rivers at both larger and smaller intervals (Figure 36 & Figure 37). This pattern is not seen in the floodplains with mean shrub cover remaining relatively similar across larger and smaller distance intervals (Figure 36 & Figure 37).

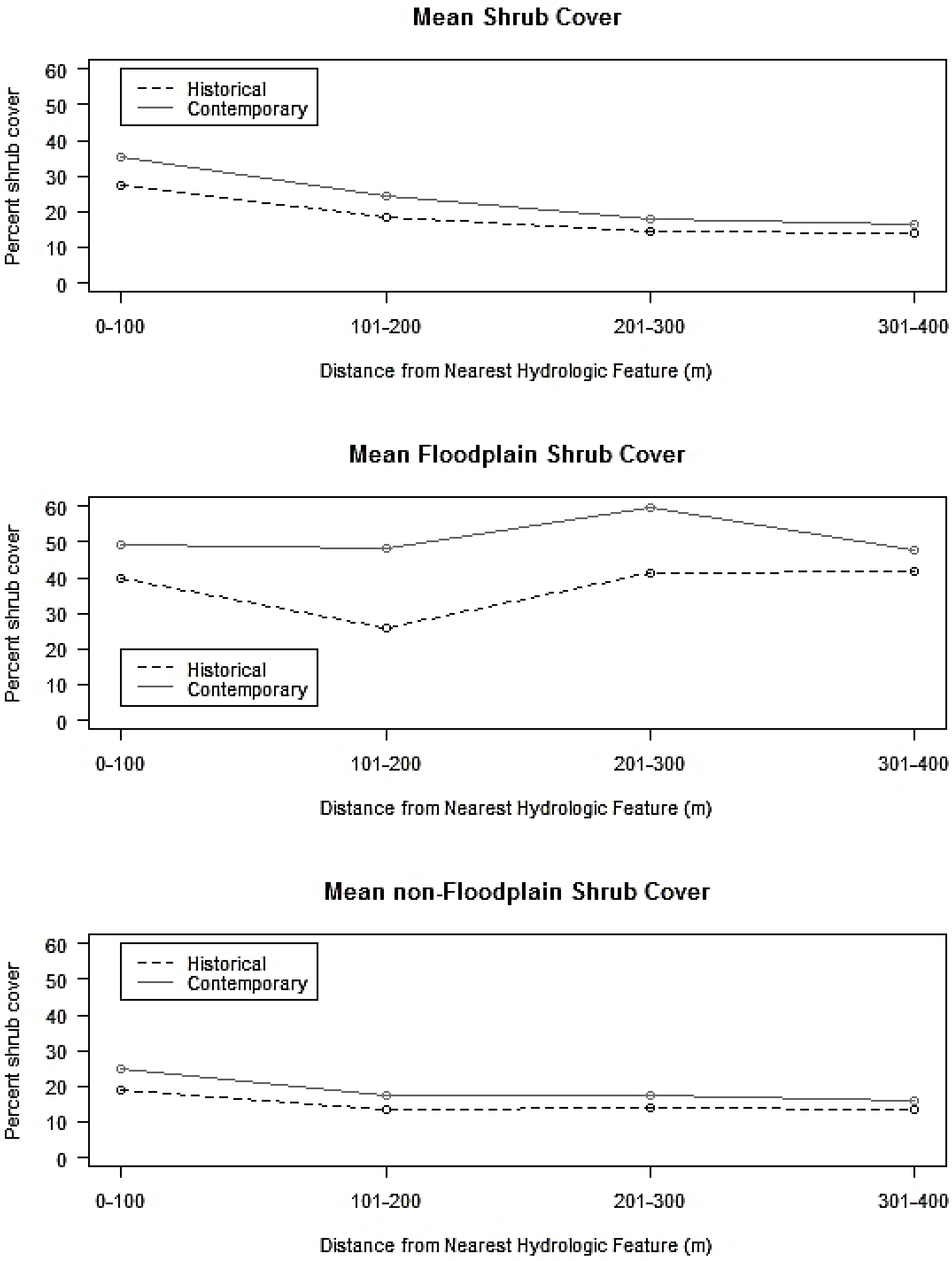

Figure 36: Mean percent shrub cover for larger distances for historical and contemporary imagery, for the whole site, floodplain only, and areas outside of the floodplain.

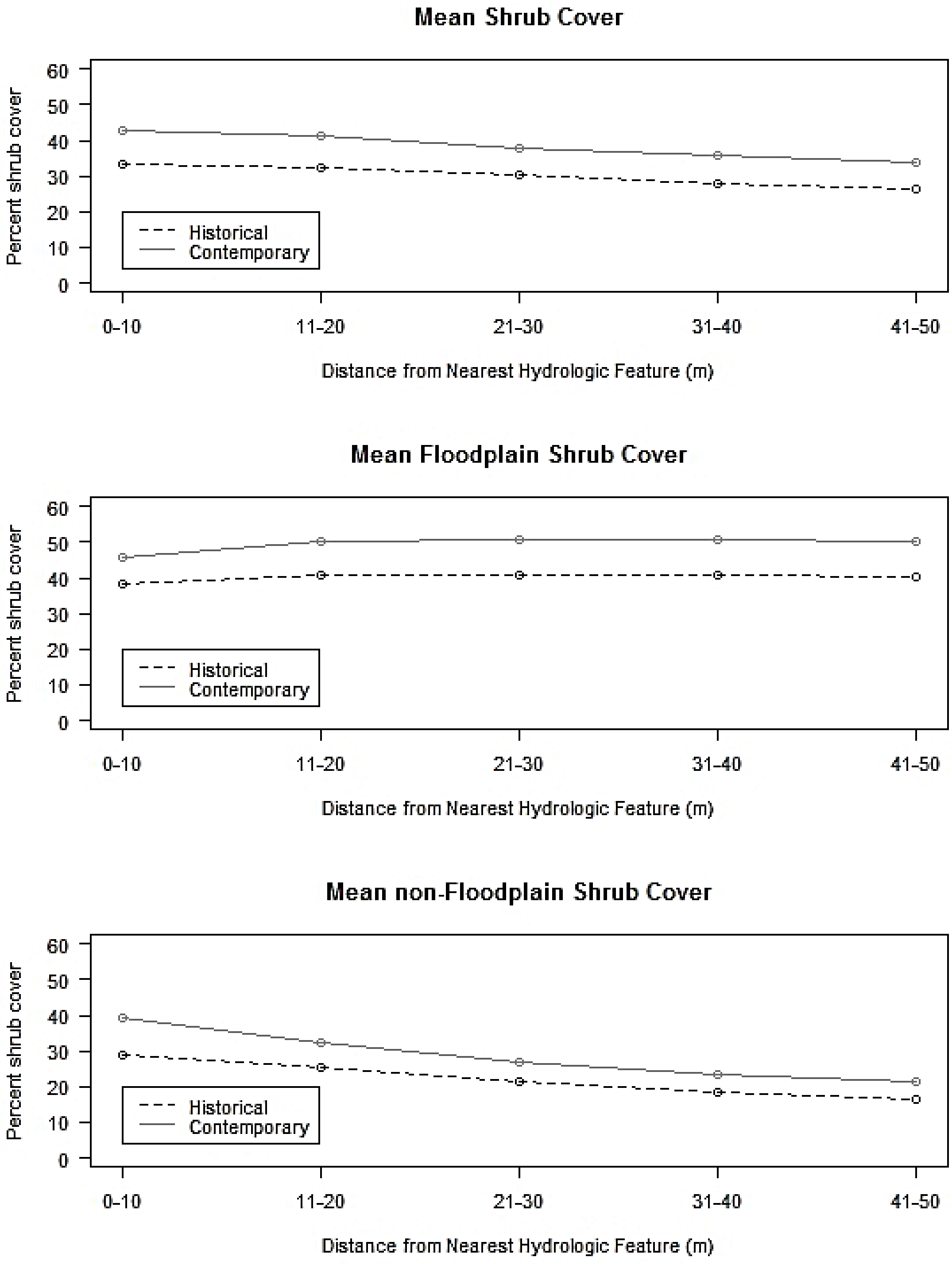

Figure 37: Mean percent shrub cover by smaller distances for historical and contemporary imagery, for the whole site, floodplain only, and areas outside of the floodplain.

The floodplain areas had higher mean shrub cover than areas outside of the floodplains, with the greatest changes generally occurring in the floodplains across all distances (Table 6 & Table 7). Outside of the floodplains, shrub cover change decreases with increasing distance from hydrologic features at the larger and smaller distance intervals (Table 6 & Table 7).

Table 6: Mean shrub cover at larger distance intervals for historical and contemporary images for the whole area, floodplain only, and outside of floodplains.

ALL DATA			
	Percent Shrub Cover		
Distance (m)	Historical	Contemporary	Change
0-100	27.5	35.3	7.8
101-200	18.5	24.5	6.0
201-300	14.3	18.0	3.7
301-400	13.7	16.2	2.5
WITHIN FLOODPLAIN			
	Percent Shrub Cover		
Distance (m)	Historical	Contemporary	Change
0-100	39.8	49.1	9.4
101-200	36.1	48.3	12.2
201-300	41.3	59.8	18.6
301-400	41.6	47.9	6.3
OUTISDE OF FLOODPLAIN			
	Percent Shrub Cover		
Distance (m)	Historical	Contemporary	Change
0-100	18.8	25.1	6.3
101-200	13.4	17.6	4.2
201-300	13.8	17.2	3.4
301-400	13.6	16.0	2.4

Table 7: Mean shrub cover at smaller distance intervals for historical and contemporary images for the whole area, floodplain only, and outside of floodplains.

ALL DATA			
	Percent Shrub Cover		
Distance (m)	Historical	Contemporary	Change
0-10	33.3	42.8	9.5
11-20	32.5	41.1	8.6
21-30	30.1	38.0	7.9
31-40	28.0	35.7	7.7
41-50	26.4	33.9	7.5
WITHIN FLOODPLAIN			
	Percent Shrub Cover		
Distance (m)	Historical	Contemporary	Change
0-10	38.5	45.8	7.3
11-20	40.8	50.4	9.6
21-30	40.8	50.8	10.0
31-40	40.6	50.5	9.8
41-50	40.5	50.3	9.8
OUTISDE OF FLOODPLAIN			
	Percent Shrub Cover		
Distance (m)	Historical	Contemporary	Change
0-10	28.6	39.5	10.9
11-20	25.6	32.5	6.8
21-30	21.4	26.8	5.5
31-40	18.2	23.6	5.4
41-50	16.4	21.6	5.2

ANOVA revealed that at the larger distances there was no significant increase in shrub cover over time for the study areas on a whole and in areas outside of the floodplain. There was, however, a significant increase in shrub cover over time in the floodplains, though there is no relationship with mean shrub cover and distance within the floodplains ($p = 0.666$). Therefore, shrub cover has increased throughout the floodplains. There was, however, a significant difference in mean shrub cover with distance across the entire study areas in the contemporary imagery (Table 8). Tukey's HSD shows that the significant differences are between the 0-100 m and 201-300 m, and the 0-100 and 301-400m distance intervals (Figure 38). Since this relationship was not present in the historical imagery (Table 8), it indicates that significant increases in shrub cover have occurred in the 100 meters adjacent to hydrologic features. At larger distances, when considering only the areas outside of the floodplains, there were no relationships between shrub cover and time ($p = 0.173$), as well as shrub cover with distance (Table 8).

Since shrub cover in the 100m adjacent to hydrologic features was found to be significantly different to shrub cover at further from the hydrologic features, further analysis at smaller distance intervals within the first 50m of hydrologic features was conducted. Overall, there was a highly significant increase in shrub cover over time within the 50m adjacent to hydrologic features. Mean shrub cover did not vary significantly according to distance across the whole study area in both the historical and contemporary imagery (Table 8). Shrub cover increased significantly over time within the floodplains, however, similar to the larger distance interval analyses, this was not related to distance. There was also a significant increase in shrub cover over time outside of the floodplains. There was no relationship between shrub cover and distance from hydrologic features in the historical imagery, however, in the contemporary imagery, there was a significant relationship between distance from hydrologic features and shrub cover in areas outside of the floodplains (Table 8). Tukey HSD shows that these significant differences are between distance intervals of 0-10m and 21-30m, 0-10m and 31-40m, as well as 0-10m and 41-50m distance intervals, with the relationship becoming stronger with increasing distance (Figure 39). This indicates that the most substantial increases in shrub cover have occurred within the 10m adjacent to hydrologic features outside of the floodplains.

Table 8: Significance of the relationship between shrub cover and distance from hydrologic features for historical and contemporary imagery.

	p-value			
	Large intervals		**Small intervals**	
Area	**Historical**	**Contemporary**	**Historical**	**Contemporary**
All Data	0.144	**0.0171**	0.461	0.251
Floodplain	0.943	0.602	0.97	0.918
Outside of Floodplain	0.785	0.357	0.119	**0.000559**

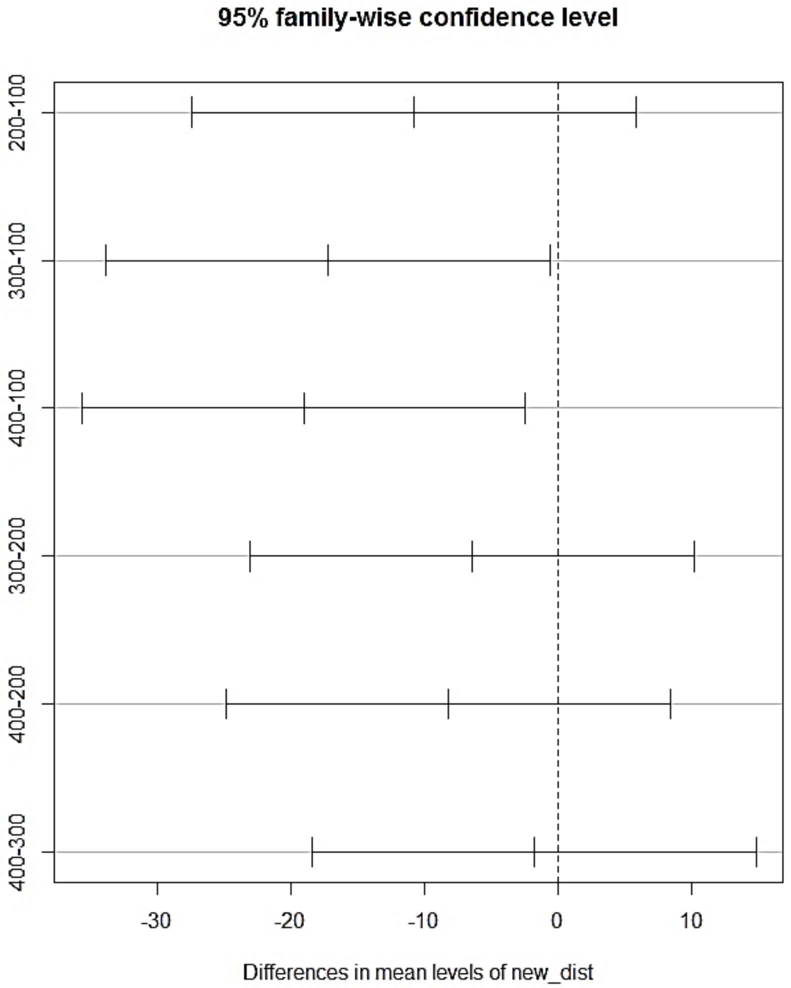

Figure 38: Results from Tukey HSD for the relationship between shrub cover and larger distances from hydrologic features in the contemporary imagery across the entirety of the study areas.

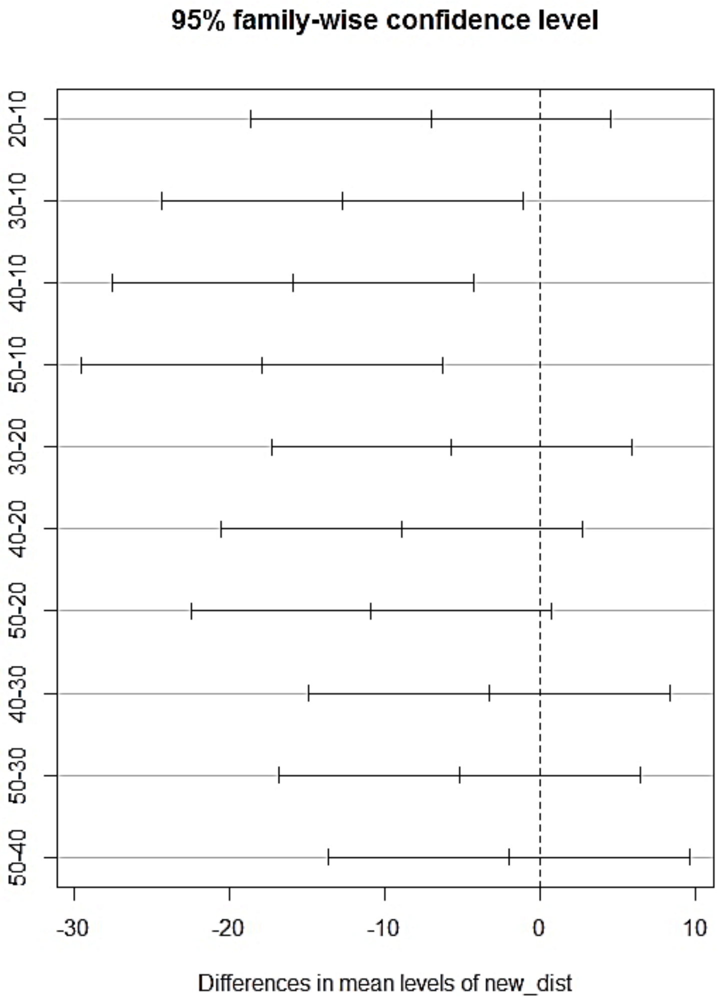

Figure 39: Results from Tukey HSD for the relationship between shrub cover and shorter distances from hydrologic features in the contemporary imagery.

4.4 Discussion

Since climate sensitivity is particularly evident in tall shrubs growing close to their latitudinal and elevational range limits (Myers-Smith et al. 2015a), the heterogeneity in favorable conditions at the landscape scale is very important in controlling the patterns of shrub cover. These results show that shrub cover and expansion is located preferentially both topographically, and in relation to distance from hydrologic features.

4.4.1 Relationships with topographic regions

These results show that at the landscape scale, for the selected sites, except one, there is an overall gain in shrub cover, with a significant difference in shrub cover between the historical and contemporary imagery, which supports other studies that report on shrub expansion (Table 4, Figure 33). However, as expected, shrub cover and expansion are not equal across the landscape. Previous studies show that the highest rates of shrub expansion are in the floodplains (Tape et al. 2006a, Naito and Cairns 2011b, Naito and Cairns 2015). Contrary to those findings, Frost, Epstein and Walker (2014) concluded that shrub expansion is likely to be prevalent in upland tundra landscapes in areas of active patterned-ground. This research shows that the highest percent shrub cover is in the floodplains (Figure 30), which coincides with Naito and Cairns (2015) who found that river valleys of the Brooks Range in Alaska are in a phase transition from tundra to shrubland, becoming more homogenous with time. However, even though the highest percent shrub cover tended to be in the floodplains (Figure 30), the highest rates of expansion were found on the floodplain slopes (Table 5, Figure 31). This is likely due to the floodplains being almost saturated with shrub cover, which forces the shrubs to expand upslope where there is less competition for space to colonize. There is a significant difference between shrub cover in the floodplains and valley slopes and interfluvial areas in the historical imagery (Figure 34), as well as the floodplains and floodplain slopes compared to the valley slopes and interfluvial areas in the contemporary imagery (Figure 35). The inclusion of the floodplain slopes as being significantly different to the valley slopes and interfluvial areas is an indication of shrub expansion moving upslope from the floodplains. Since the floodplains have reached their tipping point from tundra to shrubland (Naito and Cairns 2015), the results here indicate that the floodplain slopes could soon undergo a phase transition too.

Most of the rates of expansion from this study are generally less than others published in Tape et al. (2006a) (0.68% per annum), Tape, Verbyla and Welker (2011) (0.78% per annum), and Naito and Cairns (2011b) -0.02% to 1.50% per annum for total change, and 0.12% to 2.31% per annum for change in floodplains. This is likely due to this research not only focusing on the areas of high expansion (i.e. the floodplains), and rather incorporating shrub expansion over the whole landscape. The valley slopes and interfluvial areas have the lowest proportions of shrub cover and expansion, and also constitute the largest portion of the landscape, which indicates that while shrub expansion is happening, the greatest rates are limited to a small portion of the landscape.

4.4.2 Relationships with hydrologic features

Since the greatest changes were found in the floodplains and on the floodplain slopes in the topographic region analysis, it is important to investigate the extent of the influence of hydrologic features. Increases in shrub cover were found across the entire landscape with respect to distance from hydrologic features. There is no relationship between shrub cover and expansion and distance from the main river and channels in the floodplains.

Since shrubs have been found to prefer areas of higher moisture through flow (Naito and Cairns 2011b), it is expected that the floodplains are favorable areas for shrub growth, and therefore exhibit expansion throughout. However, since shrub cover is mostly limited to the riparian areas, there is a relationship between shrub cover and distance from hydrologic features outside of the floodplains. Outside of the floodplains, shrub cover is greatest in the 100 meters adjacent to hydrologic features (Figure 36 & Table 6). Within the first 50 meters, it is evident that shrub cover decreases with increasing distance from hydrological features (Figure 37 & Table 7).

This relationship is even more evident in the contemporary imagery than the historical imagery. At larger scales the first 100 meters adjacent to hydrologic features has significantly higher shrub cover compared to the 201-300 m and 301-400 m distance intervals (Table 8, Figure 38). At smaller distance intervals, shrub cover is significantly greater in the 10 meters adjacent to hydrologic features, compared to the 21-30 m, 31-40 m, and 41-50 m distance intervals (Table 8, Figure 39). Since these significant relationships are present in the contemporary imagery, and not the historical imagery, it indicates that the pattern of higher shrub cover closer to hydrologic features is becoming stronger, and is hence an indication of where the most shrub expansion is happening.

4.4.3 Implications

When combining the results from the topographic and hydrologic analyses, it is evident that while shrub expansion is happening across the landscape, everywhere is not equal. The greatest changes happening are occurring in the floodplains, on floodplain slopes, and within the first 10 meters of hydrologic features. This indicates that while regional factors may be favorable for shrub colonization, there are still factors at the landscape scale that limit expansion. As shown in Chapter 3, it is likely that temperature is still the dominant factor in determining shrub establishment at the regional scale. Here, it is shown that at the landscape scale there is another a limiting factor as shrubs are colonizing and expanding preferentially in flood plains and along streams. Moisture has been suggested to be another regional scale control in conjunction with temperature. This evidenced by studies that have found that the relationship between shrub proliferation and temperature is strongest when factoring in moisture (Elmendorf et al. 2012b, Ackerman et al. 2017, Bjorkman et al. 2018). Since precipitation does not vary at the landscape scale, and aspect is likely not a factor since most rivers flow south to north on the North Slope, there are likely other soil and moisture related factors that vary at the landscape scale that play a role in shaping shrub cover at this scale. Swanson (2015) found that apart from minimum summer temperatures and soil pH, favorable conditions for shrub growth included summer thaw depths greater than 80cm. In Chapter 3 it was found that there was no relationship with shrub cover and permafrost, since at the regional scale, the entire North Slope is underlain by continuous permafrost. However, for shrubs to colonize an area, there needs to be sufficient thawed ground above the permafrost for their roots, which means that permafrost depth plays a role in shaping vegetation distribution (National Research Council 2003). A study of the active-layer thickness in the Kuparuk River Basin found that thaw depths are greatest in the mature stream valleys, particularly along the courses of the Sagavanirktok and Kuparuk Rivers between the Arctic Foothills and Prudhoe Bay (Nelson et al. 1997). At upland sites there is an association between active-layer thickness and acidic and nonacidic tundra, with the nonacidic tundra having thaw depths greater than 50% than that of the acidic tundra (Nelson et al. 1997). Since the greatest shrub cover was found within the first ten meters of hydrological features, it can be suggested that the greater active-layer thickness adjacent to rivers and streams could be a contributing factor to this pattern. As conditions are most favorable along rivers and streams, the floodplains and floodplain slopes are the topographic regions which are likely to have the highest proportion of shrub cover.

4.5 Conclusions

The heterogeneity of shrub cover and expansion shown here is evidence that there are important landscape scale factors beyond regional scale factors that influence shrub establishment and growth. These results show that shrubs are expanding preferentially in floodplains, on floodplain slopes, and within the first few meters adjacent to streams outside of floodplains. At the landscape scale, it is likely that active-layer thickness is an important controlling factor. By examining rates of expansion by topographic region, it is evident that on a whole, shrub expansion rates are lower than others report (Tape et al. 2006a, Tape et al. 2011, Naito and Cairns 2011b). This knowledge is important to understand the extent to which shrub expansion in the Arctic is constrained by landscape position, and thus determining how much of the North Slope is likely to support shrub growth and expansion. Since model-based estimates of shrub expansion are largely based on temperature projections and do not count for landscape scale heterogeneity, they are often overestimations of large-scale vegetation changes (Frost et al. 2014). Future research determining how much of the North Slope of Alaska is likely to support shrub expansion by determining the amount of available landscape that meets the criteria of area likely to be colonized identified here will aid in a more accurate forecasting global changes linked to Arctic greening.

CHAPTER V

THE TRANS-ALASKA PIPELINE SYSTEM FACILITATES SHRUB ESTABLISHMENT IN NORTHERN ALASKA.*

5.1 Introduction

The Arctic is experiencing warming at a rate more than two times than the global mean (Intergovernmental Panel on Climate Change (IPCC)2007), a process known as "Arctic Amplification". Increases in regional temperatures are expected to result in widespread permafrost degradation (thermokarst), especially in areas where ground temperatures are close to freezing (Jorgenson et al. 2006, Shur and Jorgenson 2007, Grosse et al. 2011). Ice-rich permafrost is an important factor that controls the responses of Arctic systems to disturbance (Walker and Walker 1991). If thermokarst is initiated on a large scale, it can take up to 30 years after the disturbance for stabilization to occur in ice-rich, thaw unstable area (Lawson 1986, Walker and Walker 1991).

Disturbance to the surface in permafrost terrain results in a disruption of the thermal equilibrium, which can result in increased thaw (Brown 1997). Since the base of the active layer is impermeable to water and impenetrable to roots (National Research Council 2003), permafrost warming and degradation changes the hydrological and nutritional characteristics of soils, which impacts vegetation distribution, plant community structure

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and productivity in Arctic and Subarctic regions (Reynolds et al. 1996, Lloyd et al. 2003, Christensen 2004). Thus, temperature changes affect both permafrost regimes and the related changes in hydrology and vegetation (Christensen 2004).

Increasing productivity of Arctic vegetation in response to recent climate warming has been well documented (Goetz et al. 2005, Jia et al. 2006, Stow et al. 2007). A major component of these increases can be attributed to increases in deciduous shrub cover (shrubification), mostly *Betula*, *Salix,* and *Alnus* species (Myers-Smith et al. 2011a, Naito and Cairns 2015). Shrubification may also be influenced by the permafrost regime and, in turn, has the potential to impact many components of the tundra ecosystems, such as, the surface energy balance, hydrology, nutrient cycling, snow depth, and albedo (Swann et al. 2010, Naito and Cairns 2011b, Pearson et al. 2013, Myers-Smith et al. 2015a). Permafrost is not directly connected to the atmosphere due to the influence of topography, groundwater, soil properties, vegetation, snow, and the interactions of these factors; these can result in positive or negative feedbacks to permafrost stability (Jorgenson et al. 2010). While permafrost plays an important role in shaping vegetation patterns, vegetation cover also has the potential to reduce permafrost degradation (Yi et al. 2007). However, there is still uncertainty regarding the relationship between shrub expansion and active-layer dynamics (Frost et al. 2018).

In Alaska, the discovery of oil at Prudhoe Bay in 1968 initiated the start of major industrial activity and environmental research in the Arctic (Walker and Walker 1991). The Trans-Alaska Pipeline System (TAPS) was constructed over a period of three years, concluding in 1977, to move oil over 1287 km from Prudhoe Bay to the port of Valdez in a 1219 mm diameter pipeline (Brown and Kreig 1983, Hall et al. 2003). The TAPS has had a significant imprint on the landscape with oilfield infrastructure on the North Slope of Alaska, covering an area of 7429 ha (Walker et al. 1987a, Walker and Walker 1991, Raynolds et al. 2014).

Infrastructure in permafrost terrain can cause ground-ice degradation by modifying the subsurface conditions through the construction process or by the structure itself (Bommer, Phillips and Arenson 2010). Lawson (1986) found that ice-rich areas disturbed by exploratory drilling activities in the National Petroleum Reserve-Alaska took over 30 years to stabilize to a point which would allow for vegetation growth, and thermal equilibrium, whereas areas with ice-poor materials stabilized within 5 to 10 years. Pipeline burial is the preferred method of construction for such infrastructure in nonpolar environments, however, in permafrost regions this method can cause problems because the subsurface heat from the transmission of the warm fluids results in permafrost thaw in the soils surrounding the pipeline, and differential settlement (National Research Council (NRC)2003). The Arctic Foothills and Arctic Coastal Plain are mostly underlain by deep continuous permafrost, with unfrozen areas mostly limited to deep river channels and deep lake basins (Brown and Berg 1980). Since pipeline burial requires thaw-stable conditions, 57% of the pipeline north of the Yukon River was constructed aboveground (Brown and Berg 1980, Brown and Kreig 1983). Following disturbance from the pipeline construction, thaw depths increased for at least the subsequent 3 years, with some depths being 28 cm greater along the oil pipeline than control sites (Reynolds et al. 1996).

The thermal stability of a disturbed area determines the timeframe for vegetation recovery, as well as the type of vegetation that is able to colonize a site (Walker and Walker 1991). Most studies have emphasized the environmental impacts of roads, gravel sites, and the Prudhoe Bay Oil Field (Johnson 1987, Walker et al. 1987a), however, based on a survey of published literature, little is known about the current response of vegetation to the disturbance of the pipeline, across the wide range of environments it traverses. Following construction of the TAPS, revegetation attempts were made by Alyeska Pipeline Service Company using a seed mix of grasses (Johnson 1981). Initially the revegetation process along the TAPS was found to be very slow (Walker et al. 1987b). At the time of the study by Johnson (1981), revegetation on disturbed areas by native species was limited, and *Salix pulchra* and *Betula nana* cuttings also had limited establishment success. Some revegetated areas were dominated by grass cover from the seed mix of exotic species; the potential impacts of their effects on native species revegetation was not known at the time (Johnson 1981). The restoration of disturbed sites is often slow, however, even so, it has been found that revegetation can occur naturally (Forbes and Jefferies 1999). Since gravel pads are akin to riparian gravel bars, it is likely that riparian species will be more successful in colonizing gravel pads (Bishop and Chapin III 1989). Presently along the TAPS, natural colonizers that are well adapted to well-drained, nutrient poor soils have become the dominant species (Jorgenson 1997). However, there is still much to be learned regarding the impacts of energy development on tundra ecosystem processes, and how best to rehabilitate them (Reynolds et al. 1996).

Here, we aimed to assess the state of shrub presence along the TAPS north of the Brooks Range, Alaska. Our objectives were to determine: (1) whether shrub presence has increased more in the vicinity of the pipeline compared to adjacent undisturbed areas, and (2) whether the burial status of the pipeline (aboveground or buried) has an impact on shrub presence.

5.2 Methods

5.2.1 Study area

The North Slope of Alaska is the 230,000 km^2 area north of the crest of the Brooks Range. This area is divided into three regions: the Arctic Coastal Plain, the Arctic Foothills, and the Brooks Range. The North Slope is underlain by continuous permafrost (>90% coverage), and sedge tussocks and shrubs characterize the tundra vegetation. The most common shrub species are birch (*Betula nana* and *B. glandulosa*), willow (*Salix alaxensis, S. pulchra*, and *S. glauca*), and alder (*Alnus crispa*) (Tape, Sturm and Racine 2006b). Most of the oil activities are constrained to the Arctic Coastal Plain, however, the TAPS corridor stretches 1,287 km from Prudhoe Bay in the north to Valdez in the south (Figure 40).

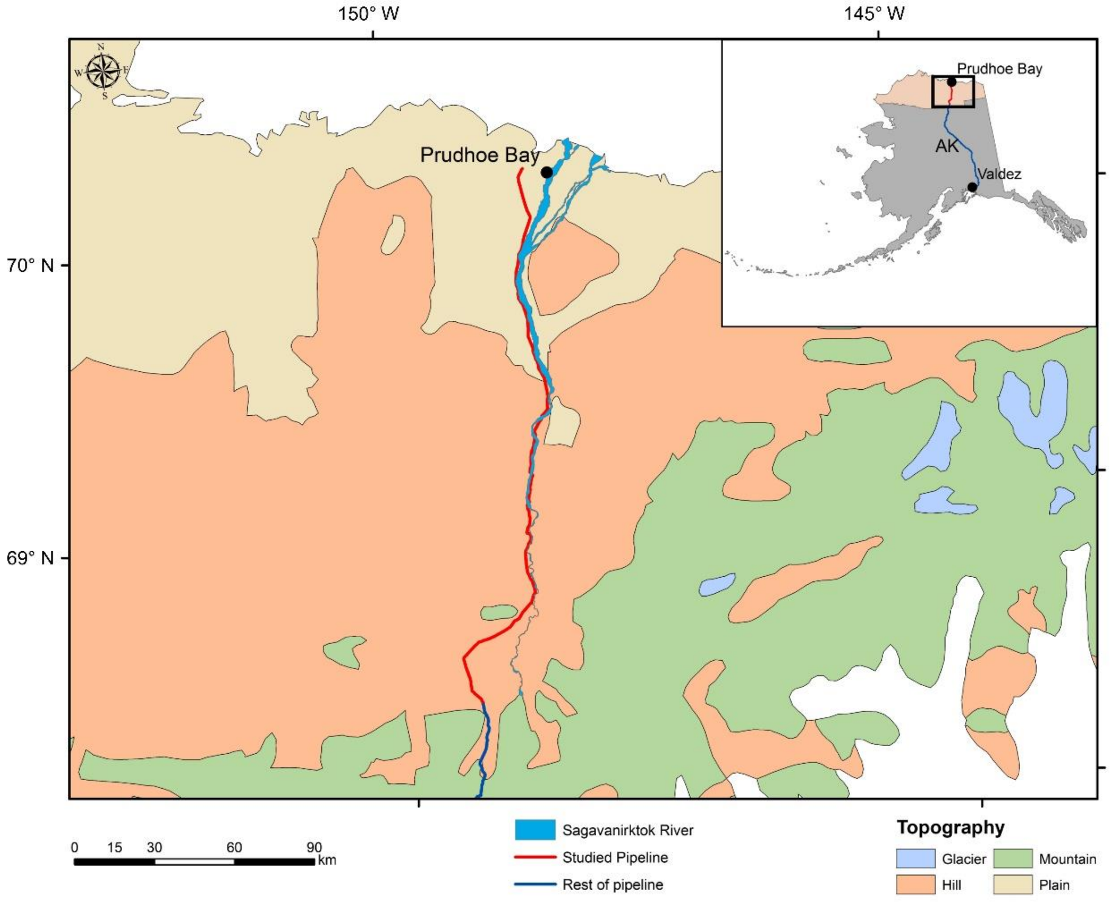

Figure 40: Path of the section of the pipeline studied, including topography and the Sagavanirktok River. Topographical data from Raynolds and Cooper (2016). Reprinted from Dwight and Cairns (2018).

5.2.2 Satellite image acquisition and analysis

Digital scans of historical black and white images from June 21, 1974, captured by the Keyhole (KH) satellite system, KH-9, with a high spatial resolution of 2-4 feet, were acquired from the United States Geological Survey Earth Resources Observation and Science (USGS EROS). The historical images were co-registered to the contemporary images using ArcMap 10.5. The contemporary panchromatic images for the entire 255 km section were sourced from the DigitalGlobe archives (DigitalGlobe, Inc., USA). The contemporary images were captured in June to September of 2010–16 by the Worldview-1 (0.5 m), Worldview-2 (0.46 m), Worldview-3 (0.31 m), and GeoEye-1 (0.41 m) satellites (DigitalGlobe, Inc., USA). Images were selected based on the lack of cloudiness and snow. The pipeline was classified as either “aboveground” or “buried”, with a total of 110 km of pipeline aboveground and 115 km of buried pipeline. Transects that were located over gravel pads or rivers were marked as “obstructed” and excluded from analysis.

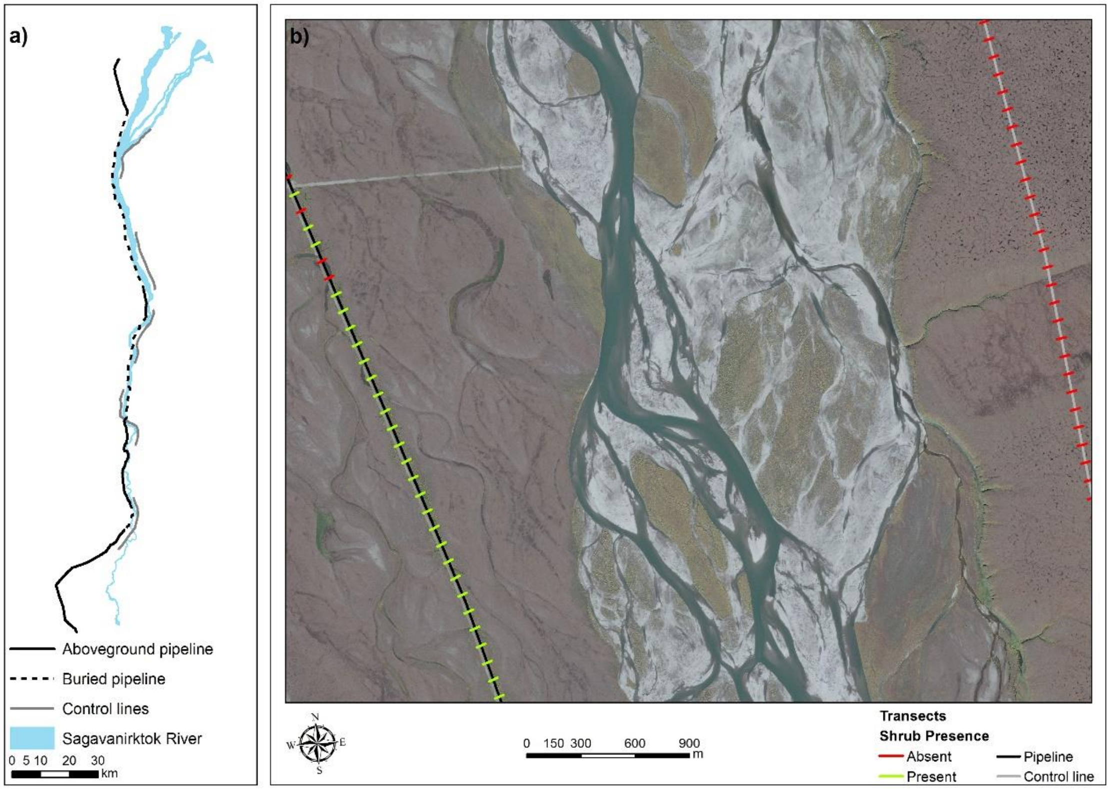

Figure 41: a) The path of the pipeline and control lines in relation to the Sagavanirktok River. b) Example of the pipeline and a control line with sample transects from WorldView-2 imagery (© 2016 Digital Globe, Inc.). Reprinted from Dwight and Cairns (2018).

To address the first objective, five control lines not affected by the TAPS were used to determine whether shrub presence has increased more along the pipeline than in the adjacent tundra over time (Figure 41). Control lines were placed parallel to the pipeline; every effort was made to put the control lines in similar settings to the adjacent pipeline. Where possible, this was done by placing the control lines on the opposite side of the Sagavanirktok River and at a similar distance from the river as what the pipeline was at that point (Figure 41). Transects, perpendicular to the pipeline, 50 m wide, spaced at 100 m intervals were created along the pipeline and control lines using ArcMap 10.5. The transects were manually classified according to whether they intersected shrub cover or not, limiting classification to the presence or absence of tall shrubs. We recorded shrub presence (“1”) or absence (“0”) along 1090 transects on the control lines of both the historical and the contemporary imagery. We then repeated this process using 1037 transects at parallel points along the pipeline to assess change in shrub presence over time (e.g. Figure 42). To quantify the contemporary association between the pipeline burial status and shrub presence for objective two, we classified a total of 2155 transects along the 255 km of studied pipeline for shrub presence (“1”) or absence (“0”). Any transects intersecting a gravel pad, river or lake were omitted from the analysis.

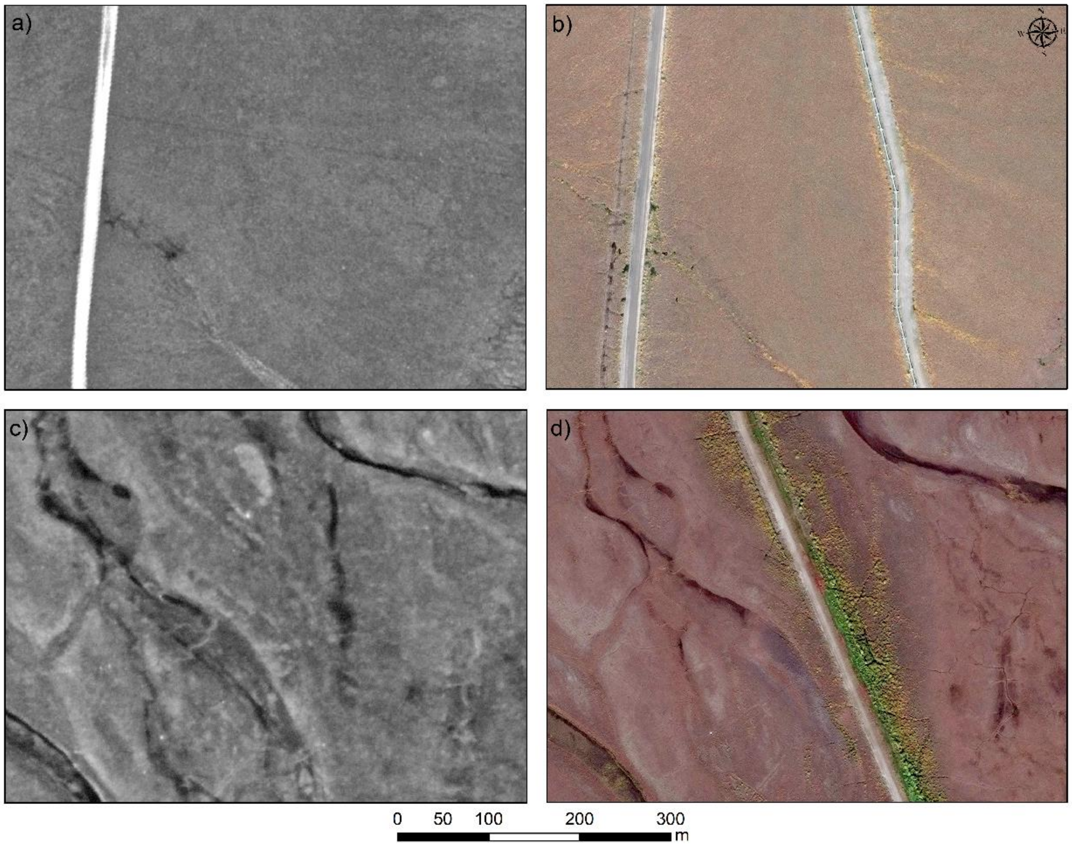

Figure 42: a) Historical image of a location where a pipeline was later constructed aboveground. b) Contemporary image of that aboveground pipeline, from WorldView-2 imagery (© 2016 Digital Globe, Inc.). The straight line at the left of both images is the Dalton Highway. c) Historical image of a location where a pipeline was later buried. d) Contemporary image of that same location with buried pipeline, from WorldView-2 (© 2016 Digital Globe, Inc.). Reprinted from Dwight and Cairns (2018).

5.2.3 Statistical analysis

Change detection was conducted by subtracting the historical classification values from the contemporary classification values. Values of "-1" represented a loss in shrub presence, "0" indicated no change, and "+1" was indicative shrub presence along a transect where there was none previously. Pearson's Chi-squared test with Yate's continuity correction was used to test for the association between shrub presence and pipeline burial status.

5.3 Results

5.3.1 Changes in shrub presence over time

In the control areas, a total of 67 of the 1090 transects (6.1%) intersected shrubs in the historical imagery. Of the 1090 transects, only 29 (2.6%) transitioned from “no shrub” in the historical imagery to “shrub” in the contemporary imagery (Figure 43). Along the pipeline, 95 of the 1037 (9.2%) transects intersected shrubs in the historical imagery. A greater increase in shrub presence was found in vicinity of the pipeline; 602 (58.1%) of the 1037 transects transitioned from “no shrub” to “shrub” in the contemporary imagery. A total of 29.6% of the sampled transects transitioned from “no shrub” to “shrub” (Figure 43). None of the sampled transects lost the presence of shrub cover along the control transects over time, however, one pipeline transect transitioned from having shrub cover in the historical imagery to not having in the contemporary imagery.

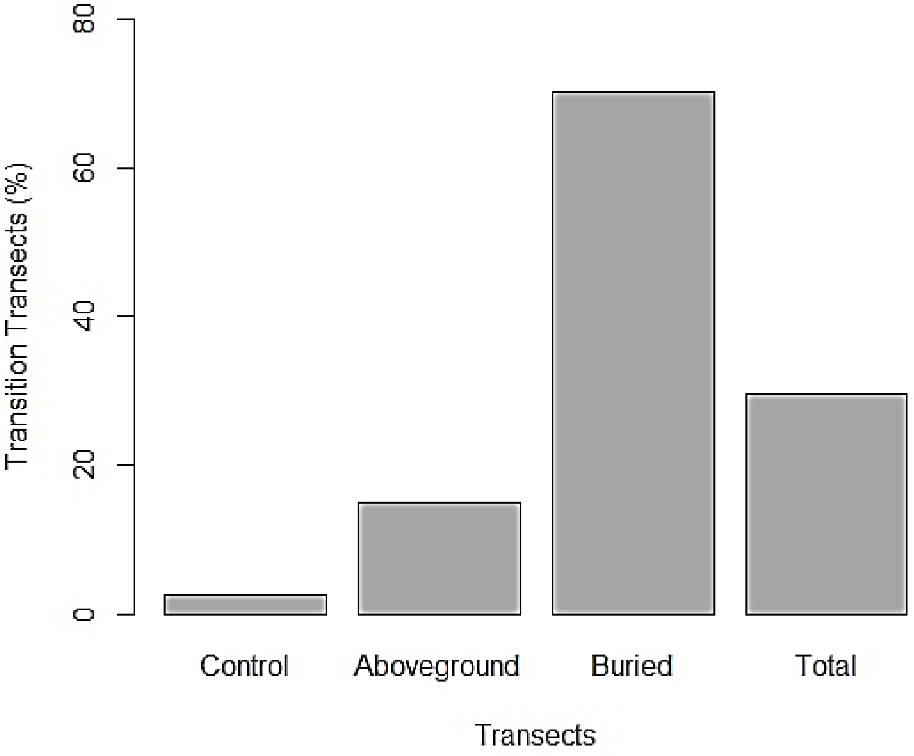

Figure 43: Influence of pipeline burial on shrub presence. Graph shows the percentage of transects (control, aboveground pipeline, buried pipeline, and total) that transitioned from absence of shrubs in the historical imagery to shrub presence in the contemporary imagery. Reprinted from Dwight and Cairns (2018).

5.3.2 The relationship between shrub presence and pipeline burial status

In areas where the pipeline is aboveground, only 14.9% of the transects transitioned from "no shrub" to "shrub" (Figure 43). In areas where the pipeline is buried, 70.2% of the transects transitioned from "no shrub" to "shrub" (Figure 43).

Chi-squared analysis was conducted to test for an association between pipeline burial status and shrub presence along the entire 255 km of pipeline north of the Brooks

Range. The associations, as seen in Table 9, yielded a highly significant relationship ($\chi^2 = 1078.2$, $p < 0.01$) between shrub occurrence and pipeline burial status. This indicates that shrubs are more likely to establish in areas where the pipeline is buried than in cases where is it aboveground.

Table 9: Associations between shrub presence and pipeline burial status, expressed in number of transects.

Pipeline Burial Status	No Shrubs	Shrubs Present	Total
Above ground	958	132	1090
Buried	183	882	1065
Total	1141	1014	2155

5.4 Discussion

5.4.1 Change over time

This study found that shrub presence increased by 58.1% in the vicinity of the pipeline, as opposed to 2.7% for the control transects. This indicates that the processes linked to the disturbance from the pipeline have likely facilitated shrub colonization. While shrub expansion in the Arctic has been widely reported, certain are areas more susceptible to shrub encroachment (Naito and Cairns 2011a, Sturm et al. 2001b, Tape et al. 2006b, Hallinger et al. 2010, Myers-Smith et al. 2011b, Elmendorf et al. 2012b, Frost et al. 2013, Naito and Cairns 2015, Ackerman et al. 2017, Martin et al. 2017, Myers-Smith and Hik 2017). The percent increase in shrub presence along the control transects is relatively low compared to some of the rates published in the studies listed above, which is due to local conditions playing a major role in facilitating shrub expansion (e.g. Tape et al. (2006b), Myers-Smith et al. (2011b), Naito and Cairns (2011b), Naito and Cairns (2015), Ackerman et al. (2017)). Jorgenson et al. (2015) found that even though shrub expansion rates were relatively low for the region of northwest Alaska on a whole, they were highly variable according to ecotype and biophysical drivers. Favorable local conditions include floodplains or areas with higher topographic wetness index values (Naito and Cairns 2011b) or frost-heaved soils (Frost et al. 2013). The disturbance of the ground from the TAPS construction process, and the pipeline itself could create similar conditions to the favorable conditions that occur naturally, and hence, facilitate shrub colonization.

5.4.2 Influence of the pipeline

While we found that increases in shrub presence were greatest in the vicinity of the pipeline, these results were not uniform along its entire length. A significant relationship ($p < 0.01$) between shrub presence and pipeline burial status was found. As can be seen in Figure 44, this relationship is highly evident, with sharp changes even occurring where the pipeline transitions from being aboveground to buried. Processes linked to the disturbance from construction and the pipeline itself have likely created favorable conditions for recruitment. The buried pipeline increases the adjacent active layer thickness (Reynolds et al. 1996), which will likely allow for greater moisture throughflow, and greater rooting depths. Chapin III and Shaver (1981) found that plants in areas affected by disturbance from vehicles had improved nutrient status, and therefore, high productivity, however, they concluded that it could not be attributed solely to increases in soil temperature and thaw depth. Gill et al. (2014) found that the environmental changes associated with road construction facilitated alder growth and recruitment along the Dempster Highway in the Northwest Territories, Canada. Such changes can include altered surface energy balance, ground thermal properties, and the temperature regime of the underlying permafrost (Forbes and Jefferies 1999, Forbes, Ebersole and Strandberg 2001, Gill et al. 2014). A study by Ackerman and Breen (2016) notes four *Poplus tremuloides* stands on abandoned gravel roads and pads, north of their range in the northern foothills of the Brooks Range, Alaska. The authors attribute this to the pads creating favorable conditions in the form of increased rooting depth, well-drained microsites, an extended growing season, and acid-buffering capacity (Ackerman and Breen 2016). While without ground observations it is beyond the scope of this study to posit the exact mechanism driving increased shrub growth along the pipeline (particularly where it is buried), similar to the studies by Gill et al. (2014) and Ackerman and Breen (2016) the recruitment of new individuals along the pipeline is likely due to the creation of more favorable conditions, probably in the form of deeper rooting depths, well-drained microsites, and increased nutrient availability.

Figure 44: Image from WorldView-3 (© 2016 Digital Globe, Inc.) showing the abrupt change in vegetation along the pipeline as it transitions from aboveground (red) to buried (black). Reprinted from Dwight and Cairns (2018).

5.4.3 Implications

Shrub expansion is limited by local conditions, making disturbance an important factor influencing shrub presence, and may even have a greater influence in the recruitment of new individuals than climate warming (Myers-Smith et al. 2011b). Shrub cover linked to disturbance can influence other parts of systems through feedbacks. Shrub proliferation along roads in the Canadian tundra resulted in a positive feedback cycle through increased snow accumulation, altered ground temperatures, and soil chemistry (Gill et al.

2014). In areas where tall shrubs were not as established, not as much snow and dust accumulated, and therefore the feedbacks were not as pronounced (Gill et al. 2014). Positive feedbacks similar to those observed by Gill et al. (2014) could be expected along the pipeline in places where shrubs trap the snow, increasing snow depth. This positive feedback could have significant implications for the stability and integrity of infrastructure in tundra environments. It is essential to obtain better knowledge of how Arctic tundra vegetation recovers from disturbance to provide an idea of its potential responses to future disturbances, which are likely to become more frequent (Chapin et al. 2005, Cray and Pollard 2015).

5.5 Conclusions

This study has shown that shrub colonization has been facilitated by processes linked to the disturbance of the TAPS. Identifying which factors are responsible for the recruitment of new individuals is imperative to quantify the impact of shrub expansion on the Arctic tundra ecosystems (Myers-Smith et al. 2011b). While this study is not able to definitively identify the causes of shrubification, the correlation between shrub presence and the disturbance of the pipeline provides useful knowledge of how the vegetation has responded, with shrubs exploiting disturbed areas. Understanding the responses of tundra to disturbance, and characterizing the vulnerability of the Low Arctic to tall shrub and tree expansion is critical for projecting possible feedbacks (Elmendorf et al. 2012a, Frost and Epstein 2014). The findings of this study align with other Arctic studies (e.g. Gill et al. (2014) and Ackerman and Breen (2016)), therefore, this study will contribute to obtaining a better understanding of the cumulative effects of anthropogenic disturbances and how the Arctic tundra environment may respond to continued disturbances.

CHAPTER VI

CONCLUSIONS

This research has quantified shrub cover on the North Slope of Alaska at multiple scales to improve the understanding of factors controlling shrub colonization and expansion. This serves to fill a gap in the literature since the focus of Arctic shrub expansion studies have been in floodplains where rapid shrub expansion has been observed.

Chapter III focused on the associations between shrub cover and latitude, and selected environmental variables at the regional scale. It was found that shrub cover exhibits a latitudinal pattern on the North Slope, with shrub cover decreasing with increasing latitude. This is likely due to controlling factors, temperature and precipitation, exhibiting this gradient too. However, some have suggested a decoupling between temperature and shrub expansion, which when combined with these results suggests that shrub cover is controlled by other regional factors that are influenced by temperature (Martin et al. 2017). Since shrub expansion may not strictly be controlled by temperature, it is important to quantify shrub cover and shrub expansion at the landscape scale.

Chapter IV found that shrub cover and shrub expansion is not evenly distributed across the landscape, which is evidence that there are important landscape scale factors that influence shrub establishment and growth. With respect to topographic regions, shrub cover was found to be highest in floodplains, and is expanding at the greatest rates on floodplain slopes. When considering the relationship between shrub expansion and hydrologic features, the greatest rates of expansion were also found within the first ten meters of streams. It is likely that these patterns are influenced by active-layer thickness, which tends to be deeper adjacent to stream valleys (Nelson et al. 1997). However, even at the more local scale there is fine-scale heterogeneity with local factors and disturbances that can facilitate shrub colonization.

Chapter V investigated the response of shrubs to the Trans-Alaska Pipeline System and found that shrub colonization has been facilitated by processes linked to disturbances related to the pipeline, especially in areas where the pipeline is buried. This study contributes to new knowledge regarding the cumulative impacts of anthropogenic disturbances on the North Slope, as well as how the Arctic tundra may respond to future disturbances.

Shifts in shrub cover will impact the local energy balance (Sturm et al. 2005b, Sturm et al. 2005a), carbon balance (Oechel et al. 2000, Sturm et al. 2005b, Sturm et al. 2005a), and result in the shift in species that utilize shrubs (Zhou et al. 2017). Therefore, identifying factors responsible for the recruitment of new individuals is essential to gaining an understanding of the impacts of shrub expansion on Arctic tundra ecosystems (Myers-Smith et al. 2011b). This multi-scalar approach aids in determining what these factors are, which is critical for characterizing the vulnerability of the Low Arctic to tall shrub and tree expansion (Elmendorf et al. 2012a, Frost and Epstein 2014). Overall, this research provides better understanding of where key areas of shrub expansion are on the North Slope of Alaska, which will aid in improving Arctic vegetation models which assume that vegetation changes are homogenous across the entire tundra biome (Frost et al. 2014, Myers-Smith et al. 2015b).

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