LANDSCAPE VARIABILITY OF VEGETATION CHANGE ACROSS THE FOREST TO TUNDRA TRANSITION OF CENTRAL CANADA

by

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Abstract

Widespread vegetation productivity increases in tundra ecosystems and stagnation, or even productivity decreases, in boreal forest ecosystems have been detected from coarse-scale remote sensing observations over the last few decades. However, finer-scale Landsat studies have shown that these changes are heterogeneous and may be related to landscape and regional variability in climate, land cover, topography and moisture. In this study, a Landsat Normalized Difference Vegetation Index (NDVI) time-series (1984-2016) was examined for a study area spanning the entirety of the sub-Arctic boreal forest to Low Arctic tundra transition of central Canada (i.e., Yellowknife to the Arctic Ocean). NDVI trend analysis indicated that 27 % of un-masked pixels in the study area exhibited a significant ($p < 0.05$) trend and virtually all (99.3 %) of those pixels were greening. Greening pixels were most common in the northern tundra zone and the southern forest-tundra ecotone zone. NDVI trends were positive throughout the study area, but were smallest in the forest zone and largest in the northern tundra zone. These results were supported by ground validation, which found a strong relationship ($R^2 = 0.81$) between bulk vegetation volume (BVV) and NDVI for non-tree functional groups in the North Slave region of Northwest Territories. Field observations indicate that alder (*Alnus* spp.) shrublands and open woodland sites with shrubby understories were most likely to exhibit greening in that area. Random Forest (RF) modelling of the relationship between NDVI trends and environmental variables found that the magnitude and direction of trends differed across the forest to tundra transition. Increased summer temperatures, shrubland and forest land cover, closer proximity to major drainage systems, longer distances from major lakes and lower elevations were generally more important and associated with larger positive NDVI trends. These findings indicate that the largest positive NDVI trends were primarily associated with the increased productivity of shrubby environments, especially at, and north of the forest-tundra ecotone in areas with more favorable growing conditions. Smaller and less significant NDVI trends in boreal forest environments south of the forest-tundra ecotone were likely associated with long-term recovery from fire disturbance rather than the variables analyzed here.

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List of Abbreviations

%IncMSE	Percent increase in Mean Squared Error
6S	Second Simulation of the Satellite Signal in the Solar Spectrum
AVHRR	Advanced Very High Resolution Radiometer
BVV	Bulk Vegetation Volume
CAVM	Circumpolar Arctic Vegetation Map
CRU	Climatic Research Unit
DEM	Digital Elevation Model
ETM+	Enhanced Thematic Mapper Plus
GIMMS	Global Inventory Modeling and Mapping Studies
GloVis	Global Visualization Viewer
GNWT	Government of Northwest Territories
IncNodePurity	Increase in node purity
ISODATA	Iterative Self-Organizing Data Analysis Technique
L1T	Landsat Standard Terrain Correction
LAI	Leaf Area Index
LaSRC	Landsat Surface Reflectance Code
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
MODIS	Moderate Resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NTS	National Topographic System
OLI	Operational Land Imager
PAR	Photosynthetically Active Radiation
PIFs	Pseudo-Invariant Features
PVC	Percent Vegetation Cover
RF	Random Forest
SLC	Scan Line Corrector
TM	Thematic Mapper
TPI	Topographic Position Index
TWI	Topographic Wetness Index
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WRS	Worldwide Reference System

Chapter 1

Introduction

1.1 Research Context

The Earth system has experienced an increase in average air temperature on the order of 1 °C since the late 1800s (IPCC, 2013). The scientific community has concluded, beyond a reasonable doubt, that this warming has occurred as a consequence of anthropogenic fossil fuel emissions (IPCC, 2013). This warming trend has had a variety of effects on the Earth system, especially at high latitudes where warming has been significantly greater than the global average. Serreze & Barry (2011) report that northern high latitudes have warmed 2 to 4 °C over the last 50 years. This phenomenon, known as Arctic amplification, is the result of a positive feedback mechanism where an initial warming (in this case sparked by global fossil fuel emissions) in the Arctic leads to increased melting of high albedo snow and ice. The loss of these reflective surfaces earlier in the spring, coupled with later accumulation in the fall, allows more insolation to be absorbed by terrestrial and marine surfaces at high latitudes. The enhanced growth of vegetation as a function of warmer temperatures and a longer growing season initiates both positive and negative feedback mechanisms. For instance, increased vegetative growth reinforces a positive feedback given its lower albedo (i.e., increased energy absorption) whereas the associated increase in CO₂ sequestration for photosynthesis is a negative feedback mechanism (Chapin et al., 2005; Wookey et al., 2009). Reduced terrestrial albedo and subsequent surface warming has also been linked with the increased emission of longwave radiation (Serreze & Barry, 2011). When taken collectively, these mechanisms have given rise to increasing temperatures at high latitudes over time.

These increasing Arctic air temperatures are triggering changes in other environmental variables that influence vegetation dynamics. Precipitation in the Arctic is projected to increase

by more than 50 % by 2100 (Kattsov et al., 2007). This is mainly attributed to increased surface evaporation as a result of Arctic amplification (Bintanja & Selten, 2014). Arctic and sub-Arctic warming has also led to a reduction in snow cover and sea ice extent (Derksen & Brown, 2012; Stroeve et al., 2007). Sea ice decline has been linked to increased vegetation growth at northern high latitudes, since the loss of high albedo surfaces (i.e., ice and snow) allows for lower elevation tundra areas near the coast to heat up more (Bhatt et al., 2010). Despite increased precipitation, studies have found a decline in surface water balance at northern high latitudes (Smith et al., 2005; Smol & Douglas, 2007); which has been linked to permafrost degradation and increased evaporation (Oechel et al., 2000; Bintanja & Selten, 2014). However, other studies have linked permafrost degradation with increased water coverage in areas with wetter moisture regimes (Jorgenson et al., 2006; Pattison et al., 2015; Raynolds & Walker, 2016). High latitude boreal forests and bordering shrub tundra regions have also experienced an increase in fire disturbance attributed to the warming climate and increases in biomass (i.e., fuel) (Higuera et al., 2008; Macias-Fauria & Johnson, 2008).

In the context of these environmental changes occurring at northern high latitudes, there has been an increase in the productivity of vegetation in Arctic and sub-Arctic ecosystems over the last half century. This is primarily spurred by the increased growth and expansion of shrubs across the circumpolar Arctic and sub-Arctic as climatic conditions become more favorable for species previously under stress and at the periphery of their range (Myers-Smith et al., 2011). This is especially evident along the forest-tundra ecotone and in adjacent tundra areas, where shrubs are extending their range into previously inhospitable areas and becoming more abundant where they are already present (Danby & Hik, 2007; Myers-Smith et al., 2011). Northward expansion of shrubs is expected over a decadal-length timescale along forest-tundra and shrubland-tundra transitions (Epstein et al., 2004). This northward expansion has been heterogeneous, with landscape-scale differences in terrain having an influence on the magnitude

of vegetation change at high latitudes (Ropars & Boudreau, 2012; Frost et al., 2014). Shrub expansion has also occurred along rivers and near recently drained lakes (Stow et al., 2004; McManus et al., 2012; Fraser et al., 2014a), illustrating a potential relationship between terrain and moisture availability. However, it should also be noted that in recent years (2011 to 2014) a decline in vegetation productivity has been observed in tundra environments, with the cause still uncertain and likely related to a variety of factors (e.g., warmer winter temperatures leading to more snow cover, increased tundra fires, pest outbreaks, herbivore population growth, etc.) (Bhatt et al., 2013; Epstein et al., 2016; Phoenix & Bjerke, 2016).

While shrub growth and expansion have been widespread, treeline advance has been mixed, advancing in some locations and remaining static elsewhere (Harsch et al., 2009). Additionally, a decrease in productivity from forest dieback has been detected in boreal ecosystems south of the forest-tundra ecotone based on remote sensing observations (Verbyla, 2008; Beck & Goetz, 2012; Guay et al., 2014). This has been attributed to higher drought stress in the summer months of the last few decades because of increasing temperatures (Barber et al., 2000; Bunn et al., 2005; Lotsch et al., 2005). Treeline advance has also not occurred at the same rates as shrub expansion because boreal tree range expansion takes longer to respond to warming in general (i.e., there is a significant lag period) (MacDonald et al., 1998; Epstein et al., 2004; Gamache & Payette, 2005). Specifically, black spruce (*Picea mariana*) has limited reproductive potential (i.e., lower seed production and less-likely seed germination) for stressed krummholz (i.e., stunted) individuals trying to expand into tundra areas (Black & Bliss, 1980; Gamache & Payette, 2004; 2005). Still, it should be noted that trees at the forest-tundra ecotone have shown accelerated height growth in the last few decades in some locations, even if range expansion has not occurred at the same rate as shrubs (Gamache & Payette, 2004).

Satellite remote sensing data have allowed researchers to quantify vegetation change over a variety of spatial scales in the northern high latitudes as well as globally. These remote sensing

measures not only allow researchers to quantify change over time but aid in the development of a more thorough understanding of the processes giving rise to the changes observed. Coarse spatial resolution satellite sensors, such as the Advanced Very High Resolution Radiometer (AVHRR), allow for the analysis of vegetation dynamics over large areas and short time scales attributed to the quick revisit time (twice per day for AVHRR) of these sensors (Stow et al., 2004; Latifovic et al., 2005). However, in order to analyze changes in vegetation dynamics at a landscape or local scale, finer spatial resolution data are required (Brown et al., 2006; Olthof et al., 2008; Epstein et al., 2012). The National Aeronautics and Space Administration (NASA) Landsat program, first launched with Landsat 1 in 1972, provides global coverage at a finer spatial resolution (White & Wulder, 2014). Since the launch of Landsat 4 in 1982, this program has provided the scientific community with a standardized repository of 30 m spatial resolution data over the entire landmass of the planet (Wulder et al., 2016). Free and open access to this repository beginning in 2008 has spurred increased study of landscape-scale vegetation dynamics across northern high latitudes (Wulder et al., 2012; Banskota et al., 2014).

Researchers concerned with high latitude vegetation dynamics generally utilize specific satellite spectral bands and spectral derivatives that best quantify vegetation characteristics. Vegetation indices have been developed to quantify vegetation change across the landscape through various combinations of these spectral bands. The most common index used to quantify vegetation biomass is the Normalized Difference Vegetation Index (NDVI). NDVI, derived for each pixel, is equal to the near infrared value minus the red value divided by the sum of those two values, and serves as a useful proxy for quantities of vegetation (e.g., percent vegetation cover, biomass) in a satellite image (Rouse et al., 1973). As a result, researchers have utilized satellite data from different years across the boreal forest to tundra transition to create time-series of NDVI, which quantify changes in vegetation over time (Jia et al., 2003; Olthof et al., 2008; Fraser

et al., 2011; Epstein et al., 2012; McManus et al., 2012; Raynolds et al., 2013; Frost et al., 2014; Guay et al., 2014; Pattison et al., 2015; Ju & Masek, 2016).

1.2 Research Rationale

The growth and expansion of vegetation across northern high latitudes as a function of warming temperatures is an important phenomenon because it influences a variety of processes; the most direct of which may be the capacity of ecosystems to store carbon. It is estimated that the northern high latitudes store 1672 Pg of carbon in permafrost (Schuur et al., 2008). Increases in vegetation growth, attributed to warming temperatures, allow for additional carbon to be released into the atmosphere rather than being stored in permafrost. In fact, high latitude environments have been net sources of carbon to the atmosphere since the 1980s because of increases in vegetation respiration, as well as from widespread permafrost thaw and general climate warming (Oechel et al., 1993; Slater & Lawrence, 2013). There is strong evidence that future temperature and subsequent vegetation biomass increases in high latitude environments will contribute to soil carbon loss to the atmosphere (Crowther et al., 2016). The release of carbon from permafrost would add significantly to the global warming process as a notable positive feedback in high latitude ecosystems (Schuur et al., 2008; Crowther et al., 2016).

Changes in vegetation biomass in high latitude ecosystems also influences the albedo, or reflectivity, of the landscape. Vegetation growth is expected to lead to an increase in winter snow depth, since forest and forest-tundra communities have deeper snow depths than tundra communities on average (Sturm et al., 2001a; Jacobs et al., 2014). Plots with shrub cover also maintain snow cover for over 30 days longer per year on average than plots without shrubs (Kambo, 2017). Deeper snow patches insulate the ground from cold winter air temperatures, thus warming soil temperatures in the winter, which has been shown to influence subsequent shrub growth (both positively and negatively) over yearly and decadal time-scales (Sturm et al., 2005a; Semenchuk et al., 2016). More recent studies have found that shallow snow depths under shrubs,

as low as 5 cm, may insulate the ground as effectively as deep snow depths (Kambo, 2017). The intricacies of the snow-shrub relationship are not yet fully understood.

Taller vegetation means that it is more likely to remain exposed above the snow through the winter, thereby decreasing the albedo of the landscape, and representing another positive warming feedback in high latitude ecosystems (Sturm et al., 2005b; Pearson et al., 2013). Shrub expansion and treeline advance at northern high latitudes would impact landscape energy absorption in that tundra has a consistently higher albedo (0.8 pre-snowmelt, 0.17 post-snowmelt) than shrubland (0.6 pre-snowmelt, 0.15 post-snowmelt) and boreal forest (0.2 pre-snowmelt, 0.11 post-snowmelt) throughout the spring and summer (Beringer et al., 2005; Sturm et al., 2005b; Chapin et al., 2005). If shrubification and treeline advance continue, the amplification of climate warming in the Arctic could increase two to seven times given these land cover shifts alone (Chapin et al., 2005). Further study of this phenomenon indicates that annual albedo will decrease by up to 18 % and spring albedo (snowmelt period) will decrease by up to 26 % across northern high latitudes by 2050 (Pearson et al., 2013).

Research on the dynamics of vegetation growth due to climate change have been carried out at many locations across northern high latitudes, yet little work has been done across the expansive forest-tundra ecotone of central Canada (Harsch et al., 2009; Myers-Smith et al., 2011). This region has become an important area of study because of the drastic decline in the population of the Bathurst caribou herd in the last few decades (Boulanger et al., 2011; GNWT, 2015a). My research will therefore extend the geographical range of vegetation change measurements to an area in need of scrutiny. The influence of landscape-scale changes on vegetation change has been noted as a topic in need of further study and this research will also assist in that regard (Myers-Smith et al., 2011). Finally, a vital aspect of this study involves the exploration of vegetation change along a latitudinal gradient, rather than an elevational gradient. Many forest-tundra ecotone studies are conducted in mountainous areas since the ecotone

changes occur on the order of hundreds of meters and are thus convenient to study. Studies along latitudinal transitions between forest and tundra are less common since ecotone changes often occur over hundreds of kilometers and are thus more difficult to examine, particularly in the context of field measurements (and associated logistics). However, remote sensing measures greatly assist in the examination of vegetation change over large spatial scales. Hence, it is important to conduct research along both gradients (i.e., elevation and latitude) in order to compare results between the different environmental gradients and thus gain a more complete understanding of the forest to tundra transition.

1.3 Research Goal and Objectives

The goal of my research was to assess recent (~35 years) vegetation changes occurring across the boreal forest to Low Arctic tundra transition of central Canada using a multispectral remote sensing vegetation index (i.e., NDVI) and to identify the landscape-scale environmental variables that most influence vegetation change across this region.

The main objectives of this study were to: (1) quantify recent vegetation changes across the forest to tundra transition of central Canada using a Landsat NDVI time-series; (2) link those trends to field measurements; and (3) determine the extent to which environmental variables (i.e., climate, land cover, topography, waterbodies) influence patterns of vegetation change across the transition. I anticipated that the results would demonstrate increases in the extent of vegetation distribution across the region, with the most significant increases occurring within and north of the forest-tundra ecotone. I also expected that vegetation expansion would have been greatest in lowland areas north of the ecotone (i.e., range extension) as well as in upland areas to the south (i.e., infilling patches). Riverine areas would likely be positively associated with vegetation expansion in the tundra, as shrubs tend to expand northward into this type of sheltered environment. These predictions were based on conclusions drawn from a variety of landscape-related vegetation growth studies across circumpolar high latitudes (Gamache & Payette, 2005;

Fraser et al., 2011; McManus et al., 2012; Ropars & Boudreau., 2012; Frost et al., 2014) but were examined here across spatial and temporal scales utilizing remote sensing data.

1.4 Thesis Outline

Chapter 1 has provided the context, rationale and specific goals and objectives for my research. Chapter 2 presents an extensive review of the scientific literature that supports this research, including recent vegetation changes across the forest to tundra transition and the application of remote sensing to monitor that process. Chapter 3 (in manuscript form) presents the methodology (including a description of the study area in north-central Canada and the collection and analyses of field measurements and Landsat satellite data), results and discussion of the findings of this research. Chapter 4 presents the overall conclusions of the study, including a summary of findings, a discussion of limitations and future opportunities.

Chapter 2

Literature Review

2.1 Recent Vegetation Change across the Forest to Tundra Transition

The region of transition from sub-Arctic boreal forest to Low Arctic tundra, of which the forest-tundra ecotone is the most abrupt transition, has become an important focus for vegetation change studies given its sensitivity to climate change. Treeline, specifically the 1:1000 tree:tundra ratio line (Timoney et al., 1992) on the Circumpolar Arctic Vegetation Map (CAVM), is the commonly accepted boundary between the sub-Arctic and Low Arctic for researchers and policy makers concerned with monitoring high latitude ecosystems (Walker et al., 2005). Studies have demonstrated that the forest-tundra ecotone and adjacent Low Arctic tundra have been key areas for significant NDVI increases (i.e., greening), especially in shrub-dominated environments (McManus et al., 2012; Myers-Smith et al., 2015). However, recent evidence on boreal ecosystem productivity has been mixed with some continental boreal forests exhibiting a significant decrease in NDVI (i.e., browning) (Verbyla et al., 2008; Beck & Goetz, 2012; Guay et al., 2014). The differences in the responses of these ecosystems to climatic and environmental pressures deserves more study, especially at finer spatial scales. In the long term, remote sensing data will facilitate the monitoring of these changes at multiple spatial and temporal scales.

2.1.1 The Modern Forest-Tundra Ecotone

The forest-tundra ecotone represents the area of transition between boreal forest and tundra communities that occurs across northern high latitudes and in alpine environments (Payette et al., 2001). The term was brought into widespread use by Clements (1936) as part of his discussion on ‘climax vegetation’, or when climate dictates the boundary between biomes. Although originally defined by Clements (1936) as an alpine transition, more recent studies have characterized the latitudinal transition connecting sub-Arctic boreal forests to Low Arctic tundra

as the forest-tundra ecotone as well (McManus et al., 2012; Berner et al., 2013). The southern limit of the forest-tundra ecotone is marked by a gradual decrease in tree cover moving away from closed-canopy boreal forests. In the north, the forest-tundra ecotone ends with the last tree found on the landscape (i.e., treeline) (Payette et al., 2001).

The forest-tundra ecotone is complex, with forested and non-forested areas in close proximity. Payette et al. (2001) described the forest-tundra ecotone as a “constellation of sub-Arctic tree lines” influenced by historical fire disturbance, bedrock geology, soil quality and topography. Epstein et al. (2004) noted two types of latitudinal forest-tundra ecotones in Alaska. The first occurs along major drainage systems, where forested ecosystems transition into shrub-dominated ecosystems over tens of meters. This more abrupt forest-tundra ecotone is attributed to the relative lack of permafrost on these floodplains and nutrient-rich soils. In non-riverine areas, the forest-tundra ecotone can stretch for many kilometers across the landscape. Timoney (1995) found examples of these ecotones in north-central Canada, such as the Thelon River tree oasis where trees can be found up to 300 km north of their counterparts in non-riverine areas (Figure 2.1). The general northern treeline shift west of Great Slave Lake is associated with fine textured and nutrient-rich soils derived from sedimentary rocks. It is also possible for sub-fossil trees and resilient krummholz patches to be found well past modern treeline as remnants of past advance (Danby, 2011; Trant et al., 2011).

The modern forest-tundra ecotone has been mapped across northern high latitudes through a combination of field expeditions and remote sensing analyses. In northern Canada, the forest-tundra ecotone was mapped from Hudson Bay to the Alaskan border by Timoney et al. (1992) (Figure 2.1). The authors analyzed aerial photographs to derive tree:upland tundra cover ratio isolines across the landscape and verified these results on the ground across multiple field seasons. Timoney et al. (1992) defined the southern boundary of the forest-tundra ecotone as the 1000:1 tree:tundra ratio line and northern boundary (i.e., treeline) as the 1:1000 tree:tundra ratio

line. Further research in this region linked intricacies of the forest-tundra ecotone to parent materials and soils, elevation and distance to rivers and lakes (Timoney et al., 1993; 1995).

Figure 2.1: Boundaries of the forest-tundra ecotone in central Canada based on tree:upland tundra cover ratios. Thelon River tree oasis circled in red. Figure from Timoney et al. (1992).

The government of Northwest Territories (GNWT) has developed detailed ecosystem classification reports describing the Taiga Shield and Southern Arctic ecological regions within the territory (Ecosystem Classification Group, 2008; 2012). The boundary between these Level II Ecoregions coincides with the transition from forest to tundra dominated environments (Figure 2.2) and follows a similar outline as Timoney et al.'s (1992) treeline (Figure 2.1). The difference between the Taiga Shield's cold continental climate and the Southern Arctic's polar climate also helps mark their boundary (Ecosystem Classification Group, 2008; 2012). A comparable ecosystem classification for Nunavut is not currently available.

Figure 2.2: Ecoregions of eastern Northwest Territories. Data from Ecosystem Classification Group (2012) and the GNWT.

Additional intricacies between sub-Arctic boreal forest and Low Arctic tundra are noted in GNWT's ecoregion classification (Figure 2.2) (Ecosystem Classification Group, 2008; 2012). In the Taiga Shield, the High Boreal ecoregion is classified as having dense forest stands, predominantly comprised of black spruce (*Picea mariana*), and discontinuous permafrost. The Low sub-Arctic ecoregion mostly contains shorter and more open black and white spruce (*Picea glauca*) forests with widespread permafrost. In the High sub-Arctic ecoregion, smaller spruce stands are found mostly in protected areas such as lakeshores, lower slopes, eskers and gullies. Permafrost is widespread and becomes continuous near the Southern Arctic ecoregion boundary. In the Southern Arctic, the Low Arctic ecoregion mainly consists of erect- and dwarf-shrub tundra underlain by continuous permafrost.

2.1.2 Shrub Expansion at, and north of the Forest-Tundra Ecotone

Increasing shrub growth and expansion has been documented at, and north of the forest-tundra ecotone in the last few decades. Sturm et al. (2001b), here deemed as the original “shrubification” paper, used repeat aerial photographs to illustrate shrub expansion in northern Alaska in the late 1900s and attributed this increase to climate warming. On the Seward Peninsula in western Alaska, shrub advances of around 100 m were found in valleys and along riverbeds (Silapaswan et al., 2001). Tape et al. (2006; 2012) built upon these early studies and documented shrub expansion across Alaska from aerial photographs, especially in riparian areas. Predictive models based on climate data and photosynthetic activity also project that shrub tundra ecosystems will continue to become more productive for the foreseeable future (Figure 2.3) (Bunn et al., 2005; Epstein et al., 2007; Pearson et al., 2013; Zhang et al., 2013). Satellite-based remote sensing analyses conducted across northern high latitudes demonstrate increased vegetation productivity in shrub-dominated environments as well (although some more recent studies indicate that tundra productivity may be decreasing), but quantifying the influence of landscape variability and other environmental pressures on those changes remains elusive over larger areas (see section 2.2).

Figure 2.3: Summer photosynthetic activity (Pg) of tundra and conifer forest ecosystems through 2050 using global climate model data and satellite observations from 1981-2000. Figure from Bunn et al. (2005).

More recent studies have found shrub growth and expansion has also occurred in Siberia. Forbes et al. (2010) found that there has been a significant increase in willow shrub (*Salix* spp.) growth since the 1940s based on an annual ring chronology. This chronology had a strong relationship with summer temperatures over this time period. In northeastern Siberia, the ring widths of various shrub species correlated positively with summer precipitation and peak summer NDVI (Blok et al., 2011). Further satellite NDVI and tree-ring studies in tundra shrublands and boreal woodlands in that region revealed that mean summer NDVI increases were primarily associated with shrub-dominated locations (Berner et al., 2013). Sites disturbed by frost-heave, which create mineral-rich sites for shrub recruitment, have been documented as key locations for shrub expansion north of treeline in Siberia (Frost et al., 2013). The long-term greening of these Siberian shrub-dominated landscapes is borne out in NDVI time-series analyses as well (see section 2.2).

In addition to Alaska and Siberia, shrub growth has also been observed in northern Canada. In the Mackenzie Delta Region there has been a 68 % increase in alder (*Alnus* spp.) stem density and a 15 % increase in general tall shrub cover since 1972 (Lantz et al., 2013). This growth is likely sensitive to temperature increases and a higher frequency of tundra fires in the area (Lantz et al., 2010; 2013). In eastern Canada, marked increases in vegetation productivity have been observed in northern Québec (Ju & Masek, 2016). Ropars and Boudreau (2012) found that hilltops and terraces in particular exhibited increases in shrub cover and that much of this growth had been associated with dwarf birch (*Betula glandulosa*). Shrub (mainly *Betula* spp.) cover increased on over 50 % of land available for expansion and infilling in this region (Tremblay et al., 2012). Climate and landscape topography have been important drivers of shrub expansion here (Ropars et al., 2015).

Broad-scale studies have looked to synthesize the information gained from the collection of local-scale efforts to demonstrate widespread shrubification. Epstein et al. (2004) found that

the current boundary between forest and tundra was primarily associated with climate, in addition to differences in permafrost coverage. Myers-Smith et al. (2011) noted that shrub growth and expansion has been found across northern high latitudes over the last century (Figure 2.4). This increase in productivity fell into three categories: infilling of existing patches, growth increase and shrubline advance (either up slope or northward depending on landscape topography). Of the 23 sites considered by Myers-Smith et al. (2011), 18 had observed shrub increase and none had observed a shrub decrease. Elmendorf et al. (2012) conducted plot-scale studies across 46 tundra locations in the Arctic and Antarctica and found that shrubs were increasing in height, growing more leaves and spreading in extent across the biome. It is thus well supported that shrub growth is occurring across northern high latitudes in areas proximal to, and north of the forest-tundra ecotone.

Figure 2.4: Shrub change studies across northern high latitudes synthesized by Myers-Smith et al. (2011). Photos (a-d) indicate different shrub responses at specific sites. Figure from Myers-Smith et al. (2011).

2.1.3 Mixed Signals of Treeline Shift

Although shrubs have exhibited significant growth increases at, and north of the forest-tundra ecotone, reports of an actual shift in treeline have been mixed (Figure 2.5). A synthesis of treeline studies published before June 2008 were collected to monitor global treeline change since 1900 (Harsch et al., 2009). It was found that treeline advance, meaning new recruitment 10 m beyond the historical position for altitudinal treeline and 80 m for latitudinal treeline, had occurred at 52 % of sites (87 of 166). Treeline remained stable at 77 of 166 sites (46 %) and receded at just 2 of the 166 sites (in both cases likely attributed to disturbance). Harsch et al. (2009) also found that 80 % of diffuse treelines, where tree density decreases gradually as altitude or latitude increases, had advanced compared to only 22 % of abrupt or krummholz treelines. Diffuse treelines were often summer temperature limited, while abrupt and krummholz treelines were often winter temperature limited or a result of damage (i.e., from wind, snow and desiccation). These environmental pressures, as well as others, that determine whether a treeline will advance or not are not yet fully understood.

Figure 2.5: Location of treeline studies analyzed by Harsch et al. (2009). Advancing sites are indicated with black circles and stable sites are indicated with gray circles. Figure from Harsch et al. (2009).

Although treeline shift has not occurred in all areas, studies have detected treeline advance in many locations across northern high latitudes. Simulations of vegetation dynamics across northern high latitudes indicate a notable northern shift of the forest-tundra ecotone in Siberia and Canada over the next century (Zhang et al., 2013). Suarez et al. (1999) found that forest stands had shifted up to 100 m into what were previously tundra ecosystems in the past 200 years based on tree age analysis at the ecotone edge in Alaska. On Alaska's Seward Peninsula, boreal forest has gradually pushed into tundra ecosystems and become more dense where it has been present since the early 1900s (Lloyd et al., 2003). In Siberia, Lloyd et al. (2011) also found significant increases in productivity in northern boreal tree populations near treeline; although more southern populations experienced decreases in productivity.

Forest-tundra ecotone studies in Canada (mostly in Yukon and northern Québec) have also noted both altitudinal and latitudinal treeline advance, as well as forest density increases below treeline. In the Kluane Range of southwest Yukon, Danby & Hik (2007) used dendroecological techniques to demonstrate that spruce trees had advanced up to 85 m on warmer south-facing slopes and that colder north-facing slopes, where treeline had remained static, did have increases in forest density since the early 1900s. Landsat data has indicated that vegetation productivity has increased in established forest stands near treeline elsewhere, which has been attributed to increases in forest density (Zhang et al., 2009). In northern Québec, trees have both increased in height and expanded slightly into tundra hilltops in the last 50 years (Gamache & Payette, 2004; 2005). Establishment has been slow because of the difficulty for krummholz to grow in dry, wind-exposed tundra sites. A shrub-based study in the region found that 25 % of plots above treeline contained tamarack (*Larix laricina*) seedlings and saplings, indicating that treeline shift into tundra could still be occurring (Tremblay et al., 2012).

Even in studies where treeline advance has been recorded, further expansion is considered potentially limited by factors such as wind, moisture availability and other landscape

variables that make new establishment less likely (Suarez, 1999; Gamache & Payette, 2005; Lloyd et al., 2011). In central Canada, MacDonald et al. (1998) found no northward advancement of spruce forest from an examination of dendrochronological and historical records. Remote sensing analysis of the forest-tundra ecotone in Northwest Territories and Québec also revealed no noticeable forest advance between 1970 and 2000 (Masek, 2001). Meanwhile, a long-term simulation of forest-tundra ecotone dynamics in northwestern Alaska indicated that it could take up to 4000 years for forests to expand onto the North Slope of the Brooks Range even with 9 °C temperature increases (Rupp et al., 2001). In this case, topography plays a major role as the Brooks Range forms a barrier to seed dispersal that is currently too inhospitable to colonize. Short-term simulations across the forest to tundra transition, which show substantial increases in tundra productivity, indicate that boreal forest productivity in general could remain relatively static or even decrease slightly (Figure 2.3) (Bunn et al., 2005).

There is little evidence of treeline itself significantly receding at northern high latitudes in recent decades. Foster & D'Amato (2015) found that forest ecotones shifted downslope for some areas of the Appalachian Mountains of the northeastern United States since 1984, likely attributable to human disturbance rather than any climate phenomenon. However, research has noted that some boreal forest ecosystems south of the forest-tundra ecotone are becoming less productive in recent decades. A dendrochronology-based study in boreal Alaska demonstrated that, contrary to trends elsewhere, tree ring growth had decreased as temperatures increased (Barber et al., 2000). Remote sensing analyses have also noted this, with results across northern high latitudes indicating significant productivity increases in tundra ecosystems matched with significant productivity decreases in some boreal ecosystems (Goetz et al., 2005; Verbyla, 2008; Guay et al., 2014; Ju & Masek, 2016) (Figure 2.6). Similar results were found in Siberia, with forest-tundra ecotone areas increasing in productivity while more southern locations were decreasing in productivity (Lloyd et al., 2011). Positive correlations between NDVI and tree ring

widths have been used to link smaller ring growth to decreased forest productivity across both Russia and Canada (Berner et al., 2011). This decrease in productivity has not been observed everywhere and in other boreal forest ecosystems productivity has been slowly increasing (McManus et al., 2012). The reasons for this dichotomy require further research.

Figure 2.6: Changes in photosynthetic activity (greening and browning) across northern high latitudes from Global Inventory Modeling and Mapping Studies (GIMMS) data (1982 - 2008). Dark colors highlight significant change ($p < 0.05$). Figure from Guay et al. (2014).

2.1.4 Why are Shrubs Expanding more than Boreal Tree Species?

Shrub growth and expansion have been occurring across northern high latitudes in almost every case. Increases in precipitation, whether it be snow or rain, provide vegetation with water during the summer; thereby facilitating increased vegetation growth, especially in tundra environments (Sturm et al., 2001a; Gamon et al., 2013). Sturm et al. (2005a) hypothesized a positive feedback where increased summer temperature initiates increased shrub growth; while in the winter, shrubs can trap snow, thereby insulating the soil and increasing winter soil temperatures. However, Semenchuk et al. (2016) found, after multiple years, that deeper snow-packs significantly reduced vegetation respiration rates during the growing season. In the end, a

combination of factors related to the Arctic amplification phenomenon, especially the decline of sea ice extent and volume, are likely spurring shrub growth and expansion in coastal locations across northern high latitudes (Bhatt et al., 2010). However, more research is required to confirm and quantify these and other environmental influences on Low Arctic tundra productivity.

The significant increase in productivity of tundra ecosystems documented since the mid-1900s has not been matched in boreal forest ecosystems. First, boreal trees (e.g., black spruce) colonize new areas at slower rates than shrubs (Black & Bliss, 1980; Gamache & Payette, 2005). Increasing temperatures, while allowing shrubs in higher moisture environments to expand, is leading to drought in dry continental boreal ecosystems as a result of increased evapotranspiration (Barber et al. 2000; Verbyla, 2008). Drought stress is a serious limitation on boreal ecosystems ability to sequester carbon, meaning that these forests may be less able to sequester carbon from the atmosphere in the future (Barber et al., 2000).

Fire disturbance is another factor that influences boreal forest productivity. This is especially true in central NWT, which has been subject to regular fire disturbance since regular monitoring began in 1965 (GNWT, 2015b). Fires in high latitude boreal forests are common, with an average of 600,000 ha burned in Northwest Territories every year (GNWT, 2015b). The forested area burned by fires has steadily increased across Canada since the late 1970s (Macias-Fauria & Johnson, 2008). Increases in fire disturbance have been associated with the transition from high biomass closed-canopy boreal forests to lichen-woodlands across parts of northern Québec (Girard et al., 2008). Fires in tundra ecosystems are less common than in boreal forests, but are becoming more common as the climate warms and vegetation biomass increases in those areas (Higuera et al., 2008). A massive fire that occurred on the Anaktuvuk River in northern Alaska in 2007 has been a focus of recent studies that link remote sensing techniques to fire disturbance in tundra environments (Jones et al., 2009; Kolden & Rogan, 2013).

2.2 Remote Sensing of Vegetation Change across the Forest to Tundra Transition

The collection, processing and analyses of remote sensing data, acquired from ground, airborne or satellite platforms, has become a common method for monitoring vegetation dynamics at northern high latitudes. Given the difficulty of mounting intensive (and extensive) field expeditions at high latitudes, remote sensing data are being relied upon to collect spatial and temporal information about vegetation properties, including change, across large areas. Today, remote sensing data are routinely collected at a range of spatial and temporal scales. These data allow for the analysis of various biogeophysical variables across space and through time. For instance, leaf area index (LAI) is commonly used to model vegetation productivity; however, LAI is not applied routinely at northern high latitudes since accurate relationships between remote sensing data and LAI are dependent on accurate field measures (Fan et al., 2009; Abuelgasim & Leblanc, 2011). NDVI studies have become more common in this regard since NDVI can be accurately derived from open access Landsat data (Wulder et al., 2012).

Ground validation of NDVI is also possible, with the metric having relationships with field measurement techniques, such as LAI and others. Based on field measures of percent vegetation cover (PVC), regression models have been developed that estimate PVC spatially at high latitudes based on NDVI data derived from satellite remote sensing platforms (Purevdorj et al., 1998; Laidler et al., 2008; Liu & Treitz, 2016). Vegetation volume has been similarly linked with NDVI (Chen et al., 2009; Gregory, 2011). Tree ring width has also been positively correlated with satellite-derived NDVI in Russia and Canada (Berner et al., 2011), although this link with wood biomass is far less clear (e.g., Brehaut 2015). Other field measurement techniques, such as fraction of absorbed photosynthetically active radiation ($fAPAR$) and biomass collection, can be linked to remote sensing NDVI measurements as well (Jia et al., 2003; Yuan et al., 2007; Epstein et al., 2012). Ground validation of remote sensing results is important to

confirm that changes observed by the satellite sensor actually reflect real changes on the ground, but are not undertaken by many remote sensing-based studies due to time and cost constraints.

2.2.1 NDVI as a Metric of Vegetation Productivity

NDVI is a metric indicative of vegetation productivity and is based on the differential response (i.e., absorption/reflectance) of vegetation to red (R) and near infrared (NIR) wavelengths (Rouse et al., 1973; Tucker, 1979):

$$\text{NDVI} = (\text{NIR} - \text{R}) / (\text{NIR} + \text{R}) \quad (1)$$

In general, healthy green vegetation absorbs PAR in the visible portion of the spectrum for photosynthesis; but more specifically, chlorophyll a and b absorb very strongly in the R portion of the visible spectrum. Meanwhile, healthy green vegetation reflects very strongly in the NIR as this wavelength is not utilized for photosynthesis. Thus, healthy vegetation appears dark in the R band (low reflectance) and bright in the NIR band (high reflectance); this relationship allows the NDVI to correlate well with the amount of healthy vegetation present in the sensor's field of view.

NDVI has been demonstrated as a useful metric for studies concerned with vegetation productivity. It was first utilized in the early 1970s to monitor vegetation growth in the U.S. Great Plains (Rouse et al., 1973). Further research by Tucker (1979) indicated that the NIR and R combination was superior for estimating photosynthetically active biomass than other band combinations. The success of NASA's Landsat program (1972-present) at providing global satellite coverage at an intermediate spatial resolution has allowed for many NDVI-based studies to be completed worldwide (Wulder et al., 2012; 2016).

Early study involving the remote sensing of high latitude vegetation began with measurements of the albedo of various sub-Arctic land-cover types in Québec and Labrador (Davies, 1962; Petzold & Rencz, 1975). NDVI-based studies in the Low Arctic were initially focused on monitoring vegetation disturbance from pollution in Siberia and elsewhere (Rees et

al., 1998). Preliminary investigations revealed that NDVI was more sensitive to land-cover type than biomass in high latitude environments (Rees et al., 1998). After interest in monitoring northern vegetation grew, studies demonstrated that NDVI correlated closely to biomass and other vegetation structural attributes (Raynolds et al., 2006; Boelman et al., 2011; Epstein et al., 2012). Rees et al. (2002) reported that NDVI derived from satellite data was the optimal method for monitoring the forest-tundra ecotone, particularly at landscape and regional scales. Research on vegetation change using spectral indices (e.g., NDVI) has occurred mostly in the last 15 years.

2.2.2 Remote Sensing Platforms used to Monitor Northern Vegetation Change

Depending on the scale of the study in question, different remote sensing platforms can be considered for examining vegetation change across northern high latitudes (Stow et al., 2004) (Table 2.1). Ground-level sensors, such as field spectro-radiometers, provide fine-scale spectral data for studies interested in plot level NDVI. NDVI cameras that capture data in the NIR and visible regions of the electro-magnetic spectrum are also used for field data collection (Liu & Treitz, 2016). Aerial photography, which provides high spatial resolution data as far back as the early 1940s, is useful for landscape-scale studies. High spatial resolution satellite data, such as commercially available IKONOS or WorldView, are able to link spectral information directly with field data (i.e., plots or local areas). Landsat data (i.e., 30 m spatial resolution) have allowed for the analysis of NDVI trends across landscapes and regions since 1984 (White & Wulder, 2014). Meanwhile, coarse spatial resolution satellite data, such as the Moderate Resolution Imaging Spectrometer (MODIS) or the Advanced Very High Resolution Radiometer (AVHRR), are useful for regional and continental scale studies looking at NDVI trends over large areas.

At fine-scales, field spectro-radiometers are used to measure NDVI values at the individual or plot level. Laidler et al. (2008) collected surface reflectance measurements across multiple large plots in a tundra environment to derive NDVI measures for comparison to IKONOS and Landsat spectral indices for vegetation types on Boothia Peninsula, Nunavut.

Boelman et al. (2011) collected plot-level measurements to demonstrate differences in NDVI associated with vegetation canopy structure at different times during the growing season. Pattison et al. (2015) utilized spectro-radiometer data to compare to coarser spatial resolution satellite data in order to detect trends in NDVI and changes in tundra vegetation composition in Alaska since 1984. These studies demonstrate the utility of surface-derived NDVI for modelling biophysical variables measured in the field (i.e., PVC, biomass, etc.). NDVI data collected at the ground-level also allow for comparison with satellite-derived NDVI, in order to compare and account for any atmospheric effects that could affect the quality of satellite data (Laidler et al., 2008; Pattison et al., 2015). Plot level NDVI data collected by spectro-radiometers are useful at fine spatial scales but the lack of a long-term data repository limits their utility for time-series analysis.

Table 2.1: Commonly used remote sensing platforms for vegetation monitoring at northern high latitudes. Satellite information from Xie et al. (2008) and Wulder et al. (2016).

Remote Sensing Platform	Spatial Resolution	Revisit Time	Temporal Range	Spatial Range	Example Studies
Ground-level Sensors (NDVI cameras; Spectro-radiometers)	Usually less than 10 cm	Determined by user in the field	1990s to present	Small Scale	Laidler et al., 2008; Boelman et al., 2011; Pattison et al., 2015
Aerial Photography	Usually less than 1 m	Variable	1940s to present	Historical flight paths. On Demand	Sturm et al., 2001b; Tape et al., 2006; Ropars & Boudreau, 2012; Tremblay et al., 2012; Fraser et al., 2014a
High Spatial Resolution Satellites (IKONOS, Worldview etc.)	0.5 to 10 m	On Demand	Late 1990s to present	On Demand	Laidler et al., 2008; Ropars & Boudreau, 2012; Simms & Ward, 2013; Frost et al., 2014; Guay et al., 2014
Intermediate Spatial Resolution Satellites (Landsat TM, ETM+, OLI)	30 m	8 to 16 days (low latitude), 2 to 8 days (high latitude)	1982 to present	Worldwide	Masek, 2001; Fraser et al., 2011; McManus et al., 2012; Reynolds et al., 2013; Frost et al., 2014; Ju & Masek, 2016
Coarse Spatial Resolution Satellites (AVHRR, MODIS)	> 200 m	1 to 2 days	1978 to present	Worldwide	Jia et al., 2003; Verbyla, 2008; Bhatt et al., 2010; Berner et al., 2011; Lloyd et al., 2011; Epstein et al., 2012

Aerial photography has routinely been collected since the 1940s. Although image quality varies, these photographs allow for high spatial resolution quantification of vegetation change over the landscape for a longer time-series than are available from any other remote sensing platform. Sturm et al. (2001b) found compelling evidence of shrub expansion in Alaska by comparing oblique aerial photographs collected in 1949 and 2000 (Figure 2.7). Tape et al. (2006) expanded on this by comparing over 200 pairs of aerial photographs from across northern Alaska and linking observed shrub expansion to increases in NDVI in those same areas. Aerial photography can also be analyzed in combination with satellite data to provide multiple scales of coverage over a study area, as has been done in northern Québec to link vegetation change to local topography (Ropars & Boudreau, 2012). Further research in northern Québec by Tremblay et al. (2012) demonstrate that aerial photographs can be used to discern between different densities of shrub cover in order to quantify those changes over 50+ years. Studies wishing to use aerial photography to conduct vegetation change analyses are limited by the lack of consistent annual revisit times, scales of acquisition and the limited extent of historical flight paths.

Figure 2.7: Oblique aerial photographs from 1949 and 2000 showing an increase in the density and extent of shrubs near the Aiyak River in Alaska. Figure from Sturm et al. (2001b).

High spatial resolution satellites provide commercially available access to 1 to 10 m spatial resolution data anywhere on Earth. Often, high spatial resolution data are used in

combination with either ground measurements or coarser spatial resolution data to observe the landscape in question at multiple scales (Laidler et al., 2008; Guay et al., 2014). An interesting example of this was reported by Frost et al. (2014), who utilized declassified U.S. military high spatial resolution satellite data from the 1960s to supplement a Landsat NDVI time-series in Siberia. Simms & Ward (2013) utilized this principle in the creation of a five image NDVI time-series (1983-2008) in the Mealy Mountains of Labrador from five different satellite platforms. Landsat MSS (80 m), TM (30 m) and ETM+ (30 m), as well as ASTER (15 m) and SPOT HRVIR (10 m) were used to monitor NDVI trends at this alpine forest-tundra ecotone. High spatial resolution data does not have as long of a temporal range as coarser spatial resolution sensors though, with most platforms in this category launching only in the late 1990s. Researchers wanting to create NDVI time-series using high spatial resolution data are also limited by the need to purchase images from these sensor platforms. The costs associated with these acquisitions, along with the lack of long-term data limit NDVI time-series mostly to coarse and intermediate spatial resolution remote sensing data.

The coarse spatial resolution AVHRR provides data extending back to the late 1970s and is useful for monitoring vegetation change at continental scales. Jia et al. (2003) utilized AVHRR data to monitor NDVI trends on Alaska's North Slope and to compare with change across northern high latitudes. More recently, the GIMMS 3rd generation dataset (based on AVHRR data) was developed specifically for the northern high latitudes and has been used in other broad-scale studies (Verbyla, 2008; Bhatt et al., 2010; Guay et al., 2014). Research in Siberia has linked GIMMS NDVI values with tree ring widths across the forest-tundra ecotone (Lloyd et al., 2011; Berner et al., 2011; 2013). The coarse spatial resolution and quick revisit time, along with a data repository dating back to 1978, make the AVHRR an ideal candidate for continental-scale, long-term, NDVI time-series analyses.

2.2.3 NDVI Time-series across Northern High Latitudes

Continental-scale NDVI time-series are generally derived from AVHRR data because of these aforementioned benefits. Verbyla (2008) created an NDVI time-series across Alaska from 1982 to 2003 that demonstrated decreasing linear trends for boreal ecosystems and increasing linear trends for tundra ecosystems. Epstein et al. (2012) utilized AVHRR NDVI data and field biomass data to quantify the heterogeneity of biomass increases across the Arctic's five bioclimate subzones (Walker et al., 2005). Guay et al. (2014) compared northern high latitude vegetation change between two different GIMMS datasets and found greening in Arctic tundra and browning in boreal forest areas. More recently, AVHRR data have indicated decreasing tundra productivity across northern high latitudes from 2011 to 2014 (Epstein et al., 2016). AVHRR data excel at these types of broad-based vegetation studies that span entire continents. However, the coarse spatial resolution of the sensor means that any landscape- and local-scale changes in vegetation productivity, including the influence of environmental variables on those changes, are often missed.

At the landscape scale, which is the main focus of my study, Landsat satellite data have been widely used by the scientific community due to easy and free access (since 2008) from the United States Geological Survey (USGS). Landsat data from the early 1980s (early 1970s for Landsat 60 m Multispectral Scanner) to present are readily and freely available, thus providing a 30+ year repository. These data have been applied to map vegetation classes and canopies in high latitude environments, including efforts across northern Canada (Brook & Kenkel, 2002; Olthof et al., 2009; Selkowitz, 2010). Earlier Landsat studies concerning vegetation dynamics followed a simpler change detection approach, where researchers would compare two images from different years (but at the same time of year). This was done by Masek (2001), who analyzed forest-tundra ecotone change in northern Québec (1974 and 1999) and eastern Northwest Territories (1972 and 2000) with two pairs of Landsat images.

With an expanding archive of imagery, northern high latitude studies examining recent vegetation change are now able to apply Landsat data to create NDVI time-series. This is usually performed by processing a ‘stack’ of images from multiple years at the same location and ideally at the same time of year (i.e., anniversary dates). Images should be collected during the peak growing season, which is generally between July 1 and August 31 and more specifically from the middle of July to early August. Selected images should then be (i) radiometrically calibrated; (ii) converted to top-of-atmosphere reflectance; and (iii) subsequently converted to surface reflectance when possible (Fraser et al., 2012). This process has been streamlined by the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) that converts raw Landsat data to surface reflectance data using the MODIS/Second Simulation of the Satellite Signal in the Solar Spectrum (6S) atmospheric correction protocols (Masek et al., 2006). Any cloud cover should be masked and then pixel level trend analyses can be conducted where the slope and significance of NDVI trends over time for every pixel in the stack can be derived (Fraser et al., 2012).

Workflows like this have been used to create Landsat NDVI time-series across northern high latitudes. Time-series (1986-2006) analyses in the Mackenzie Delta region and in northern Québec indicated that most vegetation communities exhibited increasing NDVI, but more so for vascular vegetation than for lichen-dominated communities (Olthof et al., 2008). Increasing vegetation productivity, especially in shrub-dominated valleys, was detected from 1986 to 2009 in four national parks across northern Canada (Fraser et al., 2011). On the North Slope of Alaska, an NDVI time-series (1985-2007) examined by Raynolds et al. (2013) found that greening trends depended largely on differences in glacial history and topography. In Siberia, an NDVI time-series (1985-2010) demonstrated that greening had occurred in most areas, but especially in areas that had been colonized by tall alder shrubs (Frost et al., 2014).

More recent research utilizing Landsat NDVI time-series data have involved the creation of image stacks over large spatial areas by mosaicking frames together. In northern Québec, McManus et al. (2012) created an NDVI time-series (1985-2010) covering nine mosaicked frames constituting 26 million ha across the forest to tundra transition. They found that shrub and graminoid dominated pixels were more likely to have greening trends than boreal forest pixels. Ju & Masek (2016) created an NDVI time-series over more than 90 % of Canada and Alaska between 1984 and 2012. Using automated methods, they were able to select over 85,000 mostly cloud free Landsat scenes and run per-pixel trend analyses across the entire study region. They found that 29.4 % of Canada and Alaska had greening trends, mostly in tundra areas, and that 2.9 % had browning trends, mostly in boreal forest areas.

These studies, as well as others, demonstrate that Landsat NDVI time-series have been conducted over much of the northern high latitudes. This includes the extent of my study area as well as in the case of Ju & Masek (2016). However, the forest to tundra transition of central Canada remains an understudied region in terms of remote sensing based research on vegetation change, with a lack of in-depth analyses and ground validation of NDVI trends there. In addition, most of these studies have demonstrated that vegetation productivity has increased over the last 30+ years, especially north of the forest-tundra ecotone. Some of these studies have even concluded that changes in vegetation productivity are heterogeneous and influenced by differences in terrain and other variables. However, the combined influence of environmental pressures on landscape-scale vegetation change, and how those influences change across the entirety of the sub-Arctic forest to Low Arctic tundra transition, has not yet been properly addressed.

2.3 Summary

The forest-tundra ecotone, as well as bordering boreal forest and tundra areas, is a region of interest for researchers concerned with vegetation change due to climate warming across

northern high latitudes. This transition zone, which spans across Canada, Scandinavia and Siberia, is complex with tundra, shrubland and boreal forest patches in close proximity. Landscape-scale environmental variables, such as topography and moisture regime, seem to be important factors in determining the intricacies of this changing environment. The evidence from remote sensing and field-based studies across northern high latitudes strongly suggest that shrubs are expanding their range and becoming increasingly dense where already present. However, the evidence indicates that treeline advance is not as clear. Some drier interior boreal forest ecosystems appear to be undergoing a decrease in productivity in recent decades as a result of warming, even as tundra ecosystems have mostly been increasing in productivity. Despite the large number of studies analyzing vegetation changes across northern high latitudes, central Canada remains an understudied region. Further research is required to quantify the influence of landscape-scale variables on high latitude vegetation change. Recent advances in remote sensing technologies and methods, especially in regards to Landsat NDVI time-series analyses, provide an opportunity to examine these influences in an understudied region.

Chapter 3

Landscape Variability of Vegetation Change across the Forest to Tundra Transition of Central Canada

3.1 Abstract

Widespread vegetation productivity increases in tundra ecosystems and stagnation, or even productivity decreases, in boreal forest ecosystems have been detected from coarse-scale remote sensing observations over the last few decades. However, finer-scale Landsat studies have shown that these changes are heterogeneous and may be related to landscape and regional variability in climate, land cover, topography and moisture. In this study, a Landsat Normalized Difference Vegetation Index (NDVI) time-series (1984-2016) was examined for a study area spanning the entirety of the sub-Arctic boreal forest to Low Arctic tundra transition of central Canada (i.e., Yellowknife to the Arctic Ocean). NDVI trend analysis indicated that 27 % of un-masked pixels in the study area exhibited a significant ($p < 0.05$) trend and virtually all (99.3 %) of those pixels were greening. Greening pixels were most common in the northern tundra zone and the southern forest-tundra ecotone zone. NDVI trends were positive throughout the study area, but were smallest in the forest zone and largest in the northern tundra zone. These results were supported by ground validation, which found a strong relationship ($R^2 = 0.81$) between bulk vegetation volume (BVV) and NDVI for non-tree functional groups in the North Slave region of Northwest Territories. Field observations indicate that alder (*Alnus* spp.) shrublands and open woodland sites with shrubby understories were most likely to exhibit greening in that area. Random Forest (RF) modelling of the relationship between NDVI trends and environmental variables found that the magnitude and direction of trends differed across the forest to tundra transition. Increased summer temperatures, shrubland and forest land cover, closer proximity to major drainage systems, longer distances from major lakes and lower elevations were generally

more important and associated with larger positive NDVI trends. These findings indicate that the largest positive NDVI trends were primarily associated with the increased productivity of shrubby environments, especially at, and north of the forest-tundra ecotone in areas with more favorable growing conditions. Smaller and less significant NDVI trends in boreal forest environments south of the forest-tundra ecotone were likely associated with long-term recovery from fire disturbance rather than the variables analyzed here.

3.2 Introduction

The Earth has been subject to climate warming since the late 1800s, especially at high latitudes where warming has been significantly greater than the global average (Serreze & Barry, 2011; IPCC, 2013). This high latitude warming has been linked to the increase in productivity of broadleaf shrubs in Low Arctic and sub-Arctic ecosystems as climatic conditions become more favorable for species previously under stress and at the edge of their range (Myers-Smith et al., 2011). The northward and upslope expansion of shrubs is thus expected over a decadal-length timescale in these tundra and forest-tundra ecotone environments (Epstein et al., 2004). However, the intricacies of shrub expansion are still not fully understood, with recent studies indicating that it has been heterogeneous and that landscape-scale variability can influence the magnitude of vegetation change at high latitudes (McManus et al., 2012; Ropars & Boudreau, 2012; Frost et al., 2014). Differences in land cover, topography and moisture access have been noted as possible controls on shrub expansion and other vegetation changes.

While shrub growth and expansion has been widespread, treeline advance has been mixed; advancing in some locations while remaining static elsewhere (Harsch et al., 2009). Treeline advance has not occurred at the same rates as shrub expansion because boreal tree range advance takes longer to respond to warming in general (i.e., there is a significant lag period) (MacDonald et al., 1998; Epstein et al., 2004; Gamache & Payette, 2005). However, there has been observations of accelerated height growth, patch infilling and small advances of treeline in

certain locations (Gamache & Payette, 2005). Browning, or a decrease in productivity from forest dieback, has also been observed in some boreal ecosystems south of the forest-tundra ecotone (Lloyd et al., 2011; Berner et al., 2011). This has been attributed to higher drought stress in the summer months of the last few decades because of increasing temperatures (Barber et al., 2000; Lotsch et al., 2005).

Satellite remote sensing data have allowed researchers to quantify these vegetation changes over a variety of spatial and temporal scales at northern high latitudes. Coarse spatial resolution data from the Advanced Very High-Resolution Radiometer (AVHRR) has been used to monitor vegetation changes at continental scales, which has provided evidence for widespread productivity increases in tundra regions and some productivity decreases across continental boreal forest regions (Bunn et al., 2005; Verbyla, 2008; Beck & Goetz, 2012; Epstein et al., 2012; Guay et al., 2014). Landsat data has also been widely used at landscape and regional scales for this purpose (Olthof et al., 2008; Fraser et al., 2011; McManus et al., 2012; Raynolds et al., 2013; Frost et al., 2014; Pattison et al., 2015; Ju & Masek, 2016). Ground validation, when conducted by researchers, has found a link between vegetation biomass measurements and remote sensing vegetation indices in areas without tree cover (Jia et al., 2003; Laidler et al., 2008; Gregory, 2011; Epstein et al., 2012).

In this study, recent (~35 years) vegetation changes occurring across the sub-Arctic boreal forest to Low Arctic tundra transition of central Canada were assessed using Landsat satellite imagery and ground-level validation. To this point, little research has been conducted on the dynamics of vegetation growth in this region, which has recently become an important area of study for those interested in caribou population dynamics (Boulanger et al., 2011). This study also aims to identify the landscape-scale environmental variables that influence vegetation changes across the region and understand the direction and magnitude of that influence. The influence of landscape-scale terrain variation on vegetation change has been noted as a topic in

need of further study and this research will assist in this regard (Myers-Smith et al., 2011). Hence, the main objectives of this study were to: (1) quantify recent vegetation changes across the forest-tundra ecotone of central Canada using a Landsat Normalized Difference Vegetation Index (NDVI) time-series; (2) link those trends to field measurements; and (3) determine the extent to which environmental variables (i.e., climate, land cover, topography, waterbodies) influence patterns of vegetation change across the transition.

3.3 Methods

3.3.1 Study Area

The study area for this project was a 130,000 km² transect extending from Yellowknife, NWT to Coronation Gulf east of Kugluktuk, NU (Figure 3.1). This study area was chosen because it is an understudied region in terms of northern high latitude vegetation change research. It is characterized by low rolling hills, large numbers of lakes and rivers and a variety of vegetation communities. The study area was delineated into three zones based on the forest-tundra ecotone that crosses it in the North Slave region of NWT. The area south of the 1000:1 tree:tundra ratio line, as mapped by Timoney et al. (1992), was defined as the forest zone (i.e., closed-canopy boreal forest) and the area north of the 1:000 tree:tundra ratio line was defined as the tundra zone (i.e., tree-less tundra). The area that fell between the 1000:1 and 1:1000 lines was defined as the ecotone zone (i.e., forest-tundra ecotone).

Figure 3.1: The spatial extent of Landsat frames used for remote sensing analysis. Numbers in the upper corner of each Landsat frame represent the Worldwide Reference System (WRS) path-row. The location of communities, mines and other points of interest are shown. Forest, ecotone and tundra zones are delineated by the tree:tundra ratio lines shown (based on Timoney et al., 1992). Basemap provided by Government of Northwest Territories (GNWT) Centre for Geomatics.

The study area spans the transition from the Taiga Shield to the Southern Arctic Level II Ecoregions (Ecosystem Classification Group, 2008; 2012). Permafrost coverage is discontinuous in the southern half of the study area and continuous in the north (Heginbottom et al., 1995; Throop et al., 2012). Fires have been common in the forest zone and the southern portion of the ecotone zone, but are less frequent farther north (GNWT, 2015b). The Nunavut portion of the tundra zone overlaps the calving grounds of the Bathurst caribou herd, which has seen a precarious drop in size over the last three decades from an estimated 203,800 individuals in 1986 to an estimated 16,400 in 2009 (Boulanger et al., 2011; GNWT, 2015a). Thirty-year (1981-2010) climate normals from the Environment Canada weather station at Yellowknife Airport (62° 26' N and 114° 23' W) indicate a mean annual July temperature of 17 °C and a mean annual January temperature of -25.6 °C. Climate normals at Kugluktuk Airport (67° 49' N and 115° 5' W) indicate a mean annual July temperature of 10.9 °C and a mean annual January temperature of -27.3 °C. Yellowknife Airport averages 288.6 mm of precipitation each year (157.6 mm as snow) while Kugluktuk Airport averages 247.2 mm (182.1 mm as snow).

The forest zone lowland areas north of Great Slave Lake, including the area around Yellowknife, are characterized by dense boreal forest with many bedrock outcrops (Ecosystem Classification Group, 2008). Farther north, past the abandoned Discovery Mine and towards Wekweètì in the ecotone zone, scattered woodlands become more common. Boreal forest stands with shrubby understories are often limited to more sheltered lowland areas with shrub cover dominating hilltop areas (Ecosystem Classification Group, 2008). The northern portion of the ecotone zone and the southern portion of the tundra zone also contain a notable amount of graminoid-dominated wetlands (Ecosystem Classification Group, 2008). In the southern portion of the tundra zone, such as around the Daring Lake Tundra Ecosystem Research Station, trees are mostly absent and shrubs dominate the landscape (Walker et al., 2005; Ecosystem Classification Group, 2012). Northwards through Nunavut towards the Arctic Ocean, vegetation transitions

from dense shrubland to open shrubland and graminoid tundra with lichen groundcover dominant (Walker et al., 2005). Shrubland riparian zones can be found along the edge of major rivers in the northern portion of the tundra zone, such as the Tree, Hood and Burnside Rivers.

A field expedition was conducted in the North Slave region of NWT (i.e., between Big Lake and Wekweètì along the Snare River system) during the summer of 2016. This location was chosen because of the relatively short distance between the forest zone and the tundra zone, allowing for canoe travel and sampling across the forest-tundra ecotone. This location was also relatively accessible compared to other possible routes (see Appendix A), with daily flights from the Tł̨chq̓ community of Wekweètì (64° 11' N and 114° 10' W) to Yellowknife. This field expedition followed the path of Sir John Franklin's expedition of 1819 to 1822 that aimed to explore Canada's northern coastline and map a potential northwest passage between the Atlantic and Pacific Oceans (Houston, 1994).

3.3.2 Landsat Data Collection

A Landsat time-series (1984-2016) was assembled in order to quantify recent vegetation change in the study area. Scenes from four Landsat frames that form a transect across the study area (Figure 3.1) were selected and downloaded from the United States Geological Survey (USGS) Global Visualization Viewer (GloVis). Clear-sky scenes (i.e., less than 20% cloud cover from GloVis estimates) that fell within the peak growing season (defined here as July 11 – August 11) were selected. Only scenes from Landsat 4-5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+ SLC-on) and Landsat 8 Operational Land Imager (OLI) were utilized in order to avoid comparability issues with 60 m resolution Landsat 1-5 MSS data and to avoid data-loss issues with scan-line gaps from the Landsat 7 ETM+ sensor after the scan line corrector (SLC) failed in May 2003. The quality of selected Landsat scenes was assessed by visually inspecting scenes in GloVis and in ENVI 5.3.1 (Harris Geospatial Solutions). USGS provides cloud cover estimates in GloVis but it was found that this often did not account for high

altitude cirrus clouds or smoke from forest fires. Scenes were thus ranked in terms of relative cloud cover in order to determine which scenes would have the most cloud-free pixels for Landsat time-series analysis (see Appendix B). Scenes that had a higher quality rating, were obtained at peak growing season and were Landsat standard level terrain (L1T) corrected were selected for subsequent analysis. The final selection was made in order to ensure a minimum of 10 scenes per frame and that scenes were distributed evenly throughout the 32-year period. The final image stack included 40 scenes, 10 for each of the four Landsat frames (Figure 3.2).

Figure 3.2: Temporal distribution of selected Landsat scenes (*sensu* McManus et al., 2012). The four plots represent the Landsat frames (path-row indicated in top left of each) that make up the study area from north to south. All scenes date between 1984 and 2016 and were collected between Julian day 192 and 223 (July 11 – August 11). Black circles represent Landsat TM scenes, gray circles ETM+ scenes and white circles OLI scenes. See Appendix B for more details on selected scenes.

3.3.3 Landsat Data Correction

Selected Landsat TM and ETM+ scenes were converted from digital number to top-of-atmosphere reflectance and then corrected to surface reflectance using the Landsat Ecosystem Adaptive Processing System (LEDAPS) algorithm, an automated procedure provided by the National Aeronautics and Space Administration (NASA) (Masek et al., 2006). LEDAPS corrects for atmospheric effects through the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) code that models the gases and molecules that make up the atmosphere between the satellite and the ground (Vermote et al., 1997). LEDAPS estimates aerosol optical thickness using the dense dark vegetation method, ozone concentrations from Total Ozone Mapping Spectrometer data, as well as water vapor, air temperature and surface pressure information from National Oceanic and Atmospheric Administration (NOAA) environmental prediction data (Masek et al., 2006). LEDAPS has become the most common form of atmospheric correction for broad-scale Landsat studies in the last few years (Banskota et al., 2014).

Selected OLI scenes were corrected to surface reflectance in the same process using the Landsat Surface Reflectance Code (LaSRC) algorithm (USGS, 2016; Vermote et al., 2016). LaSRC builds upon the TM and ETM+ LEDAPS algorithm and has been updated for OLI, taking into account its narrower spectral bands and the new coastal aerosol (0.4333 – 0.453 μm) band. Radiative transfer between satellite and ground is again modeled with 6S code. Aerosol optical thickness, water vapor, ozone concentrations and air temperature are calculated from Moderate Resolution Imaging Spectrometer (MODIS) climate modeling grids and surface pressure is derived from MODIS elevation data (Vermote et al., 2016). The coastal aerosol band is also used to provide aerosol properties. Together, these surface reflectance algorithms from NASA allow for a standardized in-house approach for removing the influence of atmospheric effects on Landsat data across all recent sensors.

Both LEDAPS and LaSRC surface reflectance algorithms generate a cloud mask layer (Masek et al., 2006; Vermote et al., 2016). However, the LEDAPS cloud mask struggled with

identifying wispy cirrus clouds and cloud shadows. The LaSRC cloud mask layer performed better at identifying most clouds and cloud shadows because of the addition of the “cirrus” band (1.360 – 1.390 μm), but was only available for selected OLI scenes (Vermote et al., 2016). Selected Landsat scenes were thus masked for clouds and cloud shadows manually to ensure that all cloud covered pixels were removed from further analysis (see Appendix B). The red (R) and near infrared (NIR) bands of surface reflectance scenes were then used to calculate NDVI: $(\text{NIR} - \text{R})/(\text{NIR} + \text{R})$.

Recent studies have shown that NDVI derived from Landsat ETM+ and OLI are marginally higher than NDVI derived from Landsat TM based on the overlapping areas between adjacent passes by the different sensors at higher latitudes (Holden & Woodcock, 2016; Ju & Masek, 2016; Roy et al., 2016). These differences are attributed to small variations in the Landsat sensors, rather than actual vegetation change on the ground, and thus warrant correction. Since 75 % of the Landsat scenes used in this study were Landsat TM, corrections to ETM+ and OLI were made to ensure temporal continuity with Landsat TM. A scaling factor of 0.964, based on between-sensor discrepancies (Ju & Masek, 2016), was applied to adjust Landsat ETM+ NDVI to a TM equivalent. Landsat OLI was adjusted to a TM equivalent by applying the ordinary least square transformation function between OLI and ETM+ ($\text{ETM+} = 0.0029 + 0.9589(\text{OLI})$) recommended by Roy et al. (2016) combined with the 0.964 scaling factor. NDVI trends derived from pseudo-invariant features (PIFs), a relative normalization procedure for atmospheric effects (Jensen, 2016), exhibited a moderately strong relationship with surface reflectance NDVI trends ($R^2 = 0.63$, $p < 0.001$) (See Appendix C).

3.3.4 NDVI Trend Calculation

With atmospheric effects corrected, NDVI time-series were analysed to determine if there was evidence of vegetation change across the study area. NDVI time-series were compiled as RasterStacks using the ‘raster’ package in the computer program R (R Development Core Team,

2010). Bivariate linear regressions, with NDVI as the y-axis (response variable) and time as the x-axis (predictor variable), were applied across all pixels in each RasterStack (see Appendix D for R code). The output was a mosaicked raster with pixel values equal to the slope of each linear regression (i.e., the magnitude of NDVI trend per pixel per year). A second output was a raster of the corresponding p-values (based on a two-tailed t-test) of each linear regression. NDVI trends with $p < 0.05$ were considered significant. Significant positive NDVI trends were considered ‘greening’ and significant negative NDVI trends were considered ‘browning’.

To ensure that the NDVI trends accurately represented vegetation productivity changes throughout the last three decades, pixels that were cloud covered four or more times in a RasterStack were removed from further analysis. In addition, all scenes in each RasterStack were split into decadal groups (i.e., mid-1980s to mid-1990s, mid-1990s to mid-2000s, mid-2000s to present) and pixels that were covered by clouds across all years in at least one decade group were removed from analysis. Where Landsat frames overlapped, areas with less cloud cover were preserved during the mosaicking procedure. These steps ensured that NDVI trends were only based on linear regressions that were evenly spaced across the time period in question and had sufficient cloud-free samples. Cloud cover was a concern, but over 68 % of the study area had sufficient cloud-free pixels to be useful for time-series analysis. Waterbodies (NDVI < 0, classified as water in the land-cover map) and fire scars (1965-2014) (GNWT, 2015b) were also masked and removed from the analysis.

3.3.5 Field Data Collection

A canoe-based field expedition was conducted across the forest-tundra ecotone of the North Slave region of NWT near Wekweètì (Figure 3.3). The objective of the field expedition was to obtain measurements for use in establishing a relationship between satellite-derived NDVI and an *in situ* biophysical variable, i.e., bulk vegetation volume (BVV), in order to provide ground validation for the remote sensing data analysis (Chen et al., 2009; Gregory, 2011). It was

very important that the field expedition encompass the extent of the forest-tundra ecotone in order to allow for sampling in both tundra and boreal forest dominated environments. Sample plots were thus established across Timoney et al.'s (1992) tree:tundra cover ratio lines. During the field expedition there was also an opportunity to speak with local residents to gain first-hand knowledge of the region from their perspectives.

Figure 3.3: Map of the field expedition, including the location of sample plots, in the North Slave region of NWT. Travel was by canoe from Big Lake to Wekweètì across the tree:tundra ratio lines mapped by Timoney et al. (1992). Sample plots were grouped into shrubland, forested, graminoid tundra and wetland based on dominant land-cover types encountered on the ground. The number of times each plot grouping was sampled is in parentheses.

In order to ensure there was an adequate representation of different land-cover types across sample plots, an unsupervised land-cover classification was derived to stratify the study area. This was performed using the most recent (2011) Landsat cloud-free mosaic over the two

frames corresponding to the location of the field expedition (47-14 & 47-15). An Iterative Self-Organizing Data Analysis (ISODATA) method was applied in ENVI to cluster pixels into 15 different classes (Tou & Gonzalez, 1974). ISODATA classifications were cross-referenced with high spatial resolution imagery where available, geo-referenced photographs from past travelers along the route and from book descriptions (Losey, 1973; McCreadie, 1995; Thomas, 2003; Pitt, 2014). NWT Ecosystem Classification Reports provided further land cover information on a broader scale (Ecosystem Classification Group, 2008; 2012).

Because of the canoe-based nature of the field expedition, there was a certain level of uncertainty as to where along the route sample plots could be established. A map of potential sample plots was created that was limited to homogenous areas of a single class based on the ISODATA classification. The centers of spectral classes that were a minimum of 4 x 4 pixels in size and within 5 km of the proposed route were identified as potential sampling locations. This methodology provided access to many possible sampling plots during the field expedition, allowing for a flexible sampling strategy. See Appendix A for maps of the potential sampling locations used for sample plot selection in the field.

The field expedition was conducted between July 20 and August 25, 2016, during which time 34 plots were sampled, accounting for a range of land-cover classes (Table 3.1). For the majority of cases, land cover identified in the field corresponded with the unsupervised land-cover classification. When it was not possible (because of time or travel constraints) to establish a full study plot, supplementary photos of the area of interest were acquired, descriptions were noted and GPS coordinates were collected with a Trimble GPS unit. This latter approach was done often for burn scars, non-vegetated eskers and rock gardens. Again, see Appendix A for details and descriptions of all study plots and other points of interest.

Table 3.1: Details of potential sample plots based on 15 ISODATA land-cover classes from a 2011 Landsat TM mosaic (47-14 & 47-15). Classes are color coded as they appeared in field maps (see Appendix A). Number of pixels indicates pixels within a reasonable over-land travel distance (5 km) from the field expedition route that were in the center of a homogenous area of that class and thus suitable for sampling. Note that some classes were more common than others and thus were more likely to be sampled multiple times, although efforts were made to sample across all classes. Average NDVI of potential sample pixels indicates that classes fell across a range of biomass conditions. At least one 900 m² study plot was established for all more densely vegetated classes, while photos and GPS points were recorded for sediment and lichen barren classes.

Land-cover Class (unsupervised ISODATA)	Number of Pixels (within 5 km of route)	Mean NDVI ± SD	Plots Sampled (n = 34)
Closed-canopy Boreal Forest	192	0.53 ± 0.03	1
Less Dense Boreal Forest	2522	0.58 ± 0.03	3
Woodland	1147	0.49 ± 0.02	3
Open Woodland	8281	0.50 ± 0.03	3
Rocky Woodland	43	0.42 ± 0.03	1
Dense Tall Shrubs	11293	0.63 ± 0.03	3
Dense Low Shrubs	5536	0.60 ± 0.04	4
Low Shrub Tundra	5274	0.50 ± 0.02	3
Erect Dwarf-shrub Tundra	202	0.43 ± 0.02	1
Peatland	4176	0.54 ± 0.02	4
Wetland Fen	719	0.43 ± 0.04	3
Sedge/Moss Tundra	2768	0.50 ± 0.03	3
Herb/Cryptogam Barrens	568	0.42 ± 0.03	2
Sediments – Low Vegetation	114	0.13 ± 0.07	0
Lichen Barren - Bedrock	356	0.29 ± 0.07	0

Once a suitable sample location was identified in the field, BVV was measured within a 30 m x 30 m (900 m²) plot; corresponding to the spatial resolution of Landsat. At each plot, measures of vegetation height were obtained at 49 points corresponding to a rectangular grid (Figure 3.4). The height of different vegetation functional groups was measured at each point with a tape measure, although a Vertex IV transponder (Haglöf Sweden) was used for taller trees. Functional groups used were: trees, erect-shrubs, dwarf-shrubs, herbaceous forbs, pteridophytes (primarily *Equisetum spp.*), graminoids, moss, lichen, and non-vegetated surfaces (i.e., rock, soil, gravel and water). Trees, erect-shrubs and dwarf-shrubs were identified to the species level while all other functional groups were recorded by the functional group name in order to save time when sampling. GPS coordinates, photographs and other supplementary data were also recorded at each plot. See Appendix A for additional details.

Figure 3.4: Sample plot setup (diagram at left). Plots were established as 30 m x 30 m (900 m²) squares and measurements were obtained at 49 points (red) at 5 m intervals. At each point, the height of each vegetation functional group was measured (photograph at right). Pink flags in the background of the photograph marked the edge of the sample plot.

BVV at the plot level was calculated based on these vegetation height measurements (Chen et al., 2009; Gregory, 2011).

$$\begin{aligned}
 \text{BVV} = & \\
 & \text{Average Height Trees} * 900 \text{ m}^2 * (X/49) & + & (1) \\
 & \text{Average Height Erect-shrubs} * 900 \text{ m}^2 * (X/49) & + & \\
 & \text{Average Height Dwarf-shrubs} * 900 \text{ m}^2 * (X/49) & + & \\
 & \text{Average Height Forbs} * 900 \text{ m}^2 * (X/49) & + & \\
 & \text{Average Height Pteridophytes} * 900 \text{ m}^2 * (X/49) & + & \\
 & \text{Average Height Graminoids} * 900 \text{ m}^2 * (X/49) & + & \\
 & \text{Average Height Moss} * 900 \text{ m}^2 * (X/49) & + & \\
 & \text{Average Height Lichen} * 900 \text{ m}^2 * (X/49) & &
 \end{aligned}$$

This equation is the average height of all measured individuals within a functional group multiplied by the area of the plot (900 m²) and the percent vegetation cover (PVC) of that functional group (i.e., number of points containing that functional group [X] out of 49) summed for all functional groups. BVV takes into account denser high biomass canopies, where different functional groups correspond to different layers of vegetation within the canopy. BVV calculations for each sample plot were compared using least squares regression with corresponding NDVI values derived from the 2011 Landsat data.

3.3.6 NDVI Trend Analysis

NDVI trends were compared to a variety of spatially referenced environmental variables to evaluate geographical influences on the pattern and magnitude of NDVI trends across the study area. Twelve environmental variable raster layers were acquired or generated (Table 3.2). These variables account for differences in land cover, topography (elevation, slope, aspect, topographic position and wetness), waterbody influence (distance to rivers, lakes, major lakes and major drainage systems) and climate (summer temperature and precipitation change).

Table 3.2: Descriptions of the 12 environmental variables that may influence NDVI trends. Canada Digital Elevation Model (DEM) and National Topographic System (NTS) map sheets were acquired from Natural Resources Canada (2012). Flow accumulation: the accumulated sum of all upslope pixels that flow into each downslope pixel. Yearly climate data from Climatic Research Unit (CRU) TS3.24.01 0.5° global climate grid (University of East Anglia CRU, 2008). See Appendix E to view raster images for each of these variables.

Variable	Description
Land cover	9-Class supervised classification from 2011 Landsat scene mosaic (see Figure 3.5)
Elevation	Canada DEM based on 10 m contour lines from 1:50,000 NTS maps
Slope	Slope (°) calculated from Canada DEM
Aspect	Aspect (°) calculated from Canada DEM, converted to categorical variable (i.e., northeast facing = 22.5° to 67.5°)
Topographic Position Index (TPI)	Difference (m) between center point and average elevation of a 15 x 15 pixel moving window, above 0 = exposed, below 0 = sheltered (Weiss, 2001; Jenness, 2006)
Topographic Wetness Index (TWI)	$\ln((\text{Flow Accumulation} + 1) / (\tan(((\text{Slope}) * 3.14159265) / 180)))$ Quantifies wetness of the landscape (Beven & Kirkby, 1979; Diltz, 2015).
Distance to Rivers (Rivers)	Euclidean distance (m) from nearest river (NTS maps) over 100 m long
Distance to Lakes (Lakes)	Euclidean distance (m) from nearest lake (NTS maps) over 900 m ² area (Landsat pixel size)
Distance to Major Lakes (Major Lakes)	Euclidean distance (m) from nearest major lake (NTS maps) over 10 million m ² area
Distance to Major Drainage Systems (Drainages)	Euclidean distance (m) from nearest water route (rivers and lakes that form major drainage systems in the region) with a flow accumulation of over 1 million inflowing pixels
Temperature Change (Temp Change)	Summer (June – August) temperature change (°C/year) between 1980 and 2015 * number of years. i.e., Slope of linear trend derived from a regression.
Precipitation Change (Precip Change)	Summer (June – August) precipitation change (mm/year) between 1980 and 2015 * number of years. i.e., Slope of linear trend derived from a regression.

Land cover was developed as a 9-class supervised maximum likelihood classification based on a mostly cloud-free 2011 Landsat scene mosaic of all four frames in the study area (Figure 3.5). Calibration data were applied based on personal observations gathered from the field expedition (including the preliminary 15-class ISODATA classification) and a past expedition down the Coppermine River in the summer of 2013. Available high spatial resolution imagery, geo-tagged photographs and Streetview images (NWT Highway 1 and 3) from Google Earth were also examined. NWT Ecosystem Classification Reports (Ecosystem Classification Group, 2008; 2009; 2012) in the southern portion of the study area and the Circumpolar Arctic Vegetation Map (CAVM) (Walker et al., 2005) in the northern portion of the study area provided broader scale information on land-cover classes. A fine-scale land-cover map of the area around Daring Lake was also consulted (Obst, 2011). Olthof et al.'s (2009) circa 2000 Landsat land-cover map of northern Canada provided a useful base of comparison with conditions at that time.

Topographic variables were derived from the ~20 m spatial resolution Canada DEM (Natural Resources Canada, 2012). Topographic Position Index (TPI) quantifies landscape exposure and shelter, with exposed landscapes having positive values and sheltered landscapes having negative values (Weiss, 2001; Jenness, 2006). Topographic Wetness Index (TWI) is a unitless measure of landscape wetness (Beven & Kirkby, 1979; Dilts, 2015). Waterbody influences were examined based on the distance to rivers and lakes of various sizes using the NTS map shapefiles (Natural Resources Canada, 2012). The distance to major drainage systems, such as the Hood, Snare and Yellowknife River systems, was also quantified. Summer temperature and precipitation change from 1980 to 2015 were evaluated at a regional scale using data from the CRU TS3.24.01 0.5° global climate grid (University of East Anglia CRU, 2008). All datasets were, if required, resampled (cubic convolution) to 30 m spatial resolution and projected to WGS (World Geodetic System) 1984: UTM (Universal Transverse Mercator) Zone 12N in order to align with the Landsat coverage.

Figure 3.5: Supervised 9-class land-cover classification from a mostly cloud-free 2011 Landsat mosaic. Timoney et al. (1992) 1:1000 (top) and 1000:1 (bottom) tree:tundra ratio lines that define the three zones are shown. See Appendix E for detailed class descriptions across each zone in the study area. Basemap provided by Government of Northwest Territories Centre for Geomatics.

The environmental variables were used as predictors (with NDVI trends as the response variable) for a Random Forest (RF) regression model, using the ‘randomForest’ package in R (Liaw & Wiener, 2002; R Development Core Team, 2010) (see Appendix F for R code). RF models create a large number of high variance decision trees that are built using bootstrap sampling (i.e., with replacement) from the original sample dataset (Breiman, 2001; Hastie et al., 2009). Each decision tree represents a tree-like model of binary splits optimized where the selected predictor variable has the greatest influence on the response variable. RF models can efficiently handle large datasets with low bias, portray complex interactions among input variables and are resistant to overfitting (Breiman, 2001).

The sample dataset input into the RF model was a random 1 % subset of the study area (608,807 pixels) with a 100 m proximity buffer between selected pixels. Genuer et al. (2017) found that sampling 1 % of the data provided an acceptable balance between processing time and model accuracy when using RF models for big data problems. RF models for the forest, ecotone and tundra zones were also created from the pixels in the subset that were part of each zone. Each RF model included 500 decision trees (ntree), with four environmental variables being randomly selected at each node split in each tree (mtry). The minimum terminal node size was set at 100 pixels, since smaller values had a large negative impact on processing time. Model outputs were robust over multiple 1 % subsamples.

RF modelling allows for the importance of all predictor variables to be tested in relation to the response variable. The percent increase in mean squared error (MSE) of the predicted output if the variable in question is randomly permuted (%IncMSE) is the most commonly used metric to measure variable importance in RF models. The increase in node purity from decision tree splits based on the variable in question (IncNodePurity) is also widely used to measure variable importance (Hastie et al., 2009). These two variable importance metrics were used to rank the overall importance of the environmental variables across all four RF models. The most

important environmental variables (i.e., higher %IncMSE and IncNodePurity) related to NDVI trends were evaluated further with partial dependence plots. Partial dependence plots portray the marginal influence of the variable in question on the response variable across their range of values, after averaging out (but not removing) the influence of all other variables (Hastie et al., 2009). Partial dependence plots are considered one of the most effective means of interpreting the results of a high dimensional machine learning model such as RF.

3.4 Results

3.4.1 NDVI Trends

There was an increase in NDVI across most the study area (Figure 3.6a), with 90 % of un-masked pixels having a positive trend and 10 % having a negative trend (Figure 3.7a). Fire scars, which were masked, exhibited large positive NDVI trends for older recorded fires and large negative NDVI trends for more recent fires. The statistical distribution of pixels (Figure 3.7a) indicates that the overall trends were skewed towards lower levels of annual increase. Most pixels (81 %) had a positive trend between 0 and 0.004 NDVI yr⁻¹. Overall, the mean trend increased across the study area (0.0019 ± 0.0016 NDVI yr⁻¹).

Approximately one-quarter (27 %) of all un-masked pixels exhibited a statistically significant NDVI trend (Figure 3.6b) and virtually all of those (99.3 %) were greening (Figure 3.7a). One-third (33 %) of pixels in the tundra zone exhibited greening and were mostly found in the northern portion. Slightly less than one-quarter (24 %) of pixels in the ecotone zone exhibited greening and were mostly found in the southern portion. A smaller proportion (17 %) of pixels in the forest zone exhibited greening and were clustered primarily near the west arm of Great Slave Lake. Less than 0.5 % of all pixels exhibited browning in each of the three zones. The mean trend for significant pixels was more positive than for all pixels across the study area (0.0034 ± 0.0013 NDVI yr⁻¹).

Figure 3.6: Landsat NDVI trends (1984-2016) for the study area as determined using ordinary least squares regression. (a) All NDVI trends. (b) Significant ($p < 0.05$) trends only. NDVI trends were binned into 10 levels (-5 = most negative, 5 = most positive), as seen in the legend, for visualization purposes following an approach similar to Ju & Masek (2016). Fire scars (outlined in gray) were masked and not incorporated into the analysis. Waterbodies and areas with excess cloud cover were also removed. Tree:tundra ratio lines that were used to delineate zones are shown.

There were regional differences in the extent and magnitude of NDVI trends observed across the study area (Figure 3.7b). The largest positive NDVI trends were found in the tundra zone, where over 60 % of all pixels increased more than 0.002 NDVI yr⁻¹ and over 15 % increased by more than 0.004 NDVI yr⁻¹. Smaller positive NDVI trends below 0.002 NDVI yr⁻¹ were more common in the ecotone (54 % of pixels) and forest zones (55 % of pixels). However, pixels in the ecotone zone were more likely to increase more than 0.002 NDVI yr⁻¹ and less likely to decrease in NDVI than those in the forest zone. The mean NDVI trend was smallest in the forest zone (0.0013 ± 0.0016 NDVI yr⁻¹), slightly more in the ecotone zone (0.0016 ± 0.0014 NDVI yr⁻¹) and largest in the tundra zone (0.0025 ± 0.0015 NDVI yr⁻¹). In terms of significant trends, they were mostly consistently skewed towards stronger greening across all zones, with over 85 % of significant pixels greening more than 0.002 NDVI yr⁻¹ in all cases. However, greening above 0.004 NDVI yr⁻¹ was more common in the tundra zone than elsewhere while 3 % of significant forest zone pixels exhibited browning.

Figure 3.7: Pixel distribution of NDVI trends for the study area (a) and each of the zones (b). Bars indicate the percentage of all un-masked pixels that fall into each bin, corresponding to Figure 3.6a. Points indicate the percentage of significant pixels that fall into each bin, corresponding to Figure 3.6b. NDVI trends binned and colored as in Figure 3.6 (-5 = most negative, 5 = most positive).

Significant trends varied with land cover across the study area as well (Figure 3.8). In the forest zone, 14 to 21 % of forested land-cover classes (Forest [F], Woodland [W], Lichen-Rocky Woodland [LRW]), which comprised most of the landscape, exhibited greening trends. Land-cover classes that were less densely vegetated (Lichen-Rocky Shrubland [LRS], Lichen-Barren Tundra [LBT], Sediments – Low Vegetation [SLV]) exhibited less greening and even some notable browning. Dense Shrubland (DS), Open Shrubland (OS) and Graminoid Tundra (GT) classes exhibited the most greening, but were also the least common land-cover classes in the forest zone. Similarly, in the ecotone zone, the more densely vegetated land-cover classes generally exhibited more greening than the less densely vegetated classes. The lower density forested land-cover classes (LRW and W) exhibited the strongest trends, with 34 % of LRW pixels greening in the ecotone zone.

In the tundra zone, the less densely vegetated LRS, LBT and SLV land-cover classes, which were the most common and located primarily farther north, exhibited more greening than the shrubland (DS, OS) and GT classes. Almost 50 % of LBT pixels in the tundra zone exhibited greening, with most of those pixels geographically distributed towards the edge of that class's extent. OS, which was primarily found in the southern portion of the tundra zone, only had 18 % of its pixels exhibit a greening trend. However, OS pixels located in the northern portions of the tundra zone exhibited almost 50 % greening when considered separately. In the northern portion of the tundra zone, inter-class differences were smaller than for the tundra zone as a whole and all land-cover classes present exhibited 35 to 50 % greening (see Appendix E for figure).

Figure 3.8: Percentage of Landsat pixels with significant NDVI trends in each of the three zones across the study area, split by land-cover type (*sensu* Frost et al., 2014). Values above 0 indicate greening while values below 0 (in parenthesis) indicate browning. The percentage of the zone in question that is comprised by each land-cover class is indicated as points plotted against the right y-axis. Land-cover classes are colored as in Figure 3.5: F = Forest, W = Woodland, LRW = Lichen-Rocky Woodland, DS = Dense Shrubland, OS = Open Shrubland, LRS = Lichen-Rocky Shrubland, GT = Graminoid Tundra, LBT = Lichen-Barren Tundra, SLV = Sediments – Low Vegetation.

3.4.2 Relationship between NDVI and Bulk Vegetation Volume

Of the plots sampled during the field expedition, 11 were classified on the ground as forested, 18 as shrubland, two as graminoid tundra and three as wetland (Figure 3.2). Forested plots were almost all open black spruce (*Picea mariana*) canopies (51 ± 14 tree PVC, 1048 ± 335 m³ per plot), with one lichen-woodland plot interspersed with white spruce (*Picea glauca*) and paper birch (*Betula papyrifera*). Understories of erect-shrubs (25 ± 14 PVC, 135 ± 78 m³ per plot) and dwarf-shrubs (84 ± 16 PVC, 108 ± 39 m³ per plot) were common at forested plots. Shrubland plots were mostly dominated by birch shrubs (*Betula* spp.), but alder (*Alnus* spp.) and willow (*Salix* spp.) shrubs were common and even dominant at some plots. These erect-shrubs were present at a majority (56 ± 19 PVC, 248 ± 182 m³ per plot) of shrubland sample points, while dwarf-shrubs were present at most (88 ± 7 PVC, 69 ± 35 m³ per plot) sample points. Many shrubland plots, especially those with lower BVV, were strewn with boulders. The most dominant dwarf-shrubs across all plots were northern Labrador tea (*Rhododendron tomentosum*, 51 % of dwarf-shrub volume), blueberry (*Vaccinium uliginosum*, 25 %) and low-bush cranberry

(*Vaccinium vitis-idaea*, 13 %). The most dominant erect-shrub types by volume were birch (69 % of erect-shrub volume), alder (23 %) and willow (7 %). Graminoids were the dominant vegetation in graminoid tundra (52 ± 7 PVC, 45 ± 3 m³ per plot) and wetland (73 ± 20 PVC, 108 ± 44 m³ per plot) plots. Lichen was common in all plots (59 ± 24 PVC) and moss (23 ± 20 PVC), as expected, was found mostly in wetter areas.

The BVV of all non-wetland sample plots had only a weak relationship ($R^2 = 0.221$, $p = 0.089$) with the 2011 NDVI (Figure 3.9a). Wetland plots were removed because standing water within those plots negatively influenced the NDVI signal (Raynolds & Walker, 2016). Shrubland plots had a lower mean BVV (362 ± 246 m³ per plot) than forested plots (1365 ± 367 m³ per plot) but exhibited a slightly higher mean NDVI (0.63 ± 0.07) than forested plots (0.62 ± 0.06). In general, the NDVI of forested plots was lower than expected based on their BVV. However, when the volume contributed by individual trees was removed, the relationship between this revised bulk vegetation volume ($_{NT}BVV$) and NDVI was strong, with an R^2 of 0.81 ($p < 0.001$) (Figure 3.9b). This relationship was logarithmic, with an increase in NDVI of 0.1 (i.e., 0.0031 NDVI yr⁻¹ if considered over time) equating to a 316 % increase in $_{NT}BVV$.

NDVI trends were converted to $_{NT}BVV$ trends for non-wetland sample plots based on the strength of this relationship, using the equation ($NDVI = 0.087 \ln(_{NT}BVV) + 0.1366$, $R^2 = 0.81$, $p < 0.001$) in Figure 3.9b. Field-collected $_{NT}BVV$ values from 2016 aligned well with earlier satellite-derived trends for most plots. Forested plots (Figure 3.10a) exhibited the largest positive mean $_{NT}BVV$ trend (5.05 ± 2.47 m³ per plot yr⁻¹). Four of the 11 forested plots exhibited greening and all $_{NT}BVV$ trends were positive. All three of the forested plots classified for field sampling as open woodland (Table 3.1), the lowest density forest class, exhibited greening. Shrubland plots (Figure 3.10b) exhibited a positive mean $_{NT}BVV$ trend overall, but with high variation (3.09 ± 5.22 m³ per plot yr⁻¹). Two of the 18 shrubland plots exhibited greening and 13 exhibited positive $_{NT}BVV$ trends. These two greening plots were the only shrubland plots where alders constituted

the majority of erect-shrub volume (i.e., alder-dominant sites). The two graminoid tundra plots (Figure 3.10c) exhibited a slightly decreasing mean $_{NT}BVV$ trend ($-1.43 \pm 0.63 \text{ m}^3 \text{ per plot yr}^{-1}$) and neither were significant.

Figure 3.9: The relationship (logarithmic regression) between Landsat-derived NDVI (2011) and field-measured bulk vegetation volume (m^3 per Landsat-size plot). NDVI was calculated from the same scenes used to create the ISODATA classification from which sample plots were selected. Equation, coefficient of determination (R^2) and p-value shown. These relationships are logarithmic because as the ($_{NT}$)BVV of a sample plot increased the influence of those changes on NDVI decreased. (a) All non-wetland plots using all functional group measurements (b) All non-wetland plots with the volume of individual trees removed.

Figure 3.10: Non-tree bulk vegetation volume (m^3 per Landsat-size plot) trends for (a) forested, (b) shrubland and (c) graminoid tundra sample plots based on the relationship between NTBVV and NDVI. NDVI was converted to NTBVV using the equation from Figure 3.9b. Thick colored lines indicate plots with significant linear trends, while thin colored lines represent plots without significant trends. Colored circles indicate actual NTBVV values collected for each plot during the 2016 field expedition. The dashed black line indicates the mean change in NTBVV per year across all sampled plots of each type ($\pm \text{SD}$ indicated by solid black lines).

3.4.3 Landscape and Environmental Influences on NDVI Trends

The results of Pearson's correlation analyses (Figure 3.11) illustrate that NDVI trends (NDVI yr^{-1}) across the full extent of the study area did not exhibit strong relationships with any

single environmental variable. The strongest positive relationship of any environmental variable was with temperature change ($R = 0.30$, $p < 0.01$) and the distance to major lakes ($R = 0.24$, $p < 0.01$). The strongest negative correlation was with precipitation change ($R = -0.27$, $p < 0.01$). NDVI trends also exhibited positive correlations with UTM northings (northing, $R = 0.39$, $p < 0.01$), indicating that NDVI trends were more positive at higher latitudes. Correlations between the environmental variables were low for the most part, except for between precipitation and temperature change. These correlations were consistent across multiple 1% subsamples of the original dataset.

Figure 3.11: Correlation matrix of UTM northings, NDVI trends and environmental variables for the study area. Blue squares equate to positive correlations and red squares to negative correlations, with the size and shade of the square indicating the strength of the relationship. Crosses indicate relationships that were not significant ($p > 0.01$).

Results of RF modeling indicated that environmental variables differed in their ability to account for variability of NDVI trends across the study area (Table 3.3). For the study area as a

whole, almost half of all variation was explained by the input variables. When analyzed separately, the forest zone had the lowest variation explained at 21.6 %. The ecotone zone performed better, with over 40 % of the variation explained. Meanwhile, 55.3 % of the variation in NDVI trends was explained by input variables in the tundra zone.

Table 3.3: RF model details for the study area and each of the three zones. Sample sizes represent 1% of pixels that make up the overall extent of each model. Error is the average out-of-bag mean square error (MSE). Percent (%) Variation explained is the pseudo R^2 : $(1 - \text{Error} / \text{variation in training data}) * 100$.

Extent	Sample Subset Size	Error	% Variation Explained
Study Area	608,807	1.31E-06	48.24
Forest Zone	138,010	2.02E-06	21.55
Ecotone Zone	177,803	1.19E-06	41.08
Tundra Zone	292,994	1.02E-06	55.26

Based on %IncMSE and IncNodePurity, RF models showed that land cover and temperature change were considered the most important variables for the study area and for each of the three zones in determining the direction and magnitude of NDVI trends (Figure 3.12). The one exception was the forest zone, where precipitation change was indicated as more important than temperature change. Precipitation change, distance to major drainage systems, elevation and distance to major lakes also had high importance rankings for both %IncMSE and IncNodePurity. There was a decline in importance for the other environmental variables, which focused primarily on finer scale landscape variation. A final ranking based on the average rankings of %IncMSE and IncNodePurity across the four RF models found that land cover was the most important variable overall, followed by temperature change, precipitation change, distance to major drainage systems, elevation and distance to major lakes. Distance to all lakes and rivers, slope, TPI, TWI and aspect were indicated as less important.

	%IncMSE				IncNodePurity				Average Rank
	Study Area	Forest Zone	Ecotone Zone	Tundra Zone	Study Area	Forest Zone	Ecotone Zone	Tundra Zone	
Land cover	1	1	1	1	5	1	4	5	2.375
Temp Change	3	8	3	2	1	6	1	1	3.125
Precip Change	6	3	6	5	2	3	2	2	3.625
Drainages	2	2	2	3	6	4	5	6	3.75
Elevation	5	4	4	4	4	2	3	4	3.75
Major Lakes	8	5	5	6	3	5	6	3	5.125
Lakes	4	7	7	7	7	9	9	7	7.125
Rivers	7	6	10	9	10	7	12	11	9
Slope	10	11	8	11	8	10	7	8	9.125
TPI	11	9	12	12	9	8	8	9	9.75
TWI	9	10	11	10	12	11	10	12	10.625
Aspect	12	12	9	8	11	12	11	10	10.625

Figure 3.12: Importance of environmental variables from RF models. (a) The percent increase in MSE if the variable in question has its values randomly permuted (%IncMSE). (b) The increase in node purity based on the function by which best splits are chosen in decision trees (IncNodePurity). IncNodePurity scaled to 100 for each model to gauge relative importance (Hastie et al., 2009). More important variables have higher %IncMSE and IncNodePurity. Bottom: table of importance rankings for environmental variables from 1 to 12 (1 = most important, 12 = least important) used to determine overall importance ranking (i.e., lowest average rank).

Partial dependence plots for land cover (Figure 3.13), which was considered one of the two most important variables in every RF model, indicated that the more densely vegetated classes exhibited larger positive NDVI trends than the less densely vegetated classes. DS and OS exhibited among the most positive NDVI trends and LBT and SLV exhibited the weakest trends

in all models. Forested classes also exhibited larger positive NDVI trends, especially in the ecotone zone. These results are in agreement with greening trend results, with the exception of the tundra zone where LRS, LBT and SLV were greening the most and inter-class differences were larger (Figure 3.8). This difference is attributed to the strong positive influence of temperature warming on NDVI trends in the tundra zone, which likely supersedes any large influence by differences in land cover. The differences between Figure 3.8 and 3.13 in the tundra zone thus indicate that those classes with stronger greening trends (LRS, LBT, SLV) were located primarily in the northern portion of the tundra zone where the most pronounced warming has occurred. In this northern area, all land-cover classes exhibited large positive NDVI trends and shrubland land covers (DS, OS, LRS) were the largest (Figure 3.13).

The strongest influence on NDVI trends for any partial dependence plot was attributed to temperature change in the tundra zone, where NDVI trends doubled from 0.0015 to 0.003 NDVI yr⁻¹ where more warming had occurred (Figure 3.13). Increased summer warming led to larger positive NDVI trends in general. However, the ecotone zone was the notable exception, and summer temperature warming was associated with a decline in NDVI trends in that zone. The influence of precipitation changes, which were small (< 8 mm from 1980 to 2015), on NDVI trends was variable across the study area. Across all models, NDVI trends were more positive when closer to major drainage systems. Gradual changes in elevation above sea level did not have a notable influence on NDVI trends, except for around 350 m a.s.l., where a break point occurred. In all models except for the forest zone, NDVI trends tended to be more positive at elevations below 350 m a.s.l. than above that elevation. Proximity to major lakes, which was consistently one of the two least important variables of these six, generally exhibited a negative influence on NDVI trends. In all models except for the forest zone, NDVI trends were more positive when farther away from major lakes. Overall, NDVI trends were more positive in the tundra zone than in the forest or ecotone zones for all variables.

Figure 3.13: Matrix of partial dependence plots for the six overall (across all four models) most important variables across the study area. Variable importance rankings for these six variables (shown in the top left corner of each plot) are based on both the %IncMSE and IncNodePurity ranking for each model. Partial dependence plots indicate the marginal influence of the variable in question on NDVI trends, with all other (11) variables averaged out (but not ignored). Land cover colored as in Figure 3.5 and follows same naming conventions as in Figure 3.8. See Appendix F to view the partial dependence plots for the six least-important variables considered, which generally influenced NDVI trends at a much smaller scale.

3.5 Discussion

3.5.1 NDVI Trends

NDVI trend analyses indicated that vegetation productivity has been increasing throughout the study area, but that increases have been heterogeneous across the forest to tundra transition. The majority of greening pixels and the largest positive NDVI trends were located in the northern portion of the tundra zone and southern portion of the ecotone zone, with smaller and less significant trends elsewhere. Browning pixels were rare and negative NDVI trends were generally small. The geography and magnitude of these trends are in general agreement with a Landsat NDVI time-series developed across Canada and Alaska by Ju & Masek (2016), which shows similar NDVI yr^{-1} changes as found in my study area. In terms of the overall significance of trends, a similar Landsat transect in northern Québec by McManus et al. (2012) found that 34 % of pixels exhibited significant positive NDVI trends (99 % greening). The results of trend analyses in my study area indicates slightly less (27 %) significant trends (also 99 % greening), which is not surprising given that northern Québec has experienced a recent rapid increase in vegetation productivity (Ju & Masek, 2016). Greening pixels in both areas were primarily located at, and north of the forest-tundra ecotone.

The largest increases in NDVI and the majority of greening pixels across the study area were found in the northern portion of the tundra zone. This area is primarily comprised of lichen-dominated land cover (LRS, LBT, SLV), of which about half of all pixels were greening. Similarly, Landsat-based studies in the Alaskan and western Canadian Arctic have observed greening in lichen-dominated areas (Raynolds et al., 2013; Fraser et al., 2014a) while plot-based studies have demonstrated a reduction of lichen cover and an increase in shrub cover in those regions (Walker et al., 2006). OS land cover, which is common along riparian corridors, also exhibited nearly 50 % greening in the northern portion of the tundra zone. Greening of shrubland areas has been detected using Landsat elsewhere in Arctic North America (Olthof et al., 2008;

McManus et al., 2012; Fraser et al., 2014a). Several AVHRR-based remote sensing studies conducted across northern high latitudes have also found widespread greening along much of the northern coast of mainland Canada, including in the area corresponding to the northern tundra zone (Jia et al., 2003; Goetz et al., 2005; Beck & Goetz, 2012; Epstein et al., 2012; Guay et al., 2014; Epstein et al., 2016). Greening has thus been common across this area, regardless of land cover.

Positive trends were smaller (mostly below $0.002 \text{ NDVI yr}^{-1}$) and greening pixels were less common in areas south of the northern tundra zone. These results coincide with NDVI trends derived for the same area in other studies, as well as east across the inland Low Arctic region of mainland Nunavut (Ju & Masek, 2016). This portion of the study area, which crosses into the northern portion of the ecotone zone, is dominated by OS (30 %) and GT (22 %) land-cover classes and is occupied by many small lakes and wetlands (Ecosystem Classification Report, 2008). Epstein et al. (2012) found that wet mires in the Low Arctic had the smallest phytomass increase of any vegetation type across circumpolar high latitudes in their AVHRR-based study, indicating that tundra areas with wet moisture regimes have been greening less than drier areas. NDVI is also known to be negatively influenced by standing water, which has an NDVI value of zero, as well as by high moisture content in soils (Laidler et al., 2008; Raynolds & Walker, 2016). In fact, wetland plots sampled during the field expedition were removed from analysis because the large amount of standing water present resulted in an uncertain NDVI to NTBVV relationship for those plots.

Farther south, the largest NDVI trends and highest percentage of greening pixels were found in the southern ecotone zone, which is characterized by the transition between shrubland and forest along a latitudinal gradient. Hence, it is not surprising that forested land cover had the highest percentage of greening pixels in the ecotone zone. Similarly, McManus et al. (2012) detected large positive NDVI trends in the proximity of treeline in northern Québec. However, for

their entire study area, forest land cover had the lowest percentage of greening pixels (16 %) of all land covers. In the ecotone zone for my study, forested pixels (F, W, LRW) had the highest percentage of greening (24 to 34 %). This difference is related to the delineation of zones; in the forest zone (where the majority of forested pixels were located), a similar percentage (14 to 21 %) of forested pixels were greening (as in McManus et al. 2012). It thus appears that these forested areas are more likely to be greening when closer to their range margins.

South of the forest-tundra ecotone, some continental boreal forest communities have exhibited decreases in productivity, frequently attributed to warming-induced drought stress (Barber et al., 2000). The browning of these conifer forests has been reported in Siberia, Alaska and northern Canada from a variety of remote sensing and field-based studies (Barber et al., 2000; Goetz et al., 2005; Verbyla, 2008; Berner et al., 2011; Beck & Goetz, 2012; Guay et al., 2014). In my study area, the mean trends were smallest in the forest zone (0.0013 ± 0.0016 NDVI yr^{-1}), but forested pixels were still at least 20 times more likely to be greening than browning. Even bedrock outcroppings (LBT, SLV) in the forest zone, which exhibited the lowest greening and highest browning percentages of any land cover across the study area, were four times more likely to be greening than browning. Ju & Masek's (2016) map of NDVI trends over North America similarly shows that boreal areas are browning in some locations (i.e., interior Alaska, northern Saskatchewan) but that elsewhere, including the area corresponding to the forest zone, there is little change or small increases in NDVI. The browning of boreal forests observed elsewhere has thus not occurred here (note that fire scars have been removed from this analysis).

3.5.2 Relationship between NDVI and Bulk Vegetation Volume

The canoe-based field expedition in the North Slave region of NWT was able to provide ground validation for these remote sensing results, especially for non-tree vegetation. Observations made in the field were also key to gathering information not possible from Landsat data alone, such as species-level and other local-scale influences on NDVI trends. Results

indicated a significant positive relationship ($R^2 = 0.81$, $p < 0.001$) between $_{NT}BVV$ and NDVI for sample plots, confirming that Landsat-derived NDVI is strongly indicative of vegetation volume in the study area. This means that changes in satellite-derived NDVI can be confidently associated with similar changes in vegetation volume on the ground. This methodology, adapted from Chen et al. (2009), was also shown to be strongly linked with aboveground biomass and leaf area index (LAI) across 196 plots elsewhere in the Canadian tundra. Gregory (2011) found that $_{NT}BVV$ had the strongest relationship with NDVI of any biophysical metric tested at a High Arctic site. My results further support the strong relationship between $_{NT}BVV$ and NDVI in tundra environments and demonstrate that this methodology can also be successful at sites with lower density tree cover, which was not tested in either Chen et al. (2009) or Gregory (2011).

However, this relationship overestimated the predicted NDVI of forested plots when the volume added by trees was included. It appears that trees had a negligible impact on NDVI at the scale of Landsat data. These trees, predominantly open canopies of black spruce at the edge of their habitable range, were primarily small, thin individuals with proportionately low leaf biomass compared to wood biomass. Broadleaf shrub understories, by comparison, were more densely packed with leaves (indicating a higher LAI). Shadows cast by trees on understory vegetation has been shown to have a negative influence on the NDVI of lower density coniferous forests, especially near treeline where the understory often constitutes much of the biomass (McDonald et al., 1998; Rees et al., 2002). It is thus evident that the volume, and therefore NDVI, added by needles from these trees was offset by the shadows they cast on higher LAI understory shrubs.

The $_{NT}BVV$ -NDVI relationship was logarithmic, where higher volume sites had limited additional positive influence on NDVI. Similar relationships between biophysical variables and NDVI have been noted in other studies. Jia et al. (2003) found strong correlations between NDVI and aboveground biomass in Alaskan tundra, with diminishing impact on NDVI as biomass increased. Epstein et al. (2012) also found a strong logarithmic relationship between NDVI and

biomass from 13 sites across the circumpolar Arctic subzones. The structure of this relationship is the result of NDVI saturation, where NDVI becomes increasingly insensitive to further biomass increases in high biomass environments (Raynolds et al., 2012). Frost et al. (2014) also noted this when explaining why shrub expansion in a high biomass area can lead to a smaller NDVI trend increase than the same shrub expansion in a lower biomass area.

3.5.3 Landscape and Environmental Influences on NDVI Trends

RF modelling also indicated that NDVI trends were heterogeneous across the study area and were influenced by a number of environmental variables. Variable importance indices and partial dependence plots indicated that land cover and temperature change had the most influence on NDVI trends. Precipitation change, distance to major drainage systems, elevation and distance to major lakes also notably influenced NDVI trends. The fact that these variables were highlighted by RF modelling demonstrates the importance of broader scale environmental variables on NDVI trends. Distance to all lakes and rivers, slope, TPI, TWI and aspect, all of which focus on finer scale changes, were indicated as less important and had much smaller partial dependence trends.

In the tundra zone, temperature was identified as the most important variable and positive NDVI trends were twice as large (0.0015 to 0.003 NDVI yr^{-1}) where summer temperatures have experienced greater increases. A major break point occurred at $+1.6$ °C, which geographically corresponds to the boundary between the larger greening trends of the northern tundra zone and the smaller, less significant, NDVI trends farther south. It is well established that warming temperatures have been the main driver of tundra greening across the circumpolar Arctic (Sturm et al., 2001b; Walker et al., 2006; Elmendorf et al., 2012; Fraser et al., 2014a; Myers-Smith et al., 2015 etc.). Hence, it is not surprising that increased warming in the Low Arctic tundra in the far north of my study area had the greatest influence on NDVI trends across all zones and variables. In tundra regions across northern high latitudes, this additional greening has been linked to sea ice

decline that spurs increased warming in low elevation (< 300 m a.s.l.) areas (Bhatt et al., 2010). Similarly, NDVI trends were more positive below 350 to 400 m a.s.l. in the tundra zone. It thus appears that temperature and elevation, possibly related to regional sea ice decline, are key environmental controls on trends in vegetation productivity in the tundra zone.

With temperature change in the tundra zone accounted for, the influence of different land-cover classes on NDVI trends was small. However, positive NDVI trends were slightly larger for shrubland classes (DS, OS, LRS), which were most common closer to riparian corridors (i.e., the Tree, Hood and Burnside Rivers). Furthermore, NDVI trends were more positive when closer to major drainage systems. This was especially true for areas within one kilometer of major drainages in the tundra zone, indicating a local as well as regional influence. Similarly, Fraser et al. (2011) found more greening in shrubland areas along river valleys in four of Canada's northern national parks. And the largest positive NDVI trends detected in northern Québec by McManus et al. (2012) were located along two major rivers north of the forest-tundra ecotone. The largest positive NDVI trends for my study area were similarly located in the region between the Hood and Burnside Rivers in the northern tundra zone. This particular region coincides closely with the current (since the mid-1990s) peak calving grounds of the Bathurst caribou herd (Gunn et al., 2008). Other studies have noted that caribou trampling can initiate shrub growth in lichen-dominated areas and point to this as a notable local-scale influence on greening trends (McManus et al., 2012; Fraser et al., 2014a).

Elsewhere in the North American Low Arctic, strong greening trends have been most often associated with shrubification, or the expansion of erect and dwarf-shrubs into previously inhospitable areas. In northern Alaska, shrub advance has been documented north of the forest-tundra ecotone (Sturm et al., 2001b; Silapaswan et al., 2001; Tape et al., 2006; 2012). In the Mackenzie Delta region of western Canada, shrub expansion into lichen-dominated areas has also been widespread near the Arctic Ocean coast (Lantz et al., 2013; Fraser et al., 2014a). In northern

Québec, birch shrub expansion has been widespread (Tremblay et al., 2012). Similar studies have been mostly absent in the central Canadian Low Arctic, except for around the Daring Lake Tundra Ecosystem Research Station where some birch shrub expansion has been recorded (Myers-Smith et al., 2011; Andruko, 2016). In many of these cases, shrub expansion has been occurring most rapidly on floodplains and along streams in river valleys. The strong greening trends detected for shrubland along riparian corridors and at lower elevations in the northern tundra zone are also likely indicative of shrubification, but other mechanisms (i.e., the growth and increased density of existing vegetation) cannot be discounted without the appropriate *in situ* field research.

In the tundra zone (as well as the ecotone zone), positive NDVI trends were larger at greater distances from major lakes. The relationship between NDVI trends and distance to all lakes, regardless of size, was the same but weaker, indicating that larger lakes have a stronger influence on the vegetation dynamics of the surrounding landscape. It is possible that these large lakes, which often remain ice covered longer into the summer than smaller lakes, have a cooling influence on the surrounding landscape during the growing season. Raynolds et al. (2008) found that NDVI regression residuals with the summer warmth index were negative across northern high latitudes in areas with greater than 2 % lake coverage, and that they became more negative as lake coverage increased (up to -0.4 at 50+ % lake coverage). They found that the central Canadian tundra (i.e., my study area) had lower NDVI values than predicted from its relationship with summer warmth index because of the large expanse of waterbodies in the region.

In the ecotone zone, summer temperature was also indicated as the most important variable and had the largest influence on NDVI trends. However, in this case, warming was negatively associated with NDVI trends. This was an unexpected result that does not follow the general trend as the rest of the study area and may be related to regional geography of the ecotone zone. GT, which is more common in the northern portion, exhibited smaller positive NDVI trends

(despite increased summer warming) than the main shrubland to forest transition farther south. It is possible that permafrost degradation, brought on by warmer temperatures, has led to increased water coverage in graminoid tundra and other wet areas (Jorgenson et al., 2006). Increasing water coverage has been associated with unexpectedly low NDVI trends at wet shrubland and graminoid tundra sites in northern Alaska (Pattison et al., 2015; Raynolds & Walker, 2016). Similarly, graminoid tundra plots sampled near Big Lake (i.e., just north of the ecotone zone boundary) exhibited small negative trends in $_{NT}BVV$, even as shrubland and forested plots to the south were mainly positive.

The southern extent of the ecotone zone appears to be a key secondary greening area within the study area. Elevation is lowest in this area and NDVI trends were positively associated with lower elevations in this zone. Forested land cover, followed by shrubland, also had the largest positive influence on NDVI trends in the ecotone zone. An explanation for this greening could be that spruce advance into shrubland tundra has occurred, as has been observed at some sites in Alaska and south-west Yukon (Suarez et al., 1999; Lloyd et al., 2003; Danby & Hik, 2007). However, this is challenged by MacDonald et al. (1998), who found no northward advancement of spruce forest in central Canada from dendrochronological and historical records. The ecotone forests in my study area are primarily composed of black spruce. Studies along the forest-tundra ecotone in northern Québec indicate that the recent black spruce advance into tundra has been small, where it has occurred at all, and that expansion is limited by the species' low reproductive capacity (Gamache & Payette, 2004; 2005; Dufour-Tremblay et al., 2012). Similarly, remote sensing analysis north of the east arm of Great Slave Lake (just east of my study area), found that there was no expansion of forest into tundra from the 1970s to 1990s, reflecting a lag-time between warming and treeline response (Masek, 2001; Epstein et al., 2004).

That the strongest greening trends were located primarily farther south in the ecotone zone, between the 1:10 and 1000:1 tree:tundra ratio lines (Timoney et al., 1992), indicates that

established forest stands are likely increasing in productivity rather than expanding northward. Infilling within and between adjacent stands is also a possibility. Gamache & Payette (2005) noted that black spruce seedling establishment has been more efficient in the southern forest-tundra and that notable height increases of established individuals has occurred. At an alpine ecotone site in Alaska, Stueve et al. (2011) found that proximity to trees was the most important variable for explaining seedling establishment. Similarly, forest patches encountered during the field expedition in central Canada often had many new seedlings growing within and immediately around the patches. It is also possible that positive NDVI trends in the southern ecotone zone were influenced by gradual recovery from century-old fire disturbance, especially in W and LRW areas (Girard et al., 2008). However, this does not account for the widespread greening trends, which require significant increases in vegetation volume since 1984.

It is likely that the majority of the greening observed in the southern ecotone zone is associated with the increasing productivity of shrubs, especially in the understory of forested areas. As in the tundra zone, greening trends were strongest when closer to major drainage systems. The largest drainage system in the ecotone zone is the Snare River, around which greening trends were strongest. Results from the field expedition, which crossed the ecotone zone by way of the Snare River system, indicated that open woodland plots with dense shrub-dominated understories were greening most extensively. Shrubland plots, which were sampled farther north (i.e., outside of the southern ecotone greening area), were less likely to be greening than forested plots. However, overall, shrubland (OS, DS) exhibited larger positive NDVI trends, behind only forest land cover in the ecotone zone. In particular, alder-dominated plots were found to be greening. Alder shrub expansion has been recorded in Alaska and Siberia within and north of the forest-tundra ecotone, especially in close proximity to rivers (Sturm et al., 2001b; Tape et al., 2006; Lantz et al., 2013; Frost et al., 2013; 2014; Fraser et al., 2014a).

In the forest zone, land cover was indicated as the most important variable and had the largest influence on NDVI trends. Shrubland (DS, OS) and GT land covers exhibited the largest positive NDVI trends in the forest zone. These classes, which were rare, were often located in calcium-rich thermokarst wetlands in the Great Slave Plain and Great Slave Lowland High Boreal ecoregions (Ecosystem Classification Report, 2008; 2009) where water levels have dropped slightly since 1985 (Fraser et al., 2014b). Shrub and graminoid colonization of newly exposed shorelines, especially on the north shore of Great Slave Lake, has been observed in this region by Landsat imagery and oblique photography (Fraser et al., 2014b) and would explain why NDVI trends were most positive within one kilometer of major lakes in the forest zone. These classes were also common in areas recovering from fires, some of which may not have been recorded by GNWT (2015b) and thus not removed from analysis. It is likely that disturbance, followed by subsequent succession, has positively influenced NDVI trends for these classes in the forest zone.

Of the land covers that were common in the zone, more densely forested pixels (F, W) exhibited the largest positive NDVI trends and bedrock outcrops (LBT, SLV) exhibited the smallest. As in the other zones, NDVI trends were more positive when closer to drainage systems, with the largest concentration of greening pixels in this zone found in densely forested lowlands near the west arm of Great Slave Lake; an area that consists of multiple river systems. These results indicate that lowland forests are slowly increasing in productivity while areas of shallow soil and bedrock outcroppings remain mostly static and appear to be resisting colonization by trees and shrubs. This slow increase in productivity, albeit largely not significant, was also detected in forested areas by McManus et al. (2012), who attributed it to long-term recovery from fire disturbance.

Fire disturbance, and subsequent vegetative recovery, is a factor that may be influencing the small positive NDVI trends in the forest zone as well. Although all fire scars recorded by GNWT (2015b) were removed from my analysis, this record only dates back to 1965 and does

not account for longer-term productivity and land cover changes initiated by older fires. Similar long-term fire succession has been associated with a shift from closed-canopy forest to lichen-woodlands in parts of northern Québec (Girard et al., 2008). The small positive NDVI trends attributed to the long-term post-fire recovery of these successional areas likely outweighs other climatic and environmental pressures (McManus et al., 2012). Similarly, temperature change was not considered a highly important variable in the forest zone. This was unexpected as temperature change had been considered the most important variable in the other zones and across the study area. Overall, the forest zone RF model had notably lower variation explained (21.55 %) than the other zones, indicating that the variables included in this analysis were less effective at explaining NDVI trends across this zone in particular. It thus appears that sub-Arctic boreal forest environments are responding more to different environmental pressures (i.e., fire disturbance and recovery) than forest-tundra and Low Arctic tundra environments.

Chapter 4

Conclusions

4.1 Summary

This study was able to successfully meet the three main objectives:

1. Quantify recent vegetation changes across the forest to tundra transition of central Canada using a Landsat NDVI time-series

NDVI trends (1984-2016) and their significance were calculated for a study area spanning from boreal forest environments around Great Slave Lake to coastal tundra environments near the Arctic Ocean. Results show that greening has been occurring mostly in the far north of the study area (northern tundra zone) and secondly across the transition from boreal forest to shrubland dominated landscapes (southern ecotone zone). Denser boreal forest landscapes farther south (forest zone) had smaller NDVI trends, though positive, and were less likely to be significant. These results are in general agreement with other remote sensing studies conducted across northern North America.

2. Link NDVI trends to field measurements

Field measurements across the forest-tundra ecotone in the center of the study area were successful in demonstrating a strong relationship between NDVI and bulk vegetation volume ($_{NT}BVV$). This relationship was logarithmic, with higher $_{NT}BVV$ sites having limited additional positive influence on NDVI. Exploration of this relationship over time indicated that low density forests with shrub-dominated understories and alder (*Alnus* spp.) shrublands were more likely to be greening (i.e., adding $_{NT}BVV$). This relationship did not incorporate the volume added by trees, which overestimated the volume of forested plots if included. It was determined, in these range-edge forested sites, that trees do not have a notable effect on the NDVI signal. Any volume added by needles from these individuals appears to be offset by the shadows they cast on the higher LAI (leaf area index) understory vegetation. These results indicate that changes in

satellite-derived NDVI can be confidently associated with similar changes in vegetation volume on the ground in tundra, shrubland and low density forested areas near treeline.

3. Determine the extent to which environmental variables (i.e., climate, land cover, topography, waterbodies) influence patterns of vegetation change across the study area

Random Forest (RF) modelling was able to determine that certain environmental variables had a stronger influence on NDVI trends depending on the location within the study area (i.e., forest, ecotone, tundra zones). Overall, fine-scale terrain variability was considered less useful at explaining NDVI trends than broad-scale variables. Temperature warming in the tundra zone had the strongest influence on NDVI trends of any variable in any zone, with positive NDVI trends being twice as large where the temperature had warmed more. In both the tundra and ecotone zones, NDVI trends were more positive at greater distances from major lakes. In all zones, positive NDVI trends were larger closer to major drainage systems. Forest and shrubland pixels had larger positive NDVI trends than less densely vegetated classes in all zones. Differences in topography did not have a major influence on NDVI trends, with the exception of elevation, where trends were more positive below 350 m a.s.l. than above that point in the ecotone and tundra. These results indicate that influences on NDVI trends differ across the study area, but that the strongest positive NDVI trends were associated with the increasing productivity of shrubby environments within and north of the forest-tundra ecotone in areas with more favorable growing conditions.

4.2 Limitations and Uncertainty

When selecting Landsat scenes to be used for time-series analysis, there was some uncertainty associated with the temporal distribution of data. Cloud-cover across the study area, and smoke from fires farther south, was a notable issue that limited scene selection. In addition, only ETM+ scenes from 1999 to 2002 were considered useable because of the scan line corrector (SLC) failure in May 2003. Access to a smaller selection of useable scenes meant that it was more difficult to maintain a consistent acquisition time (i.e., similar day of year and gap in years).

However, efforts were made to be as consistent as possible and all scenes selected were within a one-month period of each other during the peak growing season (July 11 – August 11). In addition, gaps between acquisition years were kept as consistent as possible, with no gap being larger than seven years and the majority of gaps being smaller than four years. Relationships between Julian day and year, as well as between Julian day and NDVI of a random selection of pixels, were mostly not significant ($p > 0.05$) across the study area. Uncertainty related to the slight variation in NDVI derived from different Landsat sensors (TM, ETM+, OLI) was also addressed and corrected (Ju & Masek, 2016; Roy et al., 2016).

There were some limitations encountered when assembling the environmental variable datasets needed for RF modelling because of the paucity of useful data. The study area is a remote region of northern Canada where high quality data across the entire extent was often not available. For example, useful data on surficial geology was not available and thus could not be included in the analysis. It would also have been interesting to study the influences of variables such as snow-pack depth or permafrost degradation, but the lack of data meant these could not be directly examined. It is possible that these variables are indirectly related to variables that were tested, such as deeper snow-pack depth with denser shrub land cover (Sturm et al., 2005a).

The fine-scale topographical variables (i.e., slope, aspect, TPI, TWI) that were found to be less important than the more broad-scale variables were all at least partly based on the Canada Digital Elevation Model (DEM). This DEM, which was the highest quality dataset that covered the extent of the study area, was built from 10 m contour intervals extrapolated to 1 m elevations. This meant that small changes in these topographical variables were not as well represented, and a “terracing” effect was evident in flat areas. Terracing was mitigated by smoothing the datasets, but it did not have a noticeable effect on the overall results. It is thus possible that the nature of the DEM may have played a role in these variables being less influential in RF results. However, other variables may have been more suitable surrogates for terrain variability. For example,

terrain variability (e.g., low rolling hills, eskers, rocky outcrops) in the study area was often accompanied by different land-cover types. Higher quality datasets would have helped with this uncertainty if available, but these issues are expected when working across large, remote regions.

4.3 Future Opportunities

Studies based on remote sensing benefit from field work, which allows for the validation of those results on the ground. Bulk vegetation volume (BVV), a non-destructive and relatively non-intensive measurement, has been shown to relate strongly with NDVI in tundra areas (Chen et al., 2009; Gregory, 2011). My study has indicated that it is also possible to achieve accurate results in low density forested areas due to the low impact of these trees on the NDVI signal. With an updated methodology for forested sites, it should be possible to relate BVV with NDVI without disregarding trees. I suggest that future work in this area could allow for the more accurate measurement of forest BVV by accounting for the lower LAI and shading effect of trees at high latitude sites.

RF modelling has shown to be a useful tool for understanding the intricacies of the relationship between NDVI trends and environmental variables across a variety of landscape-environmental conditions. This study should serve as a guide for future work and allow for researchers to focus on vegetation change in the context of some of these important environmental variables. In particular, the influence of waterbodies (i.e., drainage systems and major lakes) on vegetation changes in the northern high latitudes deserves more study. RF modelling itself is also useful in that it accounts for the overlapping influence of variables that would be overlooked when individual variables are considered separately. These machine learning techniques thus allow for the important marginal relationships to be drawn out from large and complex datasets. Thus, there is an opportunity to build on these results by using machine learning in a smaller study area where higher quality datasets are available for more variables. This would allow for uncertainty related to data selection to be reduced.

4.4 Conclusions

Climate has been warming across the planet in recent decades (IPCC, 2013). Warming has been especially strong at northern high latitudes because of Arctic amplification (Serreze & Barry, 2011). This has led to changes in vegetation productivity across northern tundra and boreal forest ecosystems (Sturm et al., 2001b; Beck & Goetz, 2012; Guay et al., 2014; Ju & Masek, 2016 etc.). Shrub expansion has been observed across northern high latitudes, while treeline advance has been mixed (Harsch et al., 2009; Myers-Smith et al., 2011). The browning of continental boreal forest ecosystems has been observed in some locations (Barber et al., 2000; Verbyla, 2008). The landscape-level influences on these vegetation changes, and how they vary across the sub-Arctic boreal forest to Low Arctic tundra transition has not been fully explored.

By delineating the forest to tundra transition of central Canada into separate zones and considering the influence of different environmental variables on NDVI trends across those zones, this study was able to identify and analyze the intricacies of vegetation change on a landscape to regional scale in a way not seen elsewhere. It is clear that vegetation in sub-Arctic boreal forests, forest-tundra ecotone areas and Low Arctic tundra ecosystems have responded differently to environmental pressures. Many past studies have observed vegetation changes occurring in boreal forest, forest-tundra or tundra regions, but they are not often considered together in a way to allow for a direct comparison. Here, RF modelling also allowed for the relative importance of many variables to be compared across the zones, highlighting those deserving further study. The influence of these variables on NDVI trends was again dependent on position within the forest to tundra transition, further indicating the complexity of vegetation changes in these regions. This study thus has provided a comprehensive understanding of vegetation changes ongoing across the forest to tundra transition of central Canada; including analysis of the geographic distribution and ground validation of trends, as well as an exploration of environmental variables that most influence the location and magnitude of trends.

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Appendix A

Field Expedition Preparation and Methodology

Field Expedition Preparation

The original plan was to begin at the Daring Lake Tundra Ecosystem Research Station and canoe to Wekweètì (Figure A.1). This would allow for logistical support from both ends of the field expedition and would cross almost all of the tree:tundra cover ratio lines. Research into this potential route indicated that it would not be feasible, however. The main issues were that this route was long (190 km) and would require the expedition to cross the boundary between the Coppermine River and Mackenzie River watersheds. This would lead to many kilometers of overland travel with heavy gear. This route has also not been extensively explored, making preparation more difficult and leading to more unknowns. It was deemed that this route would be too arduous and time consuming for this project.

Figure A.1: Field study area and proposed routes. Daring Lake to Wekweètì was eventually phased out.

The route from Big Lake to Wekweètì, which is shorter (131 km) and has been extensively traveled, was determined to be the best possible field expedition to conduct our research in the North Slave region of NWT. This route follows the same path as Sir John Franklin's expedition of 1819 to 1822 that aimed to explore Canada's northern coastline and map a potential northwest passage between the Atlantic and Pacific Oceans (Houston, 1994). The Geological Survey of Canada (GSC) conducted an expedition along this route in 1932, providing useful photographs (Figure A.2) and other information (Geological Survey of Canada, 1932; Wray, 1980). Contemporary details about the route, including potential camp sites, rapids, portage and canoe lines, flora, fauna and climate details, were collected from books (Losey, 1973; McCreadie, 1995; Thomas, 2003; Pitt, 2014). Hundreds of photographs and first-hand details on the route were provided by people who had canoed the route in the past. These travelers also provided maps of the locations of campsites, rapids, routes and portages, which were digitized in ArcGIS. The Tłıchǵ community government of Wekweètì confirmed the feasibility and permitted the field expedition on their land after discussions with them.

Figure A.2: Photographs from 1932 GSC expedition. (a) Creek flowing out of Big Lake. (b) Dogrib Rock in the distance (between Little Marten Lake and Winter Lake). (c) Remains of Fort Enterprise (camp from Franklin expedition). Photographs from Wray, 1980.

Methodology: Additional Details

Once a potential sampling area was deemed suitable (i.e., homogenous area; Figure D.3) for setting up a sample plot then general characteristics were collected. Plot number, class (ISODATA land-cover classification) and a brief visual description (vegetation characteristics) of the sample plot were recorded (Table A.1; Table A.2). The slope and aspect of the location was noted, with most plots being level or gently sloping. The percentage of the plot covered by vegetation, moisture regime, distance to nearest waterbody and any signs of fauna or fire disturbance were also noted. At least two full plot photographs were taken at each sample plot from locations that provided the best view. A ~10 cm soil profile was collected and photographed at each plot. Soil color, texture and other notable characteristics were recorded.

Sample plots were set up by placing a flag at the southwest corner and using a compass to orient plots north-south as best as possible. The north and south boundary of the plot were marked with flags at 5 m intervals. A 30 m tape measure was rolled out between each set of flags and vegetation height was measured at 5 m intervals (i.e., 0, 5, 10, 15, 20, 25, 30 m on tape measure). 49 points were thus sampled per plot. GPS coordinates were collected at the four corner points of the sample plot with a Trimble GPS unit. Elevation and GPS coordinates were also collected at the center point of the sample plot. Top-down photographs from breast height were taken of corner points and the plot center.

Vegetation heights of different functional groups were measured at each of the 49 points in all sample plots. Functional groups were set as trees, erect shrubs, dwarf shrubs, horsetail (*Equisetum*), graminoids, moss, lichen and non-vegetated surfaces (i.e., rock, soil, gravel, water). Trees were sampled at the species level with black spruce (*Picea mariana*), white spruce (*Picea glauca*) and paper birch (*Betula papyrifera*) recorded. Erect shrubs were sampled at the species level with American dwarf birch (*Betula glandulosa*), willow (*Salix* spp.), green alder (*Alnus viridis*) and dwarf birch (*Betula nana*) recorded. Dwarf shrubs were also sampled at the species level with blueberry (*Vaccinium* Spp.), black crowberry (*Empetrum nigrum*), red bearberry

(*Arctostaphylos rubra*), northern Labrador tea (*Rhododendron tomentosum*), cloudberry (*Rubus chamaemorus*), bog rosemary (*Andromeda polifolia*), cranberry (*Vaccinium vitis-idaea*) and kinnikinnick (*Arctostaphylos uva-ursi*) recorded. All other functional groups were recorded by their functional group name.

Heights were measured for the tallest individuals in each functional group at each point. This means that multiple heights could be measured at each point if different functional groups were present. Heights were most often measured with a tape measure, with the distance between the ground and the tallest part of the individual that intersected the sample point being the recorded measurement. Taller individuals (i.e., trees) were measured with a Vertex IV (Haglöf Sweden). These measurements were completed by attaching a transponder at 1.3 m height to the tree in question, pointing the Vertex IV at the transponder from at least 5 m away and then pointing the Vertex IV at the desired height.

Vegetation heights were measured at the exact point where the 5 m interval was reached on the 30 m tape measure (Figure A.4). If the tallest individual in a functional group was located within a 5 cm radius of the point then its height was measured. The red triangles on the tape measure were used to gauge this distance and decide if an individual should be measured or not. If an individual was too tall to be viewed from above in relation to the tape measure then I would get below the tape measure and look up to judge if the individual was within the 5 cm radius. Heights of the individual plant were measured where it overlapped with the 5 m interval (i.e., if there was a 1 m tall shrub but it was only 50 cm high at the measurement point, then the height would be recorded as 50 cm).

Figure A.3: Field maps from Big Lake to Wekweèti showing potential sampling areas. These maps were brought into the field (as well as input onto a Trimble GPS unit) to locate plots that were easiest to access and sample across a range of land-cover types. Points and colored lines indicate routes and campsites of past travelers

Table A.1: Sample plot ISODATA class, vegetation descriptions and UTM coordinates. Ledum = northern Labrador tea, cran = cranberry, crow = crowberry, blue = blueberry.

Name	Class	Vegetation Description	UTM E	UTM N
BL01	Herb Barrens	Low birch shrubs, lichen understory, lichen covered boulders	401492	7191982
BL02	Herb Barrens	Low birch shrubs, lichen/cranberry/ledum understory, lichen boulders	399685	7192743
BL03	Graminoid Tundra	Lichen-graminoid tundra, hummocky, a lot of graminoids/cloudberry/ledum/cran	405243	7191123
BL04	Graminoid Tundra	Lichen-graminoid tundra, hummocky, some low birch shrubs + dwarf shrubs	403438	7190637
BL05	Dense Low Shrubs	Mostly dense low shrub, berry understory	402887	7190163
BL06	Low Shrubs	Open low birch/willow shrubs, grassy understory, exposed dirt, some berries	403024	7189615
SC01	Peatland	Dense low shrub, a few mossy wet areas, graminoids	406170	7185728
SC02	Low Shrub	Open low shrub, lichen understory, dwarf shrub berries	406221	7185595
LM01	Dense Tall Shrubs	Dense tall shrubs, scattered spruce trees	404804	7172059
LM02	Peatland	Open low birch/willow shrub tundra, lichen/berry understory	404723	7171918
LM03	Dense Low Shrubs	Dense-open Alder shrubs with graminoid understory, some birch, tall blueberries	405839	7171470
LM04	Wetland Fen	Low shrubs, moss, grasses, hummocky with evidence of water in depressions but now dry	405229	7172536
LM05	Low Shrubs	Open canopy birch, hummocky, scatted lichen/crow/blue understory, gravel areas, rocky	405590	7171934
LMS01	Graminoid Tundra	Open low birch canopy, ledum/lichen understory, some blue/bear berry, rocks	398781	7166833
LMS02	Peatland	Low alder shrubland, hummocky understory	399105	7167025
LMS03	Dense Tall Shrubs	Dense ~1m canopy of alder/birch, ledum understory + blue berries	398788	7167452
LMS04	Dense Low Shrubs	Dense alder shrubland + birch, ledum/cran mix understory, some rocks	399086	7165649
LMS05	Dense Tall Shrubs	Dense 1m tall shrubs broken by game trails, tall ledum/grassy/blue berry understory	399757	7166249
LF01	Less Dense Boreal	Short/medium height black spruce, low-mixed shrub understory, tall ledums with moss/horsetail	402927	7159478
LF02	Dense Woodland	Black spruce dominated forest, seedlings, tall ledums, horsetail, grasses	402637	7159449
LF03	Open Woodland	Open stands of black spruce separated by boulder gardens/lichen dominated areas, blueberries	401901	7159927
LF04	Less Dense Boreal	Pretty dense canopy black spruce, dense understory of shrubs, wetlands, grasses, ledum, horsetail, dead trees, depressions	402431	7160192
LF05	Erect Dwarf Shrubs	Boulder strewn tundra with scatted birch shrubs, lichen/crow/cran understory	405140	7159338

LF06	Dense Low Shrubs	Alder/birch shrubland on edge of ridge, some rocks, small spruce trees in area	404448	7160450
WL01	Wetland Fen	Previously wet grassy/shrubby area bordering lichen-woodland	401465	7149588
WL02	Open Woodland	Open black spruce stands, lichen/grassy understory, wet , ledums	401207	7149709
WL03	Dense Woodland	Open-Dense black spruce, open shrub understory, ledums, some previously wet/mossy soil covered areas (but dry now)	400881	7150512
WL04	Less Dense Boreal	Open canopy thin black spruce, with mossy/blue/ledum understory, alder and birch shrubs, wet	400911	7150863
WL05	Peatland	Hummocky, open low shrub terrain, a few boulders, blueberry, grasses, ledum	402646	7150974
RR01	Open Woodland	Open canopy tall/thin black spruce, lichen dominated understory with a few shrubs/ledum/blueberry	389074	7148451
RR02	Rocky Woodland	Graminoid dominated wetland with a lot of open water, moss below grasses, a few birch shrubs here and there	390282	7148086
SL01	Dense Woodland	Dense canopy short/thin black spruce, wet areas, stream near, tall ledums, lichen	361960	7130991
SL02	Dense Boreal	Pretty dense canopy of medium/tall black spruce, shrubby understory, lichen patches	358574	7130862
SL03	Wetland Fen	Lichen-woodland: low density tall white spruce/paper birch, lichen dominated understory with some cran/crow/blue/kinnikinnick	362720	7131889

Table A.2: Additional sample plot details. Elevation in meters above sea level. Distance to water in meters.

Name	Elev	Slope-Aspect	PVC Estimate	Moisture	Distance to Water	Fauna	Fire	Soil
BL01	420	Gentle south facing	35% birch shrubs	Dry	180	Game trails	N/A	10 cm organic layer, silty-sand
BL02	415	Level	Open canopy birch	Dry	200	Game trails	N/A	6 cm organic layer, silty-sand
BL03	410	Level	5% shrubs, a few rocks	Mesic	75	N/A	N/A	8 cm organic layer, sandy-silt, cold (shallow permafrost), decomposing lichen
BL04	402	Level	15% shrubs	Mesic	50	N/A	N/A	Cold soil, sandy-silt, thawing
BL05	416	Gentle north facing	65% shrubs	Dry	200	N/A	N/A	N/A
BL06	415	Level	25% shrubs	Dry	300	Game trails	N/A	N/A
SC01	400	Level	75% shrubs	Dry-Mesic	250	Game trails	N/A	N/A
SC02	391	Level	25% shrubs	Dry	150	Game trails	N/A	3 cm organic layer, sandy-silt

LM01	385	Level	5-10% spruce, 95% shrubs	Mesic- Wet	200	Game trails	N/A	5 cm organic layer, sandy-silt, cold
LM02	390	Level	35% shrubs	Dry	250	Game trails	N/A	5 cm organic layer, sandy-silt, cold
LM03	386	Gentle south facing	45% shrubs	Mesic	100	N/A	N/A	3 cm organic layer, silty-sand, not cold
LM04	381	Level	25% shrubs	Dry/Wet	25	Game trails	N/A	All organic soil, moist, peaty deep, top = muddy, fossilized moss
LM05	398	Gentle south facing	20% shrubs	Dry	400	Game trails	N/A	Little organic layer, sandy soil
LMS01	434	Gentle south facing	25% shrubs	Dry	400	Game trails	N/A	6 cm organic layer, sandy-silt, slightly cold to touch
LMS02	403	Gentle north facing	35% shrubs	Dry	300	Game trails	N/A	9 cm organic layer, muddy, cold to touch
LMS03	401	Gentle north facing	75% shrubs	Dry	600	Game trails	N/A	3 cm organic layer, sandy-silt, cold
LMS04	404	Ridge (gentle north/south facing)	65% shrubs	Dry	300	Game trails	N/A	2 cm organic layer, sandy-silt, cool
LMS05	380	Level	75%+ shrubs	Dry- Mesic	100	Many game trails	N/A	6 cm organic layer, sandy-silt, mutli-layer, cold
LF01	362	Level	50% spruce, 25% shrubs	Mesic	150	Game trails	N/A	Small organic layer, sticky clay- silt, cold, a bit wet
LF02	358	Level	65% spruce, 25% shrubs	Mesic	200	Game trails	Gray/charred soil layer	9 cm organic layer, fine clay/silt, cold, gray (potential fire evidence), hard to break apart
LF03	369	Level	25% spruce, 10% shrubs	Dry/Wet	200	Game trails	Grayish soil	5 cm organic layer, rocky (hard to core), cold, damp, brown -> black -> grayish, sandy/clay (silty/soft at the top)
LF04	357	Level	65% spruce, 35% shrubs	Wet	100	Game trails	N/A	4 cm organic layer, clayish layer, deep gray-brown layer, cold
LF05	387	Level	20% shrub, 40% rock	Dry	200	N/A	N/A	5 cm organic layer, rocky (hard to core), sandy-silt, lighter grayish layer below

LF06	405	Gentle east facing (coming off ridge to west)	40% shrub	Dry	100	N/A	Gray/black charred soil	12 cm organic layer, silty-sand, deeper black -> gray/brown layers 14 cm down (old fire)
WL01	355	Level/Gentle NE facing	10% spruce, 35% shrubs	Wet	300	Game trails	N/A	4 cm peaty organic layer, deep gray layer, big middle brown layer, sandy-silt
WL02	354	Level	35% spruce, 25% shrubs	Wet- Mesic	400	Game trails	N/A	Small organic layer, silty-tan color soil, moist
WL03	356	Level	40 % spruce, 30 % shrubs	Dry/Wet	400	Game trails	N/A	Small organic layer (1-2 cm), Brown -> tan -> gray (big layer) -> tan -> gray, cool, silty-sand
WL04	347	Gentle north facing (into Winter Lake)	40% spruce, 25% shrubs	Wet	150	Game trails, birds	N/A	7 cm organic layer, wet/mucky soil, air holes
WL05	358	Level	25% shrubs	Dry	300	N/A	N/A	7 cm organic layer, peaty, rich soil, dark brown/black -> lighter below, silty -> sandy at bottom
RR01	390	Gentle south facing	25% spruce, 10% shrubs	Dry	300	Game trails	N/A	7 cm organic layer (light/fluffy), buried wood 8cm (root), deep mineral soil is yellow (sandy)
RR02	373	Level	5% shrubs	Very Wet	0	N/A	N/A	Mucky soil, floating matts (trampoline), too airy/mucky for good core
SL01	339	Level	35% spruce, 10% shrubs	Mesic	75	Game trails	charred stumps, soil	6 cm organic layer, below is firm sandy-silt soil, tan shades, charred wood 3-4 cm down (small more recent fire)
SL02	390	Gentle north facing	50% spruce, 30% shrub	Dry	1500	Game trails	charred stumps, soil	5 cm organic layer, sandy deep yellow layer, silty/peaty above, fire evidence just below organic layer (humus)
SL03	350	Level	15% treed	Dry	350	Game trails	charred stumps, soil	4 cm organic layer, coarse grained sand, black -> gray -> tan -> orange, roots (not much fire signs)

Table A.3: Points of interest where photographs were taken and details noted.

Name	Description	Class	UTM E	UTM N
BLS_Esker	Esker south of Big Lake	Bear Soil	404433	7185317
LMN_Boulder1	Boulder garden on "river" north of Little Marten Lake	Rocky/Bedrock	408620	7182241
LMN_Boulder2	Boulder garden on "river" north of Little Marten Lake	Rocky-Bedrock	408506	7182068
LMS_Boulder	Boulder garden at Little Marten South	Rocky-Bedrock	398966	7168069
WL_Lichen	Lichen Woodland on Winter Lake	Wetland	401545	714630
RR_Burn	Recent (~10 years) burn scar off south short of Roundrock Lake	Rocky/Bedrock	385246	7141191
Wek_Road	Gravel intersection in front of Admin building in Wekweètì	Bare Soil	345416	7122116
Wek_Airport	Gravel airport east of Wekweètì	Bare Soil	350597	7122134

Figure A.4: The highest point for each functional group that was present within a 5 cm radius of the sample point (black circle) was recorded.

Appendix B

Information on Selected Landsat Data

Table B.1: Selected Landsat scenes. 2011 pass used for PIFs and land-cover classifications in bold.

Path-Row	ID	Date	Satellite	Quality
47-13	194LGN00	7/13/2014	L8 OLI-TIRS	7
47-13	218GLC01	8/6/2011	L4-5 TM	9
47-13	217PAC00	8/5/2005	L4-5 TM	6
47-13	201EDC00	7/20/2002	L7 ETM+ SLC-on	9
47-13	212PAC01	7/30/2000	L7 ETM+ SLC-on	10
47-13	198PAC00	7/17/1998	L4-5 TM	10
47-13	222XXX00	8/10/1995	L4-5 TM	8
47-13	195PAC00	7/14/1991	L4-5 TM	10
47-13	203PAC00	7/21/1988	L4-5 TM	6
47-13	197PAC00	7/16/1986	L4-5 TM	6
47-14	194LGN00	7/13/2014	L8 OLI-TIRS	8
47-14	223LGN00	8/11/2013	L8 OLI-TIRS	9
47-14	218GLC01	8/6/2011	L4-5 TM	10
47-14	220PAC01	8/8/2006	L4-5 TM	7
47-14	201EDC00	7/20/2002	L7 ETM+ SLC-on	10
47-14	209PAC00	7/27/1996	L4-5 TM	9
47-14	195PAC00	7/14/1991	L4-5 TM	9
47-14	221PAC00	8/9/1989	L4-5 TM	8
47-14	197PAC00	7/16/1986	L4-5 TM	7
47-14	208PAC00	7/26/1984	L4-5 TM	6
47-15	216LGN00	8/3/2016	L8 OLI-TIRS	5
47-15	223LGN00	8/11/2013	L8 OLI-TIRS	10
47-15	218GLC01	8/6/2011	L4-5 TM	10
47-15	220PAC02	8/8/2006	L4-5 TM	8
47-15	201EDC00	7/20/2002	L7 ETM+ SLC-on	9
47-15	209PAC00	7/27/1996	L4-5 TM	8
47-15	214PAC00	8/1/1992	L4-5 TM	9
47-15	195PAC00	7/14/1991	L4-5 TM	8
47-15	192PAC00	7/11/1990	L4-5 TM	10
47-15	208PAC00	7/26/1984	L4-5 TM	7
47-16	223LGN00	8/11/2013	L8 OLI-TIRS	9
47-16	218GLC02	8/6/2011	L4-5 TM	10
47-16	215PAC01	8/2/2004	L4-5 TM	10
47-16	206LGS01	7/25/2001	L4-5 TM	7
47-16	214PAC00	8/2/1998	L4-5 TM	9
47-16	211PAC00	7/30/1997	L4-5 TM	9
47-16	214PAC00	8/1/1992	L4-5 TM	8
47-16	192PAC00	7/11/1990	L4-5 TM	9
47-16	221PAC00	8/9/1989	L4-5 TM	7
47-16	208PAC00	7/26/1984	L4-5 TM	7

Figure B.1: Example cloud mask. (a) Top-of-atmosphere Landsat TM scene from July 27th, 1996, frame 47-15. (b) Cloud mask for that same scene (black = cloud covered).

Figure B.2: Cloud cover sum rasters (Black = 10/10 cloud covered, white = 0/10 cloud covered). (a) Frame 47-13 (furthest north). (b) Frame 47-14. (c) Frame 47-15. (d) Frame 47-16 (furthest south).

Appendix C

Pseudo-Invariant Feature Normalization

Selected scenes were supplied from GloVis with pixel values as digital numbers (DN); 8-bit (0-255) for Landsat 4-5 and 7 and 16-bit (0-65,535) for Landsat 8. These values needed to be calibrated in order to be useful for remote sensing analysis. Scenes were then converted from DN to top-of-atmosphere (TOA) reflectance in ENVI.

$$\rho_{\lambda} = \frac{\pi L_{\lambda} d^2}{ESUN_{\lambda} \sin \theta}$$

TOA reflectance represents the reflectance measured by Landsat above the Earth's atmosphere without correction for atmospheric effects. Information needed to complete this calculation is available in the metadata for each Landsat scene. L_{λ} is radiance ($W/(m^2 * sr * \mu m)$), d is Earth-sun distance in astronomical units, $ESUN_{\lambda}$ is solar irradiance ($W/(m^2 * \mu m)$) and θ is sun elevation in degrees. L_{λ} is computed from scene metadata ($gain * DN + offset$). The output TOA reflectance value for each band ranges between 0 and 1. Once scenes were converted to TOA reflectance, PIF normalization was then applied.

This relative atmospheric correction method aimed to use pixels in the study area that are not expected to change in value over time (i.e., are pseudo-invariant). These features included deep non-turbid waterbodies, bedrock, eskers and anthropogenic features (i.e., mines, roads, buildings). In addition to having spectral characteristics that change little through time, PIFs should also be at similar elevations, be in relatively flat areas and contain minimal vegetation (Jensen, 2016). The base layer to which all other scenes would be normalized to using PIFs was from a mostly cloud free pass through all four frames taken on August 6th, 2011.

PIFs were chosen manually in each of the four frames. 25 PIFs were chosen per frame, meaning that 100 PIFs were chosen over the study area (Table C.1). PIFs were only selected in areas that were cloud free in all 10 scenes using the cloud cover sum rasters. About half of the

PIFs in each frame were chosen from the middle of larger lakes that were not ice covered in any of the scenes in the stack. The other half of the PIFs were usually chosen from rocky areas, sandy beaches and large eskers. In order to ensure that only areas with minimal vegetation were selected on land, a raster layer consisting of NDVI values between 0 and 0.2 from the 2011 base layer was used and PIFs were only chosen if they overlapped with that raster. Pixels that were not directly on the coast (to avoid influence of changing waterbody size) and close to other low NDVI values were prioritized for PIF selection. High resolution satellite imagery available in Google Earth was referenced where available to confirm quality PIF selection.

Once PIFs were chosen, regression analysis was conducted to compare R (0.63 – 0.69 μm) values of the 2011 base layer PIFs with PIF R values for each image in a frame (Figure C.1). This was completed for NIR (0.76 – 0.90 μm) values as well. These regressions are used to relate the base layer PIFs spectral characteristics with the spectral characteristics of the same pixels from the other scenes in a frame (Jensen, 2016). 18 regressions (nine R and nine NIR) were calculated for each frame, meaning 72 total regressions were created. R^2 values calculated for each regression and were above 0.95 in every case.

Regression equations (i.e., R year X vs. R 2011 and NIR year X vs. NIR 2011) were brought into ENVI and band math was used to create new normalized data for the R and NIR bands of each scene in each frame. This normalization procedure was tested by checking non-vegetated features throughout the image in order to ensure that there was no trend in the results (i.e., pixel values do not change much over time). These PIF normalized R and NIR bands were then converted to NDVI scenes $((\text{NIR} - \text{R})/(\text{NIR} + \text{R}))$ and cloud masks were applied. See results in Figure C.2. Overall PIF NDVI trends were slightly less positive than surface reflectance trends, but still with more greening than browning across the study area. Surface reflectance NDVI trends were analyzed instead of PIF trends since it allowed a more direct comparison with other surface reflectance studies and because PIF trends were less consistent between Landsat frames.

Table C.1: Selected PIFs, their associated cover type and coordinates. Each PIF is a Landsat pixel selected in an area with minimal vegetation.

Frame	Cover Type	Lat-Long
47-13	Bedrock cliff	67°45'23.96"N,111°49'34.70"W
47-13	Middle of lake	67°40'31.86"N,112°4'14.05"W
47-13	Middle of lake	67°25'35.01"N,110°42'42.98"W
47-13	Middle of lake	67°26'44.72"N,110°42'7.04"W
47-13	Middle of lake	67°38'1.42"N,111°12'19.29"W
47-13	Middle of lake	67°37'46.47"N,111°45'42.78"W
47-13	Bedrock cliff	67°42'15.67"N,112°1'22.95"W
47-13	Bedrock cliff	67°44'52.25"N,112°0'5.40"W
47-13	Bedrock	67°38'57.98"N,112°3'1.90"W
47-13	Bedrock	67°39'55.00"N,111°59'27.13"W
47-13	Bedrock	67°41'25.83"N,111°54'18.50"W
47-13	Bare soil	66°57'31.28"N,111°23'45.84"W
47-13	Middle of lake	67°11'4.33"N,110°33'52.09"W
47-13	Rocky area	67°38'35.81"N,111°56'8.35"W
47-13	Bedrock	67°36'44.88"N,112°3'2.37"W
47-13	Bedrock cliff	67°43'14.82"N,112°12'57.24"W
47-13	Bedrock	67°38'22.56"N,111°13'27.93"W
47-13	Bedrock	67°41'57.50"N,111°14'59.08"W
47-13	Bedrock	67°24'32.88"N,110°42'33.34"W
47-13	Bedrock	67°34'34.78"N,112°10'3.37"W
47-13	Bedrock	67°37'42.43"N,111°46'26.23"W
47-13	Bedrock	67°40'44.23"N,111°6'41.60"W
47-13	Bedrock	67°40'44.34"N,111°18'14.94"W
47-13	Bedrock	67°37'49.26"N,111°17'16.35"W
47-13	Bedrock	67°40'18.98"N,111°55'1.61"W
47-14	Middle of lake	65°53'28.64"N,111°59'34.58"W
47-14	Esker	65°20'35.68"N,113°41'18.27"W
47-14	Rocky area	65°18'40.74"N,113°31'36.14"W
47-14	Middle of lake	65°40'19.96"N,112°18'25.13"W
47-14	Rocky area	65°7'14.92"N,113°26'59.09"W
47-14	Middle of lake	65°44'37.90"N,112°33'29.44"W
47-14	Middle of lake	65°46'38.49"N,112°9'24.81"W
47-14	Esker	65°46'13.47"N,112°24'30.01"W
47-14	Esker	65°46'59.99"N,112°34'1.46"W
47-14	Esker	65°47'48.11"N,112°43'52.50"W
47-14	Esker	65°47'38.11"N,112°38'37.32"W
47-14	Esker	65°49'58.29"N,112°26'10.26"W
47-14	Rocky area	65°49'59.90"N,112°15'55.39"W
47-14	Rocky area	65°49'54.97"N,112°10'26.27"W
47-14	Esker	65°44'59.53"N,112°17'44.96"W
47-14	Rocky area	65°43'48.15"N,112°13'10.77"W
47-14	Rocky area	65°44'43.53"N,111°58'49.21"W
47-14	Rocky area	65°43'46.81"N,111°46'34.03"W
47-14	Esker	65°44'55.14"N,111°44'52.66"W
47-14	Rocky area	65°46'53.26"N,111°52'0.43"W
47-14	Esker	65°42'18.65"N,112°0'38.29"W
47-14	Esker	65°38'38.90"N,112°10'28.19"W
47-14	Rocky area	65°53'30.63"N,112°29'40.90"W
47-14	Rocky area	65°51'50.69"N,112°33'3.34"W

47-14	Esker	65°31'41.60"N,113°3'27.31"W
47-15	Middle of lake	64°6'27.87"N,115°5'57.79"W
47-15	Middle of lake	64°12'29.16"N,115°15'4.43"W
47-15	Middle of lake	64°19'33.54"N,114°14'20.52"W
47-15	Middle of lake	64°3'55.00"N,115°7'4.58"W
47-15	Middle of lake	63°59'24.24"N,115°1'32.44"W
47-15	Middle of lake	64°25'33.61"N,114°11'46.39"W
47-15	Esker	64°4'57.86"N,114°32'58.00"W
47-15	Middle of lake	64°1'16.59"N,114°38'45.82"W
47-15	Rocky area	64°0'49.60"N,114°26'50.63"W
47-15	Middle of lake	64°14'47.66"N,115°16'23.90"W
47-15	Rocky area	64°2'10.38"N,114°36'33.56"W
47-15	Rocky area	64°26'10.22"N,113°45'7.08"W
47-15	Rocky area	64°13'13.93"N,115°16'9.21"W
47-15	Rocky area	64°8'39.82"N,115°18'33.88"W
47-15	Middle of lake	64°4'22.41"N,114°53'4.97"W
47-15	Middle of lake	64°26'45.84"N,113°47'2.85"W
47-15	Middle of lake	64°30'12.59"N,114°20'41.37"W
47-15	Rock garden	64°21'13.01"N,114°11'4.29"W
47-15	Rocky area	64°27'24.43"N,114°14'56.43"W
47-15	Rocky area	64°2'20.58"N,114°50'42.76"W
47-15	Rocky area	64°8'33.11"N,115°6'3.85"W
47-15	Rocky area	64°9'6.46"N,115°3'39.78"W
47-15	Middle of lake	64°6'59.98"N,115°5'5.16"W
47-15	Rocky area	64°9'18.05"N,115°7'10.46"W
47-15	Rocky area	64°20'29.88"N,113°37'5.28"W
47-16	Middle of lake	62°21'46.92"N,114°22'4.47"W
47-16	Bedrock	62°42'50.84"N,115°25'20.86"W
47-16	Bedrock	62°41'17.22"N,115°21'50.32"W
47-16	Bedrock	62°39'57.48"N,115°31'34.75"W
47-16	Bedrock	62°40'40.06"N,115°41'12.90"W
47-16	Bedrock	62°35'15.36"N,115°36'36.72"W
47-16	Sandy area	62°28'46.69"N,115°18'11.49"W
47-16	Bedrock	62°32'15.95"N,115°13'25.30"W
47-16	Bedrock	62°23'23.07"N,115°47'13.99"W
47-16	Middle of lake	62°33'4.86"N,113°48'57.07"W
47-16	Bedrock	62°46'12.01"N,114°46'31.12"W
47-16	Bedrock	62°34'47.27"N,113°41'10.42"W
47-16	Bedrock	62°42'44.59"N,113°53'9.16"W
47-16	Bedrock	63°5'25.35"N,113°54'17.59"W
47-16	Middle of lake	62°42'28.09"N,114°5'27.63"W
47-16	Middle of lake	62°14'24.64"N,114°51'10.32"W
47-16	Middle of lake	62°14'37.53"N,115°4'21.74"W
47-16	Bedrock	63°21'32.52"N,115°58'27.90"W
47-16	Bedrock	63°17'41.11"N,115°56'54.46"W
47-16	Bedrock	63°22'7.95"N,115°45'35.30"W
47-16	Bedrock	63°22'18.21"N,115°34'18.73"W
47-16	Bedrock	63°34'30.62"N,115°22'47.38"W
47-16	Bedrock	63°39'4.44"N,115°12'36.46"W
47-16	Bedrock	63°21'21.50"N,115°10'37.24"W
47-16	Bedrock	63°27'21.73"N,115°5'30.10"W

Figure C.1: Example linear regressions (R and NIR) between the 2011 base layer and July 30th, 1997, scene from frame 47-16, based on selected PIFs. Regression equations were used to create PIF normalized NDVI scenes.

Figure C.2: Landsat PIF NDVI trends (1984-2016) from the study area as determined using ordinary least squares regression. NDVI trends were binned into 10 levels (-5 = most negative, 5 = most positive), as seen in the legend, for visualization purposes. (a) All NDVI trends. (b) Significant ($p < 0.05$) greening and browning trends. Note consistency issues between Landsat frames (i.e., where trends drastically change in a line).

Appendix D

NDVI Trend Code

'R' Code used to create NDVI trend and significance rasters from NDVI data. Example here is from Landsat frame 47-15.

```
#load raster, sp and rgdal packages
library(raster)
library(sp)
library(rgdal)

#set working directory
setwd("F:/Selected Landsat Images/4715")

#load 1984 raster and check attributes
NDVI1984 <- raster("1984/NDVI_1984_LC0.tif")
NDVI1984

#load 1990 raster and check attributes
NDVI1990 <- raster("1990/NDVI_1990_LC0.tif")
NDVI1990

#load 1991 raster and check attributes
NDVI1991 <- raster("1991/NDVI_1991_LC0.tif")
NDVI1991

#load 1992 raster and check attributes
NDVI1992 <- raster("1992/NDVI_1992_LC0.tif")
NDVI1992

#load 1996 raster and check attributes
NDVI1996 <- raster("1996/NDVI_1996_LC0.tif")
NDVI1996

#load 2002 raster and check attributes
NDVI2002 <- raster("2002 Corrected/C_NDVI_2002.tif")
NDVI2002

#load 2006 raster and check attributes
NDVI2006 <- raster("2006/NDVI_2006_LC0.tif")
NDVI2006

#load 2011 raster and check attributes
NDVI2011 <- raster("2011/NDVI_2011_LC0.tif")
NDVI2011

#load 2013 raster and check attributes
NDVI2013 <- raster("2013 Corrected/C_NDVI_2013_1.tif")
NDVI2013
```

```

#load 2016 raster and check attributes
NDVI2016 <- raster("2016 Corrected/C_NDVI_2016_1.tif")
NDVI2016

#change 0 value to NA
NAvalue(NDVI1984) <- 0
NAvalue(NDVI1990) <- 0
NAvalue(NDVI1991) <- 0
NAvalue(NDVI1992) <- 0
NAvalue(NDVI1996) <- 0
NAvalue(NDVI2002) <- 0
NAvalue(NDVI2006) <- 0
NAvalue(NDVI2011) <- 0
NAvalue(NDVI2013) <- 0
NAvalue(NDVI2016) <- 0

#plot NDVI rasters
plot(NDVI1984, main = "1984")
plot(NDVI1990, main = "1990")
plot(NDVI1991, main = "1991")
plot(NDVI1992, main = "1992")
plot(NDVI1996, main = "1996")
plot(NDVI2002, main = "2002")
plot(NDVI2006, main = "2006")
plot(NDVI2011, main = "2011")
plot(NDVI2013, main = "2013")
plot(NDVI2016, main = "2016")

#create raster stack
NDVI4715 <- stack("1984/NDVI_1984_LC0.tif", "1990/NDVI_1990_LC0.tif",
"1991/NDVI_1991_LC0.tif", "1992/NDVI_1992_LC0.tif", "1996/NDVI_1996_LC0.tif",
"2002 Corrected/C_NDVI_2002.tif", "2006/NDVI_2006_LC0.tif", "2011/NDVI_2011_LC0.tif",
"2013 Corrected/C_NDVI_2013_1.tif", "2016 Corrected/C_NDVI_2016_1.tif")

NDVI4715
plot(NDVI4715)

#change 0 value to NA
NDVI4715_NA <- NDVI4715
NAvalue(NDVI4715_NA) <- 0
plot(NDVI4715_NA)

#write this raster stack to working directory
writeRaster(NDVI4715, "NDVI4715.tif", "GTiff")
writeRaster(NDVI4715_NA, "NDVI4715_NA.tif", "GTiff")

#years variable
years <- c(1984, 1990, 1991, 1992, 1996, 2002, 2006, 2011, 2013, 2016)

```

```

#slope function
fun_slope <- function(y) {
  if(sum(is.na(y)) > 3) {
    NA
  } else {
    m = lm(y ~ years); summary(m)$coefficients[2]
  }
}

#p-value function
fun_pvalue <- function(y) {
  if(sum(is.na(y)) > 3) {
    NA
  } else {
    m = lm(y ~ years); summary(m)$coefficients[8]
  }
}

slope <- calc(NDVI4715_NA, fun_slope)
pvalue <- calc(NDVI4715_NA, fun_pvalue)

#plot slope
plot(slope, main = "NDVI Slope Test")

#Slope raster to working directory
writeRaster(slope, "NDVI4715_NA_Slope.tif", "GTiff", overwrite = TRUE)

#plot p-value
plot(pvalue, main = "NDVI P-Value Test")

#P-value raster to working directory
writeRaster(pvalue, "NDVI4715_NA_PValue.tif", "GTiff", overwrite = TRUE)

```

Appendix E

Details on Environmental Variables

Figure E.1: Environmental variable raster layers. Drainage systems and major lakes shown as shapefiles used to create distance rasters. The study area is shown here for these six broad-scale variables.

Figure E.2: Environmental variable raster layers. Rivers and lakes shown as shapefiles used to create distance raster layers. The area around the Tree River outlet into the Arctic Ocean is shown here for these six fine-scale variables.

Land cover Descriptions

Class F: **Forest – Shrubby Understory** (6.7 % of study area)

- **Broad description:** Dense (> 50 %) canopy cover boreal forest, shrub-dominated understory. Graminoids, lichens and mosses (wetter areas) are common groundcover.
- **Forest Zone:** Very common land-cover class (26.7 %). High Boreal ecoregion: dense black spruce canopy (also white spruce, jack pine [*Pinus banksiana*], trembling aspen [*Populus tremuloids*] and paper birch), shrubby-feathermoss understory (Ecosystem Classification Report, 2012). Fire disturbance is common. Found throughout the zone, but most common in Great Slave Lake lowlands (esp. near west arm of Great Slave Lake and east of Yellowknife) and along the Emile and Yellowknife River.
- **Ecotone Zone:** Rare land-cover class (2.1 %). Mostly black spruce (some white spruce) dense canopies with shrub-dominated understories. Occupy lower slope positions and near shorelines (Ecosystem Classification Report, 2012) in southern portion of the zone (i.e., along Snare River system near Wekweètì, around Indin Lake near the abandoned Colomac Mine and southeast of Squalus Lake).
- **Tundra Zone:** Very rare land-cover class (0.1 %). Small black and white spruce forest stands along rivers and lakes in the extreme southern portion of the zone (i.e., near Little Marten Lake, south shore of Redrock Lake).

Figure E.3: Examples of F class. (a) Closed-canopy forest typical in the High Boreal Ecoregion of NWT. (b) Aerial view of this dense forest community. Photographs from Ecosystem Classification Report (2008).

Class W: Woodland – Shrubby Understory (11.4% of study area)

- **Broad description:** Open (< 50 %) canopy cover boreal woodland, shrub-dominated understory. Trees shorter and thinner than F. Graminoids, lichens and mosses (wetter areas) are common groundcover. Differentiated from F mainly by a decrease in canopy cover and biomass of trees across the landscape.
- **Forest Zone:** Most common land-cover class (30.3 %). High Boreal and Low sub-Arctic ecoregion: black spruce canopy (also white spruce, jack pine, trembling aspen and paper birch), shrubby-feathermoss understory (Ecosystem Classification Report, 2012). Generally occupies more exposed, higher slope positions than F. Found throughout the zone, but is most common near western arm of Great Slave Lake, surrounding bedrock outcrops north of Great Slave Lake and across the northern portions of the zone where F is less common.
- **Ecotone Zone:** Common land-cover class (13.2 %). Mostly black spruce (some white spruce) open canopies with shrub-dominated understories. Occupies mid-slope and flat positions across south and east portions of the zone (i.e., around the Snare River system and areas west and east), as well as in the far north of zone (i.e., around the Coppermine River and west and south of Redrock Lake).
- **Tundra Zone:** Very rare land-cover class (1.5 %). Small black and white spruce forest stands near rivers, lakes and other sheltered areas in the southern portion of the zone (i.e., near Little Marten and Redrock lakes).

Figure E.4: Examples of W class. (a) Open-canopy woodland in the North Slave region of NWT, plot LF03. Photograph taken by Mitchell Bonney. (b). Open spruce woodlands, with dwarf-birch and lichen understory found throughout the High sub-Arctic ecoregion. Photograph from Ecosystem Classification Group (2008).

Class LRW: **Lichen-Rocky Woodland** (8.8 % of study area)

- **Broad description:** Open (> 50 %) canopy cover boreal woodland (lacking shrubby understory found in F and W). Open-canopy of mostly spruce scattered in parkland-like landscape, usually on well-drained soils. Groundcover dominated by lichens, mosses and dwarf shrubs that are rarely more than 5 cm tall. Low density forest stands interspaced by lichen-covered boulder gardens and bedrock outcrops are also contained within this class.
- **Forest Zone:** Common land-cover class (18.2 %). High Boreal and Low sub-Arctic ecoregion: lichen woodland/rock-lichen woodland with black spruce, white spruce, jack pine and paper birch on thin soils over bedrock (Ecosystem Classification Report, 2012). Often found between denser-canopy F/W and bedrock outcrops (LBT, SLV) that have not been colonized. Common across bedrock plains north of Great Slave Lake (i.e., Great Slave Upland HB ecoregion) and farther north close to the ecotone zone in lichen-dominated landscapes that are recovering from long-term fire disturbance (Girard et al., 2008).
- **Ecotone Zone:** Common land-cover class (9.7 %). Found mostly in southern portion of the zone in lichen-dominated areas near the Snare River system and areas west and east. Bedrock outcrops are less common in this zone, meaning this class is generally similar to Figure E.5a with tall white and black spruce trees (with some paper birch) scattered in a parkland landscape.
- **Tundra Zone:** Rare land-cover class (3.8 %). Mostly small, open patches of white and black spruce in rocky and lichen-dominated landscapes. Found mostly in extreme southern portions of the zone near Redrock Lake and south of Daring Lake. Some pixels in this class were mis-classified (esp. in areas where ridges cast shadows) and likely belong in shrubland classes.

Figure E.5: Examples of LRW class. (a) Lichen-woodland of scattered tall white spruce on the west coast of Snare Lake north of Wekweètì, near plot SL03. Photograph taken by Greg King. (b) Bedrock-woodlands common north of Great Slave Lake. Photograph taken from the air just north of Yellowknife by Mitchell Bonney.

Class DS: **Dense Shrubland** (7.3 % of study area)

- **Broad description:** Dense (> 50 %) canopy cover shrubland (mostly birch, with some willows and alder). Scattered trees present in some cases (but shrub cover is dominant). Dwarf shrubs and graminoids dominate the understory with lichen and moss groundcover.
- **Forest Zone:** Rare land-cover class (4.1 %). Dense canopies of tall (~1+ m) shrubs with scattered black spruce, jack pine and paper birch often present. Found in wetter areas where tree cover is low. Most common in wetter areas surrounding Great Slave Lake.
- **Ecotone Zone:** Common land-cover class (15.4 %). Dense canopies of tall shrubs, sometimes with scattered black spruce present (Figure E.6a). Found in wetter sites across the zone (i.e., in broad band across the central portion, especially around Winter Lake, and off coast of Redrock Lake). This zone overlaps closely with the Snare Plain HS ecoregion, which has a higher percentage of wetlands than elsewhere in the High sub-Arctic (Ecosystem Classification Report, 2008).
- **Tundra Zone:** Rare land-cover class (3.9 %). Dense canopies of shrubs (~50+ cm) often found near waterbodies and other areas with wet moisture regimes. Found most commonly in sheltered areas marked as riparian corridors (i.e., the outlet of the Tree River into the Arctic Ocean [Figure E.6b], near the Hood and Burnside Rivers and near the north coast of Redrock Lake) on the CAVM (Walker et al., 2005).

Figure E.6: Examples of DS class. (a) Dense ~1m shrubs, with some scattered black spruce trees, near Little Marten Lake (plot LM01). Photograph taken by Mitchell Bonney. (b) True color Landsat image of the Tree River outlet into the Arctic Ocean. Most pixels in this river valley were classified as DS.

Class OS: **Open Shrubland** (13.6 % of study area)

- **Broad description:** Open (< 50 %) canopy cover shrubland (mostly birch, with some willows and alder). Understory less dense than DS, with graminoids and dwarf berry shrubs most common.
- **Forest Zone:** Very rare land-cover class (1.4 %). Treeless, often wet, landscapes. Found in successional areas of recently drained lakes and floodplains near rivers. Most common in bedrock plains north of Great Slave Lake and in the far north of the zone.
- **Ecotone Zone:** Most common land-cover class (23.4 %). Nearly level terrain and presence of fine texture till veneers across this zone leads to development of continuous tundra cover with an open canopy of (mostly birch) low (below < 50 cm) shrubs (Ecosystem Classification Report, 2008). Found across the zone, but most common in the north and east away from forested classes (i.e., east of Snare River system, around Redrock Lake).
- **Tundra Zone:** Common land-cover class (13.4 %). Similar vegetation structure as OS in the ecotone zone; forms main land cover of Point Upland and Contwoyto Upland Low Arctic South ecoregions in south of zone before entering Nunavut (Ecosystem Classification Report, 2012). Class structure mostly similar to CAVM class S1 (Erect-dwarf shrub tundra), but also overlaps with S2 (low-shrub tundra) in some cases (Walker et al., 2005). Most common in southern portion of the zone south of Contwoyto Lake and along major drainage systems farther north.

Figure E.7: Examples of OS class. (a) An open low erect-shrub (mostly birch) site with dwarf-berry shrubs and lichen understory, south of Big Lake (plot SC02). Photograph taken by Mitchell Bonney. (b) Nearly level terrain leads to low erect-shrub cover, with lichen groundcover, across the landscape. Photograph taken east of Lac De Gras, from Ecosystem Classification Report (2012).

Class LRS: **Lichen-Rocky Shrubland** (18.1 % of study area)

- **Broad description:** Open (< 50 %) density shrubland (mostly birch, with some willows and alder). Shrubs shorter and less densely packed than OS class. Boulders/bedrock and lichen are the most common groundcover between shrubs.
- **Forest Zone:** Rare land-cover class (6.6 %). Open-canopy low shrubs are dominant vegetation cover located in fractures (scattered trees likely present) between bedrock outcrops (Ecosystem Classification Report, 2008). Found mostly at the edges of upland bedrock outcrops as they transition to more sheltered forested classes in between. Most common in the bedrock plains north of Great Slave Lake (i.e., Great Slave Upland HB ecoregion).
- **Ecotone Zone:** Common land-cover class (12.1 %). Open-canopy low birch (< 50 cm) shrubs (some alders, willows and small krummholz spruce sometimes present) interspersed between extensive boulder gardens (Figure E.8a). Lichen dominates the groundcover between shrubs and on boulders. Found scattered throughout zone in more exposed areas upslope of denser shrubland and forested classes.
- **Tundra Zone:** Most common land-cover class (27.1 %). Found throughout the zone, but most common at the edges of major river valleys as the landscape transitions to less vegetated classes (LBT, SLV). Also common in upland regions across the southern portion of the zone.

Figure E.8: Examples of LRS class. (a) Low (< 50 cm) birch shrub site strewn with boulders, lichen-dominated groundcover. Found east of Lastfire Lake (plot LF05). Photograph taken by Mitchell Bonney. (b) Aerial photographs from west of Lac de Gras show bedrock and lichen-dominated areas interspersed by low shrubs (Ecosystem Classification Report, 2012).

Class GT: **Graminoid Tundra – Moist** (13.5 % of study area)

- **Broad description:** Graminoid (i.e., grasses, rushes, non-tussock sedges) dominated landscapes. Low shrubs common but not dominant. Moss is the most common groundcover, but lichen is also present. Areas are usually moist with water table close to surface and small pockets of water often present.
- **Forest Zone:** Very rare land-cover class (0.5 %). Found mostly in Great Slave Plain and Great Slave Lowland High Boreal ecoregions around of the west arm of Great Slave Lake, in sedge-dominated calcium-rich wetland fens that do not support tree growth (Ecosystem Classification Report, 2008; 2009). This area is dotted with many small marl lakes that support these wetlands.
- **Ecotone Zone:** Very common land-cover class (21.3 %). Graminoid tundra, often with scattered birch and willow shrubs, with wet moss and lichen groundcover. Most common in western portions of the zone (west of Snare River system and south of Redrock Lake). This area corresponds to the Snare Plain HS ecoregion, which is known for its extensive wetlands near the thousands of small lakes in the region (Ecosystem Classification Report, 2012).
- **Tundra Zone:** Common land-cover class (14.8 %). Corresponds in both vegetation structure and geographic location to CAVM class G3 (non-tussock sedge, dwarf-shrub, moss tundra) within the graminoid tundra group (Walker et al., 2005). Found mostly west of Takijug Lake (Figure E.9b) and in scattered peaty-wetland areas near lakes and rivers across the zone.

Figure E.9: Examples of GT class. (a) Graminoid-dominated site at an island on Big Lake, with some dwarf shrubs and lichen groundcover (plot BL03). Photograph taken by Mitchell Bonney. (b) True color Landsat image of the lowlands west of Takijug Lake. Most pixels in this area were classified as GT and are located in the G3 class in the CAVM.

Class LBT: **Lichen-Barren Tundra** (12.4% of study area)

- **Broad description:** Exposed consolidated sediments (i.e., bedrock, boulder gardens) interspersed with lichen-dominated areas most commonly (Walker et al., 2005). Low shrubs and other tundra vegetation are present (i.e., more sheltered locations), but are not dominant.
- **Forest Zone:** Rare land-cover class (4.3 %). Represents bedrock outcrops (Figure E.10a) found across Great Slave Upland HB ecoregion (Ecosystem Classification Report, 2008). Dominant vegetation are lichens and other low growing vegetation. Shrubs and trees are rare.
- **Ecotone Zone:** Very rare land-cover class (0.8 %). Represents bedrock outcrops similar to what is found in forest zone, as well as rock gardens located where river water levels have dropped (Figure E.10b). Found scattered in small patches across the zone.
- **Tundra Zone:** Very common land-cover class (23.3 %). Corresponds closely in both vegetation structure and geographic location to CAVM class B2 (Cryptogam barren complex) within the barrens group (Walker et al., 2005; Figure E.10c). Defined as areas of exposed rock and lichens with tundra vegetation (i.e., graminoids, low shrubs) found in more sheltered areas.

Figure E.10: Examples of the LBT class. (a) Bedrock outcrops (top left corner) common in the Great Slave Upland HB ecoregion. Photograph taken from the air just north of Yellowknife by Mitchell Bonney. (b) Boulder garden, with small patches of shrubs interspersed, where the water level of rivers has dropped. Photograph taken south of Big Lake by Mitchell (point of interest LMN_Boulder2). (c) CAVM Class B2 landscape located near the Daring Lake Tundra Ecosystem Research Station (Walker et al., 2005). (d) True color Landsat image of large cliffs located near the outlet of the Tree River. Most pixels in this area were classified as LBT.

Class SLV: **Sediments – Low Vegetation** (8.1 % of study area)

- **Broad description:** Exposed unconsolidated sediments (i.e., sand and gravel) interspersed with low vegetation. Low vegetation mostly consists of lichens and dwarf shrubs. Erect shrubs and scattered trees can be found (e.g., on eskers), but are not dominant. Some class overlap with LBT.
- **Forest Zone:** Rare land-cover class (7.8 %). Represents low vegetation outcrops across Great Slave Upland HB ecoregion (Ecosystem Classification Report, 2008). More often found in areas with exposed grained sediments and lichen, rather than bedrock and lichen. Built-up areas and excavation sites are in this class (Figure E.11a).
- **Ecotone Zone:** Very rare land-cover class (1.9 %). Represents eskers (i.e., glacial landforms consisting of long and narrow ridges of unconsolidated sediments) found scattered throughout the zone (Ecosystem Classification Report, 2008). Eskers can be many kilometers in length but are rarely more than 100 m wide. Low vegetation (dwarf shrubs, lichens) can be found on eskers, as well as krummholz spruce trees in many locations (Figure E.11b,c).
- **Tundra Zone:** Common land-cover class (12 %). Found mostly in areas classified as B2 (Cryptogam barren complex) within the barrens group of the CAVM (Walker et al., 2005). Differentiated from LBT in that this class is more often found in areas closer to waterbodies. It is likely these areas have more exposed unconsolidated sediments and lichens (rather than bedrock and lichens as in LBT).

Figure E.11: Examples of the SLV class. (a) Built-up areas, excavation sites and some bedrock outcrops near Yellowknife were classified as SLV. (b) Eskers located on the north end of Little Marten Lake. (c) True color Landsat image of a long esker located west of Big Lake.

Figure E.12: Percentage of Landsat pixels with significant NDVI trends in the northern portions of the tundra zone, where the most greening has occurred. Values above 0 indicate greening while values below 0 (in parenthesis) indicate browning. The percentage of the zone in question that is comprised by each land-cover class is indicated as points plotted against the right y-axis. Land-cover classes are colored as in Figure 3.5.

Appendix F

Random Forest Code and Other Partial Dependence Plots

Random Forest (and correlation matrix) Code

```
#####load packages#####
library(randomForest)
library(ggplot2)
library(ggRandomForests)
library(randomForestSRC)
library(party)
library(reprtree)
library(corrplot)
library(Hmisc)
library(pdp)

#####define workspace#####
setwd("E:/NDVI Trend Analysis/FINAL TABLE/Raster2Point")

sample_600k_100 <- read.delim("sample_600k_100.txt")
sample_600k_100

sample_600k_100_F <- read.delim("sample_600k_100_F.txt")
sample_600k_100_F

sample_600k_100_E <- read.delim("sample_600k_100_E.txt")
sample_600k_100_E

sample_600k_100_T <- read.delim("sample_600k_100_T.txt")
sample_600k_100_T

#####correlation matrix#####
cor600k_100 <- cor(sample_600k_100)
round(cor600k_100, 2)

cor600k_NDVI <- cor(sample_600k_100[, c(3:5)])
round(cor600k_NDVI, 2)
corrplot.mixed(cor600k_NDVI)

cor600k_Vars <- cor(sample_600k_100[, -c(4:9, 12, 14, 15, 21, 22)])
round(cor600k_Vars, 2)
corrplot.mixed(cor600k_Vars)
corrplot(cor600k_Vars, method = "circle")

corrplot(cor600k_100, method = "number")
corrplot.mixed(cor600k_100)

#with pvalues#
cor600k_Vars2 <- rcorr(as.matrix(sample_600k_100[, -c(4:9,14,15, 21, 22)]))
```

```

cor600k_Vars2

cor600k_Vars2$r
cor600k_Vars2$P

corrplot(cor600k_Vars, type = "upper", tl.col = "black", tl.srt = 45)

colnames(cor600k_Vars2$r) <- c("easting", "northing", "ndvi yr-1", "elev", "slope", "aspect",
"TPI", "TWI", "lakes", "rivers", "mlakes", "drainages", "precip", "temp")
rownames(cor600k_Vars2$r) <- c("easting", "northing", "ndvi yr-1", "elev", "slope", "aspect",
"TPI", "TWI", "lakes", "rivers", "mlakes", "drainages", "precip", "temp")

par(xpd = TRUE)
corrplot(cor600k_Vars2$r, type = "upper", method = "square", p.mat = cor600k_Vars2$P,
sig.level = 0.01, insig = "pch", tl.col = "black", tl.srt = 45, mar = c(1, 0, 3, 0), diag = TRUE)

###

cor600k_100_F <- cor(sample_600k_100_F)
round(cor600k_100_F, 2)

cor600k_100_E <- cor(sample_600k_100_E)
round(cor600k_100_E, 2)

cor600k_100_T <- cor(sample_600k_100_T)
round(cor600k_100_T, 2)

#####set variables to categories#####
sample_600k_100$LANDCOVER <- as.factor(sample_600k_100$LANDCOVER)
sample_600k_100$ASPECT <- as.factor(sample_600k_100$ASPECT)

sample_600k_100_F$LANDCOVER <- as.factor(sample_600k_100_F$LANDCOVER)
sample_600k_100_F$ASPECT <- as.factor(sample_600k_100_F$ASPECT)

sample_600k_100_E$LANDCOVER <- as.factor(sample_600k_100_E$LANDCOVER)
sample_600k_100_E$ASPECT <- as.factor(sample_600k_100_E$ASPECT)

sample_600k_100_T$LANDCOVER <- as.factor(sample_600k_100_T$LANDCOVER)
sample_600k_100_T$ASPECT <- as.factor(sample_600k_100_T$ASPECT)

#####randomForest#####
variablesrf = NDVI_C ~ LANDCOVER + ELEVATION + SLOPE + ASPECT + TPI + TWI +
LAKE + RIVER + MAJLAKE + MAJRIVER + PRECIP + TEMP

rf600k_100_0_500_4_100 <- randomForest(variablesrf, data = sample_600k_100, ntree = 500,
nodesize = 100, mtry = 4, importance = TRUE)
print(rf600k_100_0_500_4_100)
round(importance(rf600k_100_0_500_4_100), 3)

```

```

rf600k_100_F_0_500_4_100 <- randomForest(variablesrf, data = sample_600k_100_F, ntree =
500, nodesize = 100, mtry = 4, importance = TRUE)
print(rf600k_100_F_0_500_4_100)
round(importance(rf600k_100_F_0_500_4_100), 3)

rf600k_100_E_0_500_4_100 <- randomForest(variablesrf, data = sample_600k_100_E, ntree =
500, nodesize = 100, mtry = 4, importance = TRUE)
print(rf600k_100_E_0_500_4_100)
round(importance(rf600k_100_E_0_500_4_100), 3)

rf600k_100_T_0_500_4_100 <- randomForest(variablesrf, data = sample_600k_100_T, ntree =
500, nodesize = 100, mtry = 4, importance = TRUE)
print(rf600k_100_T_0_500_4_100)
round(importance(rf600k_100_T_0_500_4_100), 3)

####Save/Load randomForests####
save(rf600k_100_0_500_4_100, file = "rf_600k_100_0_500_4_100.RData")
load("rf_600k_100_0_500_4_100.RData")
print(rf600k_100_0_500_4_100)

save(rf600k_100_F_0_500_4_100, file = "rf_600k_100_F_0_500_4_100.RData")
load("rf_600k_100_F_0_500_4_100.RData")
print(rf600k_100_F_0_500_4_100)

save(rf600k_100_E_0_500_4_100, file = "rf_600k_100_E_0_500_4_100.RData")
load("rf_600k_100_E_0_500_4_100.RData")
print(rf600k_100_E_0_500_4_100)

save(rf600k_100_T_0_500_4_100, file = "rf_600k_100_T_0_500_4_100.RData")
load("rf_600k_100_T_0_500_4_100.RData")
print(rf600k_100_T_0_500_4_100)

####Plot randomForest outputs####
plot(rf600k_100_0_500_4_100)
varImpPlot(rf600k_100_0_500_4_100)

plot(rf600k_100_F_0_500_4_100)
varImpPlot(rf600k_100_F_0_500_4_100)

plot(rf600k_100_E_0_500_4_100)
varImpPlot(rf600k_100_E_0_500_4_100)

plot(rf600k_100_T_0_500_4_100)
varImpPlot(rf600k_100_T_0_500_4_100)

####PDs####
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, LANDCOVER)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, TEMP)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, MAJRIVER)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, MAJLAKE)

```

```

partialPlot(rf600k_100_0_500_4_100, sample_600k_100, ELEVATION)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, PRECIP)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, LAKE)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, RIVER)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, SLOPE)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, ASPECT)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, TWI)
partialPlot(rf600k_100_0_500_4_100, sample_600k_100, TPI)

partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, LANDCOVER)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, TEMP)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, MAJRIVER)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, MAJLAKE)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, ELEVATION)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, PRECIP)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, LAKE)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, RIVER)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, SLOPE)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, ASPECT)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, TWI)
partialPlot(rf600k_100_F_0_500_4_100, sample_600k_100_F, TPI)

partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, LANDCOVER)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, TEMP)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, MAJRIVER)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, MAJLAKE)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, ELEVATION)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, PRECIP)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, LAKE)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, RIVER)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, SLOPE)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, ASPECT)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, TWI)
partialPlot(rf600k_100_E_0_500_4_100, sample_600k_100_E, TPI)

partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, LANDCOVER)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, TEMP)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, MAJRIVER)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, MAJLAKE)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, ELEVATION)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, PRECIP)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, LAKE)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, RIVER)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, SLOPE)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, ASPECT)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, TWI)
partialPlot(rf600k_100_T_0_500_4_100, sample_600k_100_T, TPI)

```

Other Partial Dependence Plots

Study Area

Figure F.1: Partial dependence plots for (a) slope, (b) aspect, (c) TPI, (d) TWI, (e) distance to rivers and (f) distance to lakes for the study area (see Table 3.2). These plots show the marginal influence of each of these environmental variables on NDVI trends (y-axis). Note that y-axis for these plots cover a much smaller range than Figure 3.13, since most plots would show nearly flat trends at that scale.

Forest Zone

Figure F.2: Partial dependence plots for (a) slope, (b) aspect, (c) TPI, (d) TWI, (e) distance to rivers and (f) distance to lakes for the forest zone (see Table 3.2). These plots show the marginal influence of each of these environmental variables on NDVI trends (y-axis). Note that y-axis for these plots cover a much smaller range than Figure 3.13, since most plots would show nearly flat trends at that scale. TPI (c) is an exception, with NDVI trends being more positive in sheltered areas than in exposed areas. This is indicative of lowland areas seeing a greater increase in NDVI than upland outcrops. Distance to rivers (e) also has a stronger influence, with NDVI trends being more positive when farther away.

Ecotone Zone

Figure F.3: Partial dependence plots for (a) slope, (b) aspect, (c) TPI, (d) TWI, (e) distance to rivers and (f) distance to lakes for the ecotone zone (see Table 3.2). These plots show the marginal influence of each of these environmental variables on NDVI trends (y-axis). Note that y-axis for these plots cover a much smaller range than Figure 3.13, since most plots would show nearly flat trends at that scale. Slope (a) and TPI (c) are an exception, with NDVI trends being more positive at steeper slopes as well as in more exposed and sheltered areas. This could be indicative of increasing vegetation productivity on hill slopes in this zone.

Tundra Zone

Figure F.4: Partial dependence plots for (a) slope, (b) aspect, (c) TPI, (d) TWI, (e) distance to rivers and (f) distance to lakes for the tundra zone (see Table 3.2). These plots show the marginal influence of each of these environmental variables on NDVI trends (y-axis). Note that y-axis for these plots cover a much smaller range than Figure 3.13, since most plots would show nearly flat trends at that scale. Distance to lakes (f) is an exception with NDVI trends being more positive farther away, similar to the relationship with major lakes but at a smaller scale of influence.