A GEOBOTANICAL ANALYSIS OF CIRCUMPOLAR ARCTIC VEGETATION, CLIMATE, AND SUBSTRATE

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A GEOBOTANICAL ANALYSIS OF CIRCUMPOLAR ARCTIC VEGETATION, CLIMATE, AND SUBSTRATE

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Abstract

The objective of the research presented in this dissertation was to better understand the factors controlling the present and potential future distribution of arctic vegetation. The analysis compares the Circumpolar Arctic Vegetation Map (CAVM) with circumpolar data sets of environmental characteristics. Geographical information system (GIS) software was used to overlay the CAVM with a satellite index of vegetation (normalized difference vegetation index, NDVI) and environmental factors that are most important in controlling the distribution of arctic vegetation, including summer temperature, landscape age, precipitation, snow cover, substrate chemistry (pH and salinity), landscape type, elevation, permafrost characteristics, and distance to sea. Boosted regression tree analysis was used to determine the relative importance of different environmental characteristics for different vegetation types and for different regions.

Results of this research include maps, charts and tables that summarize and display the spatial characteristics of arctic vegetation. The data for arctic land surface temperature and landscape age are especially important new resources for researchers. These results are available electronically, not only as summary data, but also as GIS data layers with a spatial context (www.arcticatlas.org). The results emphasize the value and reliability of NDVI for studying arctic vegetation. The relationship between NDVI and summer temperatures across the circumpolar arctic was similar to the correlated increases in NDVI and temperature seen over the time period of satellite records.

Summaries of arctic biomass based on NDVI match those based on extrapolation from ground samples. The boosted regression tree analysis described ecological niches of arctic vegetation types, demonstrating the importance of summer temperatures and landscape age in controlling the distribution of arctic vegetation.

As the world continues to focus on the Arctic as an area undergoing accelerated warming due to global climate change, results presented here from spatially explicit analysis of existing arctic vegetation and environmental characteristics can be used to better understand plant distribution patterns, evaluate change in the vegetation, and calibrate models of arctic vegetation and animal habitat.

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I had the privilege of joining the team working on the Circumpolar Arctic Vegetation Map (CAVM) in 2000. Some of the world's most experienced arctic botanists talked to me about arctic landscapes they had studied and how they should best be represented on the CAVM. When the map was published in 2003, the CAVM Team had created a very powerful tool for analyzing arctic vegetation. I undertook this PhD research to use the CAVM to better understand the factors controlling the distribution of arctic vegetation. Many thanks to the members of the Circumpolar Arctic Vegetation Map team, particularly Skip Walker, for including me in the project, teaching me about parts of the Arctic that I had not visited, and trusting me to make good use of their data and of the resulting map in my subsequent PhD research. I would like to thank Fred Daniëls, Bill Gould, Sylvia Edlund, Larry Bliss, Carl Markon, Stephen Talbot, and colleagues at the Earth Cryosphere Institute in Moscow and the

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Chapters 2-5 of this dissertation are written with co-authors. Chapter 2 was co-authored with Donald (Skip) Walker and Hilmar Maier. I formulated the research questions, designed and conducted the analyses, and wrote the paper. My co-authors helped with evaluating the results and placing them in context (Skip Walker), with GIS analysis methods (Hilmar Maier), and with revisions. Chapter 3 was co-authored with Josefino Comiso, Donald Walker and David Verbyla. I formulated the research questions, designed and conducted the analyses, and wrote the paper. Josefino Comiso provided the satellite surface temperature data and helped me understand how it was produced. My co-authors helped me place my results in a broader context based on their expertise and helped with revisions. Chapter 4 was co-authored by Donald Walker. I formulated the research questions, designed and conducted the analyses, and wrote the paper. My co-author helped design the presentation of the results and helped with revisions. Chapter 5 was co-authored by Donald Walker. I formulated the research questions, created the landscape-age data layer, designed and conducted the analyses, and wrote the paper. My co-author helped evaluate the results and helped with revisions. Chapter 6 was co-authored by Falk Huettman, Donald Walker and David Verbyla. I formulated the research questions, designed and conducted the analyses, and wrote the paper. Falk Huettman introduced me to boosted regression tree analysis, showing me its power and how to apply it to my data. My co-authors helped with revisions. Anonymous reviewers provided helpful editorial comments on Chapters 2, 3, 4 and 5.

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Chapter 1 – Introduction

1.1 General introduction

The Arctic is undergoing rapid change. The climate is changing and land use patterns are changing. Expanding resource extraction and changing cultural practices are predicted to seriously impact over half of the Arctic within the next 50 years (Nellemann et al., 2001). Climate change is occurring at a faster rate in the Arctic than other biomes and is resulting in increased summer temperatures in almost all areas of the Arctic (Comiso, 2006). This pattern matches the amplification of global changes at high latitudes seen in past climate records (ACIA, 2004). The dramatic reduction of summer sea ice in the Arctic Ocean in the last several years is a highly visible symptom of these changes, with repercussions for global climate systems (Comiso et al., 2008).

Vegetation in the Arctic is also responding to climate change, though not as dramatically as sea ice (Bhatt et al., 2009 in prep.). Twenty-five-year satellite records show an increase in vegetation greenness over tundra areas (Jia et al., 2007) and also show that spring is coming sooner, lengthening the growing season (Goetz et al., 2005). Fifty-year photo comparisons document shrubs expansion in the tundra (Tape et al., 2006), a trend that is corroborated by the results of international experiments which show that deciduous shrubs and graminoid plants increase in height in response to warming treatments (Walker et al., 2006).

All these changes have focused the world's attention on the Arctic. Its importance in regulating world climate systems and as a source for oil, gas and minerals is well-known. It is also being watched closely to see how people and ecosystems adapt to the challenges and opportunities that arise due to rapid climate change. Information about existing conditions in the Arctic is needed now more than ever. Detailed information about arctic vegetation will provide the basis for monitoring, understanding, and predicting change so as to better evaluate impacts on wildlife, human settlements and subsistence, and industry.

This research investigated the circumpolar distribution of arctic vegetation and the various environmental factors the affect that distribution, helping to clarify which environmental factors are most important for which vegetation types, and in which parts of the Arctic. Understanding how the variation in environmental factors creates the spatial distribution of vegetation that we see today in the Arctic, and examining the range of responses to environmental factors sheds light on how vegetation will respond to changes in these factors.

Changes are occurring and will continue to occur from natural disturbance, changes in human land-use, and changes in climate. Existing plant communities integrate the response of plant species to climate conditions. The gradient from north to south in the Arctic provides a model for the response of vegetation to warming climate, where the variation over space can be used as a proxy for the types of changes that might occur over time. The range of conditions in the Arctic covers much more variation than can be seen in recent climate records, and can provide some indication of changes that might occur over longer time periods of change.

The maps, tables, and especially the on-line data sets produced by this research provide valuable resources documenting the existing characteristics of arctic vegetation, for use in monitoring change and calibrating predictive models. Several papers were published in the course of this research and are presented as chapters in this dissertation (Chapters 2-5). Chapter 2 analyzes the plant biomass and NDVI of the vegetation types shown on the Circumpolar Arctic Vegetation Map. Chapter 3 examines the role of temperature in controlling arctic vegetation. Chapter 4 looks at permafrost characteristics and their relationship to arctic vegetation. Chapter 5 analyzes the effect of landscape age on arctic vegetation distribution. Chapter 6 (in preparation for publication) brings in precipitation data and uses a statistical approach to jointly analyze the effects of these environmental variables.

1.2 Circumpolar Arctic Vegetation Map

When I started this research the Circumpolar Arctic Vegetation Map (CAVM) had just been completed (CAVM Team, 2003). Previous maps that included all of the Arctic generally had only a few broad categories differentiating the vegetation (Aleksandrova, 1980). Portions of the Arctic were mapped in more detail, but with differing classification schemes (e.g. Bohn et al., 2000; Gribova and Tichomirov, 1985). Satellite data were available, but the ground data necessary to interpret these data were scarce and applied only to small field study sites. Researchers recognized the circumpolar nature of the distribution of Arctic species (Hulten, 1968; Yurtsev, 1994b), the similarity of the vegetation types found throughout the Arctic (Bliss et al., 1980; Chernov, 1985), and the need for a unifying structure to allow the study of Arctic vegetation as a whole biome (Walker et al., 1995b; Walker et al., 1994). In 1993, an international group of Arctic vegetation scientists combined their expertise to create the CAVM (Walker et al., 1995b).

The CAVM project built on the experience of Russian scientists, who had developed several bioclimate zonation approaches to studying the Arctic (Aleksandrova, 1980; Chernov, 1985; Razzhivin, 1999; Yurtsev, 1994a). They recognized that the patterns related to climate, particularly summer temperatures, could be described and used to subdivide the Arctic. Researchers studying the Canadian Arctic Islands (Edlund, 1990) and the Bering Sea island of St. Lawrence (Young, 1971) also recognized zonation patterns dependent on summer temperatures.

An international team of researchers working on the CAVM conducted studies along a transect of the Canadian Arctic in 1999 and determined that the Russian bioclimate zonation approach could also be applied to North America (Walker et al., 2002). The CAVM team adopted five latitudinal bioclimate subzones of the tundra based mainly on Yurtsev (1994b) and Elvebakk (1999), and 23 longitudinal floristic provinces (Aleksandrova, 1980). They also developed an altitudinal zonation approach that could be used to map mountainous areas, such as Greenland (Walker et al., 2002).

The other important construct used to organize CAVM vegetation descriptions was the Russian concept of zonal or "plakor" vegetation, whereby vegetation that best expresses the interaction with the climate is described from well-drained undisturbed sites without extremes of slope, snow, soil chemistry, or texture (Razzhivin, 1999). Non-zonal vegetation within a landscape can be described along a theoretical toposequence that repeats across the landscape, including vegetation typical of ridges, snowbeds, zonal or mesic sites, wetlands and riparian areas (Razzhivin, 1999). Thus the range of plant communities occurring within a polygon mapped as a zonal vegetation type could be described (Walker et al., 2002).

The CAVM mapping procedure integrated information from existing vegetation maps, ground studies, data on soils, bedrock and surficial geology, hydrology, topography, climate and satellite imagery. Polygons were hand-drawn using a 1:4 million AVHRR false-color infrared image (1 km pixel resolution) as a base map. Ancillary information was printed on transparent mylar at the same scale so that maps could be physically overlaid. Most boundaries followed physiographic landscape patterns. The minimum mapping unit was 14 km across, or 8 km for linear features (Walker et al., 2005).

The CAVM mapped the Arctic with a unified legend based on ecologically meaningful plant physiology-based vegetation types. The mapped area included all of the arctic tundra, defined as the region north of the climatic limit of trees that is characterized by an arctic climate, arctic flora, and tundra vegetation. The circumpolar legend of 15 tundra vegetation types allowed comparison between different parts of the Arctic and analysis of the Arctic as a whole (CAVM Team, 2003). A summary of the CAVM described the area of different vegetation types, their relationship to bioclimate subzones, and their occurrence in different countries (Walker et al., 2005).

1.3 Research presented in this dissertation

The objective of my research was to better understand and describe the factors controlling the distribution of arctic vegetation. The conceptual model, shown in Figure 1.1, was that vegetation distribution is a result of the interaction of arctic plants with climate and substrate. This concept was not original; in fact it was the basis of the CAVM integrated mapping approach (Walker et al., 2002). What was new was high-quality circumpolar data sets of environmental data that recently became available. Using Geographic Information Systems software (GIS), it was possible to analyze their relationship to vegetation types mapped by the CAVM, and to investigate the question of which environmental factors were most important for which arctic vegetation types, and in which parts of the Arctic.

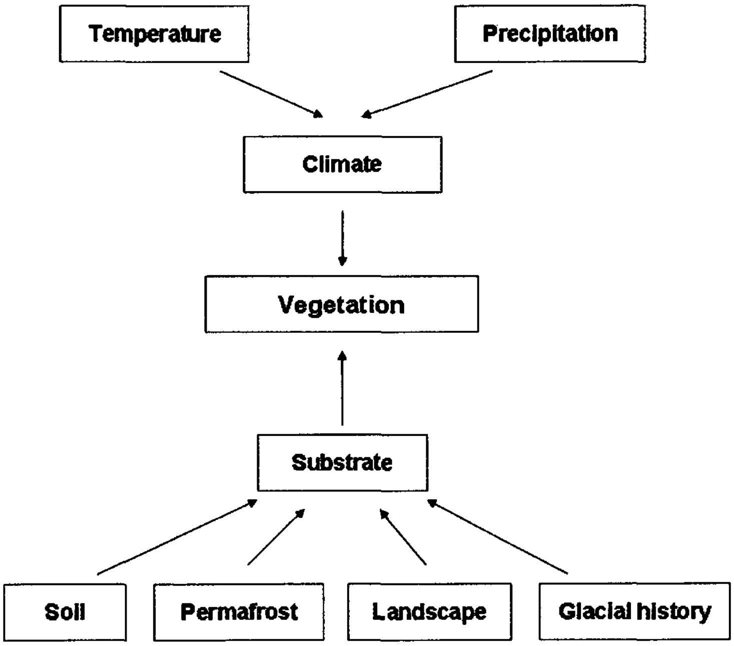

Figure 1.1 Conceptual model of environmental factors controlling the distribution of arctic vegetation

1.3.1 NDVI

Chapter 2 of this dissertation analyzes the distribution of arctic vegetation using a satellite measure of vegetation, NDVI (normalized difference vegetation index). The goal of this research was to use NDVI to characterize the vegetation types described by the CAVM, providing data for understanding arctic vegetation patterns, assessing change, and calibrating models.

NDVI was developed to maximize information about vegetation from satellite data (Tucker, 1979). By contrasting the low reflectance in the red portion of the spectrum (due to chlorophyll absorption) with relatively high reflectance in the near-infrared (due to plant cellular structure), an index is produced that is related to the amount of green plant biomass. This ratio is then normalized to minimize the effects of viewing angle, cloud cover, and angle of insolation, resulting in the equation NDVI = (NIR – R)/(NIR + R) (Tucker, 1979).

NDVI has been found to relate well to biophysical properties of arctic tundra on the ground, varying with vegetation type, and increasing with the amount of vegetation as measured by leaf area index (LAI) and plant biomass (Riedel et al., 2005; Shippert et al., 1995). NDVI also varies on different-aged glacial surfaces, which have different vegetation types (Munger, 2007; Walker et al., 1995a). NDVI has been especially useful for analyzing variation in vegetation over large, remote regions of the Arctic (Bogaert et al., 2002; Jia et al., 2002; Markon et al., 1995; Shippert et al., 1995; Walker et al., 2003a; Zhou et al., 2001). It has been used to map growing seasons and detailed bioclimate zones in Scandinavia (Karlsen et al., 2006). Long-term satellite records have been examined to look at responses of arctic vegetation to climate change (Bogaert et al., 2002; Bunn and Goetz, 2006; Jia et al., 2003; Markon et al., 1995; Olthof et al., 2008; Slayback et al., 2003; Verbyla, 2008; Zhou et al., 2001). All these temporal studies confirmed a greening response throughout most of the Arctic, though some areas had little or even negative change. Negative changes in NDVI were more commonly reported for forested areas south of the Arctic (Bunn and Goetz, 2006; Verbyla, 2008).

None of these analyses focused on the existing spatial distribution of NDVI across the whole Arctic and how that varied with environmental factors. The specific questions addressed by the research presented in Chapter 2 were:

How does NDVI vary among CAVM vegetation types?

How does the biomass of vegetation estimated from NDVI vary throughout the circumpolar Arctic?

What environmental characteristics most influence the spatial distribution of NDVI?

1.3.2 Temperature

Chapter 3 of this dissertation examines the role of temperature in controlling the distribution of arctic vegetation. Researchers have long been aware that temperature determines much of the spatial variation in arctic vegetation. Plant community composition is limited to species that are able to tolerate the coldest summer temperatures at any given location (Bliss and Petersen, 1992). Plant physiological activities, such as water and nutrient transport, photosynthesis, and respiration, all occur at minimal levels in below-freezing temperatures and increase as plant tissues warm (Lambers et al., 1998). Arctic plants have adapted to cold temperatures by reducing the temperatures at which they achieve a maximum rate of photosynthesis, but these optimum temperatures are still 5 to 10 °C warmer than average leaf temperatures in the field (Semikhatova et al., 1992). Plants are also limited by the length of the growing season (Shaver and Kummerow, 1992), nutrient availability in cold soil temperatures (Oechel and Vourlitis, 1997), and the amount of above-ground biomass that can survive the winter (Shaver and Kummerow, 1992).

The Russian Arctic has long been divided into subzones based on summer temperatures (Chernov, 1985). In the Canadian Arctic Islands, mean July temperature matched vegetation zonation patterns better than precipitation, snow cover, length of growing season, lower troposphere temperatures, cloud cover, or even mean June temperatures or total degree-days (Edlund and Alt, 1989). Studies on St. Lawrence Island determined that vegetation zonation corresponded to an index of total summer warmth (the sum of monthly mean temperature above 0 °C) better than the temperature of any specific month (Young, 1971). As in the Canadian Arctic Islands, no correlation was found between the distribution of vegetation on St. Lawrence Island and other climate characteristics such as mean annual temperature, mean annual precipitation, or day length (Young, 1971).

The bioclimate zones of the CAVM (Elvebakk, 1999; Elvebakk et al., 1999) were used to map and analyze arctic vegetation (Chapter 2; Raynolds et al., 2006), but these zones were broad generalizations based on a combination of scattered climate station data and vegetation field data (Walker et al., 2002). Modeled temperature data interpolated from ground stations were available, but these data were spatially coarse (usually 50 km pixels or larger), were based on few mostly coastal stations (Rawlins and Willmot, 2003), and had problems with reliability (Pielke et al., 2007). Land surface temperature (LST) estimated from satellite data provided a more detailed, consistent data set for the whole circumpolar Arctic (Comiso, 2006). AVHRR satellite data from 1982-2003 were used to calculate a mean summer warmth index (SWI, sum of mean monthly temperatures above 0 °C).

The specific questions addressed in this chapter were:

Does satellite-derived SWI provide a useful tool for analyzing arctic vegetation distribution, with high enough resolution and data quality?

Does the spatial pattern of satellite-derived SWI support the circumpolar bioclimate zonation mapped by the CAVM?

What is the relationship between CAVM vegetation types and SWI? What does this relationship imply about which areas and types of arctic vegetation are most and least limited by summer temperature?

What is the relationship between maximum NDVI and SWI, and which areas have more or less NDVI than would be expected by the NDVI/SWI relationship?

Does the spatial relationship between maximum NDVI and SWI match the temporal trend between NDVI and temperature recorded over the satellite record?

1.3.3 Permafrost

Chapter 4 looks at permafrost characteristics and their relationship to the distribution of arctic vegetation. Vegetation affects permafrost by changing the thermal characteristics of the soil. Vegetation shades and insulates the soil, reducing the transfer of summer warmth from air to soil (Kade et al., 2006; Shur and Jorgenson, 2007). Vegetation also cools the surface through evapotranspiration. Vegetation has the opposite effect in winter: well-vegetated areas are insulated by the plants and the snow they trap, while unvegetated soils are more exposed to winter air temperatures (Sturm et al., 2001; Kade et al., 2006; Walker et al., 2003b). The types and strength of the effects of vegetation on the climate-soil interactions vary with vegetation type and depend on the amount of total plant biomass, plant lifeforms, and continuity of plant cover (Kade et al., 2006; Walker et al., 2003b). These interactions are key to the formation of the various patterned ground features that are so common in the Arctic (Peterson and Krantz, 2008; Raynolds et al., 2008; Walker et al., 2008).

Permafrost characteristics (areal extent, ice content, and overburden) mapped by the Circum-arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1997) were analyzed with the Circumpolar Arctic Vegetation Map and maximum annual NDVI. This chapter describes the relationship between the spatial distribution of vegetation and permafrost characteristics in the arctic biome, specifically addressing the following questions:

How do permafrost extent, ice content, and overburden thickness vary with vegetation type?

How does maximum annual NDVI vary among classes of permafrost extent, ice content, and overburden thickness?

1.3.4 Glaciation

Chapter 5 analyzes the effect of landscape age on arctic vegetation distribution. Glaciation, although not an explicitly defined characteristic in the analysis in chapters 2-4, could be seen on maps and images of the Arctic as having a strong influence on vegetation distribution (e.g. Fig. 2.1a, Fig. 2.3). Bliss and Petersen (1992) described succession potential in the Arctic as due to years since deglaciation and summer warmth. Researchers have found surprisingly rapid colonization and plant succession occurring on the decadal scale on arctic glacial surfaces (Moreau et al., 2005). On the other hand, differences in vegetation characteristics have persisted for tens of thousands of years after glaciation in the Toolik Lake area (Munger, 2007; Walker et al., 1995a). Unlike the adjacent boreal forest, where trees mask the landscape and fire is a major source of patterning, vegetation differences due to landscape age and other substrate variation are relatively apparent in the Arctic.

The research presented in Chapter 5 looks at the relationship between time since deglaciation and arctic vegetation on the circumpolar scale, comparing the age that landscapes were available for colonization (after glaciation, pro-glacial lake drainage, or sub-sea glacial rebound) with the CAVM vegetation types and NDVI. Glaciation data were compiled from a summary of Quaternary glaciations available in digital format (Ehlers and Gibbard, 2004) and additional data provided in regional chapters (Ehlers and Gibbard, 2004), supplemented by references describing more recent work (Raynolds and Walker, 2009). Specific questions addressed were:

What is the pattern of landscape age in the Arctic?

What landscape ages are characteristic of CAVM vegetation types and which vegetation types occur on different-aged landscapes?

How does maximum annual NDVI vary among different-aged landscapes?

1.3.5 Combined statistical analysis

Chapter 6 describes a statistical approach used to jointly analyze the effects of a suite of environmental variables on arctic vegetation distribution. The complexity of the interactions between plants and their environment has led researchers to use various types of models to better understand existing vegetation distribution and possible changes that may occur due to climate change (e.g. Epstein et al., 2004; Kaplan et al., 2003; Thompson et al., 2005). These models are calibrated with existing vegetation and climate data, but the relationship between these factors varies spatially and is affected by substrate characteristics. Unlike model simulations, the boosted regression tree analysis used in Chapter 6 does not use estimated equations to quantify relationships between environmental factors and vegetation, but rather uses the environmental data to characterize the relationship of the vegetation to the environment, describing its ecological niche. The research presented in this chapter looked at the relationship between existing plant communities and environmental factors in a spatially explicit way, including both climate and substrate data. Recent circumpolar data sets for vegetation distribution, temperature, precipitation, snow cover, landscape age, permafrost characteristics, soil chemistry, and landscape characteristics were used in the analysis. The results describe the unique combination of environmental variables that characterizes the ecological niche of each vegetation type. The analysis provides information to calibrate models that look at the effects of changes in environmental conditions, such as those due to climate change.

The research presented in Chapter 6 addresses the questions:

Which environmental variables are most important in defining the ecological niche of each vegetation type?

Which vegetation types are most strongly defined by SWI and other variables that might change due to global climate change?

Which environmental variables best explain the current distribution of maximum annual NDVI?

Where are the areas where climate variables such as temperature and precipitation are most important in predicting vegetation type and NDVI?

1.4 Limitations of the scope of this research

Although there is considerable interest in temporal analyses of arctic vegetation - looking at change that has already occurred, or change that might occur under different climate scenarios - that is not the focus of this work. I intentionally focused on a spatial analysis. The creation of the CAVM and the availability of circumpolar environmental data sets from recent mapping efforts and satellite data provided a valuable opportunity to explore and analyze the spatial relationships between these data, to see what they could tell us about the existing distribution of arctic vegetation and its environmental controls. The results of this analysis also suggest areas that would be expected to respond most or least to predicted climate changes, and provide a spatial gradient that can be used as a proxy for change over time. The limitations of the data sets, combined with the limitations of future climate scenarios, make predictive mapping of vegetation types using this analysis unreliable. The results presented are from correlation analysis, based on existing interactions between environmental variables and vegetation. They describe existing conditions and interactions well, but are not designed to predict how those interactions might change with a new set of environmental conditions and plant communities (Elith et al., 2006). That type of prediction is better done using models (e.g. Epstein et al., 2004; Kaplan et al., 2003; Thompson et al., 2005).

The other avenue not pursued in this research is analysis of change recorded by the satellite record of arctic NDVI. This is a very important subject, but would have taken my research in a different direction. In addition, there are problems with the coverage of the Arctic in existing satellite data sets. The most commonly used NDVI time series, the GIMMS data (Tucker et al., 2004), is missing Northeastern Greenland, Wrangel Island and a part of the north coast of Chukotka. The GIMMS data also has abrupt swath boundaries in the Taimyr area of Russia, in Chukotka, and in the Canadian Arctic Islands. This swath boundary is due to calibration issues in the GIMMS processing procedure, which used SPOT Vegetation satellite data to combine separate NOAA satellite swaths into one image (Tucker pers. comm.). SPOT data were not available north of 72 °N, resulting in a distinct boundary line at that latitude. I am optimistic that strong scientific interest in arctic vegetation will result in the creation of an improved arctic NDVI time series in the near future, which will allow detailed spatial analysis of change over the last several decades.

1.5 Availability of research results

Chapters 2-5 were published in the course of this research and Chapter 6 is being prepared for publication. The maps, tables, and GIS data sets produced during this research are available on-line (www.arcticatlas.org) or from the author (fnmkr@uaf.edu).

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Chapter 2 NDVI patterns and phytomass distribution in the circumpolar Arctic[1]

2.1 Abstract

The Circumpolar Arctic Vegetation Map (CAVM) was used to analyze the distribution of NDVI and phytomass in the Arctic, providing data for understanding arctic vegetation patterns, assessing change, and calibrating models. The dominant trend in the analysis of Normalized Difference Vegetation Index (NDVI) was a decrease from south to north, correlating with bioclimate subzones and vegetation units. NDVI also decreased at higher elevations and with higher substrate pH. In the coldest bioclimate subzone, increased elevation was not correlated with decreased NDVI. In the warmest tundra bioclimate subzone, especially in Alaska, NDVI did not decrease with the first several hundred meters of elevation. NDVI in this subzone varied more by region than by elevation or substrate chemistry and was lowest in recently glaciated areas such as the Canadian Shield. Phytomass (above-ground plant biomass) was calculated from NDVI using a relationship derived from ground clip-harvest data. Phytomass for the tundra bioclimate subzone was estimated at 2.5 x 10^{12} kg, with most of this in the warmest subzone, at the lowest elevations, and on acidic substrates.

Keywords: NDVI; Phytomass; Arctic; Arctic vegetation; Bioclimate; Substrate pH; Elevation

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[1] Martha K. Raynolds, Donald A. Walker, Hilmar A. Maier. 2006. NDVI patterns and phytomass distribution in the circumpolar Arctic. *Remote Sensing of Environment* 102: 271-281.

2.2 Introduction

Arctic land use is undergoing rapid change: expanding resource extraction and changing cultural practices are predicted to seriously impact over half of the Arctic within the next 50 years (Nellemann et al., 2001). In addition, the climate is changing; some areas are cooling while most are warming (Hassol, 2004; Comiso, 2003). As a result vegetation in the Arctic is changing (Goetz et al., 2005; Stow et al., 2004), including characteristics such as phytomass (aboveground plant biomass) (Jia et al., 2003). In order to determine the scale and importance of these changes and to evaluate any actions that might be taken in response, it is necessary to understand the present distribution of Arctic vegetation and phytomass. To meet this need, an international group of vegetation scientists collaborated to produce the Circumpolar Arctic Vegetation Map (CAVM) (CAVM Team, 2003; Walker et al., 2005). This paper summarizes vegetation characteristics indicated by spatial trends in the Normalized Difference Vegetation Index (NDVI) and phytomass shown on the CAVM. This analysis provides data for assessing change on global and regional levels and is useful for modeling climate change, for land-use planning, resource development, education and conservation studies.

2.3 Methods

2.3.1 Overview of the Circumpolar Arctic Vegetation Map

The CAVM used AVHRR satellite data to produce a false-color-infrared base map for delineating circumpolar vegetation units. The mapped area included all of the arctic tundra, defined as the bioclimate zone north of the climatic limit of trees that is characterized by an arctic climate, arctic flora, and tundra vegetation. It excluded tundra regions that have a boreal flora such as the boreal oceanic areas of Iceland and the Aleutian Islands, and anthropogenic treeless areas such as parts of Iceland, Fennoscandia and the Kola Peninsula. Alpine tundra regions south of the latitudinal treeline were also excluded (Walker et al., 2005). The total area of the arctic tundra as mapped by the CAVM was 7.11 x 10^6 km^2.

2.3.2 NDVI

Spectrum ratios such as NDVI were developed for non-destructive measurement of vegetation attributes from the ground (Jordan, 1969) and were then successfully applied to satellite spectral reflectance data (Rouse et al., 1974). NDVI is a measure of relative greenness, calculated as: NDVI = (NIR – R)/(NIR +R*)*, where NIR is the spectral reflectance in the near-infrared where light-reflectance from the plant canopy is dominant, and R is the reflectance in the red portion of the spectrum where chlorophyll absorbs maximally. The NDVI data for this analysis were calculated from the CAVM Advanced Very High Resolution Radiometer (AVHRR) image, comparing the spectral reflectance in the near-infrared channel (0.725-1.1 μm) with reflectance in the red channel (0.5 to 0.68 μm) (Fig. 2.1a).

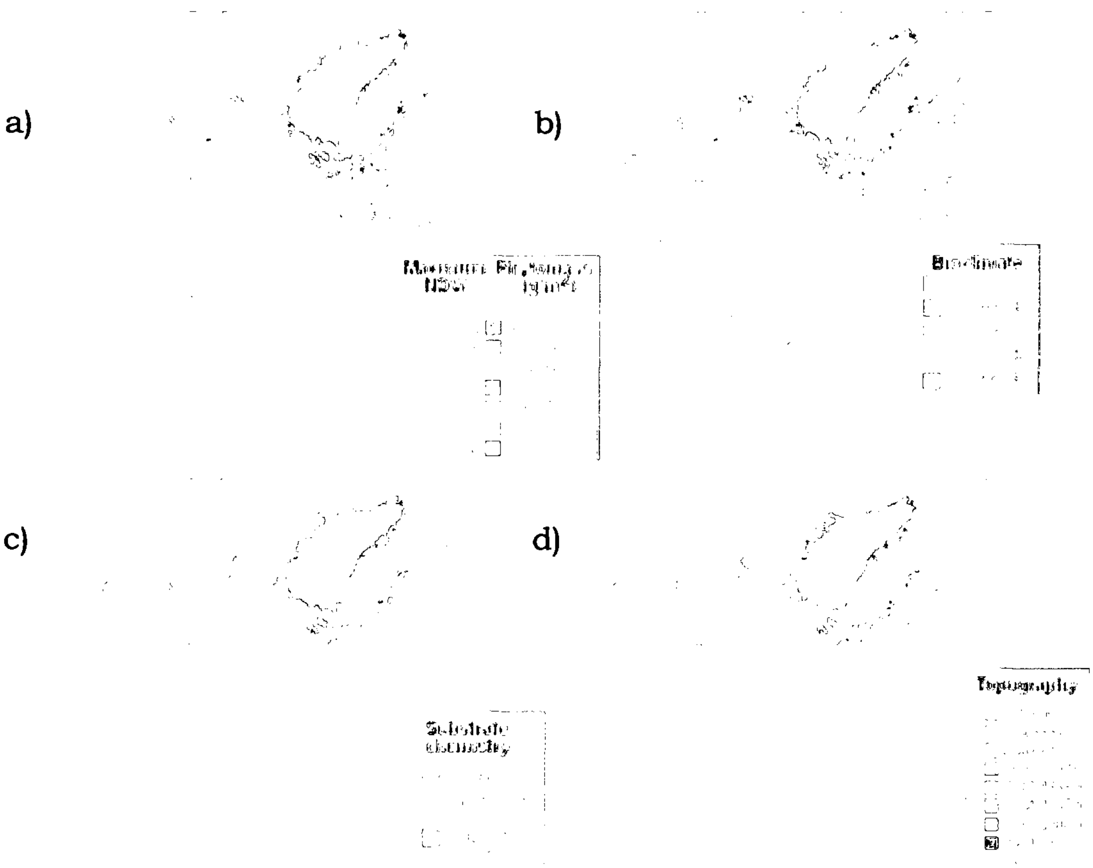

Figure 2.1 Small-scale versions of CAVM ancillary maps: a) NDVI/phytomass, b) bioclimate subzones, c) substrate chemistry, d) elevation (CAVM Team, 2003).

NDVI is affected by a variety of satellite and surface conditions, especially cloud cover and viewing angle, that can be compensated for by compositing data over time (Goward et al., 1991). Pixel data for this study were chosen for maximum greenness, selected from biweekly images from 11 July through 31 August in 1993 and 1995 (CAVM Team, 2003). Thus the data were composited first by taking the maximum value within two-week time periods, eliminating many pixels with cloud cover, then by taking the maximum of those pixels within two relatively cloud-free summers. The result was an almost cloud-free data set of peak NDVI for the circumpolar Arctic in the early 1990's.

NDVI has a theoretical maximum of 1 and is asymptotically non-linear as it approaches 1 and is therefore less sensitive to ground characteristics at higher values. NDVI essentially saturates in areas with a leaf area index (LAI) > 1 (van Wijk & Williams, 2005). This is generally not a severe problem in the Arctic where vegetation is often sparse and patchy, with an LAI < 1. Areas of dense shrub cover with NDVI > 0.6 are not well represented by this index, but do not cover large areas in the Arctic (Fig. 2.1a). The mean NDVI for the CAVM mapped area, excluding ice and water, was 0.32, well below the saturation point.

NDVI has been found to relate well to biophysical properties of arctic tundra on the ground, increasing with the amount of vegetation as measured by leaf area index (LAI) and phytomass (Riedel et al., 2005; Shippert et al., 1995). NDVI measures ground characteristics in a way that correlates well with arctic vegetation types (Hope et al., 1993; Stow et al., 1993) and age of arctic glacial surfaces (Walker et al., 1995). NDVI has been especially useful for analyzing variation in vegetation over large, remote regions of the Arctic (Bogaert et al., 2002; Jia et al., 2002; Markon et al., 1995; Shippert et al., 1995; Walker et al., 2003; Zhou et al., 2001).

2.3.3 CAVM maps

The CAVM included an integrated ARC/INFO database of 6717 polygons, coded for six geobotanical attributes, including vegetation (16 units), bioclimate subzone (5 units), floristic province (23 units), substrate chemistry (3 units), lake cover (6 units), and landscape type (7 units). The CAVM also included rastar images of elevation data (Digital Chart of the World; ESRI, 1993), and false-color-infrared (false-CIR), NDVI, and phytomass versions of the AVHRR composite image.

The CAVM divided the Tundra Bioclimate Zone into five subzones to characterize the variation in climate and flora which occurs between the polar desert and treeline (Fig. 2.1b). The primary factors defining these subzones were approximate 2 °C differences in mean-July temperature and the stature of woody vegetation (Fig. 2.2) (Walker et al., 2005).

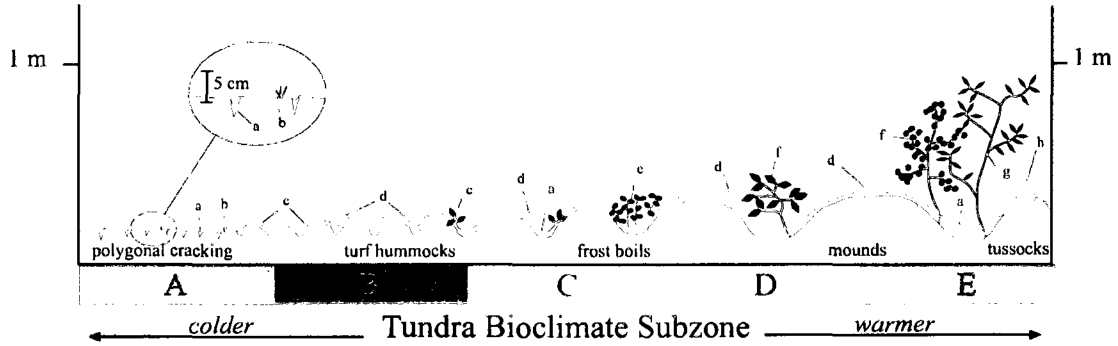

Figure 2.2 Plant physiognomy occurring in different Tundra Bioclimate Subzones: a- mosses, liverworts and lichens, b- forbs, c- prostrate dwarf-shrubs, d- non-tussock graminoids, e- hemiprostrate dwarf-shrubs, f- erect dwarf-shrubs, g- low shrubs, h- tussock graminoids.

Substrate types were divided into three major pH categories based on their effect on plant nutrient availability (Fig. 2.1c). Soils in the circumneutral range (pH 5.5-7.2) are generally rich in minerals needed by plants, whereas the full suite of essential nutrients is often unavailable in acidic soils (pH < 5.5) or in soils associated with calcareous bedrock (pH > 7.2) (Walker et al., 2003). Elevation was divided into 333-m elevation intervals to approximate adiabatic temperature shifts of 2 °C, the same approximate temperature shift that occurs between bioclimate subzones (Fig. 2.1d). Percent lake cover for each map polygon was calculated as the percent of black pixels in band 2 (0.725-1.1 µm, channel 2, value = 1). A two-pixel buffer along the coast was excluded, to reduce inclusions of ocean water in the calculations. This method underestimated percent lake cover for areas with many small ponds, as only lakes larger than 1 km^2 resulted in a pixel with a low enough NDVI to be recognized as water.

Vegetation was mapped using a single unifying legend based on plant physiognomy (general outward appearance) (Fig. 2.3). Scientists from Russia, Norway, Iceland, Greenland, Canada and the United States used a common mapping method and base map (1:4 million false-CIR derived from the AVHRR composite image) to delineate polygons with similar vegetation physiognomy (Walker et al., 2002). The mapping integrated information from existing vegetation maps, ground studies, data on soils, bedrock and surficial geology, hydrology, topography, climate, and NDVI. Detailed mapping methods, description of the legend, and area analysis of vegetation units can be found in Walker et al. (2005).

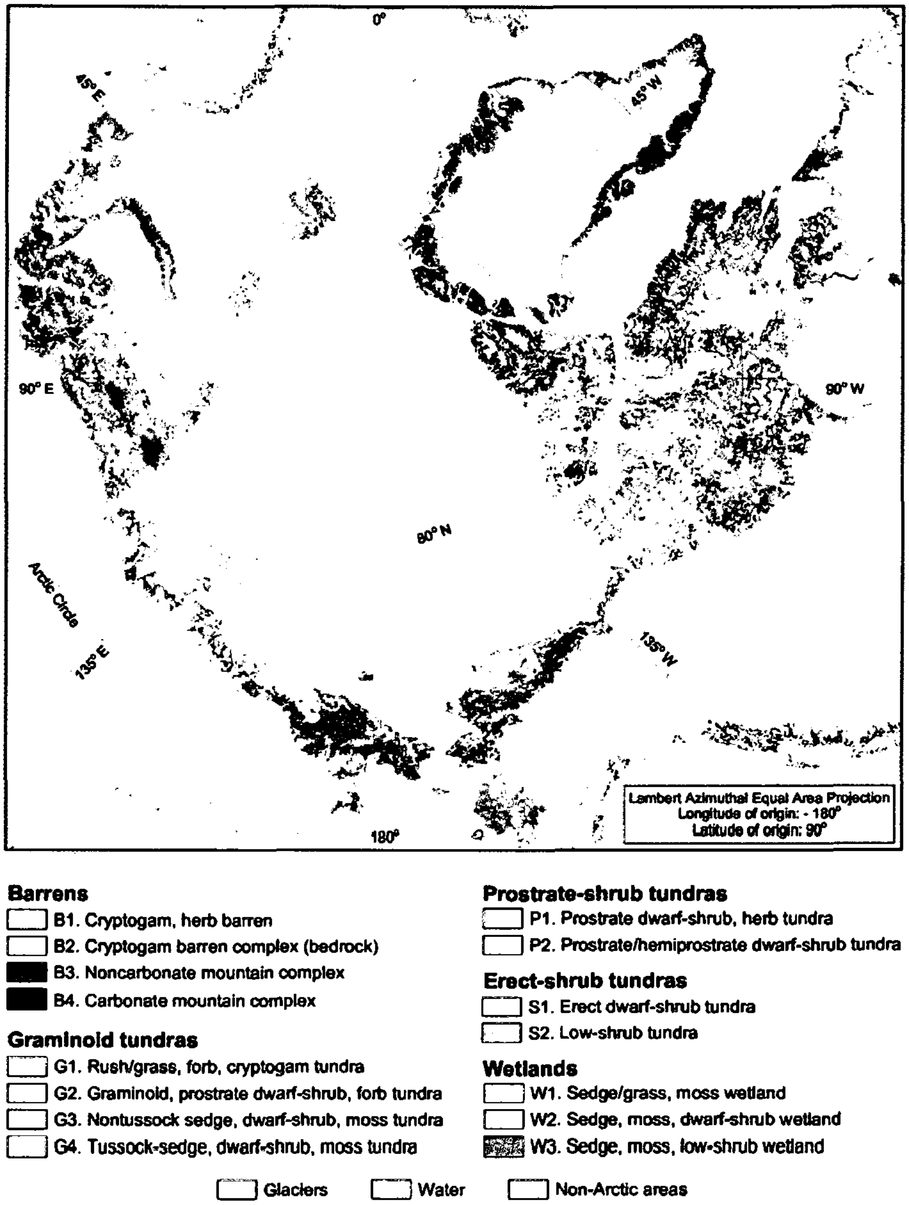

Figure 2.3 Small-scale version of the Circumpolar Arctic Vegetation Map (Walker et al. 2005).

2.3.4 Analysis of NDVI

The CAVM categories were used to stratify NDVI values of the arctic tundra. NDVI analyses excluded ice and water polygons: glaciers, nunatak regions, lakes and lagoons, reducing the original 6717 polygons to 6122 and reducing the area from 7.11 x 10^6 km^2 to 4.98 x 10^6 km^2. Mean NDVI pixel values were calculated for each bioclimate subzone, elevation class, substrate chemistry class, lake cover class, vegetation unit and floristic province. Standard deviations of the NDVI pixel categories are reported. The number of pixels is approximately equivalent to the area (each pixel is approximately 1.1 km^2), as shown in the phytomass tables. Comparative statistical tests were not run because they were not appropriate, since the NDVI values are true means of all pixels, not sample estimates.

A random sample of one out of every 1000 pixels within the mapped area was used to compare NDVI to elevation above sea level. Pixels from polygons coded as ice or water were excluded, as well as individual pixels with NDVI < 0.1 (mostly water and snow). This NDVI threshold is the same as that used to exclude snow and water pixels when tracking green-up and senescence of tundra vegetation (Jia et al., 2004). Scatter plots of NDVI by elevation were used to examine differences between countries in each of the five bioclimate subzones. Each subzone was further stratified by elevation (20 random pixels within 200-m elevation categories) and analyzed by regression.

Weighted general linear models were run to examine the variability in mean polygon NDVI weighted by area that was explained by bioclimate subzone, floristic province or country, elevation class, substrate chemistry class, and lake cover class (PROC GLM: SAS, 1989).

2.3.5 Estimates of phytomass from NDVI

NDVI has been used to estimate aboveground biomass (phytomass) for areas ranging from plots (Asrar et al., 1985) to biomes (Goward et al., 1985). Studies within arctic vegetation types have found limited correlation between NDVI and phytomass, but the relationship improves when more cover types are included (Boelman et al., 2005; Hope et al., 1993; Riedel et al., 2005). Researchers had assumed that NDVI would estimate green phytomass better than total phytomass, but for reasons that have not yet been explained the opposite has been the case (Riedel et al., 2005; Shippert et al., 1995), increasing confidence in estimates of total phytomass derived from NDVI. By using composited NDVI values such as annual peak NDVI and analyzing larger regions with a correspondingly larger range in NDVI values, researchers have found good correlation with total aboveground phytomass (Shippert et al., 1995; Walker et al., 2003).

The NDVI data used in this study, doubly composited data of the whole circumpolar arctic, should have a relatively robust relationship to phytomass. The relationship was calculated by regression, using clip harvest data (Fig. 2.4), as described by Walker et al. (2003). The phytomass data were collected on the North Slope of Alaska, with 6-10 replicates at each site, and correlated to maximum NDVI for an area of homogeneous vegetation around each sample site. Maximum NDVI was calculated from 14-day composites of 1 April to 31 October AVHRR data for 1995-1999.

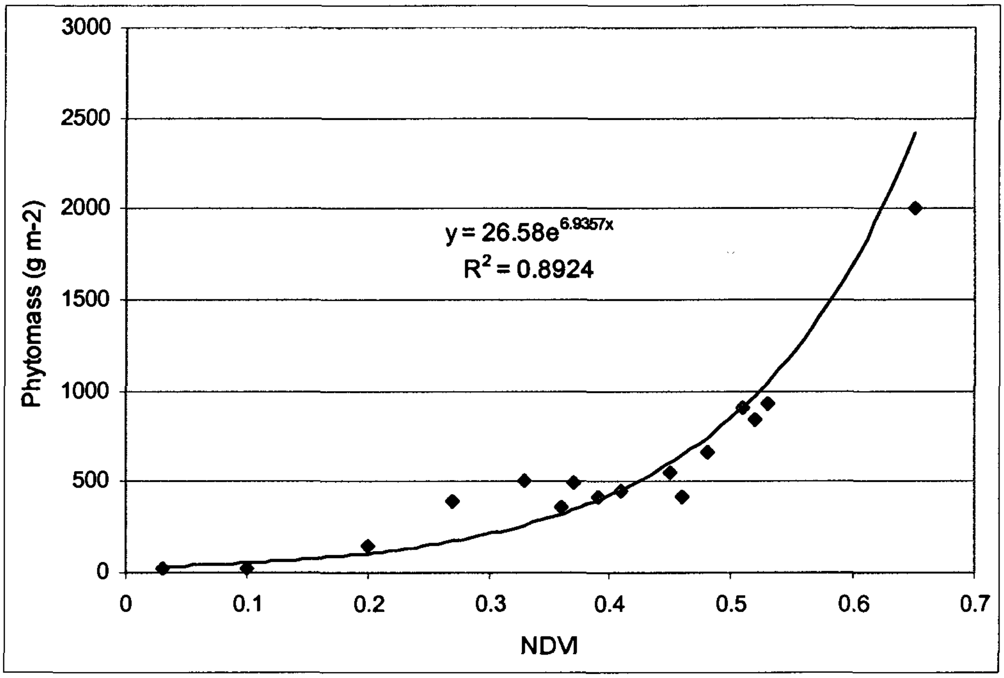

Figure 2.4 Regression relationship between aboveground plant biomass (phytomass) and NDVI (Walker et al. 2003).

Several researchers have shown linear relationships between NDVI and phytomass within arctic vegetation types (Boelman et al., 2005; Boelman et al., 2003; Hope et al., 1993; Riedel et al., 2005). However, when several vegetation types are sampled, including a larger range of NDVI values, the relationship is the curved form expected by the NDVI equation (asymptotic to 1) (Hope et al., 1993; Riedel et al., 2005; Walker et al., 2003). The relationship used in this analysis included a variety of vegetation types, but was based on a relatively small data set, with few data points for the lowest and highest values of NDVI. Attempts to increase the number of data points by including biomass data from other studies were hampered by lack of geo-referenced data and widely varying methods of harvesting and sorting samples (Walker et al., 2003). Points with high NDVI correspond to shrub communities with highly variable phytomass, so calculated phytomass values reported in this paper are only estimates. However, the relationship is useful for discerning major patterns of phytomass distribution in the Arctic.

A phytomass value for each pixel of the AVHRR image was calculated based on its maximum annual NDVI value, using the relationship shown in Figure 2.4. Phytomass data were summarized in tables for bioclimate subzones, elevation class, substrate, and chemistry class. The 23 floristic provinces were summarized by country to simplify presentation of the results. No more than two significant digits were included in the tables, acknowledging the limited precision of these figures. Due to rounding, the totals in the tables do not sum exactly.

2.4 Results

2.4.1 NDVI

Mean NDVI values for the CAVM polygons ranged from -0.04 to 0.66. The mean for all pixels in vegetated polygons was 0.32 (s.d. =0.038). NDVI in the Arctic increased from colder to warmer bioclimate subzones (Fig. 2.5), from 0.07 (s.d. = 0.005) in Subzone A to 0.44 (s.d. = 0.042) in Subzone E.

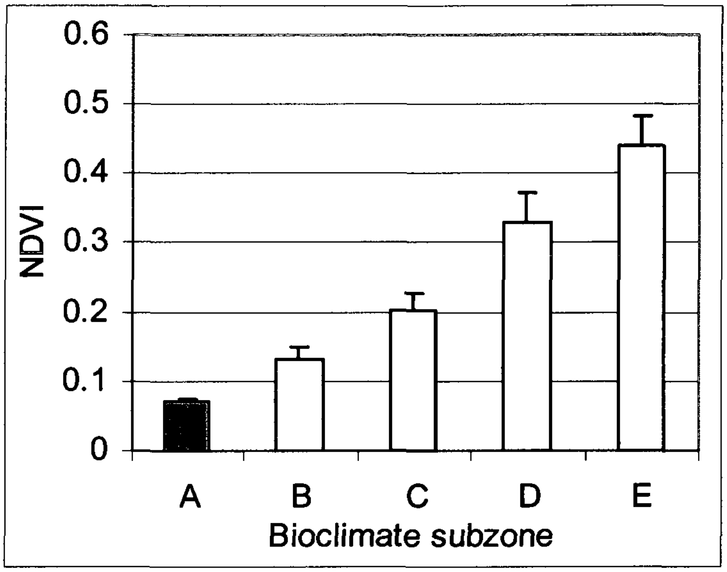

Figure 2.5 Mean NDVI of tundra bioclimate subzones, lines represent standard deviation of pixel values.

NDVI also decreased as elevation increased (Fig. 2.6). Mean NDVI for each 333-m elevation category (0 to >1667 m) were 0.32, 0.22, 0.15, 0.09, 0.14 and -0.02. There were no values for Subzone A and B at higher elevations, because these areas are permanently snow-covered. The only areas > 1667 m elevation are in Greenland in Subzones C and D, with negative values of NDVI indicating that these areas are mostly rock and ice with little vegetation. The mean NDVI values for the 0-333 m category represent the zonal NDVI values for each bioclimate subzone (0.07, 0.15, 0.23, 0.35 and 0.46 for Subzones A-E, respectively).

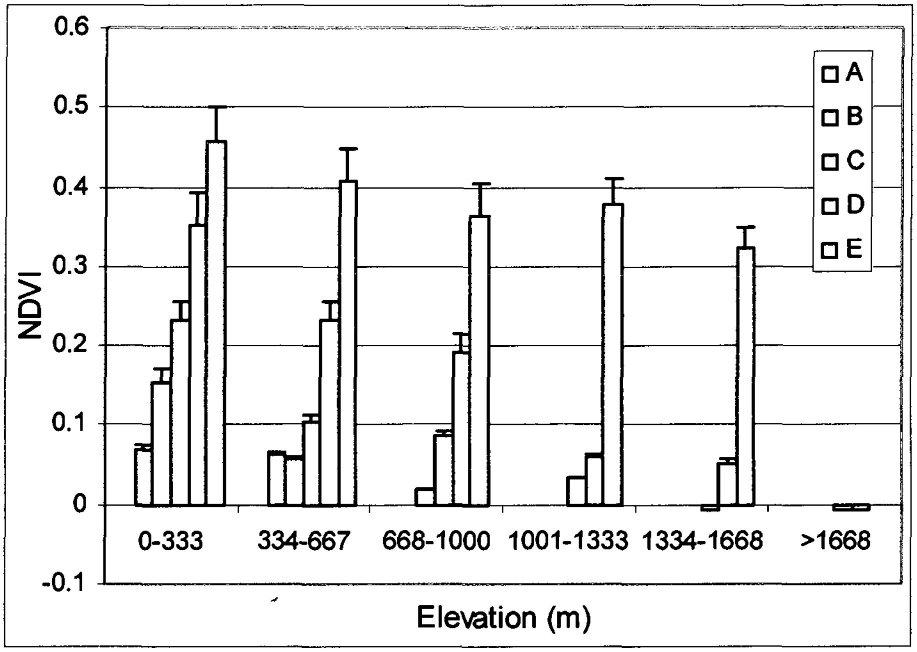

Figure 2.6 Mean NDVI of elevation classes divided by subzone, lines represent standard deviation of pixel values.

Linear regression of NDVI by elevation for a random sample of pixels (1/1000 of the total) showed little relationship, with an R^2 value of 0.08. This sample was stratified by subzone and plotted against elevation in Fig. 2.7 (a-e). In Subzone A both NDVI values and elevation values were low, with little correlation ($R^2 = 0.01$) (Fig. 2.7a). In Subzones B through D, NDVI values decreased with elevation, though there were also many low elevation pixels with low NDVI (Fig. 2.7b-2.7d). Regression

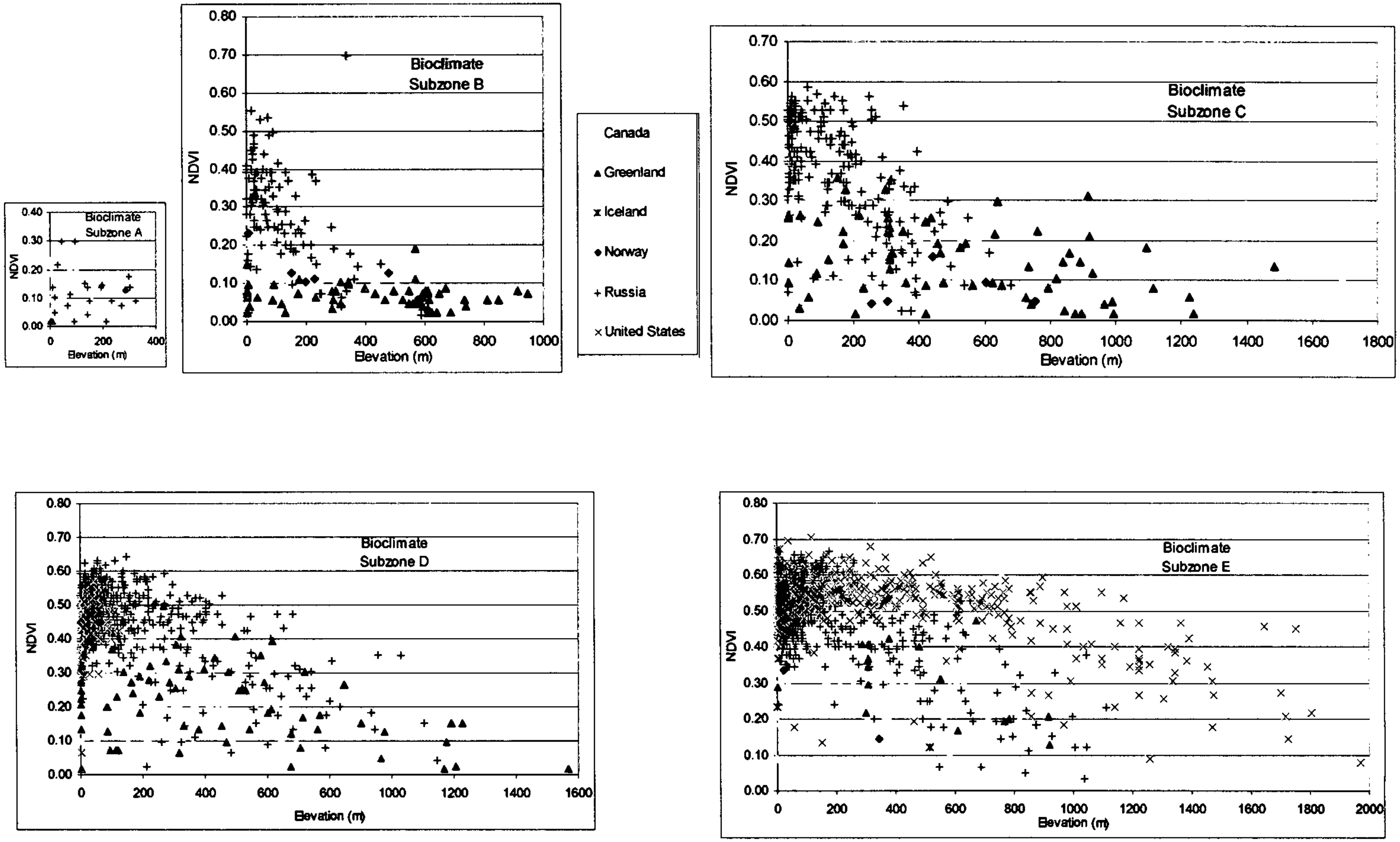

Figure 2.7 Mean NDVI value of CAVM polygons by elevation for Bioclimate Subzones A-E.

yielded R^2 values of 0.13, 0.18 and 0.13 for Subzones B, C and D, respectively. In Subzone E regional differences were pronounced (Fig. 2.7e). NDVI in Canada showed no relationship with elevation, while both Russia and the United States showed decreases in NDVI after 300 m and 600 m elevation, respectively. R^2 values within Subzone E were 0.02, 0.26, 0.35 and 0.35 for Canada, Greenland, Russia and the United States respectively. Norway and Iceland had too few points in this bioclimate subzone to carry out a regression. Stratifying by elevation within subzone did not change the regression relationship; the highest R^2 value was still only 0.41, in Subzone D.

Another factor controlling NDVI was the pH of the underlying substrate: NDVI increased with decreasing pH values (Fig. 2.8). The effect of changes in substrate on vegetation can be quite obvious on the ground (Fig. 2.9) and was evident in the NDVI analysis when all of the Arctic was combined, even without controlling for factors such as bioclimate subzone or elevation.

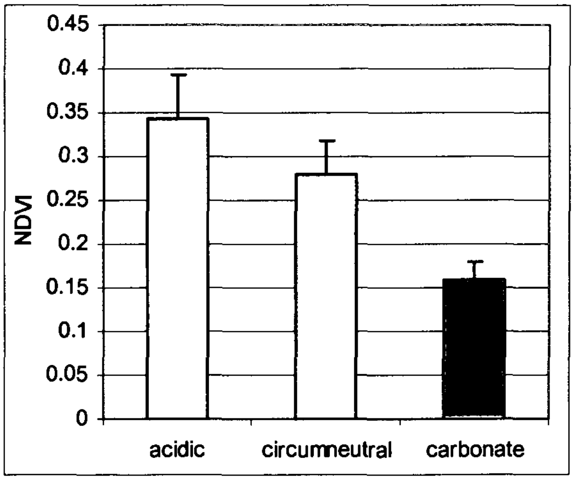

Figure 2.8 Mean NDVI of arctic substrate chemistry classes, lines represent standard deviation of pixel values.

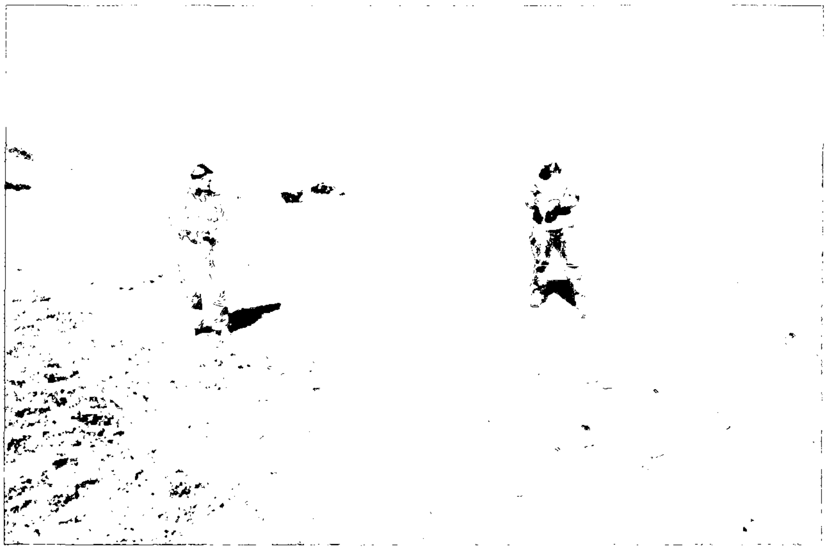

Figure 2.9 Variation in phytomass due to substrate chemistry, with more phytomass on the substrate on the left and less on the carbonate acidic area to the right (Council, Alaska, photo D.A. Walker).

NDVI did not change uniformly in response to lake cover: it was highest for polygons with 10-25% lake cover and lower for those with either less or more lake cover (Fig. 2.10). Polygons with the most lake cover (>75%) had the lowest NDVI. NDVI varied considerably between physiognomic vegetation units (Fig. 2.11), increasing from vegetation units typically found in more northern bioclimate subzones to those found in southern bioclimate subzones. NDVI of floristic provinces ranged from 0.03 in Svalbard – Franz Joseph Land, a region in the extreme High Arctic to 0.57 in the Kanin-Pechora province, a region with relatively mild winter climate, little permafrost and dense shrubs (Table 2.1).

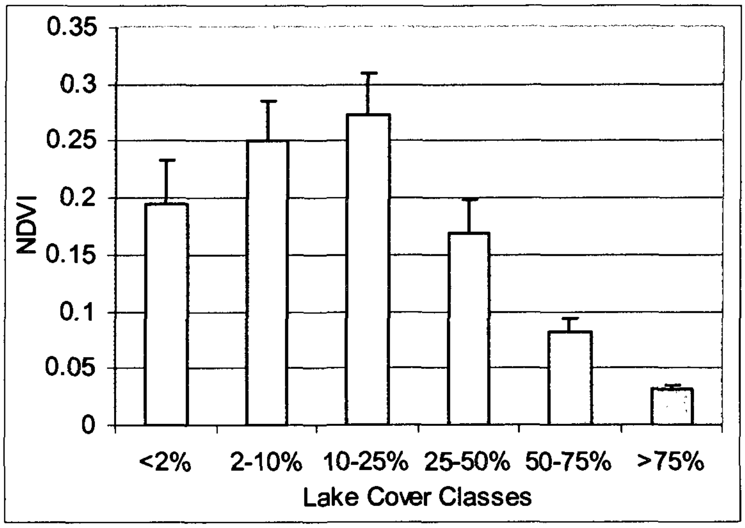

Figure 2.10 Mean NDVI of arctic lake cover classes, lines represent standard deviation of pixel values.

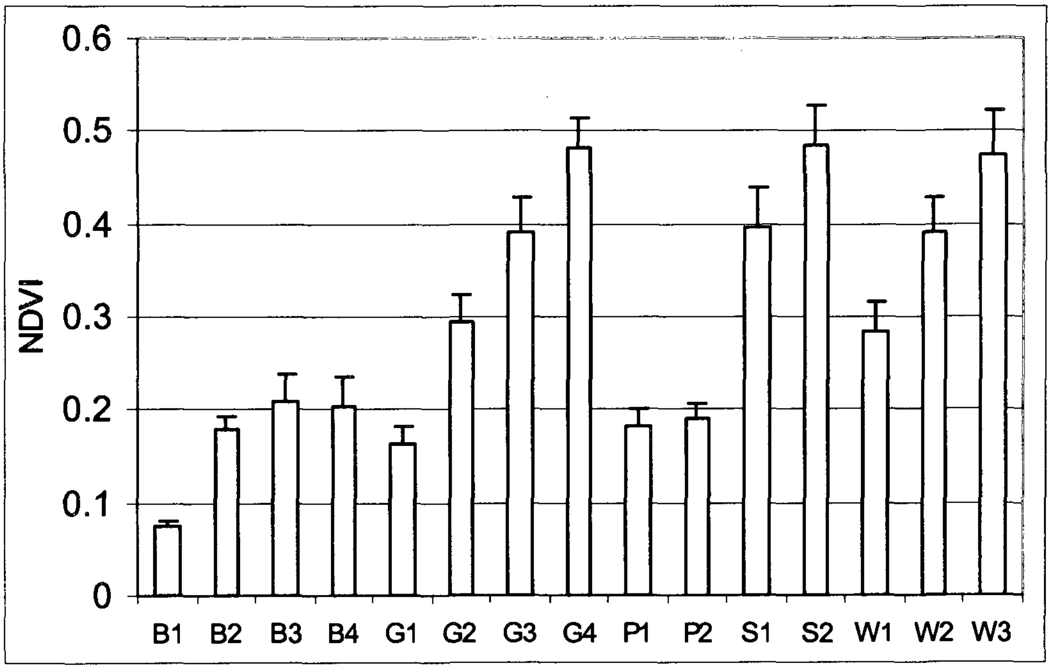

Figure 2.11 Mean NDVI of CAVM vegetation types, lines represent standard deviation of pixel values. B = barren, G = graminoid, P = prostrate shrub, S = erect shrub, W = wetland. For legend of vegetation units, see Figure 3.

Table 2.1 NDVI of Floristic Provinces of the Arctic Bioclimate Zone (mean and standard deviation of pixels)

Floristic Province	*Mean NDVI*	s.d.
North Beringian Islands	0.38	0.03
Beringian Alaska	0.51	0.04
Northern Alaska	0.44	0.04
Central Canada	0.23	0.03
West Hudsonian	0.22	0.03
Baffin - Labrador	0.22	0.02
Ellesmere-North Greenland	0.05	0.00
Western Greenland	0.20	0.02
Eastern Greenland	0.06	0.00
North Iceland - Jan Mayen	0.36	0.05
North Fennoscandia	0.34	0.04
Svalbard – Franz Joseph Land	0.03	0.00
Kanin - Pechora	0.57	0.04
Polar Ural - Novaya Zemlya	0.27	0.05
Yamal - Gydan	0.47	0.03
Taimyr	0.39	0.05
Anabar - Olenyek	0.42	0.04
Kharaulakh	0.39	0.03
Yana - Kolyma	0.42	0.05
West Chukotka	0.38	0.04
East Chukotka	0.39	0.04
South Chukotka	0.45	0.03
Wrangel Island	0.31	0.02

The results of the general linear models showed that all effects (country, floristic province, bioclimate subzone, elevation class, substrate chemistry class, and lake cover class) were highly significant ($p < 0.001$). This result was not surprising, given the large sample size (6717 polygons). The amount of variability accounted for by the models increased with the addition of each variable. The model that included all variables (country, bioclimate subzone, elevation, substrate chemistry and lake cover) accounted for 83.4% of the variance in NDVI (r-square coefficient).

2.4.2 Phytomass

Estimated total aboveground plant biomass (phytomass) of the Arctic was 2.5 x 10^{12} kg (Table 2.2). The combination of increasing NDVI towards the south and the increase in area of subzones as one goes from north to south, created a rapid rate of increase of phytomass with warmer subzones; 60% of the total phytomass of the Arctic was found in Subzone E.

Table 2.2 Area and phytomass of arctic tundra bioclimate subzones

Tundra bio-climate subzone	**Area** 1000 km^2	**Phytomass** kg x 10^9	*(%)*
A	114	6	*(<1)*
B	450	53	*(2)*
C	1179	220	*(9)*
D	1564	680	*(27)*
E	1840	1500	*(60)*
glaciers	1975	40	*(2)*
Total	**7122**	**2500**	***(100)***

The area covered by each successively higher elevation class decreased, except for elevations >2000 m, which included a large portion of the Greenland Ice Sheet (low phytomass, but large area) (Table 2.3). As shown in Figure 2.6, NDVI (and thus phytomass) decreased with elevation. The combination of these trends resulted in the lowest elevation class (0-333 m) accounting for 83% of the total phytomass in the Arctic.

Table 2.3 Arctic area and phytomass of elevation classes

Elevation class	Area 1000 km^2	Phytomass kg x 10^9	 *(%)*
0-333	4035	2100	*(83)*
334-667	945	300	*(12)*
668-1000	245	55	*(2)*
1001-1333	170	24	*(1)*
1334-1667	25	4	*(<1)*
1668-2000	5	<1	*(<0.1)*
>2000	1697	36	*(1)*
Total	**7122**	**2500**	***(100)***

Acidic substrates cover more area than circumneutral and carbonate areas together (Table 2.4). That effect, combined with the greater NDVI on acidic substrates resulted in 68% of the Arctic phytomass occurring on acidic areas. Because the "other" category (especially glaciers) covers such a huge area, small inclusions of vegetated areas added up to 2% of total phytomass.

When averaged by country, the NDVI of the arctic portions of Greenland (including the Greenland Ice Sheet) was the lowest (0.004), then arctic Norway (mostly Svalbard) at 0.05, arctic Canada at 0.21, arctic Iceland at 0.38, arctic Russia at 0.41, and arctic United States at 0.48. Similar patterns were seen in phytomass values (Table 2.5). Both Iceland and Norway, due to their small arctic areas, contributed only small amounts to total arctic phytomass. Most arctic phytomass (57%) was found in the Russian Arctic.

Table 2.4 Arctic area and phytomass of substrate chemistry classes

Substrate chemistry class	**Area** 1000 km^2	**Total phytomass** kg x 10^9	*(%)*
Carbonate *(pH > 7.2)*	370	58	*(2)*
Circumneutral *(pH 5.5-7.2)*	1789	690	*(27)*
Acidic *(pH < 5.5)*	2949	1700	*(68)*
Other *(glacier, lakes, saline)*	2015	60	*(2)*
Total	**7122**	**2500**	***(100)***

Table 2.5 Arctic area and phytomass of countries

Country	**Arctic area** 1000 km^2	**Total phytomass** kg x 10^9	*(%)*
Canada	2553	500	*(20)*
Greenland	2137	74	*(3)*
Iceland	7	5	*(<1)*
Norway	63	4	*(1)*
Russia	1872	1400	*(57)*
United States	491	510	*(20)*
Total	**7122**	**2500**	***(100)***

2.5 Discussion

2.5.1 Sources of variation in NDVI and phytomass

Arctic vegetation communities have similar physiognomies around the globe and share many species, but their distribution is far from uniform. The heterogeneity of the climate and environment due to factors such as latitude (Elvebakk et al., 1999; Razzhivin, 1999), elevation (Yurtsev, 1994), substrate (Walker & Everett, 1991), lake cover, glacial history (Hodkinson et al., 2003) and continentality, has large effects on the distribution of plant community types and distribution of biomass within the Arctic.

The dominant trend in the NDVI and phytomass of arctic vegetation is an increase from north to south (Subzone A to E). Arctic plant communities vary from sparsely vegetated types with very limited vascular flora in the coldest areas, to dense shrub stands and communities with up to 500 species near treeline (Elvebakk et al., 1999). Higher NDVI values in warmer subzones are a result of greater horizontal and vertical cover of plants, which in turn are due to more and larger plants, and more canopy layers. This expected pattern is corroborated by other researchers, who have documented increases in phytomass, LAI and NDVI correlated to increased summer warmth index and more southern latitudes (Jia et al., 2002; Walker et al., 2003).

NDVI also decreases with increasing elevation. Air temperatures decrease with elevation due to adiabatic cooling, reducing plant growth. Conditions in hills and mountains can also be less favorable to plant growth due to wind, thin soil, erosion, and poor sun exposure. Analysis of the CAVM data shows that the relationship between NDVI and elevation is not simple, and even when divided by bioclimate subzone the correlation is not very good. Most of Subzone A is low elevation, and all the pixels have relatively low NDVI values. Plants in this region are already well-adapted to cold, short growing seasons, and thus variations in elevation do not affect these communities much, so long as they are not frozen or snow covered year-round. In Subzones B-D, there is more decrease in NDVI with elevation, though regression R^2 coefficients are all < 0.2. In Subzone E, regional patterns are strong, with low NDVI values for Greenland regardless of elevation and many low elevation-high NDVI pixels in arctic Russia. For the United States (arctic Alaska), there is little change in NDVI with the first 666 m of elevation because the increase in elevation is combined with increasing distance from the coast. Thus the adiabatic cooling is offset by warmer summer temperatures due to continentality.

The effect of differences in substrate pH is evident in the NDVI analysis. Low NDVI values in carbonate areas reflect low nutrient availability and poor soil-forming properties of carbonate rocks. This result agrees with ground studies in Alaska which found more phytomass in acidic than non-acidic areas (Hope et al., 2003; Walker et al., 2001). Although areas with circumneutral substrates are richer in soil nutrients and have greater plant diversity, the abundance of forbs, lack of acidophilic shrub species, and prevalence of cryoturbation with resulting bare patches lead to lower NDVI values (Walker et al., 2001). The effect is compounded by the fact that a greater proportion of acidic substrates occur in Bioclimate Subzone E where plant biomass and NDVI values are higher, whereas a greater proportion of circumneutral soils are found in colder subzones. Higher plant productivity in warmer subzones leads to the development of insulating organic layers, which in turn leads to shallower active layers, wetter soils, more moss growth, and acidification of the substrate (Walker et al., 2001).

Polygons with < 10% lake cover have low NDVI values, indicating these areas are too dry for optimal plant growth. Areas with 10-15% lake cover have the highest NDVI values. These areas on average have optimal amounts of soil moisture to support plant growth, resulting from a combination of precipitation, soil texture, slope and drainage. They also include enough land area to maximize phytomass. Polygons with over 25% lake cover have the lowest mean NDVI values, as would be expected due to the inclusion of many water pixels with low NDVI value.

The strongest pattern in the NDVI of CAVM vegetation units is the higher NDVI values for types found in more southern bioclimate subzones. Barren types (B1-B4) have lower NDVI than other types. In Bioclimate Subzones B and C, graminoid and wetland units (G2, W1) have higher NDVI than the prostrate shrub unit (P2). This is because the prostrate shrub type occurs in drier areas, with larger proportions of bare ground. The graminoid and wetland types occur in more moist areas and more often have complete vegetative cover. This difference is not so pronounce in Bioclimate Subzone A (G1 vs. P1), because both of these types include high proportions of bare ground. Well-vegetated areas are rarer in Subzone A, usually occurring along drainages that are too small to map at the scale of the CAVM. In the warmest subzones (D and E), the graminoid, shrub and wetland vegetation units all have similar mean NDVI. Units occurring primarily in Subzone D (G3, S1, W2) have lower values than those found mostly in Subzone E (G4, S2, W3).

Each country's average NDVI value is a result of a combination of the factors discussed above. As the general linear model showed, each of the factors is significant in explaining variation in NDVI. Arctic Norway's low NDVI is due to the fact that 69% of the area is in Bioclimate Subzone A in Svalbard. Greenland's low value is due partly to its high average elevation (562 m). Arctic Canada's low value is partly due to a high proportion (48%) of non-acidic substrates (pH > 5.5) and large proportion of area in the High Arctic (46% in Subzones A, B and C). The high average NDVI in arctic Russia is partly due to relatively low mean elevation (134 m) and high proportion of area in the Low Arctic (77% in Subzones D and E). Similarly, 83% of the United States' arctic area is in Bioclimate Subzone E, resulting in high NDVI values. The highest NDVI values in the Arctic are found in European Russian, the southern Taimyr, northwestern Alaska and the Yukon-Kuskokwim Delta area, in areas of shrub tundra in the warmest subzone (E), on low-elevation, non-carbonate substrates, often with well-developed alluvial soils, and where permafrost is absent, discontinuous or sporadic (Brown et al., 1997).

Another factor affecting NDVI that has not been addressed by this analysis is recent geologic history. Large regions of the Arctic with low NDVI in warmer subzones were recently glaciated. Glaciation removed soil and created a rocky landscape with many lakes. Decreased vegetation cover and the increased water cover both lower NDVI values. Low NDVI values due to glaciation are especially prevalent in the Canadian Shield area. This is an area of moderate elevation and favorable substrate chemistry that extends into the southern latitudes of the Arctic, where one would expect high NDVI values. Yet, as can be seen in Figure 2.2a, the area around Hudson Bay (the epicenter of the Laurentide Ice Sheet) has low NDVI values. Differences in the degree of glaciation of the landscape and age since deglaciation are still evident after tens of thousands of years, as shown by studies on the Alaska North Slope where older glacial surfaces were shown to have higher NDVI values than younger surfaces (Walker et al., 1995).

These trends in NDVI translate into similar trends in phytomass. Greenland, with slightly less arctic area than Canada has only 15% of Canada's arctic phytomass because most of its area is covered by the Greenland Ice Sheet. Canada, though it has over five times as much arctic area as the United States, has less arctic phytomass than the U.S. Most of the arctic phytomass is found in Subzone E, below 333 m elevation, and on acidic substrates. Most of the arctic phytomass grows in the Russian Arctic, which has large areas meeting these criteria.

2.5.2 Modeling distribution of arctic vegetation

Researchers modeling the effect of warming on arctic tundra vegetation have sometimes modeled all arctic tundra as one or two cover types and have often assumed that warming will produce a simple shift north in vegetation types. More realistic results were produced by Kaplan et al. (2003) modeling plant functional types in a carbon and water flux model, but spatial distribution of the five tundra vegetation types was not well represented, especially in the glaciated areas of arctic Canada. The model is based on inputs of climate (temperature, sunlight and precipitation) and soil data (texture and depth). The results of this study indicate that including elevation and substrate, as well as better spatial resolution of climate and soils data would likely improve the results of this model.

2.6 Conclusion

The climate of the Arctic is changing, and there is strong interest in understanding how vegetation will respond to and contribute to this change (Hassol, 2004). One approach to answering this question has been a coordinated set of international experiments to examine how tundra responds to warming (ITEX experiments, (Walker et al., 2006). Another approach is to look at the existing variation in Arctic vegetation corresponding to bioclimate subzones. Because the trend of increasing phytomass with warmer bioclimate subzones is so strong, it is tempting to use that trend alone to predict climate-induced changes in vegetation characteristics. However, different factors control phytomass in different parts of the Arctic, as shown by this analysis of NDVI. In the coldest subzone (A), NDVI and phytomass values are not much affected by changes in elevation or substrate, and are similar in all regions of the Arctic. In this subzone there is a limited vascular flora and all species are at the coldest extreme of their growing range. Since these plants are so constrained by climate, there is little variation in NDVI due to factors other than temperature. In the intermediate subzones (B-D), factors such as elevation, substrate and regional characteristics begin to exert a stronger influence. Increased plant diversity and a wider range of habitable conditions allow more competition and specialization of plant communities, resulting in a larger range in NDVI values. In the warmest subzone (E), much of the variation in NDVI and phytomass is due to geologic history. Mountains, wetlands, glaciations, sea-level fluctuations, and fluvial depositions all affect how long soils have had to develop and how long plants have had to colonize and evolve into communities. Climate, substrate and flora all have to be optimal to reach maximum NDVI. This study shows that modelers interested in including arctic phytomass in their systems should not assume that phytomass will increase uniformly across the Arctic with increases in temperature. As subzones warm, existing local and regional environmental factors have more influence on variation in plant growth and phytomass. Policy makers should not assume that vegetation types that are now present farther south will simply move north. This analysis of NDVI and phytomass distribution in the Arctic demonstrates that predictions of climate-induced changes in vegetation in the Arctic need to take into account factors such as elevation, substrate chemistry and glacial history.

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Chapter 3 Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI[1]

3.1 Abstract

Arctic vegetation distribution is largely controlled by climate, particularly summer temperatures. Summer temperatures have been increasing in the Arctic and this trend is expected to continue. Arctic vegetation has been shown to change in response to increases in summer temperatures, which in turn affects arctic fauna, human communities and industries. An understanding of the relationship of existing plant communities to temperature is important in order to monitor change effectively. In addition, variation along existing climate gradients can help predict where and how vegetation changes may occur as climate warming continues. In this study we described the spatial relationship between satellite-derived land surface temperature (LST), circumpolar arctic vegetation, and normalized difference vegetation index (NDVI). LST, mapped as summer warmth index (SWI), accurately portrayed temperature gradients due to latitude, elevation and distance from the coast. The SWI maps also reflected NDVI patterns, though NDVI patterns were more complex due to the effects of lakes, different substrates and different-aged glacial surfaces. We found that for the whole Arctic, a 5 °C increase in SWI along the climate gradient corresponded to an increase in NDVI of approximately 0.07. This result supports and is of similar

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[1] Martha K. Raynolds, Josefino C. Comiso, Donald A. Walker, David Verbyla. 2008. Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI. *Remote Sensing of Environment* 112: 1884-1894.

magnitude as temporal studies showing increases of arctic NDVI corresponding to increases in growing season temperatures over the length of the satellite record. The strongest positive relationship between NDVI and SWI occurred in partially vegetated and graminoid vegetation types. Recently de-glaciated areas, areas with many water bodies, carbonate soil areas, and high mountains had lower NDVI values than predicted by SWI. Plant growth in these areas was limited by substrate factors as well as temperature, and thus is likely to respond less to climate warming than other areas.

3.2 Introduction

The goal of this research was to use a circumpolar temperature data set to show how long-term temperature-means relate to the existing distribution of arctic vegetation. Climate change is occurring at a faster rate in the Arctic than other biomes, and is resulting in an increase of summer temperatures in almost all areas of the Arctic (Comiso, 2006; Hassol, 2004). Understanding the relationship between existing plant communities and temperature is important in order to effectively monitor changes. In addition, variation along existing climate gradients can help predict where and how vegetation changes may occur as climate warming continues.

We focused on temperature data to investigate the distribution of arctic vegetation, because the existing distribution is largely controlled by climate. Plant community composition is limited to species that are able to tolerate the coldest summer temperatures at any given location (Bliss and Petersen, 1992). Plant physiological activities, such as water and nutrient transport, photosynthesis, and respiration, all occur at minimal levels in below-freezing temperatures and increase as plant tissues warm (Lambers et al., 1998). Arctic plants have adapted to cold temperatures by reducing the temperatures at which they achieve a maximum rate of photosynthesis, but these temperatures are still 5 to 10 °C higher than average leaf temperatures in the field (Lambers et al., 1998). As a result, plant energy budgets in the Arctic are limited by summer temperatures, which restrict the amount of plant vegetative growth and reproductive effort possible in any year. Plants that are not well-adapted to photosynthesizing in cold temperatures end up with negative energy balances and do not survive.

Arctic plants communities have been shown to respond to experimental increases in summer temperature. Meta-analysis of standardized tundra warming experiments determined that deciduous shrub and graminoid vegetation increased and non-vascular vegetation decreased (Walker et al., 2006). These types of vegetation changes interact with snow, soil, and permafrost characteristics (Walker et al., 2006; Sturm et al., 2001) with resulting impacts on arctic animals, human communities, infrastructure and industries that rely on tundra ecosystems.

In addition to temperature, arctic plants can also be limited by dispersal, especially in recently de-glaciated areas. However, a study of the Svalbard flora found that the effect of cold summer temperatures on plant establishment was much more limiting to colonization than seed or propagule availability (Alsos et al., 2007). Substrate conditions such as soil moisture or chemistry can also limit plant growth and favor different groups of species (Walker et al., 2001). These substrate limitations are super-imposed on the larger-scale climatic limitations.

To characterize the distribution of arctic vegetation, we used maps and satellite data. The distribution of 15 arctic vegetation types was mapped and described on the Circumpolar Arctic Vegetation Map (CAVM) (CAVM Team, 2003; Walker et al., 2005). The map's unifying circumpolar legend facilitated analysis of the entire Arctic.

The most informative satellite data for studying arctic vegetation are summarized in the normalized difference vegetation index (NDVI), a measure of relative greenness. NDVI is calculated as: $NDVI = (NIR - R)/(NIR + R)$, where NIR is the spectral reflectance in the near-infrared where reflectance from the plant canopy is dominant, and R is the reflectance in the red portion of the spectrum where chlorophyll absorbs maximally. NDVI has a theoretical maximum of 1 and its relationship to vegetation characteristics such as biomass, productivity, percent cover and leaf area index is asymptotically nonlinear as it approaches 1. As a result, NDVI is less sensitive to ground characteristics at higher values and essentially saturates when leaf area index > 1 (van Wijk and Williams, 2005). This is not a severe problem in the Arctic where vegetation is often sparse and patchy: the mean NDVI for the Arctic, excluding ice and water, was 0.32, well below the saturation point (Raynolds et al., 2006).

NDVI has been found to relate well to the biophysical properties of arctic tundra on the ground. NDVI values increase with the amount of vegetation as measured by leaf area index (LAI) and phytomass (Riedel et al., 2005; Shippert et al., 1995). NDVI values correlate well with ground characteristics of arctic vegetation and can be used to distinguish between vegetation types (Hope et al., 1993; Stow et al., 1993).

Most studies comparing arctic NDVI and temperature have looked at change over time, focusing on the effects of anthropogenic climate change. Myneni et al. (1997), Bogaert et al. (2002), Jia et al. (2003), Zhou et al. (2003) and Goetz et al. (2005) all found increases in arctic NDVI related to increases in temperature over time. There have been questions as to whether these results were an artifact of the satellite record due to orbit degradation and changes in sensors between satellites (Fung, 1997; Kaufmann et al., 2000). Ground studies have been able to document changes in shrub cover in some areas (Tape et al., 2006), but have had difficulty measuring large-scale changes in vegetation cover in the Arctic (Callaghan, 2005). A few studies have looked for effects in the opposite direction: the influence of arctic and boreal vegetation on surface temperatures (Hope et al., 2005) (Kaufman et al., 2003), but in the Arctic the effect is much stronger in the other direction, with summer temperatures determining NDVI values (Kaufman et al., 2003). Changes in arctic NDVI with latitude have been correlated with bioclimate zones (Raynolds et al., 2006) and on the North Slope of Alaska with total summer warmth (Jia et al., 2002).

This study looked at the whole circumpolar Arctic to determine the relationship between long term means of summer land-surface temperatures, NDVI, and vegetation type distribution. We also looked at the spatial change of NDVI with temperature, to verify the correlation reported in the time-series analyses of satellite data.

3.3 Methods

We compared three data sets: a circumpolar surface temperature data set derived from AVHRR data (Advanced Very High Resolution Radiometer) (Comiso, 2006), a circumpolar vegetation map (CAVM Team, 2003), and NDVI data derived from AVHRR data (CAVM Team, 2003; Tucker et al., 2004).

3.3.1 Temperature data set

Land surface temperatures were calculated from AVHRR data. Geolocation and orbital drift were corrected using standard NOAA procedures (Comiso, 2000). Daily differencing and moving window techniques were used to eliminate cloud-contaminated pixels (Comiso, 2000). A constant emissivity value of 0.94 was used to calculate temperature from the thermal infra-red channels 3 (3.5 – 3.9 μm), 4 (10.3 – 11.3 μm) and 5 (11.5 – 12.5 μm). The data were geographically mapped to 12.5 km pixels in a North Pole Stereographic projection and composited into monthly means from 1982-2003 (Comiso, 2003; Comiso, 2006).

We chose the AVHRR temperature data because of the relatively detailed spatial resolution over the entire polar region and the long time period spanned by the record. The AVHRR is a horizontally scanning radiometer with a swath width of 2900 km and a field-of-view of 1 mrad, thereby providing data at a spatial resolution of 1.1 km at nadir. Continuous global coverage, however, is available only in a sub-sampled format at about 5 by 3 km resolution. The AVHRR temperature data provide better spatial resolution than modeled data sets, which interpolate between climate stations. Arctic climate stations are few, unevenly distributed around the pole, and located mostly along coasts (Rawlins and Willmot, 2003). The station data have been found to have numerous problems that bring into question the reliability of their time-series data (Pielke et al., 2007). The interpolated data sets derived from the station data tend to have high temporal resolution, but relatively coarse spatial resolution (55-100 km pixels, (Rawlins and Willmot, 2003; Rigor et al., 2000), whereas the finer spatial resolution and coarser temporal resolution of the AVHRR temperature data are more appropriate for analyzing vegetation distribution.

The AVHRR data were compiled from 1982 to 2003, providing the longest satellite temperature record available. The length of this record, especially the inclusion of the earliest years, was important in producing a mean that characterized the conditions that created the present distribution of arctic vegetation. Arctic vegetation communities are only beginning to respond to recent climate changes and our goal was to minimize this effect in the temperature data.

The AVHRR temperature is the surface skin radiant temperature of approximately the first 50 μm of leaf surfaces (Lillesand and Kiefer, 1989). This surface temperature characterizes the environment of low growing tundra plants better than climate station temperature data, which are measured 2 m above the ground in shelters that protect against sun, wind and precipitation. In many situations, especially throughout the winter, there is little difference between ground and surface temperatures (Comiso, 2003). However, when snow melts and albedo of the surface drops, the soil surface warms from the sun's radiation. Differences start to appear for temperatures above 0 °C and are largest for sunny days and warmest temperatures (Comiso, 2003; Karlsen and Elvebakk, 2003). On a monthly basis, arctic mid-summer land surface temperatures are warmer than air temperatures at 2 m by about 2 °C (AVHRR LST warmer than NOAA data from Umiat Alaska 1982-2000: 2.18 °C in June, 2.08 °C in July; AVHRR LST warmer than Toolik LTER data 1989-2003: 2.92 °C in June, 0.83 °C in July).

Summer warmth index (SWI) was calculated from the AVHRR temperature data (Comiso, 2006). This index characterizes the plant growing season by summing monthly mean temperatures, with a 0 °C threshold required for a month to be included. The months of May-September were evaluated for each year. This index combines the effect of both the length and the warmth of summer temperatures, and is the climate variable found to correlate best with variations in arctic vegetation distribution (Edlund, 1990; Young, 1971).

3.3.2 CAVM classified attributes

The second data set used in this analysis was the Circumpolar Arctic Vegetation Map (CAVM) (CAVM Team, 2003). The map was created by an international team including scientists from Russia, Norway, Iceland, Greenland, Canada and the United States. The mapped area included all of the arctic tundra, defined as the region north of the climatic limit of trees that is characterized by an arctic climate, arctic flora, and tundra vegetation. Existing data on vegetation distribution and key environmental and biological factors were compiled, using a false-CIR AVHRR image as a base map. The unified circumpolar legend of 15 tundra vegetation types was based on the general outward appearance of the vegetation (physiognomy) (Raynolds and Walker, 2006; Walker et al., 2005).

The CAVM polygon data were used for this analysis. In addition to vegetation type, each polygon also had data on bioclimate subzone, elevation, lake cover, substrate chemistry and landscape type (Walker et al., 2005). Maps of these attributes can be seen on the web site www.arcticatlas.org.

3.3.3 NDVI data

A 1 km-resolution maximum-NDVI data set was used for this study. These data were from the U.S. Geological Service EROS AVHRR polar composite of NDVI data for 1993 and 1995 (CAVM Team, 2003; Markon et al., 1995). Daily data were collected by AVHRR sensors onboard NOAA satellites for channel 1, red (0.5 to 0.68 µm) and channel 2, near-infrared (0.725-1.1 µm). These were the same sensors that collected the data for the temperature calculations, though different bands were used. The daily NDVI values were calculated and then composited into one maximum value for 10-day periods. NDVI is affected by a variety of satellite and surface conditions, especially cloud cover and viewing angle, that can be compensated for by compositing data over time (Goward et al., 1991). The maximum values during two relatively cloud-free summers (11 July - 31 August in 1993 and 1995) were used to create an almost cloud-free data set of maximum NDVI for the circumpolar Arctic in the early 1990s.

Summarizing composited NDVI into maximum NDVI eliminated seasonal variation in NDVI (Riedel et al., 2005).

The authors tried using the GIMMS AVHRR NDVI data set (Tucker et al., 2004), which covered the same time period as the temperature data, provided a long time-period for compositing, and was a commonly used, easily available data set with the latest calibrations and corrections. However, the GIMMS data set did not provide good coverage of the Arctic. Northeastern Greenland, Wrangel Island and a part of the north coast of Chukotka were missing. The data set also had very abrupt swath boundaries in the Taimyr area of Russia, in Chukotka, and in the Canadian Arctic Islands. This swath boundary is due to calibration issues in the GIMMS processing procedure, which used SPOT Vegetation satellite data to mosaic separate swaths. SPOT data were not available north of 70° N (Jia, pers. comm., Tucker pers. comm.), resulting in a distinct boundary line at that latitude.

A comparison between a subset of the GIMMS and CAVM NDVI data is shown in Figure 3.1. Alaska was chosen as a portion of the Arctic that did not have any missing GIMMS data and minimal swath boundary contrast (most of Alaska is south of 70° N). Maximum annual NDVI for 1982-2003 was calculated for the GIMMS data (Tucker et al., 2004). NDVI values for CAVM map polygons of different vegetation types were calculated and expressed as an index of the mean for easier comparison. The indexed NDVI values for the GIMMS and the CAVM data were similar for all vegetation types except for glaciers, lakes and lagoons. These ice and water cover types had significantly lower NDVI values than surrounding areas (Raynolds et al., 2006), as can be seen in the CAVM values in Figure 3.1. They had higher values in the GIMMS data because the larger 8 km pixels of the GIMMS data recorded a mixed signal of land and water or ice. The lower values shown by the 1 km CAVM data more correctly characterize the CAVM polygons. Two vegetation types with smaller differences (P2 and W1) were the least common types in the Alaska map area and occurred as small polygons that were also not well represented by the GIMMS 8 km pixels.

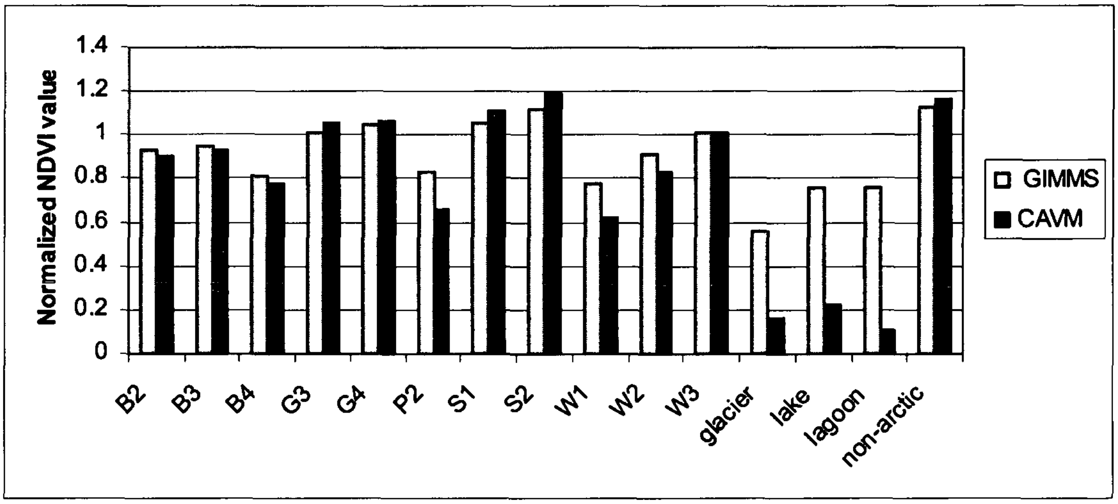

Figure 3.1 Comparison of arctic Alaska portion of GIMMS 8 km NDVI data (maximum for 1982-2003) and CAVM 1 km NDVI data (maximum for 1993 and 1995). NDVI mean values of CAVM vegetation types were normalized by the mean of each data set for ease of comparison. See Table 2 for full name of vegetation types.

The CAVM data set provided much higher spatial resolution than the GIMMS data set (1 km vs. 8 km) and the data were complete and uniform for the entire Arctic, so we used the CAVM NDVI data for the circumpolar analysis. The close correspondence of the indexed NDVI values for different common vegetation types in the CAVM and GIMMS data for Alaska demonstrated that the two years included in the CAVM data characterized the vegetation in a similar way as the 22-year GIMMS data set. Interannual variance in AVHRR maximum annual NDVI on two transects across the North Slope of Alaska during the 1990's ranged from 0.03 to 0.05, averaging about 0.04, and was very spatially heterogeneous (Jia et al., 2006). This interannual difference in NDVI is smaller than most of the differences discussed in this study. In addition, this study compared NDVI of large areas, which reduced the spatially heterogeneous interannual variation evident on the 1-km scale (Jia et al., 2006).

3.3.4 Analysis

The land surface temperature data were used to create a digital map of the 22-year mean of SWI for the Arctic. The CAVM bioclimate subzone and vegetation maps were compared with the raster SWI data. Mixed pixels that included water along coastlines were removed using a 1-pixel (12.5 km) buffer. Mean SWI was calculated for each CAVM vegetation type. For the bioclimate subzone analysis, mountain, water and ice pixels were eliminated, because the CAVM zonation map is a generalized vector map that did not separate out these extra-zonal areas. Mountain zonation was too spatially heterogeneous to map at the CAVM scale of 1:7.5 million. Ice and lakes were eliminated from the analysis because their temperatures do not represent the temperature of zonal vegetated areas. Lake temperatures lag behind land temperatures in the summer due to the higher heat capacity of water and are thus cooler than land, with lower SWI values. Pixels with elevation > 333 m in the Digital Chart of the World (ESRI, 1993), or ones that corresponded to areas mapped as glaciers, nunataks, lakes or lagoons in the CAVM were removed from the SWI grid before the zonal analysis. The remaining pixels were used to calculate mean SWI for each CAVM bioclimate subzone.

Simple linear regression was used to model NDVI as a function of SWI. The 1 km NDVI data set was re-sampled, increasing the pixel size from 1 km to 12.5 km to match the pixel size of the LST data set. Mixed water or ice pixels were avoided by using the coastal-buffered data set described above. Pixels in areas mapped as lakes, lagoons or glaciers in the CAVM were excluded, but all elevations were retained, resulting in 25,690 pixels for the analysis. The regression was carried out with two temperature data sets: the mean SWI for the full 22-year period 1982-2003, and for the two years that matched the NDVI data (1993 and 1995). Using the shorter temperature data set improved the correlation somewhat, but the magnitude of the relationship was almost identical (see Results section below; 22-year data set: $y = 0.0137x - 0.0204$, $R^2 = 0.5814$; 2-year data set: $y = 0.0134x - 0.0351$, $R^2 = 0.6073$). Interannual variability in NDVI resulted in a slightly better fit better for the two-year data set, but the circumpolar pattern of vegetation is based on the long-term climate. Since the goal of this paper was to examine spatial variation in arctic vegetation, not temporal variation, the longer-term temperature data set was used in the analysis.

The regression equation was used to create a map of residuals, showing pixels with greater or lower NDVI values than those calculated by the equation. Linear regression was also used to model NDVI as a function of SWI within CAVM categories for vegetation, substrate chemistry, elevation, and percent lake cover. General linear models (GLM) using combinations of factors were run to determine which model accounted for most of the variation in NDVI between CAVM polygons (R Development Core Team, 2006).

3.4 Results

3.4.1 SWI

The map of Summer Warmth Index based on a 22-year mean of AVHRR land surface temperatures (Figure 3.2) showed a range from 0 to 49.1 °C. The coldest areas were surrounding glaciers and along the coasts of arctic islands, areas that had few months with a mean temperature > 0 °C and means that barely reached above zero during those months. The areas with the warmest summers were the Selawik area in NW Alaska and the Kanin peninsula area in Western Siberia, which had up to 5 months with means > 0 °C and warm mean monthly temperatures. The temperature gradient from colder northern areas to southern warmer areas was evident on large continental land areas, such as the Taimyr Peninsula and mainland Canada. Steeper coastal temperature gradients occurred and were especially noticeable on islands. Cooler temperatures not matching the latitudinal gradient were seen at higher elevations in mountain ranges, such as the Brooks Range in northern Alaska, the Kuskokwim Mountains in southwestern Alaska, and the mountains of Chukotka.

The SWI map corresponded well with the map of Tundra Bioclimate Subzones from the CAVM (Figure 3.2), with the exception of mountainous areas, which were not delimited on the bioclimate subzone map. The raster SWI map provided more detail than the vector CAVM map, largely because it was based on continuous data rather than interpolation between scattered ground data points (Walker et al., 2005).

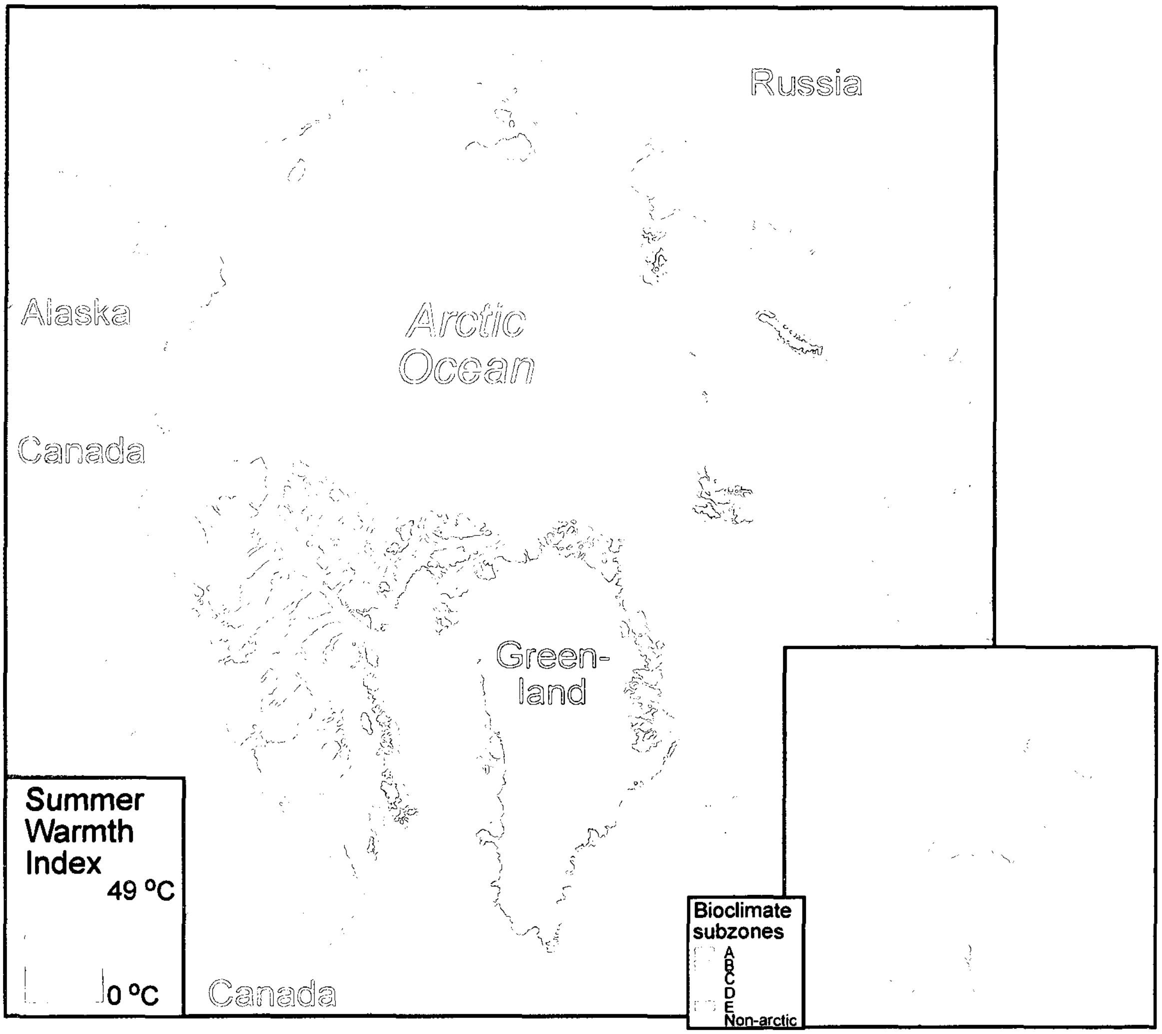

Figure 3.2 Map of twenty-two-year mean of summer warmth index (SWI) of arctic tundra, based on AVHRR land surface temperature data 1982-2003 (inset - arctic bioclimate subzones according to the Circumpolar Arctic Vegetation Map).

Histograms of SWI values for areas mapped as different CAVM bioclimate subzones showed the means and total area increasing from subzone A to subzone E (Figure 3.3). The SWI values from Figure 3.2 were buffered 1 pixel from coasts, and elevations > 333 m and areas mapped as ice or water in the CAVM were not included. The satellite SWI temperatures were warmer than the range described in the CAVM definition of the subzone (Table 3.1). This was expected since the CAVM definitions were based on station data, while the SWI values were based on radiative land surface temperature (see Methods Section 2.1). The difference was compounded by each additional month included in the SWI, so differences were least for Subzone A and

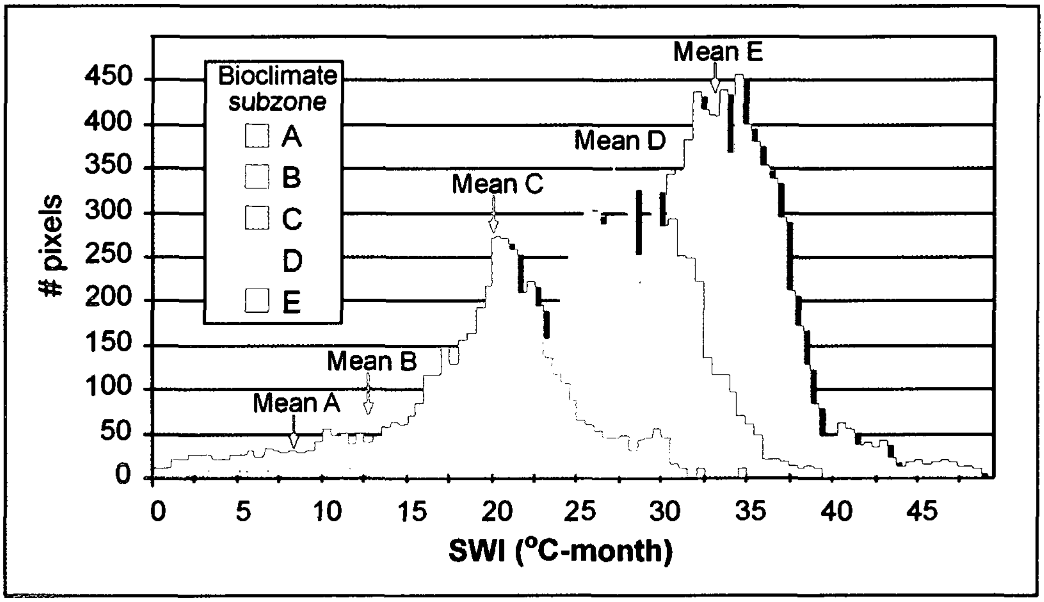

Figure 3.3 Summer warmth index (SWI) of CAVM tundra bioclimate subzones A-E , based on mean of AVHRR land surface temperature data 1982-2003, buffered from coasts and excluding non-zonal areas of glaciers, lakes and elevations > 333 m.

Table 3.1 Summer warmth index (SWI) of tundra bioclimate subzones according to CAVM definitions and AVHRR land surface temperature (LST). Coastal pixels, water, ice and elevations > 333 m were excluded from the SWI data.

Tundra bioclimate subzone	*CAVM SWI (°C)*	*LST SWI ± s.d. (°C)*
A	<6	8.2 ± 3.4
B	6-9	12.6 ± 5.8
C	9-12	19.8 ± 5.1
D	12-20	27.0 ± 4.9
E	20-35	33.2 ± 4.4

increased for warmer subzones. For Subzone E, the satellite SWI was on the warm end of the defined range, which was much broader than other subzones (20-35 °C). The data showed the expected increase in SWI from Subzone A (the coldest) to Subzone E (the warmest). The warmest parts of Subzone E were the Selawik area in northwestern Alaska, southern Yamal, Gydan and western Siberia. These areas in Russia were also the warmest parts of subzones B, C, and D.

CAVM vegetation types had characteristic SWI values (Table 3.2). The warmest types, with SWI > 25 °C, were all shrub-dominated vegetation types and included Units G3, G4, S1, S2, and W3 (see Table 2 for full vegetation unit names). The coldest types were all partially vegetated areas with cryptogam-dominated vegetation communities and included Units B1, G1, Nunataks, and Glaciers. Variability (as shown by s.d.) was highest for Mountains (Units B3 and B4) and Lakes where large variations in SWI occurred on a sub-pixel scale, and lowest for Glaciers and Nunataks where SWI values were consistently low.

Table 3.2 Summer warmth index (SWI mean 1982-2003) and Normalized Difference Vegetation Index (maximum NDVI 1993 and 1995) of CAVM vegetation types, from AVHRR data. Coastal pixels were excluded.

Physiognomic vegetation type	*CAVM unit*	*SWI (Mean ± s.d.)*	*NDVI (Mean ± s.d.)*
Cryptogam, cushion-forb barren	B1	11.0 ± 5.3	0.09 ± 0.05
Cryptogam barren (bedrock)	B2	21.2 ± 6.6	0.18 ± 0.09
Non-carbonate mountain complex	B3	19.4 ± 9.7	0.26 ± 0.16
Carbonate mountain complex	B4	18.5 ±11.2	0.26 ± 0.20
Rush/grass, cryptogam tundra	G1	9.6 ± 5.3	0.16 ± 0.12
Graminoid, prostrate dwarf-shrub, forb tundra	G2	23.1 ± 7.4	0.30 ± 0.13
Non-tussock sedge, dwarf-shrub, moss tundra	G3	28.3 ± 5.6	0.39 ± 0.12
Tussock sedge, dwarf-shrub, moss tundra	G4	31.4 ± 5.1	0.48 ± 0.11
Prostrate dwarf-shrub, herb tundra	P1	20.9 ± 7.2	0.21 ± 0.12
Prostrate/hemiprostrate dwarf-shrub tundra	P2	17.7 ± 6.3	0.18 ± 0.08
Erect dwarf-shrub tundra	S1	30.5 ± 5.2	0.40 ± 0.11
Low-shrub tundra	S2	32.8 ± 4.0	0.47 ± 0.10
Sedge/grass, moss wetland	W1	20.9 ± 6.7	0.29 ± 0.13
Sedge, moss dwarf-shrub wetland	W2	27.0 ± 4.7	0.39 ± 0.10
Sedge, moss, low-shrub wetland	W3	36.7	0.48 ± 0.10
Nunatak		4.5	NA
Glacier		2.8	NA
Lake		23.4	NA
Lagoon		24.2	NA

Examination of maps of SWI within vegetation types (maps not presented here) showed increases from the northern parts of the range of a vegetation type to the southern parts and increases in SWI from higher to lower elevations for mountain types. Exceptions to these general trends occurred in southwestern Alaska, which included cool parts of the ranges of S1 and S2 in the Kuskokwim Mountains area and a coastal-inland gradient rather than a north-south gradient for W3 on the Yukon-Kuskokwim Delta. The coldest part of some vegetation types followed elevational gradients rather than latitudinal gradients, such as B2 and P2 in the glaciated mountains of eastern Baffin Island and G4 and S1 in the Brooks Range in northern Alaska. Victoria Island and the Canadian mainland to the south of Victoria Island had the warmest parts of the ranges of B1, B2, G2 and P1. The warmest parts of several vegetation types that bordered treeline were found along river valleys: for G2 the Lena and Indigirka Rivers, for G3 the Mackenzie River, for S2 the Mackenzie, Pechora and Ob Rivers, and for G4 the Kobuk and Noatak Rivers.

3.4.2 NDVI as a function of SWI

The regression of NDVI as a function of SWI showed a highly significant positive relationship, with least variation around the regression line in the coldest and warmest parts of the Arctic (Figure 3.4) and a slope of 0.0137 NDVI / °C SWI. A map of the regression residuals, showing pixels with more or less NDVI than the regression equation was created (Figure 3.5). Negative numbers showed areas where there was less NDVI than would be expected given the temperatures. The pixels with the lowest negative residuals were mostly water. Other areas with negative residuals were places where limitations besides temperature occurred: glaciated areas on Baffin Island and the Canadian Shield, carbonate soil areas in the western Canadian Arctic Island and adjacent mainland, steep mountains in Chukotka, Taimyr Peninsula and Novaya Zemlya. Positive numbers (green areas in the map) showed areas with higher NDVI values than would be expected given the temperatures. These included the Kuskokwim Mountains in Alaska, areas of the Taimyr Peninsula, and the Yugorsky Peninsula in Western Siberia.

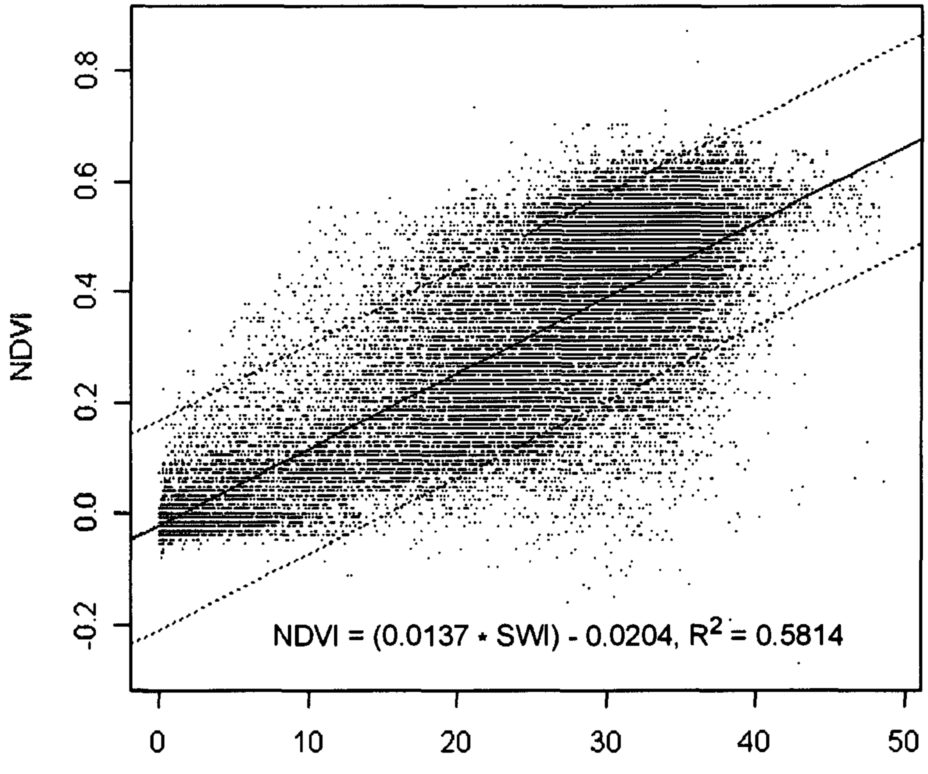

Figure 3.4 Regression analysis of Normalized Difference Vegetation Index (NDVI) as a function Summer Warmth Index (SWI, °C), regression line (solid) ± 1 s.d. (dotted lines). The NDVI values are maximum NDVI from AVHRR data from 1993 and 1995. The SWI values are mean AVHRR land surface temperatures 1982-2003, buffered from coasts and excluding lakes and ice.

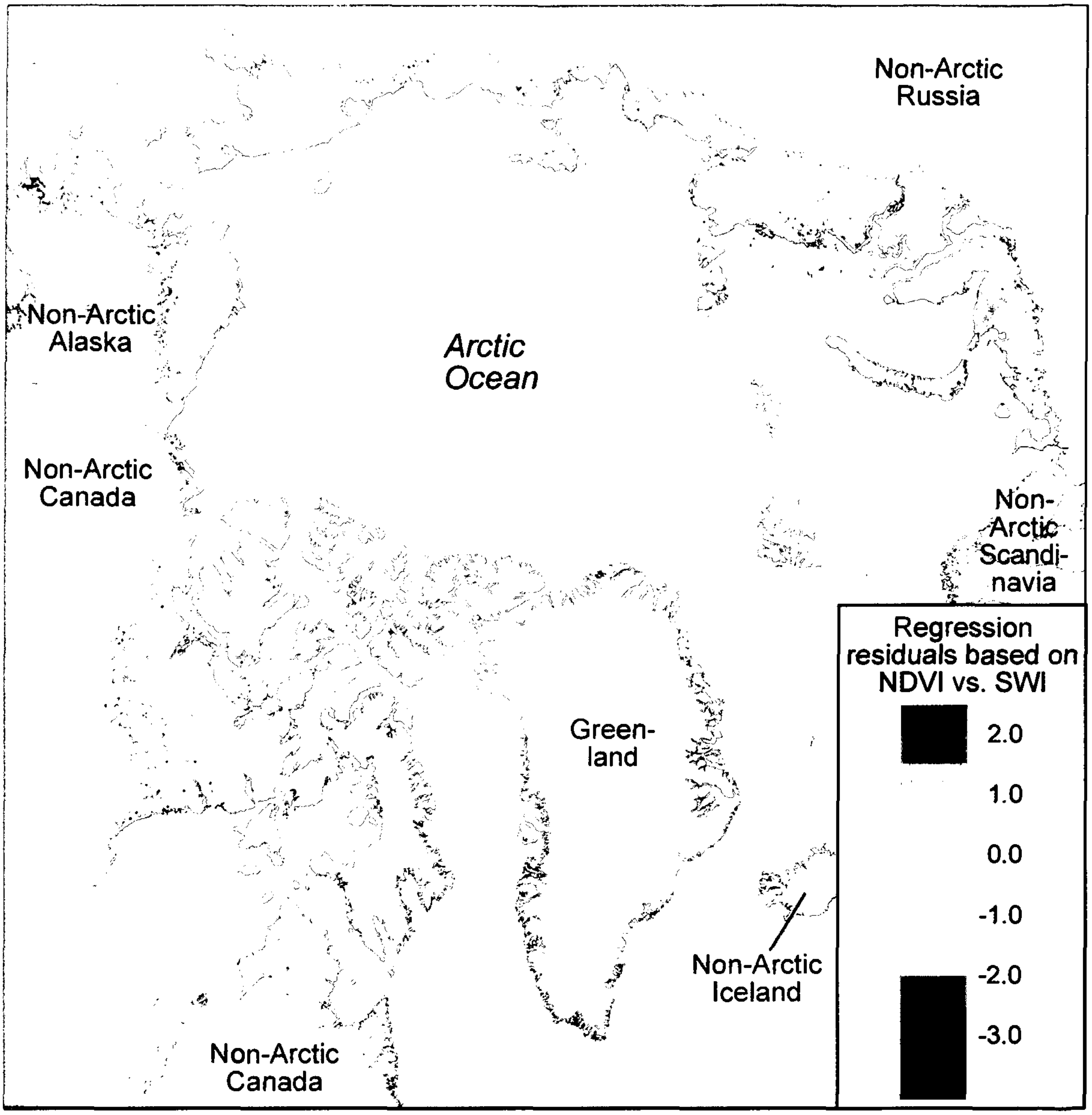

Figure 3.5 Map of regression residuals from analysis of maximum NDVI (1993-1995) as a function of SWI (mean 1982-2003) (units are standard deviations of NDVI). Pixels with greater NDVI values than predicted based on their SWI have positive residuals, those with lower NDVI values have negative residuals. Pixels within 1 pixel of the coast and those mapped by the CAVM as water or ice were excluded from the analysis.

Analysis of the regression residuals by CAVM categories showed the effect of several different attributes (Figure 3.6). Substrate chemistry played a large role: areas with carbonate and saline soils had strongly negative regression residuals. Analysis by elevation showed that most areas above 666 m elevation had positive regression residuals, especially areas between 1333 and 1666 m, while areas above 1666 m had negative residuals. Regression residuals were negative for all areas with > 2% lake cover and the effect increased with percent lake cover. Residuals were negative for two barren vegetation types (B1- Cryptogam, cushion-forb barren, B2-Cryptogam barren (bedrock)) and two prostrate shrub types (P1-Prostrate dwarf-shrub, herb tundra, P2-Prostrate/hemiprostrate dwarf-shrub tundra). Regression residuals were especially high for one graminoid type (G4 - Tussock sedge, dwarf-shrub, moss tundra).

Linear regression of NDVI as a function of SWI within different vegetation types were all highly significant due to large sample sizes ($p < 0.0001$) (Table 3.3). Much of the variability in NDVI was not explained by SWI: R^2 values were < 0.5 for all but the mountain complexes (B3 and B4) and were < 0.1 for two southern vegetation types, G4 and S2. B3, B4, G1, W1, and G2 had the highest slope values (> 0.01 NDVI / °C SWI), meaning that the NDVI values of these types increased the most with increasing SWI. B1 and G4 had the lowest slope values (< 0.004 NDVI/°C SWI). B1 is mostly barren, with a consistently low mean NDVI value (mean = 0.09). G4, tussock tundra, had a much higher mean NDVI (0.48), but it was fairly constant and did not change much with SWI.

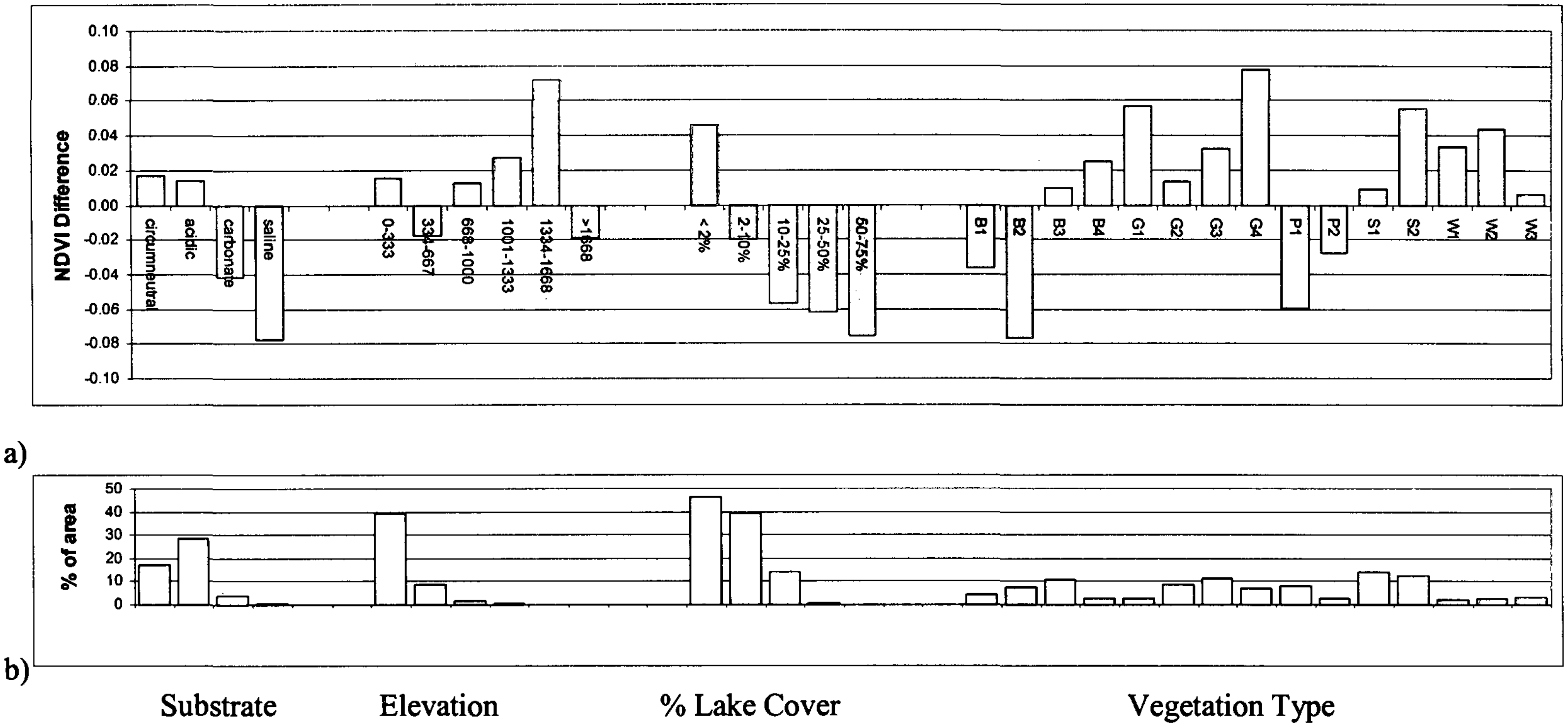

Figure 3.6 a) Regression residuals from analysis of NDVI (maximum1993 and 1995) as a function of SWI (mean 1982-2003) for CAVM mapped categories: substrate chemistry, elevation, percent lake cover, and physiognomic vegetation type (see Table 2 for full name of vegetation types). Pixels within 1 pixel of the coast and those mapped by the CAVM as water or ice were excluded from the analysis. b) Percent of analyzed area (land area of Arctic) in each category.

Table 3.3 Results of linear regression of maximum NDVI (1993 and 1995) as a function of SWI (mean 1982-2003) for CAVM vegetation types ($p < 0.0001$ for all regressions). Coastal pixels, water and ice were excluded.

*CAVM vegetation unit**	*Slope (NDVI/SWI)*	*Intercept*	*R^2*	*n (# 12.5 km pixels)*	*Area (1000 km^2)*
B1	0.0033	0.0512	0.1045	779	224.9
B2	0.0064	0.0472	0.2400	2186	371.8
B3	0.0128	0.0124	0.5902	2590	538.9
B4	0.0153	-0.0141	0.7502	636	131.8
G1	0.0145	0.0194	0.4130	326	140.8
G2	0.0102	0.0626	0.3366	1814	428.7
G3	0.0098	0.1104	0.2056	2973	568.9
G4	0.0045	0.3363	0.0411	1995	335.7
P1	0.0062	0.0791	0.1438	1792	399.4
P2	0.0073	0.0531	0.3323	597	139.6
S1	0.0093	0.1180	0.1866	3852	689.3
S2	0.0076	0.2262	0.0907	3338	612.9
W1	0.0117	0.0496	0.3473	223	101.1
W2	0.0091	0.1467	0.1626	501	136.0
W3	0.0083	0.1775	0.1215	780	159.1
ALL**	0.0137	-0.0204	0.5814	25690	4978.9

* see Table 3.2 for full name of vegetation types

** see Figure 3.4 for graph of regression

3.4.3 General linear model of NDVI

Comparing general linear models of the data, a model that included SWI, lake cover, substrate chemistry, landscape type and vegetation physiognomy accounted for 73.6% of the variation in NDVI. All of the factors were significant, but SWI accounted for most of the variation (68.5%), lake cover for 3.6%, and the other factors together accounted for 1.5% of NDVI variation.

3.5 Discussion

3.5.1 Warmest parts of the Arctic

Treeline expansion and loss of tundra area can be expected to occur first in the warmest parts of the Arctic, though treeline advance may be limited by the presence of permafrost, soil moisture, fire and insects (Callaghan, 2005; Lloyd, 2005). The map of summer warmth index clearly showed the areas of the Arctic where plants experienced the warmest growing conditions between 1982 and 2003. The areas with the highest SWI were the Selawik area in northwestern Alaska, the southern Yamal and Gydan Peninsulas, and the Kanin Peninsula area in Western Siberia. Other parts of the southern Arctic had monthly means > 15 °C in mid-summer but had fewer warm months, summing to lower total SWI. Many arctic river valleys had the warmest portions of several vegetation types. These areas along the Mackenzie River in Canada, the Yukon, Kobuk and Noatak Rivers in Alaska, and the Lena, Indigirka, Ob and Pechora Rivers in Russia are areas where vegetation types are likely to change with climate warming.

3.5.2 NDVI as a function of SWI

Summer temperatures are the most important factor controlling the distribution of arctic vegetation. In the linear regression analysis, 58% of the variation in circumpolar maximum NDVI was explained by SWI, which is the same proportion found by Jia et al. (2006) in their analysis of AVHRR NDVI data from two transects across the North Slope of Alaska during the 1990's. The magnitude of the relationship is also similar to previous work analyzing changes in NDVI over time. In the twenty years between 1981 and 2001, SWI based on northern Alaska climate station data increased 3.2-6.8 °C, while the annual maximum NDVI (AVHRR data) increased 0.078 ± 0.026 during the same time period (Jia et al., 2003). According to the regression equation calculated by this study, a 5 °C increase in SWI (the mid-point of Jia's range) correlated to an increase of 0.069 in NDVI, so the increase in NDVI seen in the AVHRR data for northern Alaska over time is similar in scale to what was seen in the circumpolar SWI-NDVI spatial relationship.

3.5.3 Residuals of NDVI as a function of SWI regression

The residual map showed areas where factors other than temperature limited vegetation growth, and conversely, where conditions were optimal for vegetation growth. The effect of glaciation on arctic vegetation could be clearly seen in the negative residuals throughout the Canadian Shield and other glaciated areas. Similarly limitations due to carbonate soils were evident in some parts of the Canadian Arctic. Areas with both carbonate soils and relatively recent deglaciation, like southern Victoria Island, had especially low residuals. On the other hand, areas with high residuals showed where vegetation responded to warmer temperatures with increased vegetative growth. Since NDVI correlates well with biomass in the Arctic (Shippert et al., 1995; Walker et al., 2003a), these areas can be interpreted as especially productive areas, where conditions were optimal for vegetation growth. They included areas unglaciated during the last glacial maximum 20,000 years ago (northern Alaska, southern and western Taimyr Peninsula,Yakutia) (Ehlers and Gibbard, 2004) and areas with high precipitation (Western Siberia, Kuskokwim Mountains) (Treshnikov, 1985).

3.5.4 Effects of environmental characteristics on NDVI

The CAVM attributes were useful in exploring environmental characteristics controlling arctic vegetation. Plant growth in areas with large negative residuals was limited by factors other than SWI, and thus is likely to respond less to climate warming than other areas. The effect of lake cover on NDVI was evident: increased lake cover resulted in higher negative residuals and lake cover was the second most important variable (after SWI) in the general linear model for NDVI. Substrate chemistry played a strong role in carbonate and saline soil areas, which had large negative residuals, but these areas only account for 4.0 % of the Arctic. The positive regression residuals for elevations > 666 m and increasing residuals up to 1666 m elevation indicated a positive effect of elevation on NDVI. This was likely due to increased slope and precipitation associated with increased elevation. Lower elevations tend to have flatter slopes, which have wetter soils and shallower active layers (Jorgenson, 2001), limiting the amount of soil nutrients available to plants. Better drained conditions are more favorable for shrubs, which form communities with higher NDVI than graminoid-dominated vegetation types (Riedel et al., 2005).

3.5.5 NDVI as a function of SWI for different arctic vegetation types

The regression of NDVI as a function of SWI for different vegetation types showed the highest slopes for partially vegetated High Arctic vegetation types and graminoid vegetation types. These are the types where increases in temperature are likely to result in the largest percentage increases in NDVI. This matches results from tundra warming experiments, where increases in biomass were greatest in colder locations (Jonasson et al., 1999). Increases in NDVI are also likely to occur where vegetation physiognomy changes to include larger plant lifeforms, such as the boundaries between graminoid and shrubs types and between shrub and forest types (Epstein et al., 2004; Tape et al., 2006).

Regression R^2 values of SWI vs. NDVI were low for individual vegetation types partly because each occurred in only a portion of the total arctic SWI range and had a limited characteristic range of NDVI values. The two mountain complex types (B3 and B4) had the greatest slopes and R^2 values and as complexes of different vegetation types that occurred throughout the Arctic, included the full range of SWI and NDVI values. Tussock tundra (G4) and low shrub (S2) had particularly low slopes and R^2 values. These types grow only in the warmest areas of the Arctic and had relatively small ranges of SWI values, but wide ranges of NDVI values. In the southern Arctic, there is more variation in vegetation cover than occurs in the northern Arctic, ranging from partially barren areas with prostrate vegetation along rivers and ridges to tall shrub thickets along drainages. This variation can exist as inclusions within areas mapped as predominantly G4 or S2. Slope, aspect, and variations in soil chemistry and moisture all have larger effects on vegetation physiognomy (and thus NDVI) in the warmer than in colder parts of the Arctic.

3.6 Conclusions

The results of this study confirmed the validity of the satellite-derived land surface temperature data set, demonstrating expected temperature gradients with latitude, elevation and distance from coast. The map of SWI based on satellite data gives the best picture available of the spatial patterning of the climate variable that is most important to arctic plants. The map is more spatially detailed than maps interpolated from climate stations, or bioclimate maps based on known plant distribution. The relatively small scale (12.5 km pixels) and continuous coverage of the temperature data make this data set a valuable tool for understanding the distribution of arctic vegetation, characterizing existing vegetation types, and understanding which areas may be most vulnerable to changes in vegetation due to climate change.

One of the most important results of this study is the confirmation of satellite studies showing changes in arctic NDVI, countering the possibility that the results were an artifact of the satellite record. This study found similar-scale changes in NDVI with changes in SWI over a spatial dimension as those reported from time-series analyses. This result provides important support for the trends seen in satellite NDVI data during recent decades, even though scientists have not yet been able to confirm them through vegetation sampling on the ground.

3.7 Acknowledgements

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Chapter 4 – Circumpolar relationships between permafrost characteristics, NDVI, and arctic vegetation types[1]

4.1 Abstract

An understanding of the distribution and characteristics of vegetation found on different types of permafrost is necessary input for modeling permafrost response to climate change. Interactions between climate and soil thermal regime are modified where vegetation exists and > 75% of permafrost on land in the Arctic is covered by non-barren vegetation types. A circumpolar spatial analysis was conducted to compare mapped permafrost characteristics with Normalized Difference Vegetation Index (NDVI), mapped vegetation types, and environmental characteristics. A General Linear Model (GLM) analysis found that when added to a model that included climate and lake cover, permafrost characteristics accounted for an additional 11% of the variation in NDVI. High ice content in permafrost had the strongest effect, lowering NDVI. Over 65% of areas with thin overburden are vegetated by low-stature, low-cover, low-biomass vegetation types that have little impact on thermal regimes. This climbs to > 82% for areas that also have high ice content permafrost. Over 83% of areas with thick overburden have vegetation types with denser, taller vegetation, which alters the interaction between climate and permafrost. Including vegetation characteristics in

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permafrost models will be particularly important in areas with thick overburden and medium or high ice content.

Keywords: Permafrost; NDVI; arctic vegetation; Circum-Arctic Map of Permafrost and Ground Ice Conditions; Circumpolar Arctic Vegetation Map

4.2 Introduction

Permafrost, its characteristics and its vulnerability to change, are increasingly in the public eye as a result of attention focused on climate change and the Arctic. Climate change is occurring at a faster rate in the Arctic than other biomes, and is resulting in an increase in temperatures in almost all parts of the Arctic (Comiso, 2006; Hassol, 2004). The effects on the Arctic Ocean have resulted in dramatic loss of summer sea ice, especially in the summer of 2007 (Comiso et al., 2008). The effects on land, both to permafrost and vegetation, are a focus of on-going research, particularly during the 2008 International Polar Year.

Most permafrost, even in the Arctic, is covered with vegetation, and the interactions between the permafrost and the vegetation affect both the growing environment for arctic plants and the thermal environment of the permafrost. Permafrost strongly affects vegetation by affecting landscape and soil characteristics. Permafrost underlying the annually-thawed active-layer limits soil drainage and results in cryogenic features such as polygons, gelifluction lobes, circles, and mounds (Washburn, 1980). Permafrost ice content can raise surface elevations through aggradation or lower it due to degradation (Jorgenson et al., 2001). Permafrost affects the characteristics of the active layer, such as its depth, soil temperatures, and soil moisture (Schuur et al., 2007).

Vegetation affects permafrost by changing the thermal characteristics of the soil. Vegetation shades and insulates the soil, reducing the transfer of summer warmth (Kade et al., 2006; Shur & Jorgenson, 2007). Vegetation also cools the surface through evapotranspiration. Vegetation has the opposite effect in winter: well-vegetated areas are insulated by the plants and the snow they trap, while unvegetated soils are more exposed to winter temperatures (Kade et al., 2006). The types and strength of the effects of vegetation on the climate-soil interactions vary with vegetation type and depend on the amount of total plant biomass, plant lifeforms, and continuity of plant cover (Kade et al., 2006; Walker et al., 2003).

In order to understand the effects of climate change on permafrost, it is important to understand the distribution of vegetation types in permafrost areas and the characteristics of those vegetation types that affect the thermal regime of the soil. This study compares vegetation distribution in the Arctic, the area north of the treeline, with permafrost characteristics. The vegetation was characterized using both a vector vegetation map and satellite raster data of the normalized difference vegetation index (NDVI). This spatial comparison of arctic vegetation types and NDVI with permafrost distribution helps define areas where vegetation has the strongest influence on permafrost, with implications for the possible effects of climate change.

4.3 Methods

4.3.1 The permafrost map

The extent and ground ice content of permafrost and depth of overburden in the Northern Hemisphere (20° to 90° N), were mapped on the Circum-arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1997; http://nsidc.org/data/ ggd318.html) and summarized by Zhang et al. (1999). The map was printed at 1:10-million scale and the digital format at 12.5-km pixel resolution was used for this study. Permafrost extent was mapped as continuous (94% of Arctic land area), discontinuous (3%), sporadic (2%) or isolated (1%). Ground-ice content was divided into low (54%), medium (15%) and high (31%) categories, referring to the volume of visible ice in the upper 10-20 m. Two landscape categories were mapped. Lowlands, highlands and intra- and inter-montane depressions characterized by thick (>5-10 m) overburden (any soil or other material that lies above the bedrock horizon in a given area) covers 36% of Arctic land areas. Mountains, highlands, ridges and plateaus characterized by thin (< 5-10 m) overburden cover and exposed bedrock covers 64% of the Arctic.

4.3.2 Satellite data (AVHRR NDVI)

The normalized difference vegetation index (NDVI) is a measure of relative greenness calculated as: NDVI = (NIR – R) / (NIR + R), where NIR is the spectral reflectance in the near-infrared where reflectance from the plant canopy is dominant, and R is the reflectance in the red portion of the spectrum where chlorophyll absorbs maximally. NDVI has a theoretical maximum of 1 and its relationship to vegetation characteristics such as biomass, productivity, percent cover and leaf area index is asymptotically nonlinear as it approaches 1. As a result, NDVI is less sensitive to ground characteristics at higher values and essentially saturates when leaf area index > 1 (van Wijk & Williams, 2005). This is not a severe problem in the Arctic where vegetation is often sparse and patchy: the mean NDVI for arctic land areas in the data set used in this study was 0.32, well below the saturation point (Raynolds et al., 2006).

NDVI values in the Arctic increase with the amount of vegetation as measured by leaf area index (LAI), phytomass, and productivity (Riedel et al., 2005; Shippert et al., 1995). NDVI values correlate well with ground characteristics of arctic vegetation and can be used to distinguish between vegetation types (Hope et al., 1993; Stow et al., 2004).

A 1-km-resolution maximum-NDVI data set was used for this study. These data were derived from the U.S. Geological Survey EROS AVHRR polar composite of NDVI data for 1993 and 1995 (CAVM Team, 2003; Markon et al., 1995). Daily data were collected by AVHRR sensors onboard NOAA satellites for channel 1, red (0.5 to 0.68 μm) and channel 2, near-infrared (0.725-1.1 μm). Satellite measurement of NDVI is affected by a variety of conditions, especially cloud cover, viewing angle and seasonal variation, that can be compensated for by compositing data over time (Goward et al., 1991; Riedel et al., 2005). Daily NDVI values were composited into 10-day maxima. The maximum values of these composited data during two relatively cloud-free summers (11 July - 31 August in 1993 and 1995) were used to create an almost cloud-free data set of maximum NDVI for the circumpolar Arctic in the early 1990s.

4.3.3 The vegetation map

The third data set used in this analysis was the Circumpolar Arctic Vegetation Map (CAVM Team, 2003; www.arcticatlas.org). The map extent includes all land areas north of the northern limit of trees. The map was created at 1:7.5-million scale with minimum polygon diameter of 8 km and is available digitally as a vector map. The integrated vegetation mapping approach used to create the vegetation map was based on the principle that a combination of environmental characteristics controls the distribution of vegetation. Vegetation-type boundaries were based on existing ground data and vegetation maps, bioclimate (Tundra Subzones A-E), floristic regions, landscape categories, elevation, percent lake cover, substrate chemistry, and surficial and bedrock geology, drawn on an AVHRR false-color infrared base map. The distribution of 15 arctic vegetation types (Table 4.1) was mapped and described on the CAVM, using a unifying circumpolar legend which enables analysis of the entire Arctic (CAVM Team, 2003; Walker et al., 2005).

4.3.4 Analysis

In each of the permafrost categories, the area of different vegetation types and average NDVI values were tabulated. Spatial-distribution characteristics were analyzed using GIS software. The CAVM was mapped at finer resolution than the permafrost map, so the most common permafrost category for each CAVM polygon was determined. Results of the analysis were summarized graphically, showing vegetation types occurring on different types of permafrost, using symbols proportional to area.

The NDVI raster data were analyzed by calculating the average NDVI value for different categories within the permafrost map and summarizing these results using bar graphs. This analysis of over 7 million 1-km^2 pixels represents the true mean of the classes, so comparative statistical test based on sampling were not appropriate.

Table 4.1 Vegetation types of the Circumpolar Arctic Vegetation Map (CAVM Team, 2003).

Code	*Vegetation Type*
B1	Cryptogam, herb barren
B2	Cryptogam barren complex (bedrock)
B3	Noncarbonate mountain complex
B4	Carbonate mountain complex
G1	Rush/grass, forb, cryptogam tundra
G2	Graminoid, prostrate dwarf-shrub, forb tundra
G3	Nontussock sedge, dwarf-shrub moss tundra
G4	Tussock-sedge, dwarf-shrub, moss tundra
P1	Prostrate dwarf-shrub, herb tundra
P2	Prostrate/Hemiprostrate dwarf-shrub tundra
S1	Erect dwarf-shrub tundra
S2	Low-shrub tundra
W1	Sedge/grass, moss wetland
W2	Sedge, moss, dwarf-shrub wetland
W3	Sedge, moss, low-shrub wetland

General linear models (GLM) (R Development Core Team, 2006) were run to determine the importance of permafrost variables in accounting for variation in NDVI in the Arctic. Attributes mapped as characteristics of the CAVM polygons, weighted by area, were used as input data. A basic model including variables known to be important in controlling NDVI (Raynolds et al., 2006) was run first, using the CAVM classes for bioclimate zone and percent lake cover. These variables accounted for the latitudinal variation in NDVI due to climate and for the reduction in NDVI due to cover of water (NDVI of water is essentially zero). Variables from the permafrost map: extent, ice content, overburden, and the combined code (a unique number for each combination of extent, ice content and overburden) were added to the model one-at-a-time to evaluate their effect on the model. The amount of variation accounted for by the different variables in each model and the significance of the variable in the model were tabulated.

4.3.5 Interdependence of data sets

Climate and landscape characteristics including slope, elevation, geologic and glacial history have important effects on all three variables: NDVI, permafrost and vegetation. In some cases these characteristics will vary together, especially in extreme conditions. For example, steep, high elevation mountains, will generally have low NDVI, continuous, low ice-content permafrost with little overburden, and barren vegetation types. In more moderate terrain, the type of vegetation which will grow on a given type of permafrost varies. In these areas, the vegetation map and the NDVI data provide valuable information about the distribution of vegetation on different types of permafrost.

4.4 Results

Most of the Arctic has continuous permafrost, underlying 4.68 million km^2 of land surface (excluding ice and water). Arctic areas without continuous permafrost include southern Greenland, European Arctic Russia, and in Alaska the Seward Peninsula and southern parts of the Kuskokwim River Delta. Continuous permafrost in the Arctic supports a mix of vegetation types. Over 83% of areas with thick overburden commonly is vegetated by erect shrub tundras (S1, S2), graminoid-shrub tundra (G3, G4), or low-shrub wetlands (W3) (Fig. 4.1). All of these vegetation types have relatively high stature, high biomass, and complete cover (Walker et al., 2005). Over 65% of areas with thin overburden have barren vegetation types (B1-B4), sparse graminoid (G1, G2) or prostrate dwarf-shrub (P1, P2) vegetation types with low stature, low biomass and partial ground cover (Walker et al. 2005). Areas with thin overburden and high ice content are likely to be vegetated with either cryptogam, herb barrens (B1), graminoid, prostrate dwarf-shrub (G2), or prostrate dwarf-shrub herb tundra (P1), with > 82% of these areas vegetated by vegetation types that have low-stature, low cover, and low biomass.

In areas of discontinuous permafrost, tussock tundra (G4) and erect-shrub (S1, S2) vegetation types are common. Areas with sporadic permafrost support mostly low-shrub vegetation (S2) and sedge, moss, low-shrub wetland (W3). Areas with isolated permafrost are dominated by non-carbonate mountain vegetation complexes (B3).

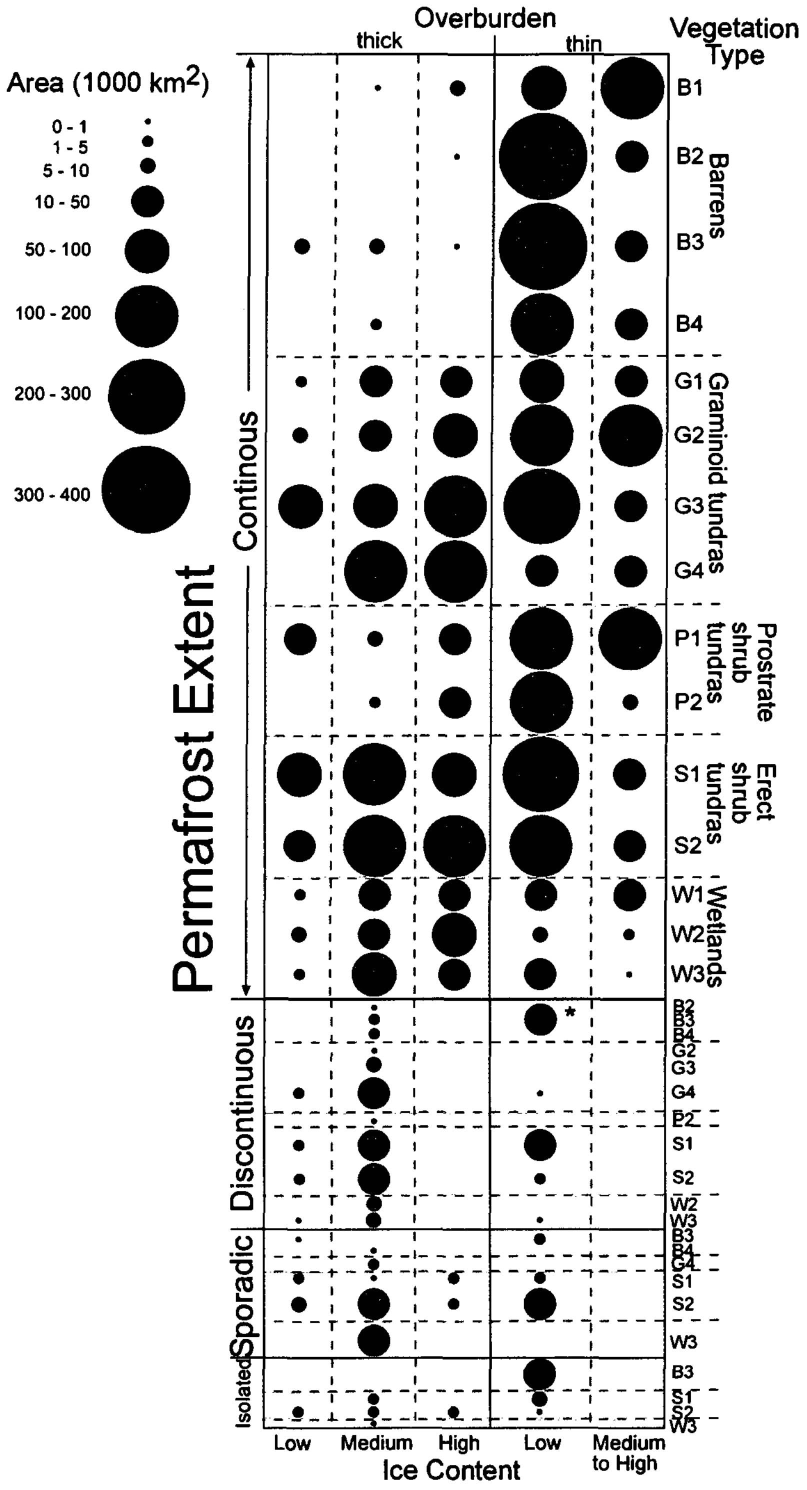

Figure 4.1. Area of Arctic in different types of permafrost categories (Brown et al. 1997) and different vegetation types (CAVM Team 2003).

* The area represented by this symbol was all vegetation type B3.

Low ice-content permafrost is characterized by barren types (B2, B3) and shrub types (S1, S2). Medium ice-content permafrost supports graminoid- (G4) and shrub-dominated (S1, S2) vegetation, as well as wetlands (W3). High ice-content permafrost is most commonly vegetated by graminoid-dominated vegetation types (G2, G3, G4), prostrate dwarf-shrub (P1), or cryptogam barrens (B1).

Examination of the types of permafrost that characterize vegetation types reveals that only three vegetation types have < 90 % continuous permafrost: non-carbonate mountain complex (B3); low shrub tundra (S2); and sedge, moss, low-shrub wetland (W3). Vegetation types that occur mostly on low ice-content permafrost include the barren types (B2, B3, B4) and types common on the Canadian Shield (P2, S1). Cryptogam herb barrens (B1) characteristic of the High Arctic and wetland vegetation types (W1, W2, W3) occur mostly on medium or high ice content permafrost. Tussock sedge, dwarf-shrub, moss tundra (G4) occurs mostly on areas with thick overburden and medium or high ice content.

NDVI varied inversely with permafrost extent, increasing from continuous to discontinuous to sporadic (Fig. 4.2), as would be expected, following the climate gradient from colder to warmer (Raynolds et al. 2006). NDVI was lowest for isolated permafrost, which occurred mostly in the mountainous areas of southern Greenland, where steep slopes and exposed bedrock limit plant cover.

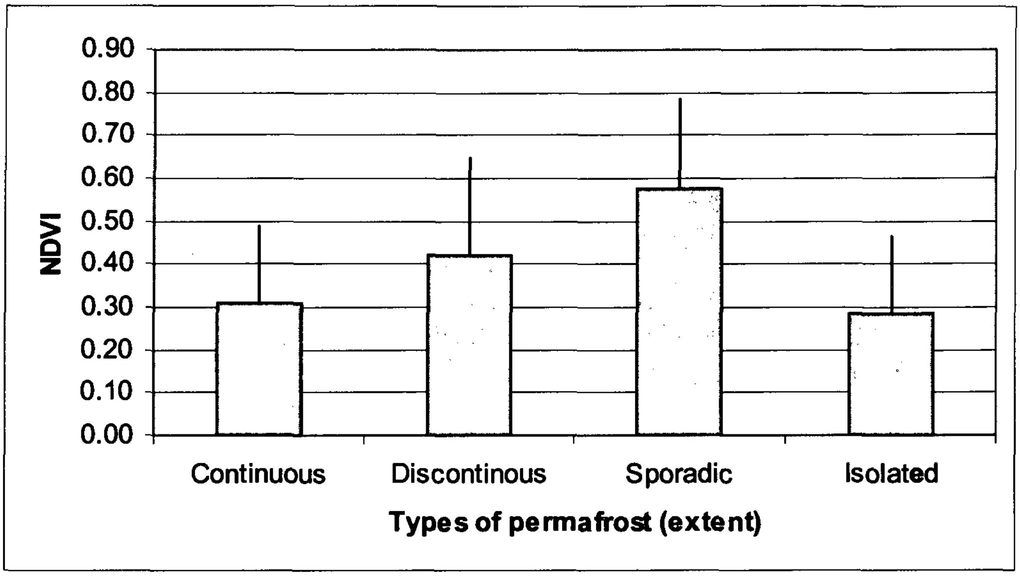

Figure 4.2 Average NDVI of Arctic areas with differing extent of permafrost (lines = s.d.).

The largest differences in NDVI values occurred between overburden categories: NDVI was much greater in areas with thick overburden than thin (Fig. 4.3). Thin overburden occurs in glaciated areas such as the Canadian Shield, on mountains, ridges and plateaus. Thick overburden is less common in the Arctic and occurs at lower elevations and in depressions where sediments can accumulate. Areas with thick overburden are more commonly vegetated by graminoid (G3, G4) or erect-shrub (S1, S2) vegetation types with high NDVI values, while areas with thin overburden often have sparse vegetation with low NDVI values (B1, B2, B3, Fig. 4.1).

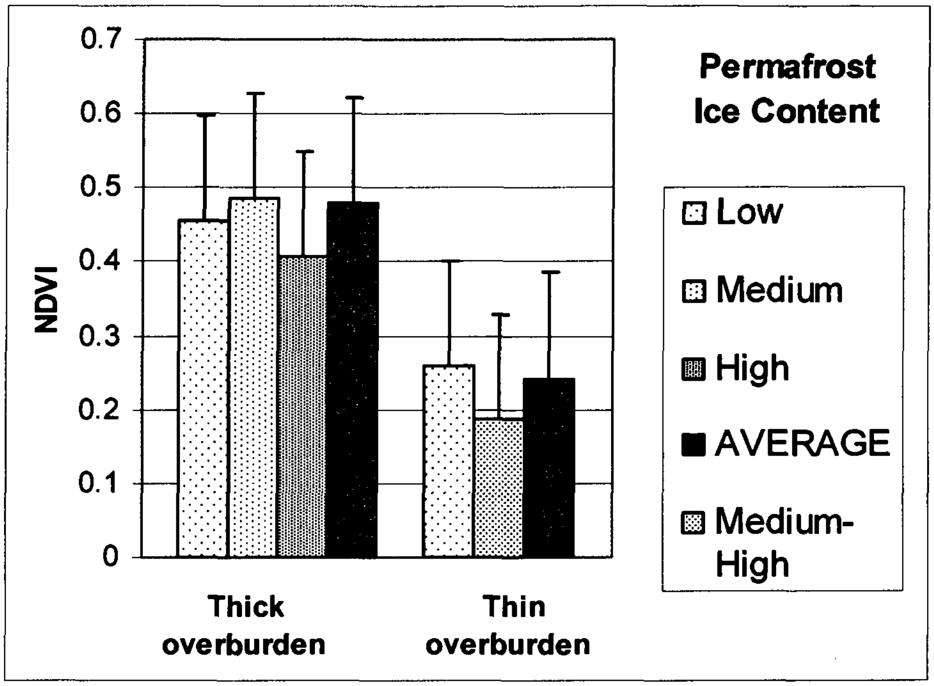

Figure 4.3 Average NDVI of Arctic areas with shallow vs. deep overburden over bedrock, and different levels of ice content (lines = s.d.).

NDVI values varied less by ice content within overburden types (Fig. 4.3). High and medium-to-high ice-content permafrost had lower NDVI than average. Areas with thick overburden and high ice-content permafrost are largely covered with graminoid vegetation types, while medium ice-content permafrost areas are more commonly vegetated by shrub-dominated types (Fig. 4.1). Areas with thin overburden and medium-to-high ice-content permafrost mostly occur in high-latitude areas (such as the Canadian Arctic Islands) and have barren or sparse, prostrate vegetation (B1, P1, G2).

Permafrost characteristics accounted for 11.9% of the variation in arctic NDVI in a general linear model that included bioclimate zone, percent lake cover and permafrost characteristics (Table 4.2). The CAVM variables accounted for 54.9% of the variation, with bioclimate zone responsible for 38.6% and percent lake cover for 16.3%.

Permafrost ice content accounted for more of the remaining variation than either extent or depth of overburden.

Table 4.2 Results of GLM analysis of variation in NDVI. Models included 3 variables, bioclimate subzone and percent lake cover plus one of the other variables. Results are from the Type 1 sums of squares, with terms added sequentially.

Model variables	*% of variation in NDVI accounted for by variables*	*Significance (p)*
Bioclimate zone	38.6	$< 2 \times 10^{-16}$
Percent lake cover	16.3	$< 2 \times 10^{-16}$
+ Permafrost ice content	6.1	$< 2 \times 10^{-16}$
+ Permafrost extent	4.2	$< 2 \times 10^{-16}$
+ Overburden	1.4	$< 2 \times 10^{-16}$
+ Permafrost combination	11.9	$< 2 \times 10^{-16}$

4.5 Discussion

The comparison of the Circum-arctic Map of Permafrost and Ground Ice Conditions, the Circumpolar Arctic Vegetation Map, and satellite NDVI values emphasized the importance of the difference between areas with thick overburden (> 5-10 m) and thin overburden (< 5-10 m). The thick overburden areas had NDVI values almost twice as high as those of the thin overburden areas, indicating a much greater amount of vegetation cover (Shippert et al., 1995). NDVI would be expected to be lower in areas with thin soils, but the distinction between overburden < 5 m and > 5 m occurs far below the rooting depth of arctic plants. GLM models showed that once climate and percent lake cover were accounted for, overburden depth was much less important. Areas with thin overburden had more lake cover (especially on the Canadian

Shield) and a more northerly distribution than areas with thick overburden, both effects reducing the average NDVI.

The model results showed that ice content correlated with variation in NDVI and the map summaries showed that medium-high ice-content permafrost with thin overburden has especially low NDVI values. These conditions occurred mainly in the northern areas of the Arctic: the Canadian Arctic Islands and Novaya Zemlya.

About one-quarter of the Arctic land area is covered by barren vegetation types. In these areas, the vegetation plays a minimal role in the soil thermal regime and the permafrost is climate-driven. The rest of the continuous permafrost in the Arctic would be considered climate–driven, ecosystem-modified permafrost, according to Shur & Jorgenson (2007). The effect of the vegetation modification is to reduce soil temperatures in summer and to increase them in winter (Kade et al., 2006). Vegetation types that have the most plant cover, thickest moss layers, and deepest organic soils insulate the soil most from summer warming (Kade et al., 2006). Types with the tallest vegetation trap the most snow in winter and insulate the soils from winter cooling (Sturm et al., 2001).

The net effect of vegetation on soil thermal regimes depends largely on the thickness of the moss/peat layer and the height of the vegetation. For example, tussock tundra (G4) at Happy Valley on the North Slope of Alaska has a thick peat layer (12 cm) developed from dead tussocks and mosses, a relatively thick layer of live moss (5 cm), and also a dwarf-shrub layer (25 cm tall) (Walker et al., 2008). The vegetative factors in tussock tundra decreasing absorption of summer warmth by the soil outweigh the factors warming the soil in winter, resulting in thinning of the active layer and aggradation of ice at the top of the permafrost (Shur & Jorgenson, 2007). This process had been recognized by arctic researchers as paludification, a process whereby soils become progressively wetter and more acidic as reduced thaw depth restricts soil drainage (Mann et al., 2002; Walker et al., 2003). The shallower thaw and saturated soils in turn favor peat-producing species like sphagnum mosses and tussock sedges, in a positively reinforcing cycle.

The vegetation types with characteristics resulting in the greatest effect on the soil thermal regime are graminoid-erect dwarf-shrub (G3, G4, W3) and erect-shrub (S1, S2) types (Walker et al., 2008). These vegetation types are common in areas with thick overburden and medium or high ice-content permafrost, which occur mostly in the foothills and coastal plains of the southern Arctic. These vegetation types are also common in areas with thin overburden and low ice-content permafrost, which occur mostly on the Canadian Shield and mountainous areas.

Areas with thin overburden and low-ice content permafrost are shown as having mostly low to medium risk of subsidence due to climate change in a study that modeled IPCC climate predictions, soils and permafrost data (Nelson et al., 2001). Risk of subsidence increases with ice-content and areas with medium and high ice-content permafrost on deep overburden are more commonly mapped as having medium or high risk of subsidence (Nelson et al., 2001).

Medium ice-content permafrost extends into discontinuous and sporadic permafrost, where the permafrost is preserved by the effects of the vegetation (climate-driven, ecosystem-protected; Shur & Jorgenson, 2007). Although researchers have recognized the importance of predicting the effects of climate change on permafrost in these areas because of the high risk of subsidence (Nelson et al., 2001), the complex interactions between the climate, the vegetation, and the soil are difficult to quantify. Vegetation cover varies from shrub- (42% S2, 13% S1) to graminoid-dominated (14% G4, 5% G3), and 20% of the area is wetlands (W3), in a mosaic of vegetation types with differing thermal attributes. Not surprisingly, different models project either thawing or persistence of this permafrost (Anisimov and Reneva, 2006). Spatially detailed models that include vegetation data will be required to understand the effects of climate change on permafrost in these areas.

An additional complicating factor is that vegetation is not a static characteristic, but will in many cases change in response to changes in permafrost. Changes in surface elevation and stability due to subsidence and erosion will change vegetation, usually to wetter types (Jorgenson et al., 2006). Increases in active layer depths in southern tundra is likely to increase shrubbiness (Schuur et al., 2007). Complete thawing of permafrost that allows previously saturated soils to drain will improve conditions for tree-line advance (Lloyd et al., 2003).

4.6 Conclusions

This study highlights both the effects of permafrost on vegetation, and conversely, the effects of vegetation on permafrost. A GLM analysis found that when added to a model that included climate and lake cover, permafrost characteristics accounted for an additional 11% of the variation in NDVI. High ice-content permafrost with shallow overburden was most strongly correlated with lower NDVI.

Over 75% of permafrost on land in the Arctic is covered by non-barren vegetation types, resulting in some degree of ecosystem-modification of the permafrost. Vegetation insulates the soil from both summer warmth and winter cold, with the net effect depending on vegetation characteristics. Thick moss layers and erect shrubs have the greatest effects on soil thermal regimes, and vegetation types with both occur in areas with medium to high ice-content permafrost and in areas of non-continuous permafrost. Including thermal characteristics of vegetation and the spatial distribution of different vegetation types, though complex, will be important for predicting the effects of climate change on permafrost in these areas.

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Chapter 5 – The effects of deglaciation on circumpolar distribution of arctic vegetation[1]

5.1 Abstract

An understanding of the factors controlling the distribution of arctic vegetation will allow better prediction of the effects of climate change. This study examines the effect of the age of landscapes on the distribution of arctic vegetation. We compared time since deglaciation with the distribution of vegetation types and Advanced Very High Resolution Radiometer (AVHRR) satellite measures of greenness (normalized difference vegetation index, NDVI). Most of the older arctic landscapes occur between the Taimyr Peninsula in Russia and the Mackenzie River in Canada. The vegetation types most commonly associated with the oldest landscapes include 'tussock-sedge, dwarf-shrub, moss tundra' and 'sedge-shrub wetlands'. Most of the Arctic, including most bioclimate subzones and most vegetation types, showed increasing NDVI with increasing landscape age. Landscapes showed rapid increases in NDVI during the first several thousand years after deglaciation. Relatively low NDVI values occurred on landscapes 5 000-15 000 years old, as on the Canadian Shield. Higher NDVI values occurred on landscapes older than 20 000 years. Landscape age accounted for 34% of the variation in NDVI for landscapes younger than 900 000 years. The coldest parts of the Arctic (Subzone A) and vegetation types that grow primarily in these areas did not show any trend with landscape age.

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Keywords: glaciation, last glacial maximum, NDVI, vegetation colonization

5.2 Introduction

Recent concern about climate change has focused on the Arctic. This concern is appropriate based on records of past climate changes, which document the amplification of global changes at high latitudes and evidence of recent amplification in warming in the Arctic (Hassol, 2004). The dramatic reduction of summer sea ice in the Arctic Ocean in the last several years is a highly visible symptom of these changes, with repercussions for global climate systems (Comiso et al., 2008).

Vegetation in the Arctic is also responding to climate change, though not as dramatically as sea ice (Bhatt et al. in prep.). Twenty-five year satellite records show an increase in vegetation greenness over tundra areas (Jia et al., 2007), and also show that spring is coming sooner, lengthening the growing season (Goetz et al., 2005). Fifty-year photo comparisons document shrubs expansion in the tundra (Tape et al., 2006), a trend that is corroborated by the results of international experiments which showed that deciduous shrubs and graminoid plants increased in height in response to warming treatments (Walker et al., 2006).

Although arctic tundra plants are extraordinarily responsive to changes in air temperature, plant production can also be limited by a wide variety of other site factors, such as nutrient and water availability, cold soil temperatures, short growing seasons, and winter desiccation and abrasion. In fact, most arctic plants are so well adapted to cold temperatures that factors other than temperature often limit their distribution

(Billings, 1997). A better understanding of these limiting factors will help predict where and how arctic vegetation will respond to climate change. This study focuses on the importance of time since deglaciation, which is related to soil development and nutrient and moisture regimes, in controlling the distribution of arctic vegetation.

Glacial effects in the Arctic are recent and obvious in many locations. Almost all of the Canadian Arctic was glaciated during the Last Glacial Maximum 20 000 years ago and deglaciated within the last 10 000 years (the Holocene) (Ehlers and Gibbard, 2004). Earlier glaciations which occurred during the Pleistocene are evident in other parts of the Arctic, with the largest ones centered around 70 kya (thousand years ago), 200 kya, 600 kya, and 800 kya (Ehlers and Gibbard, 2004). Unlike the adjacent boreal forest, where trees mask the landscape and fire is a major source of patterning, vegetation differences as a function of landscape age are relatively apparent in the Arctic. In this study, we investigated how arctic vegetation is related to landscape age, with the goal of understanding how time since deglaciation will influence the Arctic's response to climate change.

5.3 Methods

5.3.1 Landscape age since emergence

Glaciers not only covered land with ice, they also depressed the surface of the earth with their weight. As the ice melted, the weight was released and the land surface rose again, a process called isostatic rebound. Sea level was also lowered during the glacial intervals due to the large amount of water tied up in the continental ice sheets.

Deglaciation was accompanied by world-wide sea-level rises, which occurred more quickly than isostatic rebound. The combination of depressed land surfaces and rising sea levels caused marine transgressions, where ocean water covered low elevation land. Glaciers also dammed rivers, especially north-flowing rivers and creating large proglacial lakes. All these factors made land unavailable for plant colonization, so we will be considering the time since emergence, whether it was from ice, ocean or lake.

The age of most recent deglaciation, emergence from the sea, or drainage of proglacial lakes was obtained from a compilation of Quaternary glaciations, available in digital format (Ehlers and Gibbard, 2004). Supplemental data provided in the some of the regional chapters were especially useful (Astakhov, 2004; Barendregt and Duk-Rodkin, 2004; Duk-Rodkin et al., 2004; Dyke, 2004; Funder et al., 2004; Kaufman and Manley, 2004). Although landscape age estimates are bound to change as research continues, the compilation used in this study includes the best available current estimates and provides a relatively robust data set for analysis at a circumpolar scale.

All dates in this study are in calendar years. Dates for Canada were converted from ^{14}C years to calendar years (Dyke, 2004). Data for glaciations in southwest Alaska and the Seward Peninsula were supplemented by Brigham-Grette (2001) and for the North Slope by Hamilton (2003). Data for the Mackenzie River area were from Murton et al. (2005) and Andrews & Dunhill (2004). Data for the Queen Elizabeth Islands were supplemented by England et al. (2006) and Atkinson (2003). Briner et al. (2003, 2005) found that areas of northeast Baffin Island had been glaciated much more recently than previously thought, by nonerosive ice-sheets that formed on top of older deposits (the source of previous dating). Data for eastern Canada were supplemented by Ochietti et al. (2004).

Details for the Disko Bay area were obtained from Lloyd et al. (2005) and Long et al. (2003). Dates for Northeastern Greenland were confirmed by Cremer et al. (2008). Dates for Svalbard, Franz Josef Land and Novaya Zemlya were from Forman et al. (2004). In European Russia, the date of Quaternary maximum glaciation was estimated at 140 kya (Astakhov, 2004), with deglaciation of the Kanin Peninsula around 60-50 kya (Paus et al., 2003). Raab et al. (2003) showed evidence of marine transgression on the islands of Severnaya Zemlya and earlier deglaciation (~45 kya) on these islands than Ehlers and Gibbard (2004) (25 kya). The work of Mangerud et al. (2004) was used to map the extent of proglacial lakes in European Russia. A continual record of Quaternary deposits on the New Siberian Islands (Schirrmeister et al. 2002) confirmed the lack of glaciation mapped by Ehlers & Gibbard (2004). Similarly, evidence from Wrangel Island showed minor glaciation on the north coast during the Pleistocene (Gualtieri et al. 2003). The work of Brigham-Grette and Gualtieri (2004) supported Ehlers & Gibbard's mapping of mountain glaciations in Chukotka during the Pleistocene.

5.3.2 Circumpolar Arctic Vegetation Map

In this study we used the bioclimate definition of the Arctic adopted for the Circumpolar Arctic Vegetation Map (CAVM Team, 2003). It is the region north of the Arctic treeline with tundra vegetation and an Arctic climate (Fig. 5.1). The map was created at 1:7.5-million scale with a minimum polygon diameter of 8 km and is

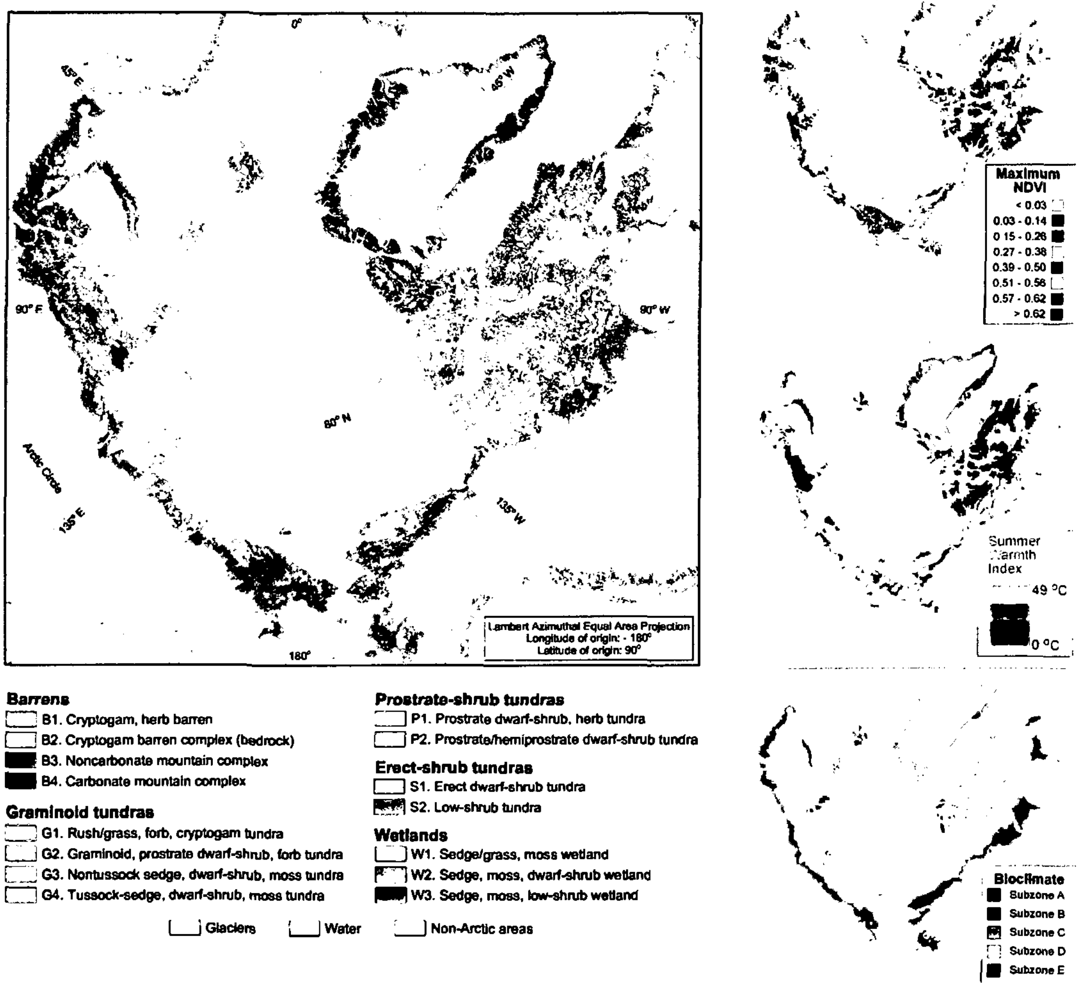

Figure 5.1 Maps of circumpolar vegetation types, maximum NDVI, summer warmth index (SWI) and arctic bioclimate subzone (CAVM Team, 2003; Raynolds et al, 2008).

available digitally as a vector map (www.arcticatlas.org). The integrated vegetation mapping approach used to create the vegetation map was based on the principle that a combination of environmental characteristics controls the distribution of vegetation. Vegetation-type boundaries were drawn on an AVHRR false-color infrared base map, based on existing ground data and vegetation maps, bioclimate (Tundra Subzones A-E), floristic regions, landscape categories, elevation, percent lake cover, substrate chemistry, and surficial and bedrock geology. The distribution of 15 arctic vegetation types was mapped and described on the CAVM (Fig. 5.1), using a unifying circumpolar legend which enables analysis of the entire Arctic (CAVM Team, 2003; Walker et al., 2005).

5.3.3 NDVI data

The normalized difference vegetation index (NDVI) is a measure of relative greenness calculated as: NDVI = (NIR – R) / (NIR + R), where NIR is the spectral reflectance in the near-infrared where reflectance from the plant canopy is dominant, and R is the reflectance in the red portion of the spectrum where chlorophyll absorbs maximally. NDVI has a theoretical maximum of 1 and its relationship to vegetation characteristics such as biomass, productivity, percent cover and leaf area index is asymptotically nonlinear as it approaches 1. As a result, NDVI is less sensitive to ground characteristics at higher values and begins to show signs of saturation for leaf area index > 1 (van Wijk and Williams, 2005). This is not a severe problem in the Arctic where vegetation is often sparse and patchy: the mean NDVI for arctic land areas in the data set used in this study was 0.32, well below the saturation point (Raynolds et al., 2006). NDVI values in the Arctic increase with the amount of vegetation as measured by leaf area index (LAI), phytomass, and productivity (Shippert et al., 1995; Riedel et al., 2005). NDVI values correlate well with ground characteristics of arctic vegetation and can be used to distinguish between vegetation types (Hope et al., 1993; Stow et al., 1993).

A 1-km-resolution maximum-NDVI data set was used for this study (Fig. 5.1). These data were derived from the U.S. Geological Survey Earth Resources Observation Systems AVHRR polar composite of NDVI data for 1993 and 1995 (Markon et al., 1995; CAVM Team, 2003). Daily data were collected by AVHRR sensors onboard NOAA satellites for channel 1, red (0.5 to 0.68 μm) and channel 2, near-infrared (0.725-1.1 μm). Satellite measurement of NDVI is affected by a variety of conditions, especially cloud cover, viewing angle and seasonal variation, that can be compensated for by compositing data over time (Goward et al., 1991, Riedel et al., 2005). Daily NDVI values were composited into 10-day maxima. The maximum values of these composited data during two relatively cloud-free summers (11 July - 31 August in 1993 and 1995) were used to create an almost cloud-free data set of maximum NDVI for the circumpolar Arctic in the early 1990s.

5.3.4 Analysis

Digital maps from Ehlers & Gibbard (2004) were converted into the same projections as the CAVM, so the maps could be overlaid. A landscape age was assigned to each CAVM integrated terrain-unit map polygon and new polygons were created where CAVM boundaries did not match the glacial emergence data. Data from more recent references were incorporated in the deglaciation map.

Spatial distribution of different CAVM categories were analyzed using geographical information system (GIS) software and results were summarized graphically. Means were calculated using an area-weighted average of polygon data. The NDVI data were analyzed by calculating the average NDVI value for landscapes with different emergence ages. Lakes and glaciers were assigned an emergence age of 0, since they are still not available for plant colonization, and were excluded from analyses of land area. Areas which had not been glaciated during the Pleistocene (age > 900 kya or unknown) were excluded from any analysis involving a mathematical calculation using age.

To further investigate the relationship between NDVI and emergence age, landscapes were stratified by CAVM categories. Landscape age data were transformed using a log transformation, as the dates of more recent deglaciations are known much more precisely than older ones. Linear regressions between the transformed data and NDVI were run (R Development Core Team, 2006). General linear models (GLM) were used to determine the importance of emergence age in a suite of characteristics known to be important in controlling NDVI in the Arctic (R Development Core Team, 2006; Raynolds et al., 2006). Attributes mapped as characteristics of the CAVM polygons, weighted by area, were used as input data. These attributes included summer warmth index (SWI = sum of monthly mean temperatures > 0 °C) (Fig. 5.1), tundra bioclimate subzone (A-E, cold to warm) (Fig. 5.1), elevation, and percent lake cover (CAVM Team, 2003).

5.4 Results

The glaciation data were used to create a map of landscape age since emergence from Quaternary ice, marine transgressions or proglacial lakes (Fig. 5.2). Much of the Arctic is still under ice (27 % of land area), including 1.7 million km^2 in the Greenland Ice Cap. Most of the ice-free land area (65 %) was deglaciated since the Last Glacial Maximum (LGM, 20 kya, during the Late Wisconsin period of the Late Pleistocene). The most common age category is 8-7 kya, during the Holocene and includes most of

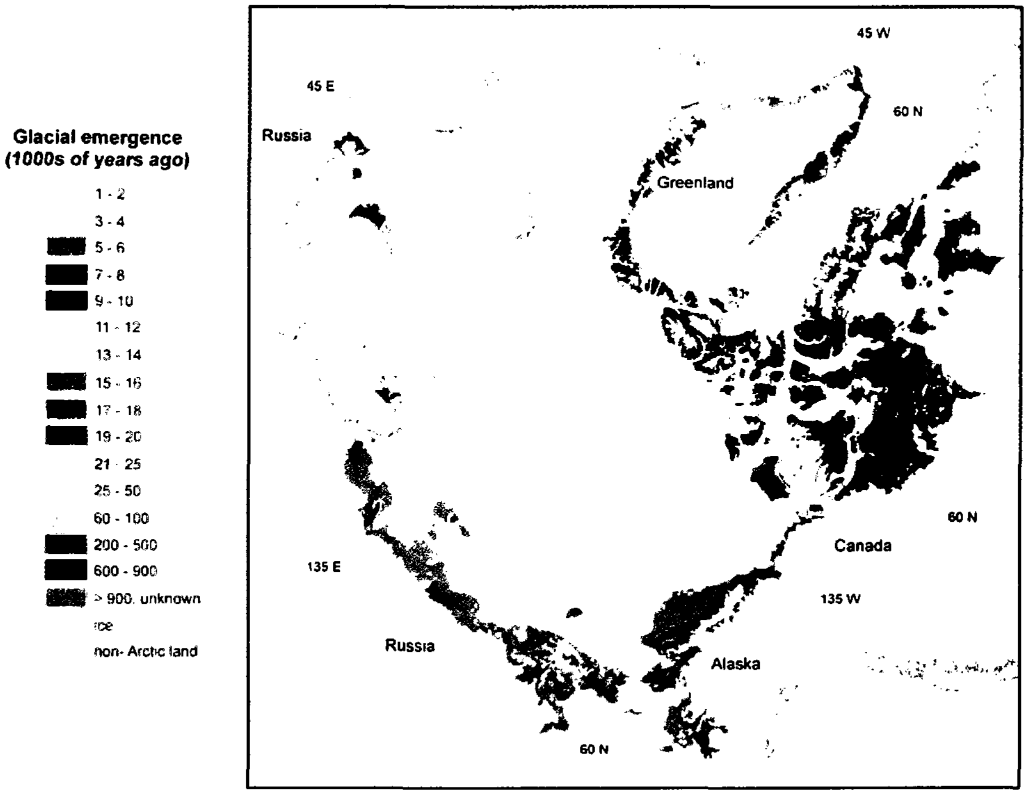

Figure 5.2 Map showing time since emergence of Arctic landscapes from Pleistocene glaciation, marine transgressions or proglacial lakes. Scale in thousands of years.

the Canadian Arctic (Fig. 5.3, blue areas on Fig. 5.2). Large areas of European Russia and parts of Alaska (24 % of the Arctic) were glaciated at some point in the Late Pleistocene, but earlier than the LGM. Chukotka, Novaya Zemlya and the Kanin Peninsula were deglaciated during the late Wisconsin (35–10 kya). Western Siberia was deglaciated or emerged from extensive marine transgressions or pro-glacial lakes during the middle-early Wisconsin (80-35 kya). Parts of the Brooks Range in northern Alaska and Banks Island in the southwest Canadian Arctic Archipelago were deglaciated in the Middle Pleistocene (900-200 kya). There is no evidence of glaciations over large areas of Yakutia and low elevation areas in Chukotka and Alaska, so these areas are assumed to have been ice-free for over 900 kya (12 % of the Arctic). The oldest areas are east of

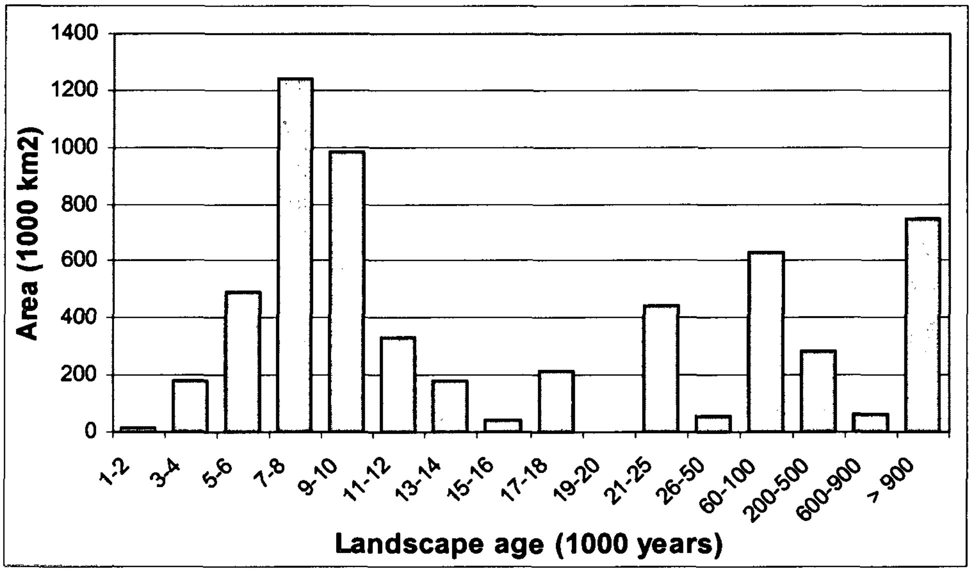

Figure 5.3 Area of arctic landscapes of different ages. Note non-regular age categories.

the Taimyr Peninsula and west of Canada's Mackenzie River. The youngest areas are on Baffin Island, the Ungava Peninsula, and parts of Greenland.

Comparing only those areas of the Arctic that were glaciated during the Pleistocene, the oldest landscapes are in Subzone E, the warmest bioclimate subzone, where the average emergence is over 120 kya (Fig. 5.4). The contrast between Subzone E and the colder subzones is striking. This effect could be due to the combination of the warmer climate and greater distance from oceanic sources of moisture resulting in less frequent glaciation of Subzone E compared to the other four subzones.

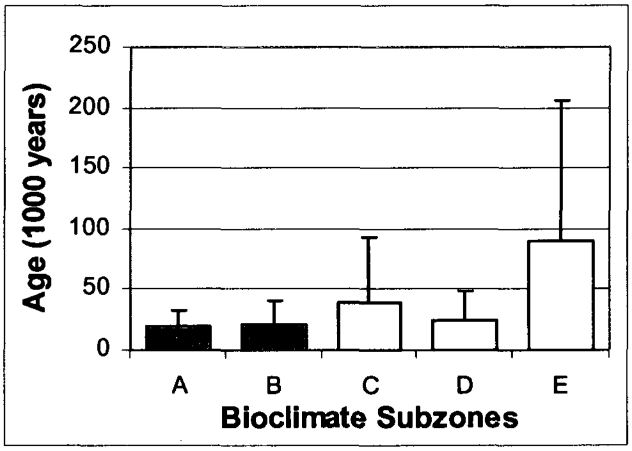

Figure 5.4 Average time since emergence in different tundra bioclimate subzones (A-E, coldest to warmest). Includes only areas deglaciated during the Pleistocene (< 900 kya). Bars indicate standard deviation.

The areas with the fewest lakes are also the oldest (Fig. 5.5). There is a large contrast between the age of areas with < 2% lake cover and areas with > 2% lake cover. A comparison of different vegetation types shows that tussock-sedge, dwarf-shrub, moss tundra (G4) is much older than most other vegetation types (Fig. 5.6). Carbonate mountain complexes (B4) are generally older than noncarbonated mountain complexes (B3) because the carbonate mountains occur mostly in the oldest areas of Pleistocene glaciation, such as the Brooks Range of Alaska.

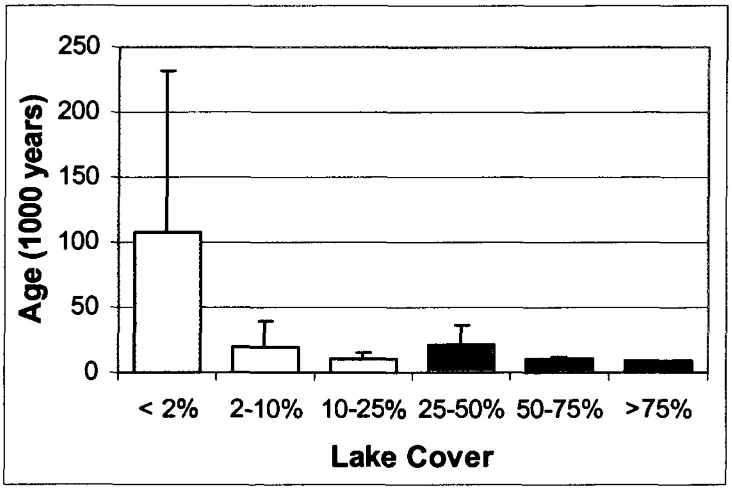

Figure 5.5 Average time since emergence for different lake cover categories. Includes only land areas deglaciated during the Pleistocene (< 900 kya). Bars indicate standard deviation.

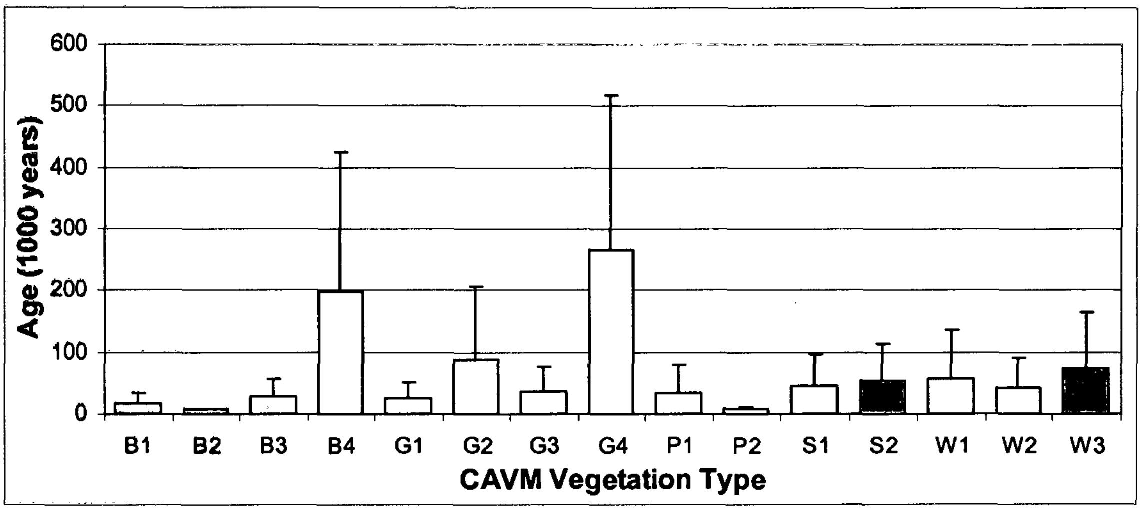

Figure 5.6 Average time since emergence for different arctic vegetation types (see Figure 1 for full names of vegetation types). Includes only areas deglaciated during the Pleistocene (< 900 kya). Bars indicate standard deviation.

Figure 5.7 shows low NDVI on arctic landscapes for the first several thousand years after glacial emergence, as plant colonization occurs. There is a quick rise in NDVI to about 0.2 in the first 4 000 years, but there follow several thousand years of slightly declining NDVI, from around 4 000 to 14 000 years, after which NDVI climbs to a level around 0.4-0.45. The anomalously low NDVI value for the 26-50 kya age-category was because the only arctic areas of this age were located in northern Taimyr and the offshore islands of Severnaya Zemlya, mostly in the coldest Subzones A and B which have very low NDVI.

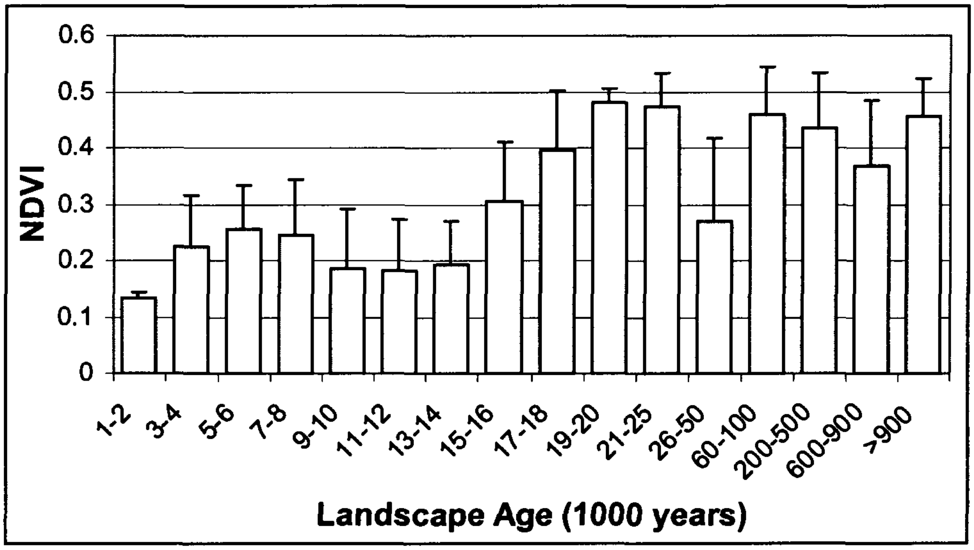

Figure 5.7 Average NDVI of arctic landscapes of different ages. Note non-regular age categories. Bars indicate standard deviation.

Results of linear regression showed the relationship between age of landscape emergence and NDVI was positive and accounted for 34% of the variation in NDVI between polygons in the whole Arctic. NDVI generally increased with age over the length of the Pleistocene, with a linear relationship to the log-transformed age and an intercept very close to zero (Table 5.1). The coldest parts of the Arctic (Subzone A) and vegetation types that grow primarily in these areas (G1, P2) did not show a significant trend in NDVI with landscape age. There was also no trend for B2, the cryptogam barren complex that grows on recently glaciated bedrock, because all of this type has a

Table 5.1 Results of linear regression of NDVI by log-transformed landscape age for entire Arctic, tundra bioclimate subzones and vegetation types.

	Slope	*Intercept*	R^2	*Significance,* p
All Arctic	0.2047	0.0215	0.3418	$< 2 \times 10^{-16}$***
Subzone				
A	-0.0133	0.0745	0.0034	0.4154
B	0.2410	-0.1447	0.3688	$< 2 \times 10^{-16}$***
C	0.1793	-0.0023	0.2569	$< 2 \times 10^{-16}$***
D	0.2588	-0.0034	0.4013	$< 2 \times 10^{-16}$***
E	0.0908	0.2993	0.2918	$< 2 \times 10^{-16}$***
Vegetation Type				
B1	0.0404	0.0253	0.0318	0.00423**
B2	-0.0561	0.2175	0.0105	0.109
B3	0.2480	-0.1156	0.3658	$< 2 \times 10^{-16}$***
B4	0.2104	-0.1182	0.7013	$< 2 \times 10^{-16}$***
G1	0.0286	0.0866	0.0121	0.103
G2	0.1291	0.1219	0.2558	$< 2 \times 10^{-16}$***
G3	0.1564	0.1860	0.4777	$< 2 \times 10^{-16}$***
G4	0.0619	0.3569	0.3955	4.06×10^{-15}***
P1	0.1691	-0.0282	0.2839	$< 2 \times 10^{-16}$***
P2	0.0239	0.1320	0.0020	0.5721
S1	0.1540	0.1834	0.4368	$< 2 \times 10^{-16}$***
S2	0.0729	0.3821	0.1841	$< 2 \times 10^{-16}$***
W1	0.0851	0.1670	0.1290	5.93×10^{-6}***
W2	0.1194	0.2382	0.2199	1.45×10^{-6}***
W3	0.0729	0.3601	0.2085	2.94×10^{-8}***

Note: see Figure 1 for full names of vegetation types. Includes only land areas deglaciated during the Pleistocene (< 900 kya).
** $p < 0.01$, *** $p < 0.001$

similar, recent age (Fig. 5.6). The regression relationships accounted for the most variation in carbonate mountain complexes (B4), nontussock sedge, dwarf-shrub moss tundra (G3), and erect dwarf-shrub tundra (S1) (Table 5.1).

In a general linear model including summer warmth index and the log transformed age of emergence, the summer warmth index accounted for 63% of the variation in NDVI and the age of the landscape accounted for 8.3% (Table 5.2). The interaction was significant, meaning that the effect of landscape age on NDVI varies with climate. Within bioclimate subzones, landscape age accounts for 13.4 to 20.1 % of the variation in NDVI. Variation in summer warmth index was most important within subzones B, C and D, and percent lake cover was most important in subzone E (Table 5.2).

Table 5.2 Results of general linear model of NDVI and age of landscape emergence.

All Arctic (*n = 5921*)	*NDVI ~ SWI * log(AGE)*		
Variable	*Deviance*	*% Total Deviance*	*Significance, p*
SWI	133.472	63.1	$< 2 \times 10^{-16}$***
log(age)	17.649	8.3	$< 2 \times 10^{-16}$***
SWI * log(age)	1.547	0.7	$< 2 \times 10^{-16}$***
Subzone A (n = 271)	**NDVI ~ SWI + log(AGE) + ELEV + LAKE**		
SWI	0.12764	14.0	1.88×10^{-10}***
log(age)	0.12216	13.4	2.22×10^{-3}**
elevation	0.07842	8.6	1.74×10^{-13}***
lake cover	0.07943	8.7	4.11×10^{-10}***
Subzone B (n = 693)	**NDVI ~ SWI + log(AGE) + ELEV + LAKE**		
SWI	3.8206	38.4	$< 2 \times 10^{-16}$***
log(age)	1.6048	16.1	$< 2 \times 10^{-16}$***
elevation	0.3195	3.2	1.45×10^{-13}***
lake cover	0.0266	0.3	3.66×10^{-2}**

Table 5.2 Continued

Subzone C (n = 1505)	**NDVI ~ SWI + log(AGE) + ELEV + LAKE**		
SWI	13.1398	42.1	$< 2 \times 10^{-16}$***
log(age)	4.5508	14.6	$< 2 \times 10^{-16}$***
elevation	1.2472	4.0	$< 2 \times 10^{-16}$***
lake cover	1.6006	5.1	$< 2 \times 10^{-16}$***
Subzone D (n = 1549)	**NDVI ~ SWI + log(AGE) + ELEV + LAKE**		
SWI	18.192	44.5	$< 2 \times 10^{-16}$***
log(age)	5.499	13.5	$< 2 \times 10^{-16}$***
elevation	0.513	1.3	$< 2 \times 10^{-16}$***
lake cover	6.585	16.1	$< 2 \times 10^{-16}$***
Subzone E (n = 1872)	**NDVI ~ SWI + log(AGE) + ELEV + LAKE**		
SWI	6.467	18.7	$< 2 \times 10^{-16}$***
log(age)	6.933	20.1	$< 2 \times 10^{-16}$***
elevation	0.0004	0.0	$< 2 \times 10^{-16}$***
lake cover	11.084	32.1	$< 2 \times 10^{-16}$***

** $p < 0.01$, *** $p < 0.001$

5.5 Discussion

The results show that NDVI did not increase with time at the coldest subzones. Although initial plant colonization occurred, the short summers provide little time for vegetation growth and reproduction. Plant community development is also hindered by how few plants can survive in Subzone A, which is characterized by its depauperate vascular flora (Elvebakk, 1999). Soil development processes are also slow due to cold temperatures. Even during the short summer, temperatures are not far above 0 °C.

However, the perception that plant colonization and the formation of Arctic plant communities is slow, taking millennia, has proven to be false. Arctic plants are actually well adapted to changing geographic ranges, as they have had to migrate due to glacial cycles throughout the last several million years. Between 3 and 1 million years ago, glacial cycles occurred every 41 000 years with smaller 23 000 year cycles. Since about 900 kya, larger glacial cycles have occurred approximately every 100 000 years (Ruddiman, 2001). The glacial climate cycles are extreme enough in the Arctic to completely change the vegetation, even in areas not directly affected by glacial ice (Lozhkin et al., 2007).

Despite cold climates, revegetation of fresh surfaces in the Arctic happens relatively quickly. In Svalbard, areas deglaciated since the Little Ice Age (in the last 150 years) have vegetation covering most of the surface, with mature tundra species replacing colonizing species (Moreau et al., 2005). Change continues at a rapid rate, resulting in measurable changes in community composition over 30 years (Moreau et al., 2008 (in press)). In a study looking at the likelihood that Arctic plants persisted in refugia in the North Atlantic through the LGM, Brochmann et al. (2003) concluded that the fossil evidence shows no sign of refugia, but does show high migration rates and very rapid recolonization of deglaciated areas, even in the coldest areas. This trend is seen in the spatial analysis presented in this study, with the rapid rise in circumpolar Arctic NDVI shown within the first several thousand years after deglaciation.

After the initial rise in NDVI for newly deglaciated areas, NDVI stays relatively constant for areas deglaciated 2 000 to 20 000 years ago. This is the time scale at which paludification and peat accumulation occur (Fig. 5.8). Paludification is the process of wetland formation on previously well-drained terrain. In the Arctic, paludification involves the accumulation of organic material, which insulates the soil, reduces the active layer, restricts soil drainage and transforms former dry mineral soils to wet peaty soils (Walker and Walker, 1996; Mann et al., 2002; Walker et al., 2003; Shur and Jorgenson, 2007). Soils become progressively colder and more acidic, which in turn favors peat-producing species like sphagnum mosses and tussock sedges, in a positively reinforcing cycle. This can have a wide variety of ecosystem consequences including reduction of soil heat flux, increased carbon sequestration in the soils, and increased methane flux (Walker et al. 1998). Extensive peatlands developed remarkably recently in deglaciated areas, sequestering 180-445 Pg of carbon since the LGM (MacDonald et al., 2006). Peatland initiation generally occurred 1000-2000 years after deglaciation and peaked 7-8 kya (Gorham et al., 2007).

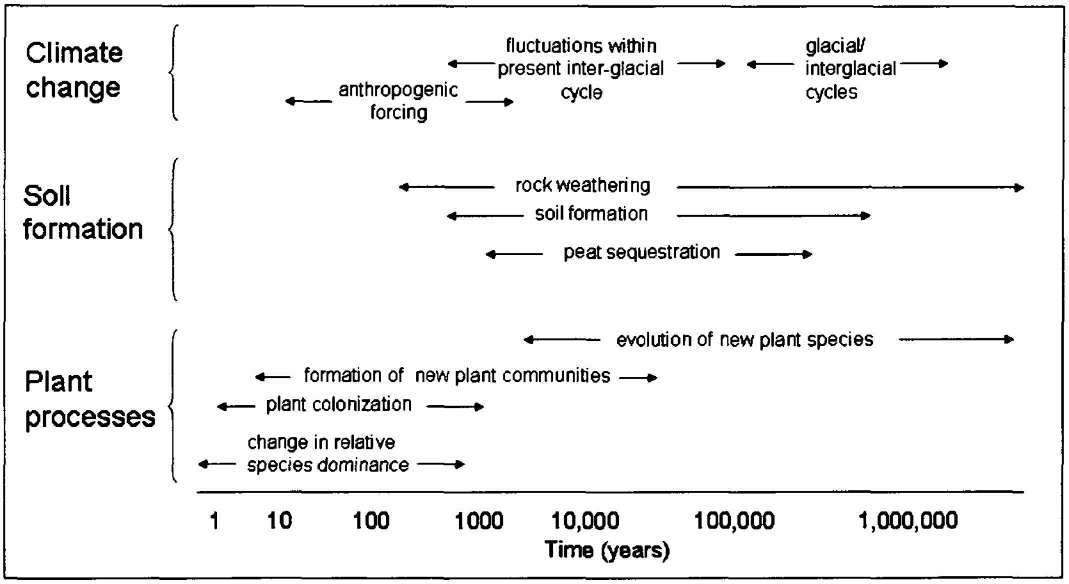

Figure 5.8 Logarithmic time scale of different vegetation, soil and climate processes.

For landscapes older than 18-20 kya, landscapes not glaciated during the LGM, there is a big jump in NDVI values. These landscapes are old enough for a whole different set of processes to become significant, characterizing the differences between the younger landscapes of the Canadian Arctic and the older glaciated landscapes of Alaska and Russia. Tens of thousands of years is the time frame required for soil development in the Arctic (Birkeland, 1978). It is also long enough for lakes to fill with sediments and vegetation (Campbell et al., 1997). The ages of the oldest landscapes are due to erosional and depositional processes, rather than glaciation.

Pollen records from unglaciated areas in the southern Arctic shows changes from cold, dry herb-dominated steppe-tundra in glacial periods to warmer, wetter shrub-dominated tundra in the inter-glacial periods (Bigelow et al., 2003). Pollen cores from a lake in Chukotka record four glacial cycles over about 300 000 years, represented by repeating cycles in pollen assemblages. Researchers recognized three assemblages: shrub-dominated, mixed herb- and shrub-dominated, and herb-dominated, and attributed the changes in pollen composition to changes in species abundance and spatial distribution (Lozhkin et al., 2007).

The vegetation type with the oldest average landscape age is tussock tundra, which consists of a group of plants that are well adapted to wet, acidic soils resulting from (and contributing to) paludification. Through repeated glacial cycles, these areas would re-vegetate in the inter-glacial periods with similar acidophilic species such as tussock sedges, dwarf-shrub birch and ericaceous shrubs, and sphagnum moss, resulting in tussock tundra.

Pollen data show major changes in vegetation from climate fluctuations even within the most recent inter-glacial (the last 20 000 years), such as the cool Younger Dryas event (12.8-11.5 kya; Peteet, 1995). Other studies show changes in tree and shrub distribution since the Little Ice Age, 150 years ago (Suarez et al., 1999; Tape et al., 2006). Thus existing arctic plant communities are not stable, climax communities, but rather what we see now is one moment in the continually changing mix of arctic plants species. The communities we see today result from a continual process of adaptation to changing conditions, including relatively recent climate changes and older geologic events (see Fig. 5.8 for time-scales). On older landscapes, vegetation communities have come and gone with climate fluctuations and their effects on the soil are superimposed on the much slower process of soil development through chemical and physical weathering.

On regional and local scales, the effects of glaciation are very heterogeneous. Glaciations not only killed vegetation by covering the land with year-round ice, they also eroded landscapes and left deposits including unsorted moraines and till, sorted glacio-fluvial deposits and eskers, and ice blocks that created countless kettle ponds. In addition to this spatial heterogeneity, glacial landscapes also show evidence of glaciations from many different time periods. It has even been shown that relatively recently melting ice sheets can uncover much older, un-eroded landscapes (Briner et al., 2005). These cold-bottomed glaciers re-set the clock for plant community development, but only stopped the clock for soil development. As a result, a small area can include large differences in types of glacial deposits and can have adjacent glaciations of very different ages (Hamilton, 1986). The present distribution of communities reflects differences between substrates of varying glacial ages and types (Walker et al., 1995). Whether the soil is scraped to bedrock, whether an underlying soil is left intact, whether the glacier deposits fresh till or sorted sands – all these have effects on plants and can be as important as whether the glaciation that caused these effects was 10 kya or 10 000 kya.

An examination of the importance and the relative time scales of the various processes affecting arctic vegetation distribution shows that recent climate change in the Arctic will impact plants on several different time scales. Temperature is the most important factor affecting NDVI of vegetation types in all but the warmest parts of the arctic (Bunn et al., 2005; Raynolds et al. 2008). Annual fluctuations in NDVI in response to temperature are superimposed on the longer-term trends of increasing NDVI and temperature (Jia et al. 2003). These longer-term trends will change relative species dominance in communities, such as the increase in shrubs seen in the southern Arctic (Tape et al., 2006). The changes that we have seen in Arctic vegetation since the 1970's match this understanding that changes in plant community composition and structure will show up on the decadal scale at the earliest. Warming will also accelerate processes that are happening on the geologic scale because chemical processes occur more rapidly at warmer temperatures, but this acceleration in rock weathering, soil formation, and peat sequestration will not be evident for decades or hundreds of years.

5.6 Conclusions

This study presents a map of landscape age in the circumpolar Arctic, based on time that landscapes have been available for plant colonization and community development since they emerged from glacial ice, sea or lake. A large portion (38%) of the Arctic was deglaciated relatively recently, 7-10 kya, mostly Arctic Canada, the site of the Laurentide Ice Sheet. Russian and Alaskan arctic landscapes are much older, with the oldest areas remaining unglaciated throughout the whole Pleistocene. The vegetation types most commonly associated with the oldest landscapes include tussock-sedge, dwarf-shrub, moss tundra and sedge-shrub wetlands.

Most of the Arctic, including most bioclimate zones and most vegetation types, showed increases in the normalized difference vegetation index (NDVI) with increases in landscape age. Landscapes showed rapid increases in NDVI during the first several thousand years after deglaciation. Landscapes 5 000-15 000 years old, the age of the most rapid peat accumulation, had relatively low levels of NDVI. Landscapes older than 20 000 years had higher NDVI levels. These landscapes are old enough to show the effects of soil development and in-filling of lakes, and are much more common in the less frequently glaciated southern Arctic than in the north.

Landscape age accounted for 34% of the variation in NDVI for landscapes younger than 900 000 years. The coldest parts of the Arctic (Subzone A) and vegetation types that grow primarily in these areas did not show any trend with landscape age. This could change due to anthropogenic warming, as the difference between Subzone A and Subzone B is about 2 °C in mean July temperatures, a level of change we are likely to see occur in the Arctic (Hassol, 2004). Warming in Subzone A would increase vegetation colonization, succession, and soil formation processes, which would over time lead to increases in vegetation cover and NDVI.

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Chapter 6 – Environmental controls of the present distribution of arctic vegetation and likely responses to climate change[1]

6.1 Abstract

Decreasing summer sea ice and increasing temperatures are affecting the vegetation of the Arctic. Results presented here from spatially explicit analysis of existing arctic vegetation and environmental characteristics can be used to better understand plant distribution patterns, evaluate change in the vegetation, and calibrate models of arctic vegetation and animal habitat. The Circumpolar Arctic Vegetation Map (CAVM) distribution of vegetation types and a satellite measure of vegetation (NDVI) were analyzed using circumpolar environmental data including temperature, precipitation, snow-water-equivalent, landscape age, elevation, substrate chemistry, landscape type, permafrost characteristics, distance to sea and percent lake cover. Boosted regression tree analysis described ecological niches of vegetation types, controlled by various sets of environmental characteristics. Summer warmth index (SWI) was the most important factor determining vegetation types, though a suite of other environmental factors were also important. NDVI was primarily correlated with landscape age and summer temperatures. Response curves showed the importance of snow depth to both vegetation types and NDVI. The optimal niche for maximizing NDVI is a place with warm summer temperatures, on a very young or very old

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landscape, with over 100 mm snow-water-equivalent in its snow-pack, below 150 m elevation, > 300 km from the ocean, > 120 mm of annual precipitation, low lake cover, and acidic substrate chemistry. Predicted response of NDVI to a conservative 2 °C increase in temperature showed the largest increases in northern partially vegetated areas.

Key words: CAVM, NDVI, boosted regression tree, TreeNet, summer warmth index, SWI, landscape age, glaciation, snow depth, climate change.

6.2 Introduction

The Arctic is the focus of much attention as the area of the globe that is changing most rapidly in response to climate change (ACIA, 2004). During the 20th century, air temperatures over extensive land areas of the Arctic have increased by up to 5 °C (Anisimov et al., 2007). Past climate fluctuations have recorded a polar amplification similar to that being presently documented, with surface air temperatures warming at approximately twice the global rate during recent decades (Anisimov et al., 2007). The dramatic reduction of summer sea ice in the Arctic Ocean in the last several years is a highly visible symptom of these changes, with repercussions for global climate systems (Comiso et al., 2008).

Vegetation in the Arctic is also responding to climate change, though not as dramatically as sea ice (Bhatt et al., 2009 in prep.). Twenty-five year satellite records show an increase in vegetation greenness over tundra areas (Jia et al., 2007) and also show that spring is coming sooner, lengthening the growing season (Goetz et al., 2005). Fifty-year photo comparisons document shrub expansion in the tundra (Tape et al., 2006), a trend that is corroborated by the results of international field experiments which show that deciduous shrubs and graminoid plants increase in height in response to warming treatments (Walker et al., 2006).

The large spatial extent and the complexity of the interactions between vegetation and climate in the Arctic have led researchers to use model simulations and multivariate statistical analyses to better understand existing vegetation distribution and possible changes that may occur due to climate change. Models have been developed using data from existing ecosystems to parameterize variables and quantify the interactions between them. They have been used to model equilibrium situations that would occur as a result of a static set of environmental conditions, including possible past or future scenarios (Kaplan et al., 2003; Thompson et al., 2005). They have also been used to investigate the transitions in vegetation as environmental parameters change (Epstein et al., 2004).

Statistical methods such as boosted regression tree analysis have also been used to analyze large amounts of inter-related data from ecosystems. Unlike model simulations, these statistical approaches do not use estimated equations to quantify relationships between environmental factors and vegetation, but rather use the environmental data to characterize the relationship of the vegetation to the environment, describing its ecological niche. Once these relationships are quantified, the effects of changes in environmental conditions can be investigated. An analysis of the boreal forest and tundra of Canada showed that forests summer NDVI (normalized difference vegetation index, a measure of vegetation based on satellite data) was most closely related to the preceding spring minimum temperature, and tundra summer NDVI was most closely linked to maximum summer temperature (Bunn et al., 2005). Regression tree analysis of circumpolar trends in northern NDVI between 1982-2003 compared to vegetation cover characteristics found that land cover type and forest density accounted for 58.8% of the variability in late summer (July-August) NDVI (Bunn and Goetz, 2006).

The research presented in this paper used boosted regression tree to analyze the relationship between existing arctic tundra vegetation types and a suite of environmental factors, including substrate and climate characteristics. The analysis included the full range of existing variation in environmental factors and vegetation in the Arctic to summarize the relationship in a spatially explicit method. Boosted regression tree has been found to be a robust, accurate approach for analyzing factors affecting species distribution (Elith et al., 2006) and was applied here to analyze the relative importance of different environmental variables to the distribution of arctic vegetation types and NDVI. Recent circumpolar data sets for vegetation, temperature, precipitation, snow cover, landscape age, permafrost characteristics, soil chemistry, and landscape characteristics were used in the analysis. The results describe the unique combination of environmental variables that characterize the ecological niche of each vegetation type and determine the most important environmental characteristics controlling vegetation type and NDVI. These analyses provide information to calibrate models of arctic vegetation and animal habitat, including those that look at the effects of changes in environmental conditions such as climate change. The GIS data layers and maps used as input to and produced by the analysis are available on the web (www.arcticatlas.org) or through the author, and are useful for land-use planning, education, and conservation studies.

6.3 Methods

The Circumpolar Arctic Vegetation Map (CAVM) was used as the data layer for vegetation types (Fig. 6.1a; CAVM Team, 2003). This map was the result of an international collaboration including scientists from Russia, Norway, Iceland, Greenland, Canada and the United States. The mapped area included all of the arctic tundra, defined as the region north of the climatic limit of trees that is characterized by an arctic climate, arctic flora, and tundra vegetation. The unified circumpolar legend of 15 tundra vegetation types allowed for the first time a comparison between different parts of the Arctic and an analysis of the Arctic as a whole. The map was published at a 1:7.5 million scale, which translates approximately to 8-km pixels (Walker et al., 2005).

Satellite data from arctic vegetation were also available for this study. The most informative satellite data for studying arctic vegetation were summarized in the normalized difference vegetation index (NDVI) (Tucker, 1979). NDVI is calculated as: $\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R})$, where NIR is the spectral reflectance in the near-infrared where reflectance from the plant canopy is dominant, and R is the reflectance in the red portion of the spectrum where chlorophyll absorbs maximally. NDVI values correlate

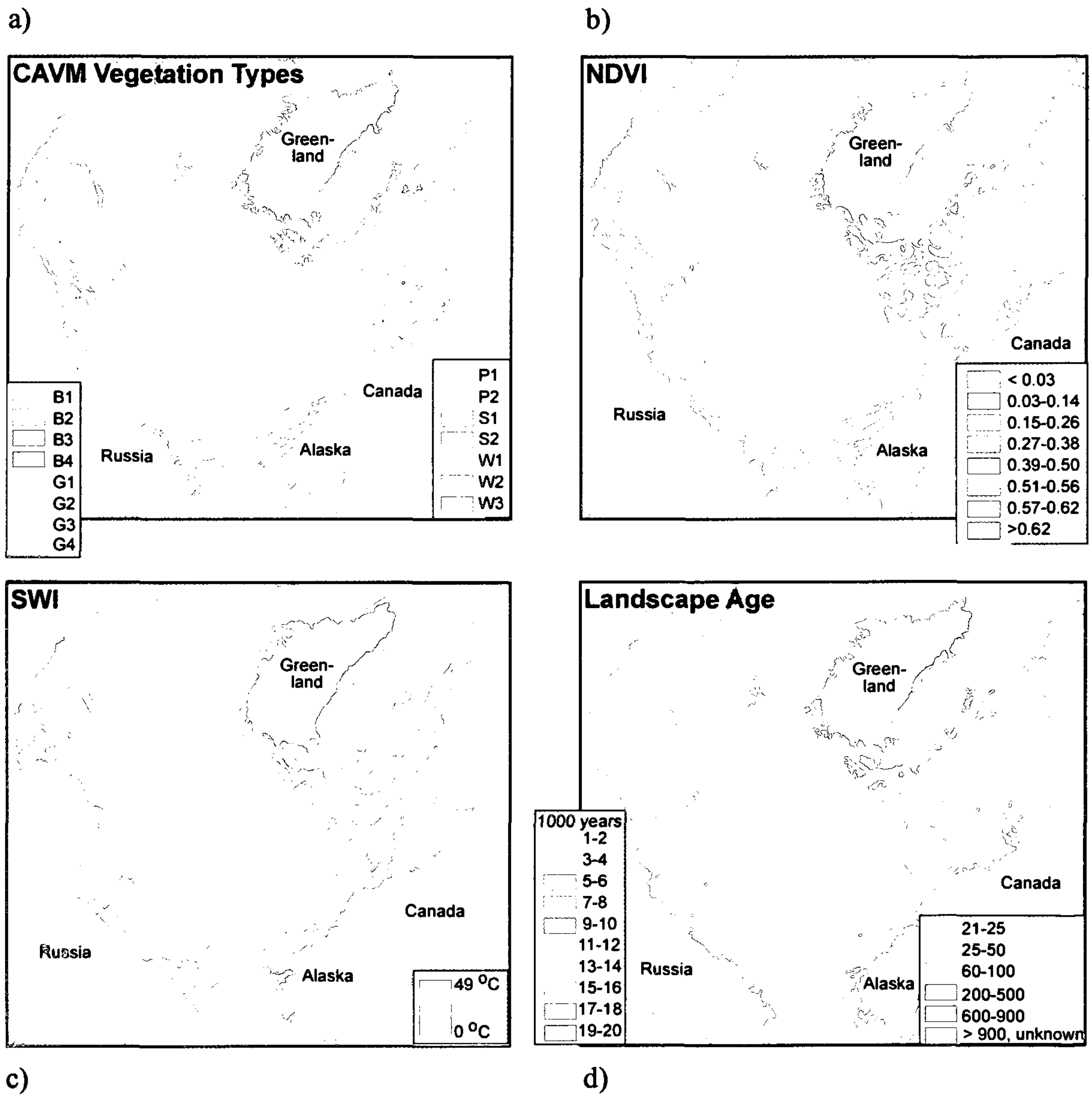

Figure 6.1 Maps of a) CAVM vegetation types, b) maximum NDVI, c) summer warmth index (SWI) and d) landscape age.

well with ground characteristics of arctic vegetation. NDVI values increase with the amount of vegetation as measured by leaf area index (LAI) and phytomass (Riedel et al., 2005; Shippert et al., 1995) and can be used to distinguish between arctic vegetation types (Hope et al., 1993; Stow et al., 1993). Estimates of total arctic plant biomass based on NDVI (Raynolds et al., 2006) agreed well with estimates based on field samples (Walker et al., 2008).

The Advanced Very High Resolution Radiometer (AVHRR) aboard NOAA satellites collects data to produce NDVI. The satellites' polar orbit and resolution (1-km pixels) make them an ideal source of arctic data. The satellites pass over the pole often, so data can be collected even from areas with frequent cloud cover. The 1-km resolution provides enough detail for regional studies, and yet is coarse enough that the entire Arctic can be analyzed as one data set. A 1-km maximum NDVI data set was produced by the U. S. Geological Survey EROS office, compositing maximum NDVI for two relatively cloud free summers (11 July – 31 August in 1993 and 1995). The data were composited into maximum values for 10-day periods, then the highest value for the entire time period was kept. The result was an almost cloud-free data set of maximum NDVI for the entire Arctic in the early 1990s (Fig. 6.1b; (CAVM Team, 2003; Markon et al., 1995).

The two data sets describing arctic vegetation, the CAVM and the NDVI, were used as response variables in the boosted regression tree analysis. Data sets for environmental variables were assembled in the same spatial format as the vegetation data. The most important variables thought to influence arctic vegetation distribution include temperature, precipitation, landscape age, permafrost, elevation, lake cover, and distance from the coast (Billings, 1997) (Table 6.1).

Table 6.1 Environmental data used as predictors in boosted regression tree analysis.

Environmental Variable	*Description (units)*	*Source*
SWI	Summer Warmth Index (sum of monthly means > 0 °C)	AVHRR satellite thermal data (Raynolds et al., 2008a)
Annual precipitation	Sum of monthly means Jan-Dec (mm)	Global Precipitation Climatology Centre (GPCC) (Beck et al., 2004)
Summer precipitation	Sum of monthly means Jun-Aug (mm)	Global Precipitation Climatology Centre (GPCC) (Beck et al., 2004)
Winter precipitation	Sum of monthly means Sep-May (mm)	Global Precipitation Climatology Centre (GPCC) (Beck et al., 2004)
Snow depth	Maximum monthly value, snow-water equivalent (mm)	National Snow and Ice Data Center (NSIDC) (Armstrong et al., 2005)
Landscape age	Years since deglaciation, proglacial lake drainage or sub-sea rebound (years)	Based on (Ehlers and Gibbard, 2004) and others ((Raynolds and Walker, 2009 (in press))
Permafrost characteristics	Permafrost extent, ice content, and substrate depth	(Brown et al., 1997)
Substrate chemistry	Acidic, circum-neutral, carbonate or saline	(CAVM Team, 2003)
Elevation	Elevation above sea level (m)	Digital Chart of the World (ESRI, 1993)
Landscape type	Plain, hill, plateau, mountain, glacier, lake	(CAVM Team, 2003)
Distance from coast	(km)	Digital Chart of the World (ESRI, 1993)
Lake cover	Percent of 1 km pixels	CAVM image, AVHRR band 2 (Raynolds et al., 2006)

Arctic land surface temperature were calculated from the same AVHRR sensors used to collect NDVI data (Comiso, 2003; Comiso, 2006). This data set provided a more detailed and consistent record than temperature data based on extrapolation from scarce arctic weather stations (Pielke et al., 2007; Rawlins and Willmot, 2003). Summer warmth index (SWI) was calculated from the AVHRR land surface temperature. This index characterizes the plant growing season by summing monthly mean temperatures warmer than 0 °C, combining the effect of both the length and the warmth of summer temperatures. SWI is the climate variable found to correlate best with variations in arctic vegetation distribution (Edlund, 1990; Young, 1971). The mean SWI of the arctic AVHRR data set (1982-2003) was calculated (Fig. 6.1c; Raynolds et al., 2008a). The length of this record, especially the inclusion of the earliest years, was important in producing a mean that characterized the conditions that created the present distribution of arctic vegetation. When comparing with SWI based on station data, it must be remembered that the satellite land surface temperatures used to calculate SWI for this study are warmer than the station data collected at 2 m elevation by about 2 °C (Raynolds et al., 2008a), and that this difference is compounded for each additional month included in SWI.

Monthly precipitation data at 0.25 degree resolution (approximately 25 km) were downloaded from the Global Precipitation Climatology Centre (GPCC) (Beck et al., 2004). This data set is based on data from 50,650 stations, with monthly means available for the period 1951-2000. Means of summer (June-August), winter (September-May) and annual precipitation were calculated. Snow-water-equivalent data were acquired from the National Snow and Ice Data Center at 25 km resolution, in monthly means averaged from November 1978 through June 2003 (Armstrong et al., 2005). The maximum of the monthly values for each pixel was used in the analysis to characterize winter snow depth.

Circumpolar data for several substrate characteristics were available from the CAVM, including elevation and distance from the coast based on the Digital Chart of the World (ESRI, 1993), substrate chemistry, and landscape category (CAVM Team, 2003). Permafrost characteristics were taken from the Circum-arctic Map of Permafrost and Ground-Ice Conditions, available in digital format at 12.5-km pixel resolution (Brown et al., 1997). Glaciation data were compiled from a summary of Quaternary glaciations available in GIS format and in data provided in regional chapters (Ehlers and Gibbard, 2004), supplemented by more recent work (Fig. 6.1d; Raynolds and Walker, 2009 (in press)). A brief description of the CAVM vegetation types and a summary of their environmental characteristics are listed in Table 6.2.

All data were summarized as characteristics of CAVM mapping polygons. Quantitative pixel data, including NDVI, SWI, precipitation characteristics, elevation, and percent lake cover were averaged for each polygon. Distance from coast was calculated from polygon centers. Categorical map data, including landscape age and type, permafrost characteristics and substrate chemistry were added as attributes of CAVM polygons, dividing the polygons where necessary to match the additional data layers. All input data are available on the web (www.arcticatlas.org) or from the author.

Table 6.2 Vegetation types of the Circumpolar Arctic Vegetation Map, their environmental characteristics, and most important niche characteristics. NDVI means are from Raynolds et al. (2006), SWI means from Raynolds and Walker (2006), permafrost characteristics from Raynolds and Walker (2008), landscape age from Raynolds and Walker (2009 (in press)), and most important niche characteristics as determined by boosted regression tree analysis results presented in this paper.

Physiognomic vegetation type	*CAVM unit*	*Description*	*NDVI (Mean ± s.d.)*	*SWI (°C, mean ± s.d.)*	*Most common permafrost type**	*Landscape age (years, mean ± s.d.)*	*Environmental niche characteristics*
Cryptogam, cushion-forb barren	B1	Dry to wet barren landscapes with very sparse, very low-growing plant cover. Scattered herbs, lichens, mosses and liverworts.	0.09 ± 0.05	11.0 ± 5.3	Chr	18,000 ± 16,000	precip. < 140 mm SWI < 20 °C
Cryptogam barren (bedrock)	B2	Areas of exposed rock and lichens interspersed with lakes and more vegetated areas, as found on the Canadian Shield.	0.18 ± 0.09	21.2 ± 6.6	Clr	7,000 ± 1,000	acidic substrate age < 10,000 yr.
Non-carbonate mountain complex	B3	Mountain vegetation on noncarbonate bedrock. The variety and size of plants decreases with elevation and latitude.	0.26 ± 0.16	19.4 ± 9.7	Clr	28,000 ± 29,000	mountain landscape acidic substrate
Carbonate mountain complex	B4	Mountain vegetation on carbonate bedrock. The variety and size of plants decreases with elevation and latitude.	0.26 ± 0.20	18.5 ± 11.2	Clr	199,000 ± 226,000	mountain landscape non-acidic substrate

Table 6.2 Continued

Rush/grass, cryptogam tundra	G1	Moist tundra with moderate to complete cover of very low-growing plants. Mostly grasses, rushed, forbs, mosses, lichens and liverworts.	0.16 ± 0.12	9.6 ± 5.3	Clr	26,000 ± 25,000	SWI < 17 °C precip. < 170 mm
Graminoid, prostrate dwarf-shrub, forb tundra	G2	Moist to dry tundra, with open to continuous plant cover. Sedges are dominant, along with prostrate shrubs.	0.30 ± 0.13	23.1 ± 7.4	Clr Chr	88,000 ± 118,000	non-acidic substrate SWI < 22 °C
Non-tussock sedge, dwarf-shrub, moss tundra	G3	Moist tundra dominated by sedges and dwarf shrubs < 40 cm tall, with well-developed moss layer. Barren patches due to frost boils and periglacial features are common.	0.39 ± 0.12	28.3 ± 5.6	Clr Chf	37,000 ± 38,000	SWI > 17 °C age < 50,000 yr.
Tussock sedge, dwarf-shrub, moss tundra	G4	Moist tundra dominated by tussock cottongrass and dwarf shrubs < 40 cm tall. Mosses are abundant.	0.48 ± 0.11	31.4 ± 5.1	Chf Cmf	265,000 ± 252,000	SWI > 26 °C age > 250,000 yr.
Prostrate dwarf-shrub, herb tundra	P1	Dry tundra with patchy vegetation. Prostrate shrubs < 5 cm tall are dominant, with graminoids and forbs.	0.21 ± 0.12	20.9 ± 7.2	Chr Clr	35,000 ± 43,000	non-acidic substrate precip. < 200 mm
Prostrate/ hemiprostrate dwarf-shrub tundra	P2	Moist to dry tundra dominated by prostrate and hemiprostrate shrubs < 15 cm tall.	0.18 ± 0.08	17.7 ± 6.3	Clr	8,000 ± 3,000	age < 10,000 yr. SWI < 22 °C

Table 6.2 Continued

Erect dwarf-shrub tundra	*S1*	*Tundra dominated by erect dwarf-shrubs, mostly < 40 cm tall.*	*0.40 ± 0.11*	*30.5 ± 5.2*	*Clr Cmf*	*45,000 ± 51,000*	*SWI > 26 °C*
Low-shrub tundra	S2	Tundra dominated by low shrubs > 40 cm tall.	0.47 ± 0.10	32.8 ± 4.0	Clr Cmf	54,000 ± 60,000	SWI > 28 °C
Sedge/grass, moss wetland	W1	Wetland complexes in colder areas of the Arctic, dominated by sedges, grasses and mosses.	0.29 ± 0.13	20.9 ± 6.7	Chf	55,000 ± 82,000	SWI < 23 °C
Sedge, moss dwarf-shrub wetland	W2	Wetland complexes in milder areas of the Arctic, dominated by sedges, grasses and mosses, but including dwarf shrubs < 40 cm tall.	0.39 ± 0.10	27.0 ± 4.7	Chf	42,000 ± 49,000	elevation < 50 m SWI > 22 °C
Sedge, moss, low-shrub wetland	W3	Wetland complexes in warmer areas of the Arctic, dominated by sedges and low shrubs > 40 cm tall.	0.48 ± 0.10	36.7 ± 4.2	Cmf	75,000 ± 89,000	SWI > 30 °C elevation < 100 m

* Permafrost types: categories are based on extent (Continuous, Discontinuous, Sporadic, Isolated), ice content (high, medium or low), and overburden (thick = f, thin = r).

The vegetation and environmental data sets were analyzed using boosted regression tree analysis. This method summarizes the results from a set of linked decision trees, improving the strength of the trees in selecting relevant variables by carrying out successive analyses using different random portions of the data (i.e. boosting) (Elith et al., 2006). This approach is more appropriate to complex inter-related data than simple regression or general linear models. Rather than having to specify a model to begin with (such as additive or with specified interactions), the decision trees uncover the structure of the data (Breiman, 2001; De'ath and Fabricius, 2000). Decision trees partition the response variable into groups having the most homogeneous responses to predictors. They then fit a constant to each group, with classification trees fitting the most probable class and regression trees fitting the mean response for the group (Elith et al., 2008). This non-parametric analysis has been shown to work well with complex and correlated data sets, can handle a mix of classified and continuous data, a large number of predictor variables, non-linear interactions, missing data, and does not require data transformations to meet statistical assumptions (Elith et al., 2008; Salford Systems, 2005). Single decision trees have been found to be less accurate that other methods, but 'boosting' the data creates stable, accurate solutions. Boosting involves an iterative resampling process, whereby each new tree is created to best reduce the remaining unexplained variance (Elith et al., 2008). Boosted regression tree analysis has been found to describe species distribution in relation to multiple environmental characteristics better than other types of statistical analyses (Elith et al., 2008; Prasad et al., 2006).

Analyses were run using several versions of boosted regression tree software, including the R gbm package (Elith et al., 2008; R Development Core Team, 2008), the RandomForest software (Salford Systems, 2005; http://www.salford-systems.com), and TreeNet software (Friedman, 1999; Salford Systems, 2005). Results were similar for all analyses. TreeNet results are reported here, as that software package had the most convenient interface for running the multiple-level classification analysis needed for the vegetation types.

A grid of points at 1 km spacing was created covering the circumpolar Arctic. 1/1000 of these points were randomly selected for the boosted regression tree analysis. Points on ice and water were removed, reducing the number of points from 14,349 to 10,019. An independent set of points was created to test the accuracy of the analysis. These points were from a regularly spaced 50 km grid, which yielded 1990 points on land. The vegetation characteristics (CAVM vegetation type and maximum NDVI) were used as response variables and the environmental variables (Table 6.1) as predictors for each point in the analyses.

A TreeNet analysis was performed for the NDVI data using the regression option for continuous data. The subsample size was set at 0.5, meaning that a random half of the data would be used to develop each additional tree. The learning rate, set at 0.1 for large data sets (Salford Systems, 2005), shrinks the contribution of each tree to <1 to prevent overfitting (Elith et al., 2008). The number of nodes/tree (the number of levels of branching in each classification tree) was set at 6. These settings were the default TreeNet settings, but were used only after testing other settings showed no improvement in the results. The number of trees was set to 5000. The residual variance decreased rapidly with the addition of each tree at first, and leveled off at about 1000 trees. There was no optimal number of trees, but each additional tree after 1000 improved the solution only slightly (R^2 for 1000 trees = 0.961, R^2 for 5000 trees = 0.976). To look at the sensitivity of NDVI to increases in temperature, we ran the boosted regression tree NDVI analysis with a conservative increase of 2°C in annual mean temperature.

A TreeNet analysis was run for the CAVM vegetation types using the classification option, to match the classified response data. Again, the TreeNet defaults were used for subsampling, learning rates, nodes/tree and balanced classes after testing other settings. The optimum number of trees for this analysis, where the most variance was explained, was 408. The same set of environmental variables was used for testing this analysis as for the NDVI analysis (Table 6.1). The classification analysis produced a joint result for all the CAVM vegetation types as a group and individual results for each CAVM vegetation type.

Several different types of TreeNet results are presented below. The NDVI results were evaluated using the R^2 value. The R^2 values of boosted regression tree analysis are typically high, as this is not a classic regression, but rather a representation of the ability of the set of trees to account for the variation in the dependent variable. The large number of trees in the boosted regression tree method usually account for much of the variation present in the input data. The solution is then applied to the test data and the relationship between the value predicted by the analysis and the actual value in the test data is presented as an R^2 value, with a mean residual. These values show how well the analysis predicted the NDVI values of the test points, given the environmental characteristics of those points.

The CAVM classification results were evaluated using a contingency table. The boosted regression tree solution was applied to the test data to predict the most likely vegetation type for each test point, given the environmental characteristics. The predicted vegetation types were compared to the mapped vegetation types, giving a tally of omission and commission errors for each vegetation type and total accuracy.

Importance values for different environmental variables were reported. These values are calculated from the variation accounted for by all splits using a given variable. They are scaled at 100 for the most important variable, providing a relative measure of each variable's contribution to the predictive power of the final tree. The actual amount of variation accounted for by each variable depends on the accuracy of the total analysis (Salford Systems, 2005).

The response curves of selected environmental variables are presented. These graphs show the partial dependence of the set of trees on a particular environmental variable, after accounting for the average effect of all other predictor variables. The graphs are displayed using a random subsample of 200 points to make them more readable (Salford Systems, 2005). The vertical axis shows the strength of the negative or positive effect of that environmental variable on the response variable. The horizontal axis shows the range of values of the environmental variable. Units vary depending on the variable and are shown as bars for classified variables. These response curves are useful for understanding the relationship between environmental variables and response variables, to check for positive or negative responses and for the possible existence of threshold values.

6.4 Results

The boosted regression tree analysis for NDVI had an R^2 of 0.976 and a mean residual of -0.00043 NDVI units, when values for the test points calculated using environmental variables were compared with the actual NDVI values of those points (for scale comparison of the residual, the average NDVI of arctic land areas is 0.32 (Raynolds et al., 2006)). The test data points, although independently located from the points used to develop the trees, were from the same spatial extent (the Arctic) and had the same range of environmental characteristics as the input data. The high R^2 value and low mean residual of the test data show that the environmental variables included in the analysis were relevant and important in predicting NDVI, and that boosted regression tree analysis is a valid tool for exploring important nonlinear variable responses within this spatial domain.

The most important variables in the NDVI analysis were landscape age and SWI (Table 6.3). Examination of the response curves for different environmental variables showed that NDVI increased with landscape age and SWI (Fig. 6.2a, b). NDVI showed a threshold response to snow-water-equivalent , with low values below 75 mm and a large increase above that point (Fig. 6.2c).

Table 6.3 Importance of environmental variables in boosted regression tree analyses of NDVI, CAVM vegetation types (as a group), and individual CAVM vegetation types. Values are scaled in relation to the most important variable in each analysis, which is set at 100.

	SWI	*annual precipitation*	*summer precipitation*	*winter precipitation*	*snow*	*landscape age*	*permafrost*	*substrate chemistry*	*elevation*	*landscape type*	*distance to sea*	*lake cover*
NDVI	86	23	25	24	29	100	20	16	26	20	26	23
All CAVM vegetation types	100	68	72	68	65	71	43	96	90	79	75	44
B1	91	100	74	60	51	42	29	54	73	56	71	27
B2	68	53	52	51	74	90	34	100	82	43	51	42
B3	20	26	20	33	18	16	17	88	31	100	22	9
B4	8	3	7	3	7	12	3	100	35	85	20	6
G1	100	90	58	79	44	86	39	73	77	46	46	21
G2	96	61	100	74	48	71	38	99	74	70	89	33
G3	100	62	62	67	79	90	67	83	62	32	73	48
G4	87	47	65	68	100	100	35	72	71	50	62	43
P1	76	90	80	72	69	60	45	100	82	53	83	38
P2	95	62	74	89	45	100	39	62	84	52	91	32
S1	100	65	85	66	83	87	37	74	87	71	78	52
S2	100	49	52	59	56	39	47	39	69	42	62	41
W1	100	44	77	47	50	31	29	48	83	54	83	60
W2	79	58	80	62	65	55	59	68	100	21	74	46
W3	100	31	40	34	34	16	16	25	91	17	46	36

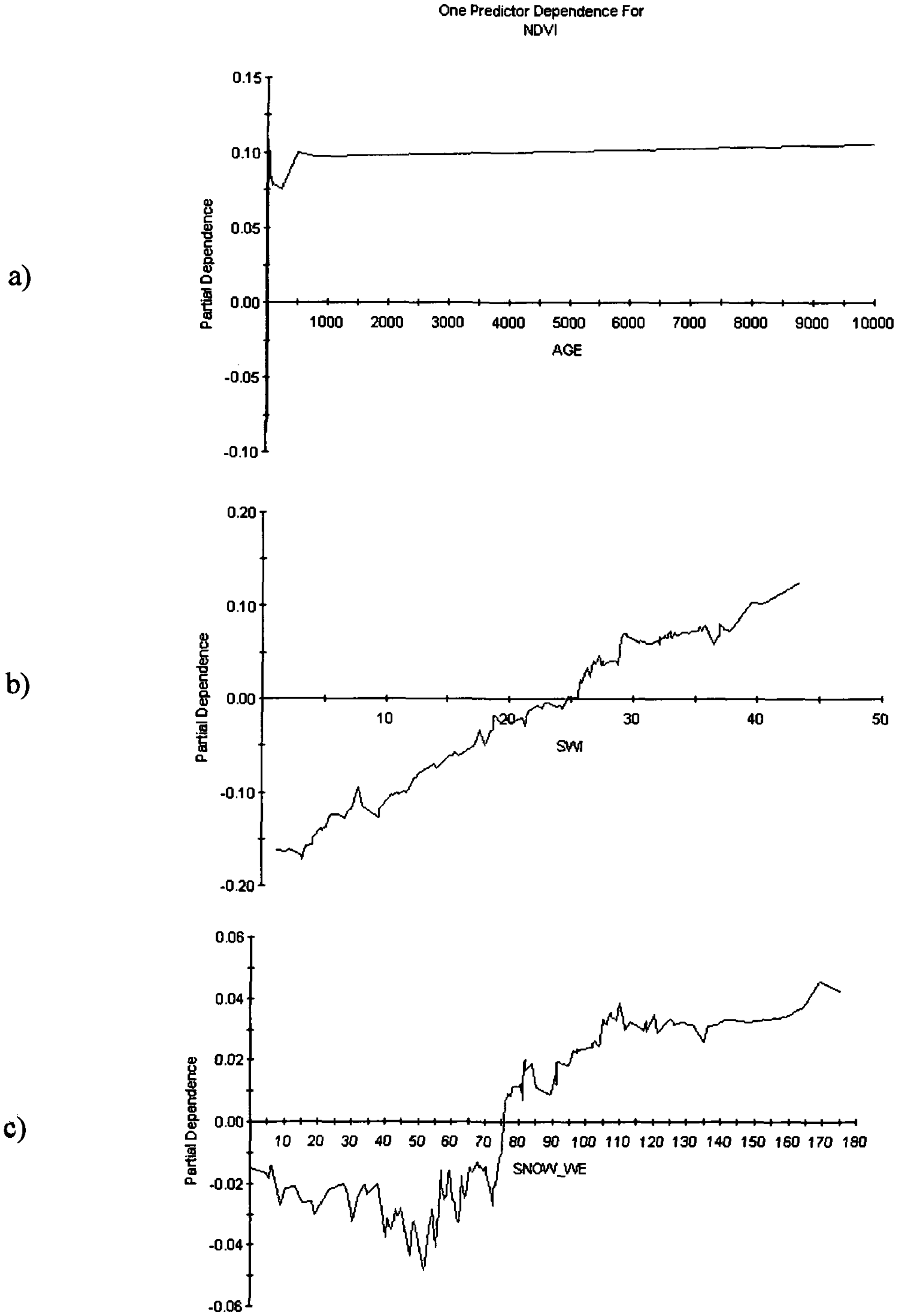

Figure 6.2 Partial dependence of predictor variables in boosted regression tree analysis of maximum arctic NDVI. The vertical axis shows the strength of the negative or positive effect of the environmental variable on the response variable (NDVI). The horizontal axis shows the range of values of the environmental variable. a) landscape age (1000 years), b) SWI (°C), c) snow-water equivalent (mm water).

NDVI also showed a threshold response to elevation, with high values for areas below 150 m and decreases with further gains in elevation (all other response curves can be found in Appendix 6.1). Distance to sea had a bimodal response, with high NDVI values within 25 km of the sea, low values from 25 km to 150 km, and highest values at around 300 km (the southernmost parts of the Arctic). NDVI increased with precipitation and then leveled off at about 120 mm summer precipitation and 350 mm annual precipitation. NDVI decreased with lake cover. NDVI was high for permafrost categories that occurred only in areas of erect or dwarf-shrub vegetation. NDVI was low for mountain landscapes and for areas of carbonate or saline substrate.

Mean residuals between predicted and actual NDVI for the test data set varied by vegetation type. Vegetation types with the smallest residuals, indicating that their NDVI values were the best predicted, were carbonate mountains and rush/grass, cryptogam tundra (Table 6.4). Vegetation types with the largest residuals were wetland types (W1, W2, W3) which have an unpredictable mix of high NDVI values from productive land area and low NDVI from areas of water.

The boosted regression tree analysis for CAVM vegetation types predicted the correct vegetation type based on the environmental variables for 93.8% of the test points (Table 6.5). The table is not a true accuracy assessment, as neither the map nor the predicted vegetation type is actual ground truth. As with the NDVI analysis, this high prediction accuracy shows that the environmental variables included in the analysis were relevant and important in predicting vegetation type and that boosted regression tree analysis is a valid tool for exploring important variable responses within this spatial domain.

Table 6.4 Mean residuals from boosted regression tree analysis between predicted NDVI and AVHRR NDVI, summarized by CAVM vegetation types.

CAVM vegetation type	*Δ NDVI*
B1	0.0012
B2	0.0009
B3	-0.0009
B4	< ± 0.0001
G1	< ± 0.0001
G2	0.0024
G3	0.0005
G4	0.0008
P1	-0.0004
P2	-0.0019
S1	0.0001
S2	0.0004
W1	0.0043
W2	-0.0028
W3	0.0028

The accuracy assessment table shows that most vegetation types were predicted well by the boosted regression tree analysis (Table 6.5). Classification errors were mostly between similar vegetation types that often occurred in adjacent polygons. Review of individual misclassified points showed that for 79% of the points it was not possible to determine if the map or the classification was more likely to be correct. For 14% of the points the predicted vegetation was not likely to be correct, for 6% the map was likely in error, as explained below.

Table 6.5 Vegetation classification of 1990 points (50-km spacing throughout the Arctic) using boosted regression tree analysis and a set of environmental variables (Table 6.1) compared to vegetation mapped on the Circumpolar Arctic Vegetation Map. Total accuracy = 93.8%.

	*Predicted vegetation type**															
Mapped vegetation type*	B1	B2	B3	B4	G1	G2	G3	G4	P1	P2	S1	S2	W1	W2	W3	Omission errors
B1	83	0	0	1	4	0	0	0	2	0	0	0	2	0	0	9.8
B2	1	149	0	0	1	0	1	0	0	0	1	0	0	0	0	2.0
B3	1	0	209	0	0	0	0	0	0	0	1	0	0	0	0	0.5
B4	0	0	1	58	0	0	0	0	0	0	0	0	0	0	0	0.0
G1	2	0	2	0	50	0	0	0	0	0	1	0	0	0	0	1.9
G2	2	0	0	0	2	156	1	0	5	0	0	1	3	2	0	7.0
G3	0	0	0	0	0	3	202	1	0	0	4	1	2	0	0	3.8
G4	0	0	0	0	0	1	1	129	0	0	1	5	0	1	1	5.8
P1	2	0	0	0	0	2	2	0	150	0	0	0	1	0	0	0.7
P2	0	2	1	0	0	0	0	0	1	50	1	0	0	0	0	1.9
S1	0	3	2	0	0	1	7	2	0	1	267	8	1	1	0	3.5
S2	0	0	1	0	0	1	0	2	1	0	5	235	0	0	2	0.9
W1	0	0	0	0	0	4	0	0	0	0	0	0	34	1	0	2.7
W2	0	0	0	0	0	0	0	0	0	0	0	1	4	45	1	11.8
W3	0	1	0	0	0	0	0	1	0	0	1	2	0	0	49	9.3
Commission errors	8.8	3.9	3.2	1.7	12.3	7.1	5.6	4.4	5.7	2.0	5.3	7.1	27.7	10.0	7.5	

*See Table 6.2 for description of vegetation types

The misclassified points were distributed throughout the Arctic without any obvious spatial pattern or relationship to environmental variables. Sedge/grass moss wetland (W1) had the most commission errors (points that were predicted to be W1 but mapped as another vegetation type). Most of these were low elevation coastal areas. Determining whether these points were actually wetlands or not would require additional data from higher resolution imagery or ground visits. It is possible that data for some additional environmental variable that was not included in the analysis would be required to correctly predict these points. Sedge, moss, dwarf-shrub wetland (W2) had the most omission errors (points that were mapped as W2, but predicted to be another vegetation type). Most of these errors were between W2 and W1. Since this distinction is based largely on SWI which mostly controls the presence of dwarf-shrubs (CAVM Team, 2003) and the analysis used more detailed temperature data than the generalized bioclimate subzones of the CAVM, the analysis is more likely to be correct than the map.

The most important environmental variable in predicting vegetation types was SWI (Table 6.3). Substrate chemistry, elevation, landscape type, distance to sea, summer precipitation, and landscape age all had importance values > 70 (relative to 100 for the most important variable in the analysis). Percent lake cover and permafrost type were the environmental characteristics that had the least influence on vegetation type. A comparison of the environmental variables in the NDVI analysis and the vegetation type analysis showed that NDVI was primarily dependent on landscape age and SWI, while the CAVM vegetation type analysis depended on a much broader group of variables (Fig. 6.3).

Boosted regression tree analysis for each individual vegetation type suggested that different environmental characteristics were most important for different vegetation types. The three most important environmental variables in the boosted regression tree analysis for each vegetation type were summarized in the final column of Table 6.2, and their response curves are shown in Appendix 6.2.

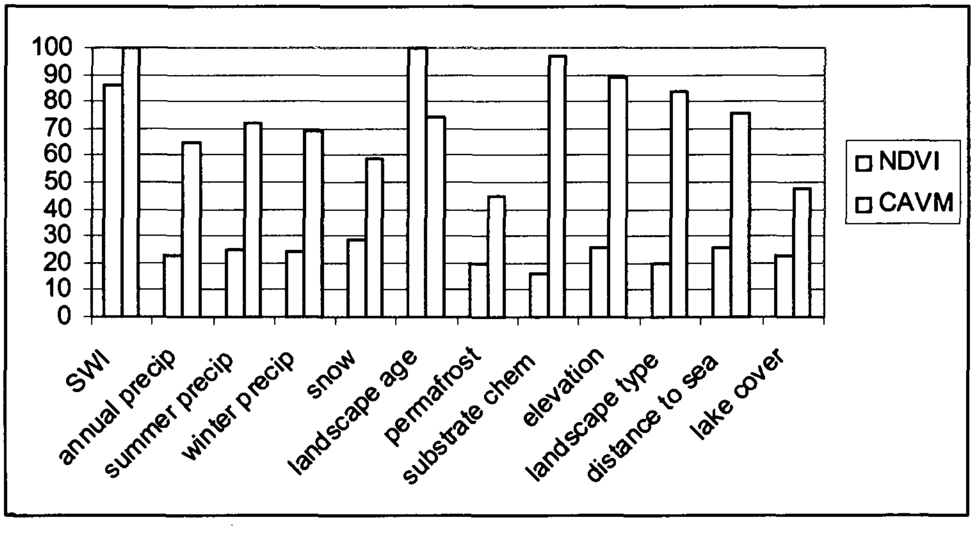

Figure 6.3 Importance of various environmental variables in boosted regression tree analysis of NDVI and CAVM vegetation type.

Mountain complexes (B3 and B4) were defined by a mountainous landscape category. Carbonate mountains were differentiated from acidic mountains based on the substrate chemistry of the bedrock (Walker et al., 2005). The analysis of cryptogam, cushion-forb barren type (B1) showed that low precipitation (< 140 mm/yr) and low temperatures were important characteristics for this vegetation type (Table 6.2). Low precipitation was also important for two other High Arctic vegetation types (G1, P1). Age was an important characteristic for vegetation types found on young, recently deglaciated areas (B2, P2) and for tussock tundra (G4), which grows on the oldest landscapes. Shrub-dominated types occurred only on the warmest areas, with erect dwarf-shrubs in areas with SWI > 26 °C (mean 30.5 °C) and low shrubs in areas > 28 SWI (mean 32.8 °C) (Table 6.2). Wetland types were divided by bioclimate subzone in the mapping process (Walker et al., 2005), as species composition and growth forms differentiated wetlands in the warmer and colder parts of the Arctic. The analysis showed this dependence, with W1 characterized by SWI < 23 °C, W2 by SWI > 22 °C, and W3 by SWI > 30 °C (Table 6.2).

A map of the spatial distribution of these factors showed that summer warmth index was the most important environmental factor for determining vegetation type in much of the southern Arctic and on many islands (Fig. 6.4). Substrate chemistry and precipitation were most important in the Canadian Arctic Islands. Landscape age was most important in much of Beringia.

Results of the analysis with temperatures increased by 2°C show the largest increases in predicted NDVI in vegetation types that are partially vegetated and that grow in the colder parts of the Arctic (Fig. 6.5). Vegetation types that typically have 100% plant cover (G3, G4, S1, S2, W2, W3) ((Table 6.2; Walker et al., 2005) showed less predicted increase in NDVI with increased temperature.

Figure 6.4 Map of most important environmental variable controlling vegetation type, based on boosted regression tree analysis. SWI = summer warmth index, Chemistry = substrate chemistry, Landscape = landscape category, Age = landscape age, Annual precip. = annual precipitation, Summer precip. = June – August precipitation, Elevation = elevation. See Table 6.1 for more detail about environmental variables.

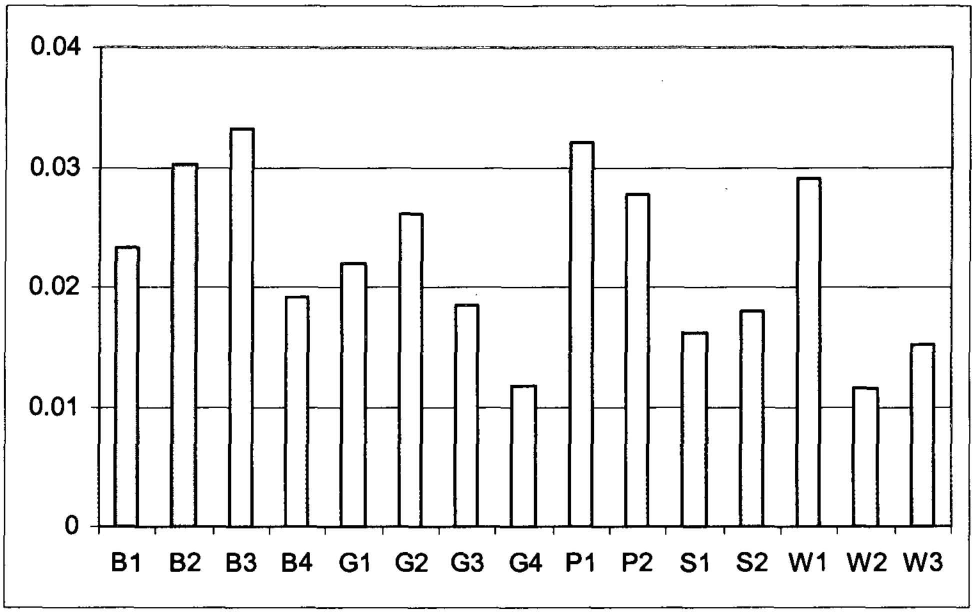

Figure 6.5 Change in NDVI produced by an increase of 2 °C in annual mean temperature in boosted regression tree model input data.

6.5 Discussion

6.5.1 Boosted regression tree analysis

The boosted regression tree approach produced statistical analyses for both NDVI and vegetation types that accounted for most of the variation in the data for the Arctic. The results were much more consistent and accounted for more of the variation than previous GLM analyses, which produced R^2 values of 0.83 or lower, depending on the variables included (Raynolds and Walker, 2009 (in press); Raynolds et al., 2006). This improvement from using boosted regression tree analysis is similar to that reported by other researchers (Elith et al., 2006; Prasad et al., 2006).

The analysis of NDVI emphasized the importance of landscape age and SWI, two factors whose effects can be seen on circumpolar images of the Arctic (Fig. 6.1). The increase of NDVI with increasing SWI and landscape age matches the results reported in earlier analyses (Raynolds and Walker, 2009 (in press); Raynolds et al., 2008a). Other environmental factors added to the accuracy of the analysis, but were much less important (Fig. 6.3). According to the analysis, the optimal location for maximizing NDVI would be a place with warm summer temperatures, on a very young or very old landscape, with over 100 mm snow-water-equivalent in its snow-pack, below 150 m elevation, > 300 km from the ocean, > 120 mm of annual precipitation, low lake cover, and acidic substrate chemistry. Minimal NDVI was found in cold, recently glaciated areas.

The analysis of NDVI showed an interesting relation with snow-water-equivalent. The 75 mm threshold, after which NDVI increased, translates to approximately 28 cm of snow (based on average snow densities measured on the Alaska North Slope of 270 kg/m^3; Liston and Sturm, 2002). It is also close to the 80 mm threshold seen in the boosted regression tree analysis of G4, tussock tundra. Almost three-quarters of the area with > 75 mm snow-water-equivalent was mapped as G3, G4, S1, or S2. All of these vegetation types include erect dwarf or low shrubs (Walker et al., 2005) and have relatively high NDVI values. The depth of the snow pack is very important to vegetation in the Arctic, as anything that stands above the snow is subject to long periods of desiccation, extreme cold temperatures, and abrasion from wind-blown particles, as well as herbivory (Hakkarainen et al., 2007). Vegetation types in northern Alaska differ between different snow-water equivalent categories (Evans et al., 1987). Vegetation bends down as snow load increases, but bending of tundra shrubs has been found to increase with colder temperatures (Ray and Bret-Harte, 2009 (in prep.); Ray et al., 2009 (in prep.)), so the shrubs would be less flexible in the autumn during initial snow falls. The 28 cm snow depth corresponds to the height of erect dwarf shrubs and is taller than prostrate dwarf shrubs and graminoid vegetation (Walker et al., 2005). There was also a less-pronounced positive response in NDVI to snow depth at about 105 mm (Figure 6.2c). This threshold may correspond to the lower snow densities (Liston and Sturm, 2002) and taller shrubs found in the southern-most parts of the Arctic (Walker et al., 2005), where snow depths > 60 cm are common (Raynolds et al., 2008b), protecting the growth of taller low shrubs.

The vegetation analyses showed the unique combination of environmental characteristics controlling each vegetation type and provided some quantification of the relationships. Temperature was an important factor controlling the distribution of all but mountain complex vegetation types, which were controlled more by substrate characteristics than climate. Climate in mountainous areas often varies with aspect and elevation at a smaller scale than the data used in this analysis. The vegetation types most affected by precipitation were found in the High Arctic, where precipitation is low. Our results agree with the equilibrium model BIOME4, which found that arctic vegetation was most sensitive to growing season warmth, snow cover and soil moisture (Kaplan et al., 2003). Although we did not have circumpolar data for soil moisture to include in the TreeNet analysis, many of the substrate factors included relate indirectly to soil moisture, such as annual precipitation, permafrost type, elevation and landscape age (related to soil development).

6.5.2 Relevance to climate change

The most pressing question regarding arctic vegetation is how will it respond to climate change? The analysis presented in this study provides information about the existing spatial relationships between environmental factors and arctic vegetation. It can be used to examine possible effects of changes in the environmental factors, but with caution. The vegetation analysis cannot show new vegetation types that might result from changes in species composition. The NDVI analysis produced very good results within the range of input parameters provided (present environmental conditions in the Arctic), but the strength of the analysis is not known for novel combinations of environmental factors (Elith et al., 2006). Results from field experiments found that warming of arctic vegetation favored deciduous shrubs over evergreen shrubs and reduced cover of non-vascular plants (Walker et al., 2006). The BIOME4 model suggested that non-analogous vegetation types are likely to develop, that do not fit into existing vegetation categories (Kaplan et al., 2003), as species respond individualistically to climate change (Gleason, 1939). In addition, like an equilibrium model, the boosted regression tree analysis does not shed any light on the rate of change or the processes involved. However, keeping these limitations in mind, it is possible to explore some implications for climate change pointed out by the analysis.

The map in Figure 6.4 shows the most important environmental factors controlling vegetation according to the boosted regression tree analysis. Changes in temperature are most likely to change the vegetation type in the southern Arctic in western Russia and the eastern Canadian Arctic. These are areas where treeline might advance, or increased growth of shrubs could change vegetation types to more shrub-dominated types. Precipitation is the most important factor in the Canadian Arctic Islands. Vegetation types in this area have large amounts of bare ground that could become more vegetated if temperature or precipitation increases. Areas where substrate characteristics are the most important factor determining vegetation type are less likely to change vegetation type in response to climate change. This includes much of the Canadian Shield, Greenland, the mountainous areas of Novaya Zemlya, Taimyr and Chukotka, and the old landscapes of Beringia.

Change in vegetation type is not the same as change in NDVI. Some vegetation types have a wide range of NDVI and could experience changes in species cover without changing their overall vegetation type (such as mountain complexes). Others have a very narrow range of NDVI; for example an area mapped as cryptogam barrens (B1) would be called a different type if it became more vegetated. The results of the boosted regression tree analysis with an increase of 2°C in annual mean temperature confirm and expand on those seen in a simple regression analysis of temperature and NDVI (Raynolds et al., 2008a). The reason that vegetation types with incomplete cover showed the most response may be partly due to the nonlinear relationship between NDVI and vegetation parameters such as leaf area index (LAI) and aboveground biomass. NDVI increases exponentially with LAI and biomass (Walker et al., 2003a), showing signs of saturation when LAI > 1 (van Wijk and Williams, 2005).

Increases in NDVI were least for G4, tussock tundra. This is a vegetation type that already has a relatively high NDVI value, and also has many mechanisms buffering its response to increases in temperature. It has relatively thick moss and organic soil layers (Walker et al., 2008), both of which insulate the soil from summer warming (Kade et al., 2006). This results in cold soils, with shallow thaw depth above permafrost. The permafrost restricts soil drainage, keeping the soils close to saturation. These conditions favor the growth of mosses, which acidify the soils (Walker et al., 2003b). The cold, saturated, acidic soil conditions and the lack of bare ground make it hard for any colonization by new species to occur.

Increases in precipitation and winter snow depths are predicted for the Arctic by many climate models (Bates et al., 2008). The boosted regression tree analysis showed the importance of precipitation for High Arctic vegetation types and the threshold response of NDVI to snow depth. Increases in precipitation were found to have a much larger positive effect on above ground net primary productivity of shrub types than graminoid vegetation types (Knapp et al., 2008). Examination of the relationship between snow depth and NDVI in the Arctic found that the two vegetation types that occur in the southernmost Arctic, S2 and G4, did not show much of a relationship between snow depth and NDVI (linear regression $R^2 < 0.03$). The vegetation types found just north of these (S1, G3) have erect dwarf-shrubs but with more scattered cover and showed a stronger relationship between snow depth and NDVI ($R^2 > 0.3$).

These are vegetation types where increased precipitation would be expected to cause increases in NDVI, likely due to increases in shrub cover.

Not only will increased precipitation and snow depth allow arctic plants to grow taller, but there is a feedback effect, whereby the plants trap snow, reducing sublimation and compaction of the snowfall, and thereby increase the depth and insulative effect of the snow-pack (Sturm et al., 2001). This in turn warms the soils over the winter, making a more favorable rooting environment in terms of depth of thaw and nutrient availability (Sturm et al., 2005).

The spatial pattern of the sensitivity of NDVI to temperature increases does not correspond well with existing images of changes in NDVI in the Arctic recorded over the last several decades (Bunn et al., 2007; Jia et al., 2003; Verbyla, 2008). This is not unexpected, as our predictions were an equilibrium result based on a uniform 2 °C increase for the whole Arctic, and included no changes in precipitation or other related environmental factors. Arctic vegetation is not in equilibrium with recent climate changes. Climate change has also not brought uniform warming to the Arctic, in fact some areas in Russia have cooled (Comiso, 2003).The actual changes in climate that have occurred are a spatially heterogeneous mix of mostly increases with some decreases in both temperature and precipitation. Trend calculations are very sensitive to the spatial and temporal scale and extent of the data included. Even areas shown to have large positive trends in temperature may show different trends at smaller spatial or time scales. For example, the North Slope of Alaska is one of the areas that shows the largest increases in temperature between 1981-2001 (Comiso, 2003), yet local site measurements at Toolik Lake showed a slight decrease in temperature and a 28% increase in precipitation during the period 1994-2002 (Wahren et al., 2005).

Disturbance is a factor that was not included in this analysis. Recent studies have shown that disturbance could have large effects on arctic vegetation. The UN GLOBIO project estimated that human activities will directly impact over half of the Arctic within the next 50 years (Nellemann et al., 2001). Indirect effects of climate change, such as increased frequency of fires, insects, diseases, and thawing of permafrost could affect large areas much more rapidly than vegetation response to climate (Hinzman et al., 2005; Lantz, 2008).

6.6 Conclusion

Boosted regression tree analysis successfully used environmental variables to account for the spatial variation of arctic vegetation types and NDVI. The vegetation analysis described the environmental niche of each vegetation type, and ranked the importance of the environmental variables. Summer warmth index (SWI) was an important factor controlling the distribution of all but mountainous vegetation types. Substrate chemistry, elevation, landscape type, distance to sea, summer precipitation, and landscape age were all important in predicting vegetation type. Precipitation was most important to vegetation in the Canadian High Arctic. Landscape age and summer temperature were the most important factors explaining the variability of NDVI. A threshold response corresponding to approximately 28 cm snow depth was seen, with NDVI increasing for areas with deeper snow. This response is likely due to greater shrub cover in areas protected by deeper snow. Increases in snow depth are likely to cause changes in NDVI in vegetation types with partial cover of dwarf-shrubs. Predicted response of NDVI to 2 °C increase in temperature showed the largest increases in partially vegetated areas.

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Appendix 6.1

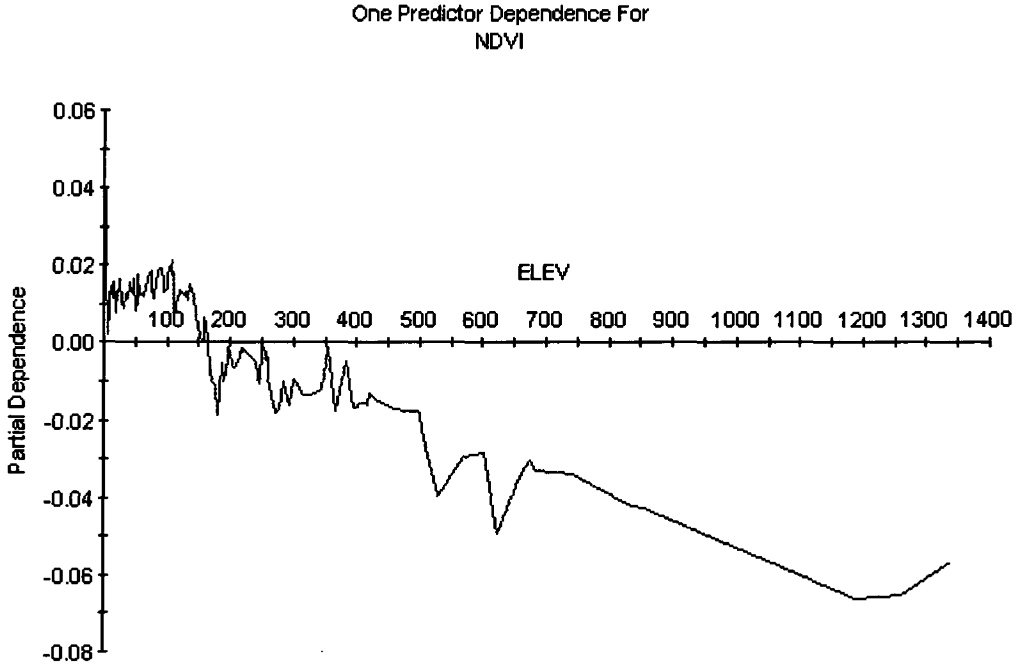


Figure A6.1a) Response curve of NDVI to elevation (m).

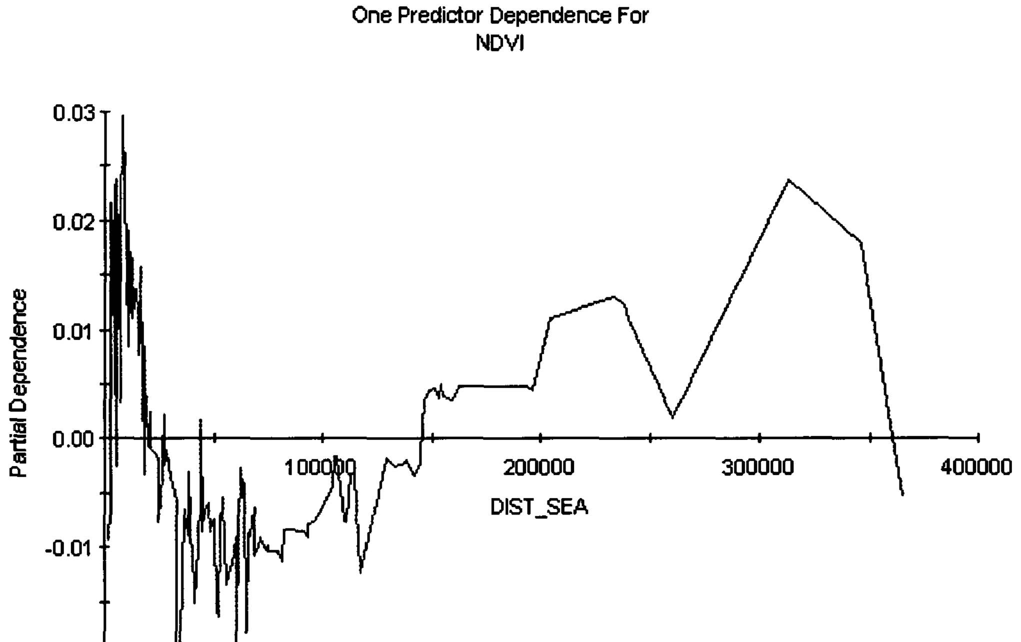


Figure A6.1b) Response curve of NDVI to distance to sea (m).

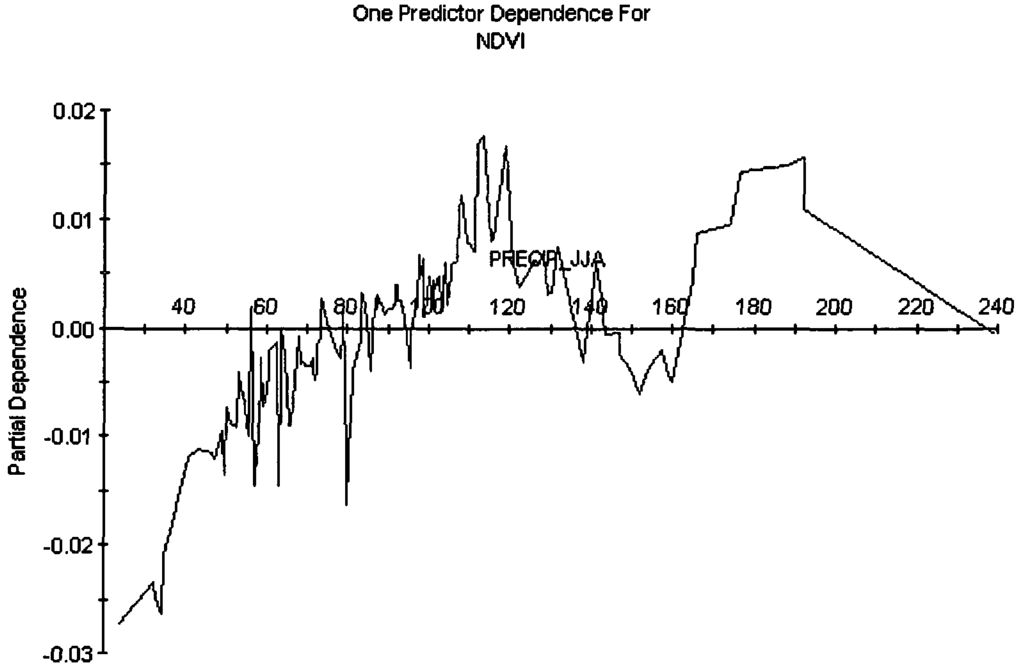


Figure A6.1c) Response curve of NDVI to summer precipitation (mm, June, July, August).

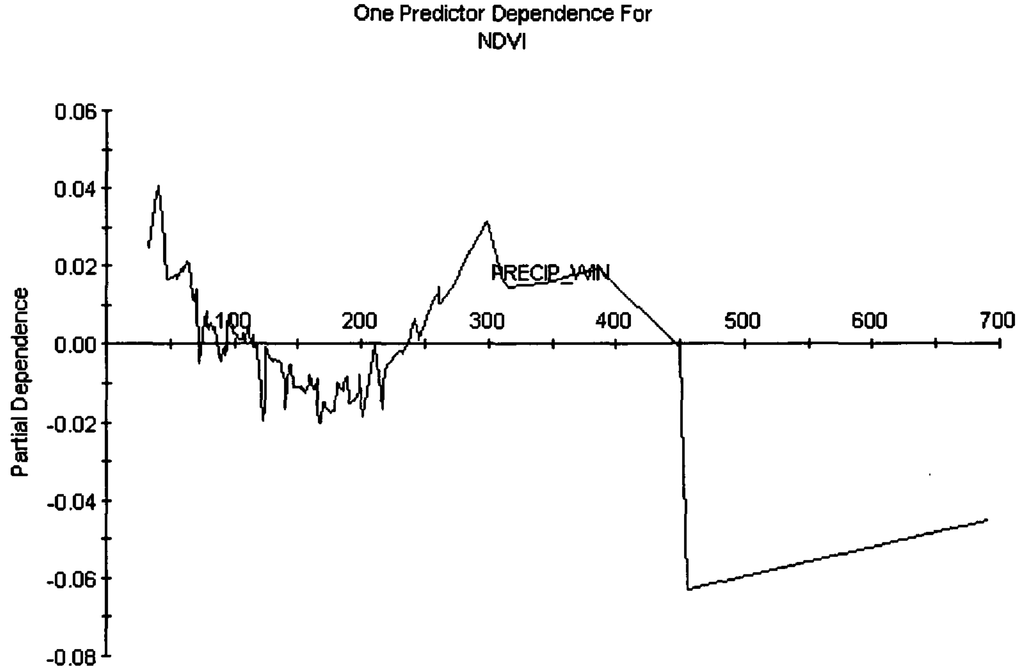


Figure A6.1d) Response curve of NDVI to winter precipitation (mm, Sept - May).

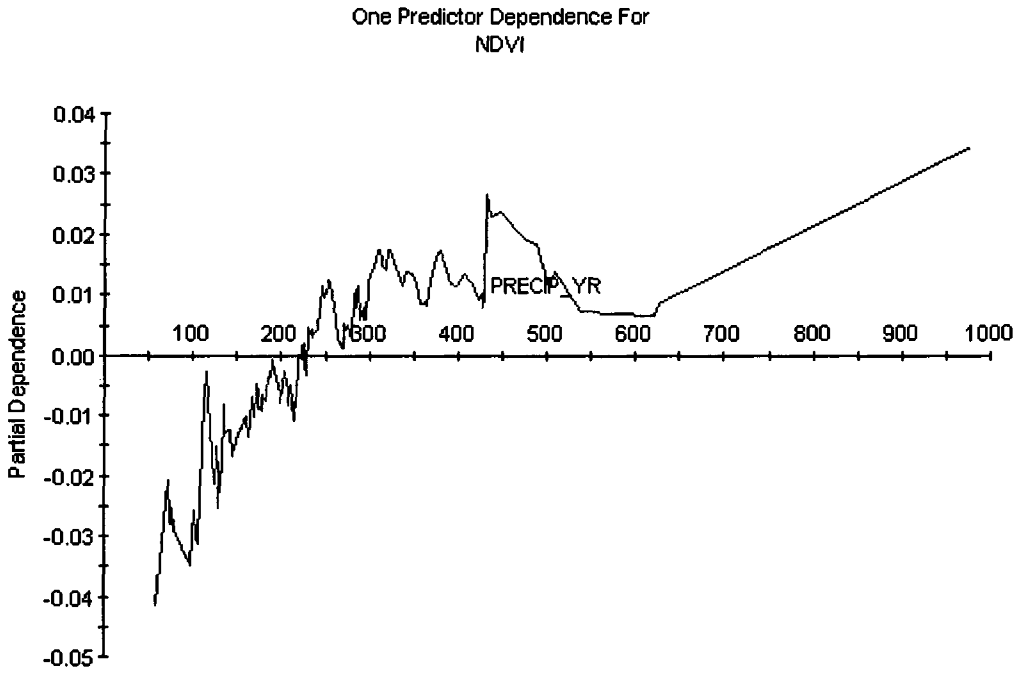


Figure A6.1e) Response curve of NDVI to annual precipitation (mm).

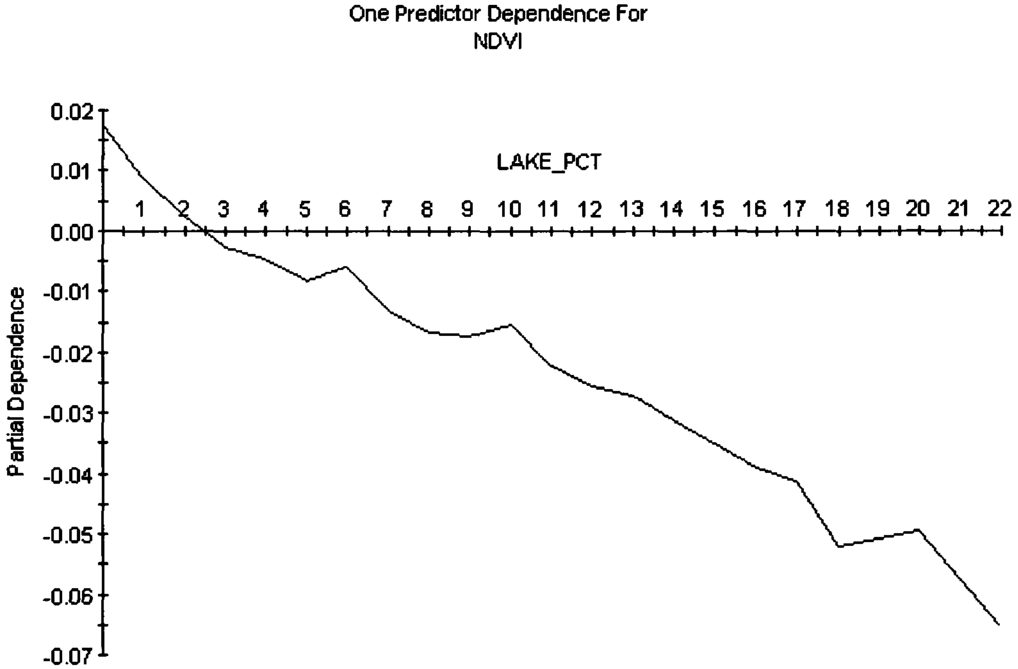


Figure A6.1f) Response curve of NDVI to percent lake cover.

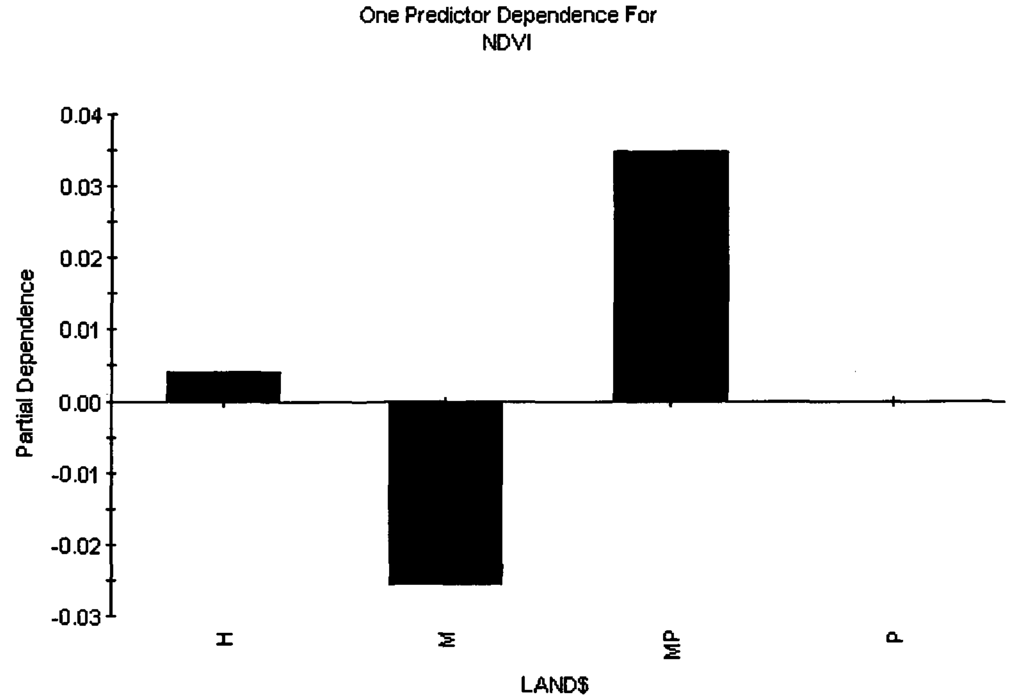


Figure A6.1g) Response curve of NDVI to landscape category (H- hill, M – mountain, MP – plateau, P – plain)

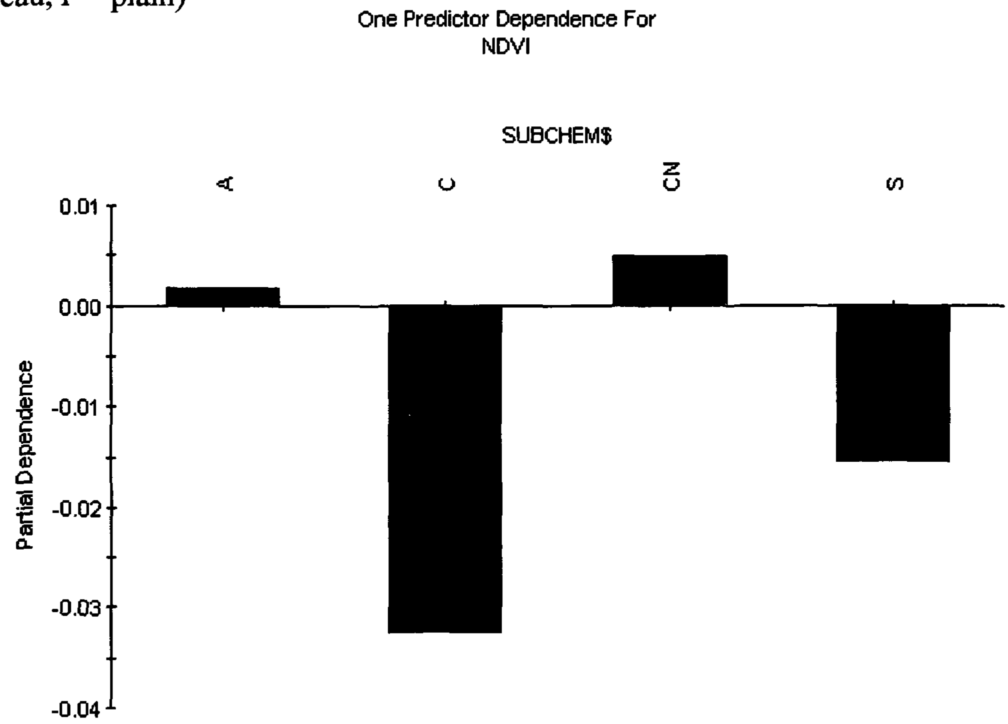


Figure A6.1h) Response curve of NDVI to substrate chemistry category (A – acidic, C – carbonate, CN – circumneutral, S – saline).

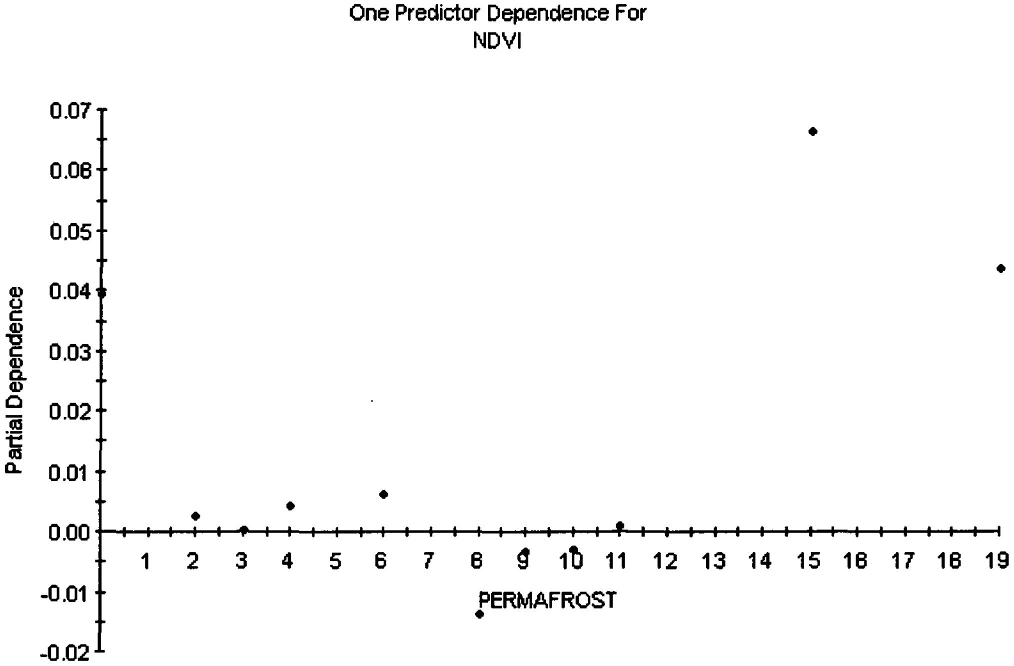


Figure A6.1i) Response curve of NDVI to permafrost category based on extent (Continuous, Discontinuous, Sporadic, Isolated), ice content (high, medium or low), and overburden (thick = f, thin = r) (1 = Id, 2 = glacier, 3 = Ilr, 4 = Dlr, 5 = Clr, 6 = Smf, 7 = Dmf, 8 = Dlf, 9 = Chr, 10 = Cmf, 11 = Clf, 12 = Chf, 13 = lake, 14 = lagoon, 15 = Slf, 16 = Slr, 17 = Imf, 18 = rock, 19 = Ihf, 20 = Shf, 21 = Ilf).

Appendix 6. 2

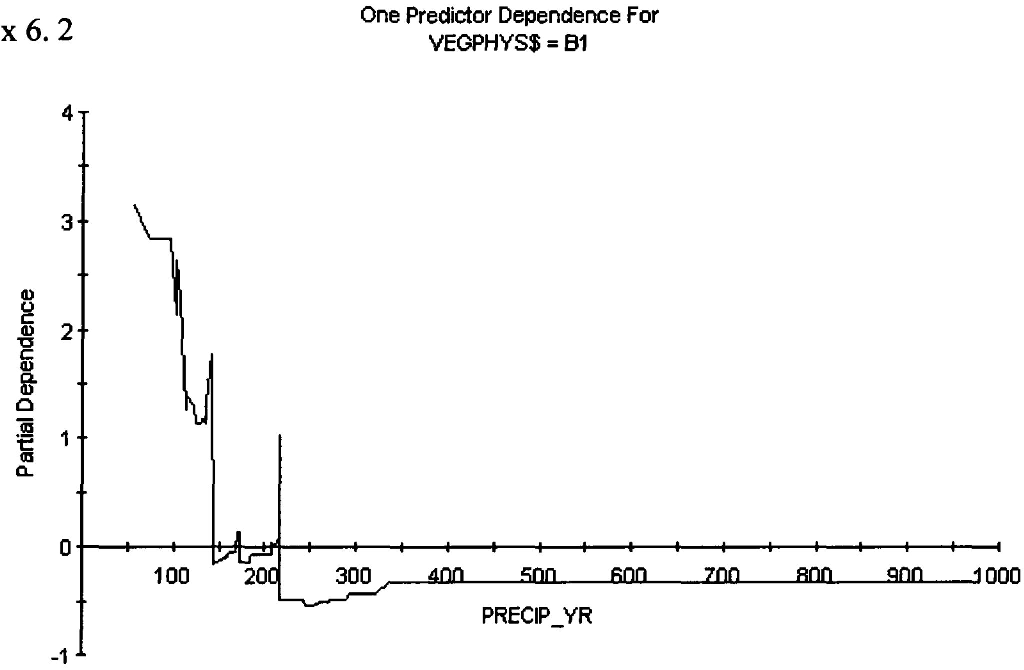


Figure A6.2a) Response curve for CAVM vegetation type B1 to annual precipitation (mm).

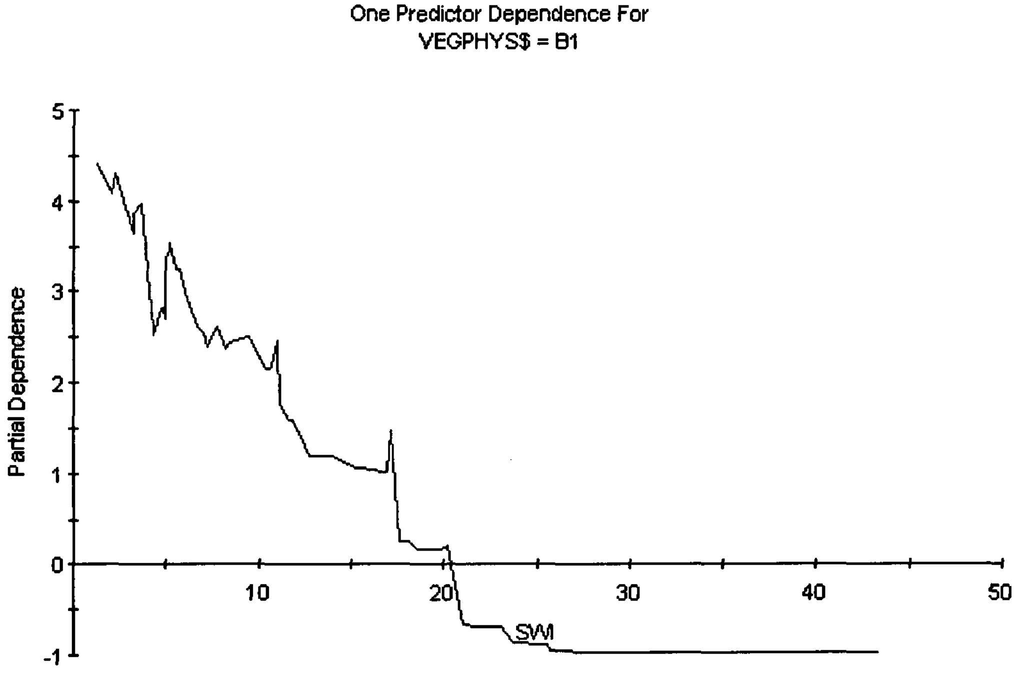


Figure A6.2b) Response curve for CAVM vegetation type B1 to summer warmth index (SWI, °C).

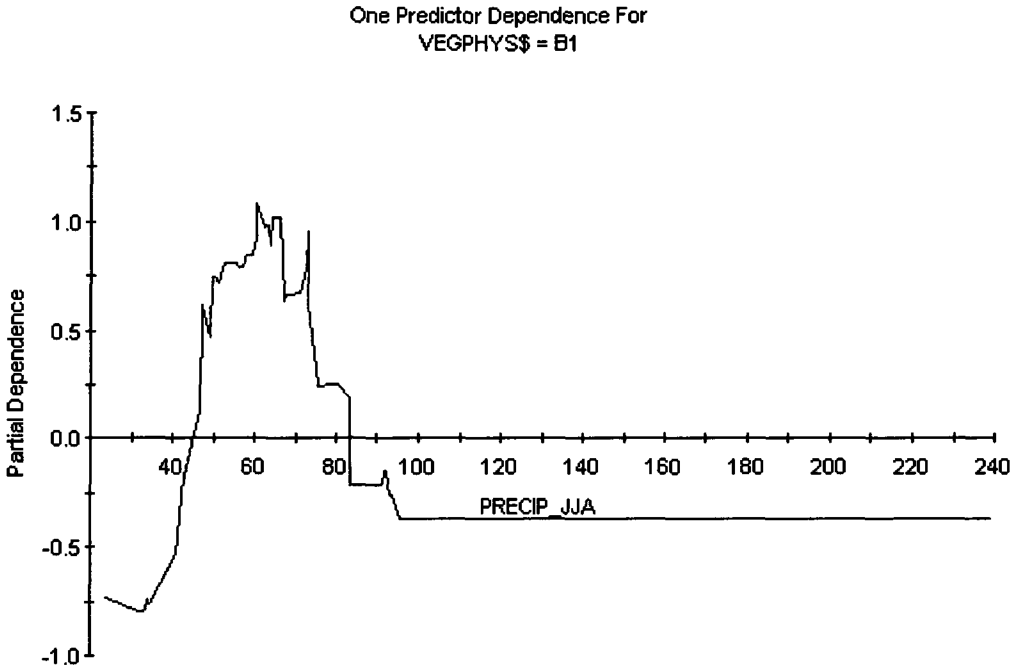


Figure A6.2c) Response curve for CAVM vegetation type B1 to summer precipitation (mm).

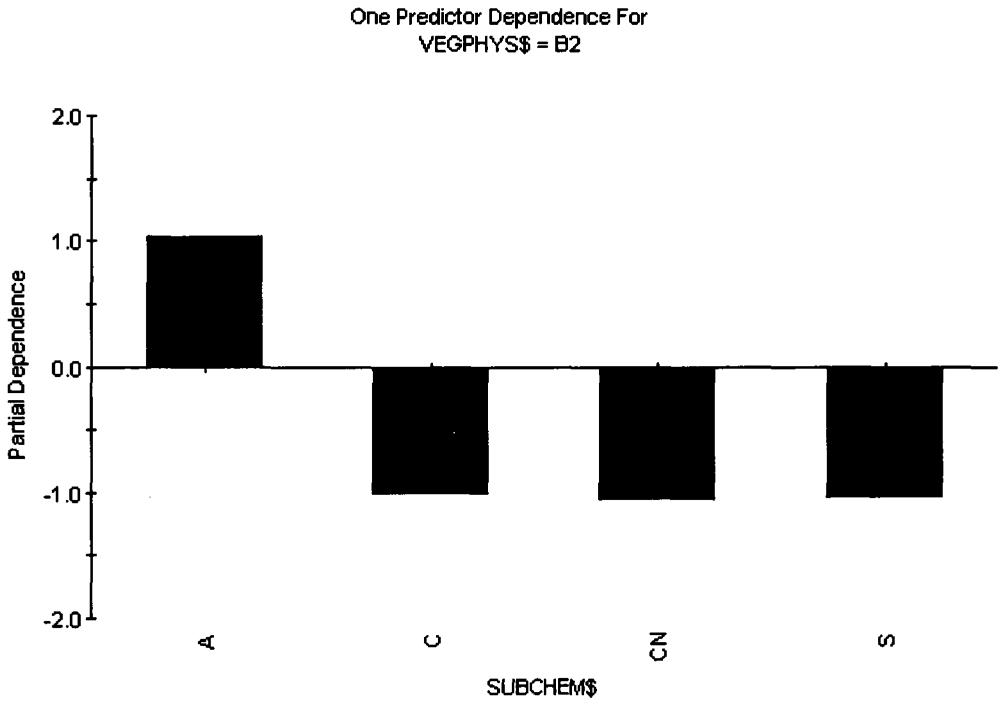


Figure A6.2d) Response curve for CAVM vegetation type B2 to substrate chemistry category (A – acidic, C – carbonate, CN – circumneutral, S – saline).

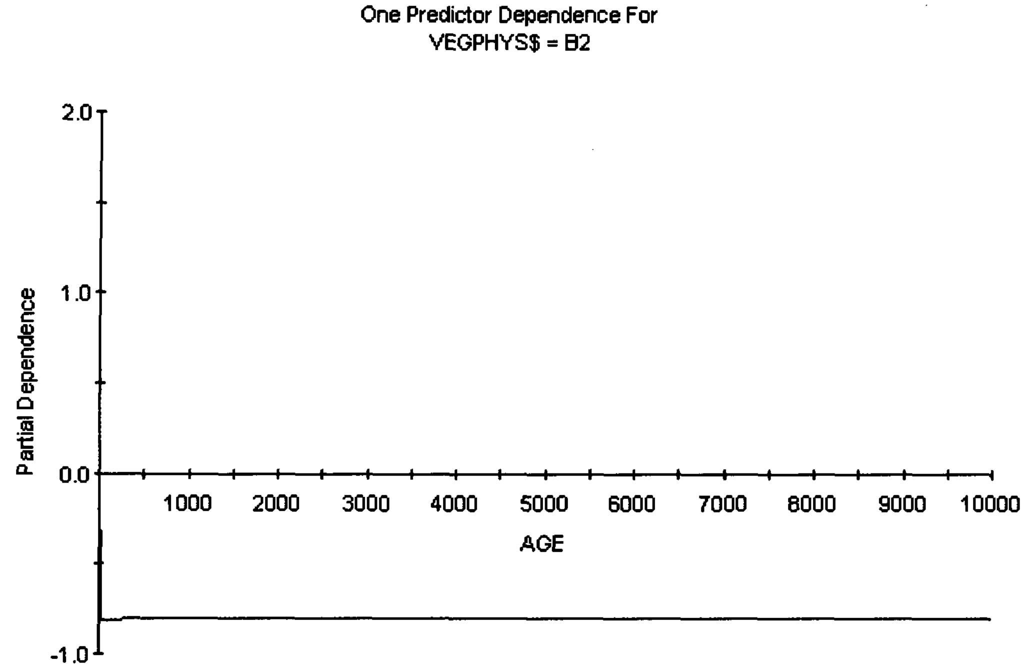


Figure A6.2e) Response curve for CAVM vegetation type B2 to landscape age (1000 years).

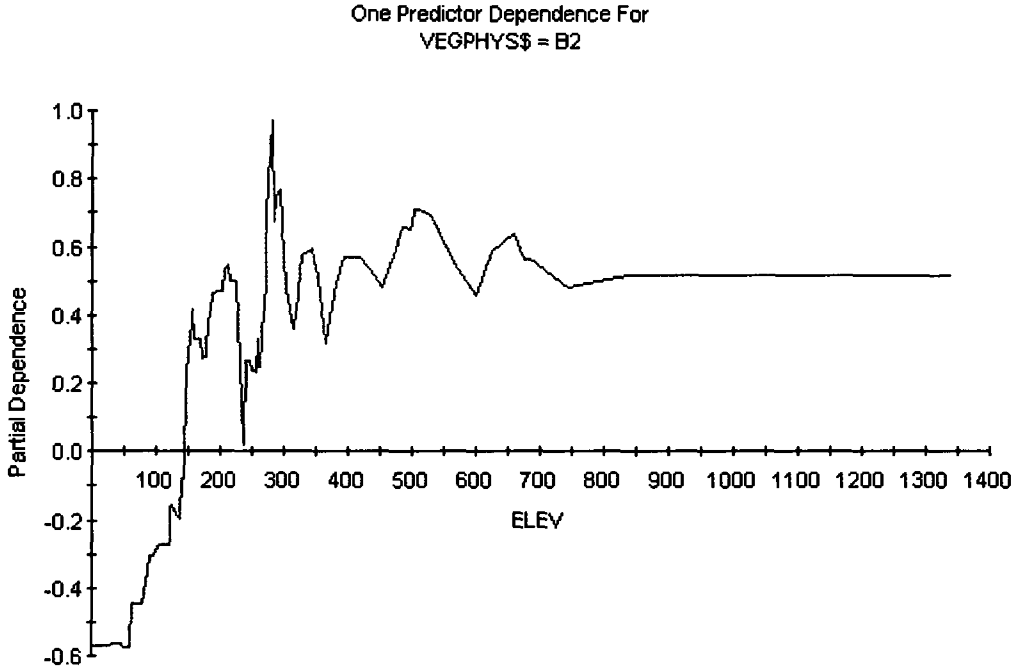


Figure A6.2f) Response curve for CAVM vegetation type B2 to elevation (m).

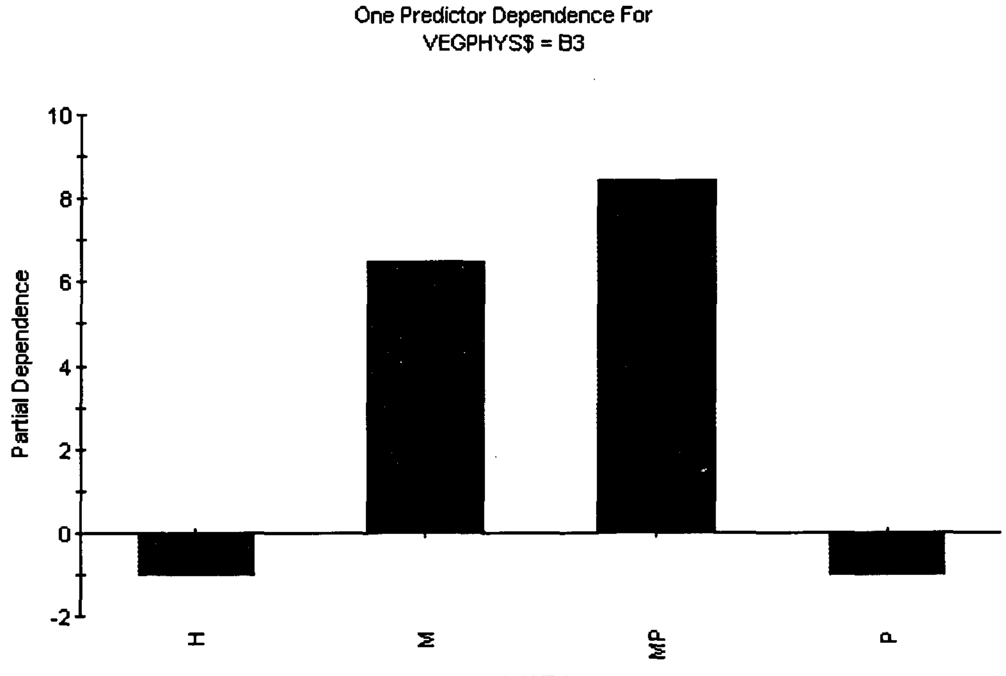


Figure A6.2g) Response curve for CAVM vegetation type B3 to landscape category (H- hill, M – mountain, MP – plateau, P – plain).

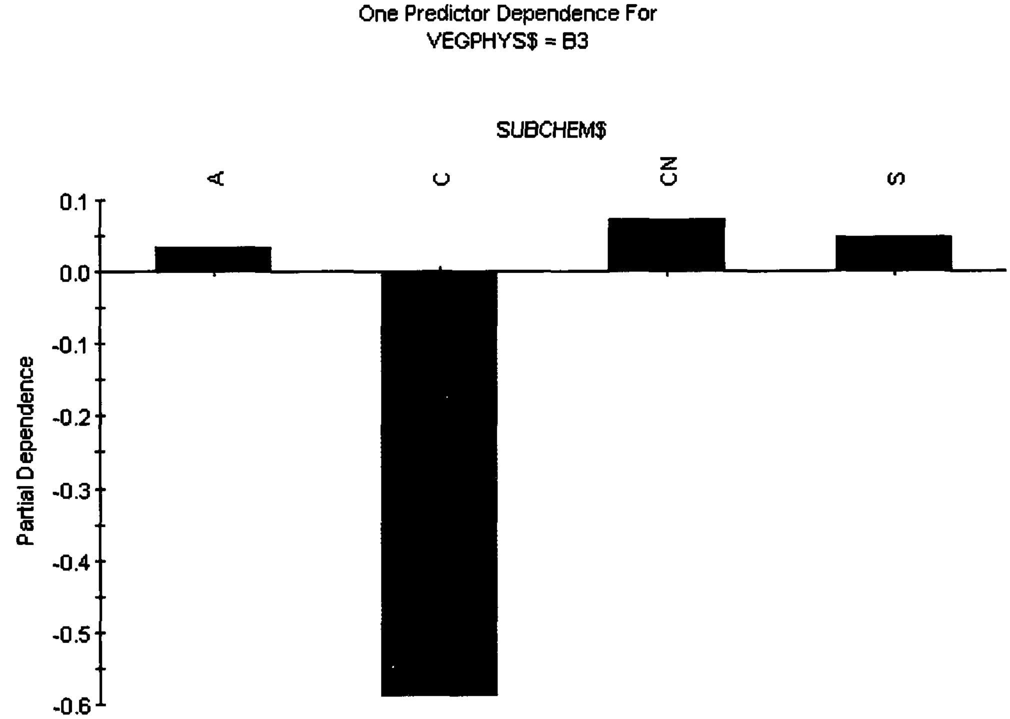


Figure A6.2h) Response curve for CAVM vegetation type B3 to substrate chemistry category (A – acidic, C – carbonate, CN – circumneutral, S – saline).

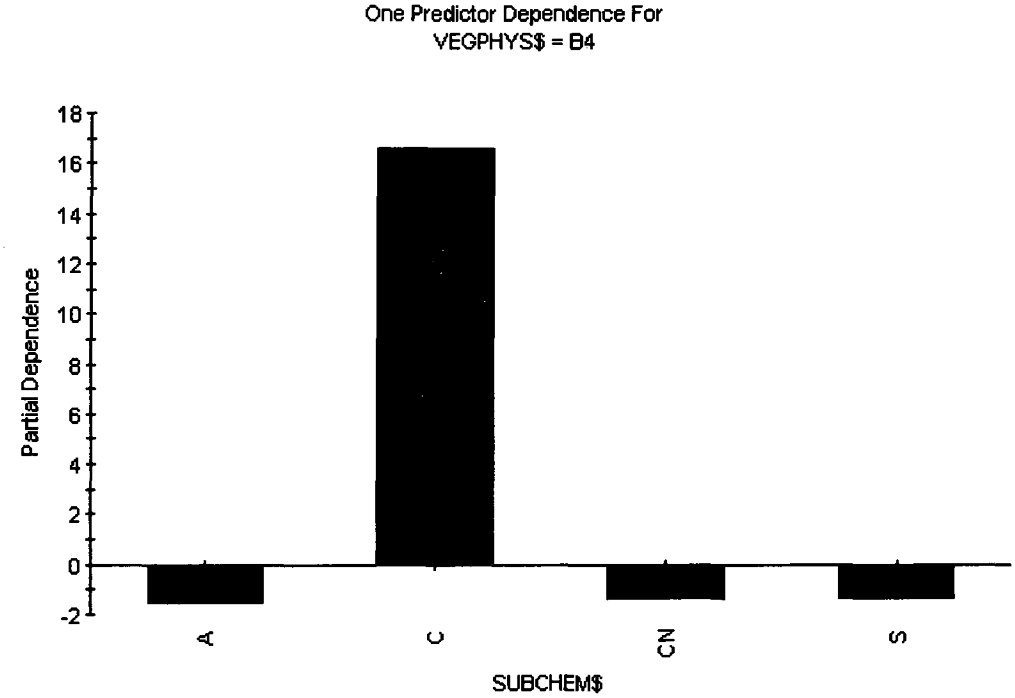


Figure A6.2i) Response curve for CAVM vegetation type B4 to substrate chemistry category (A – acidic, C – carbonate, CN – circumneutral, S – saline).

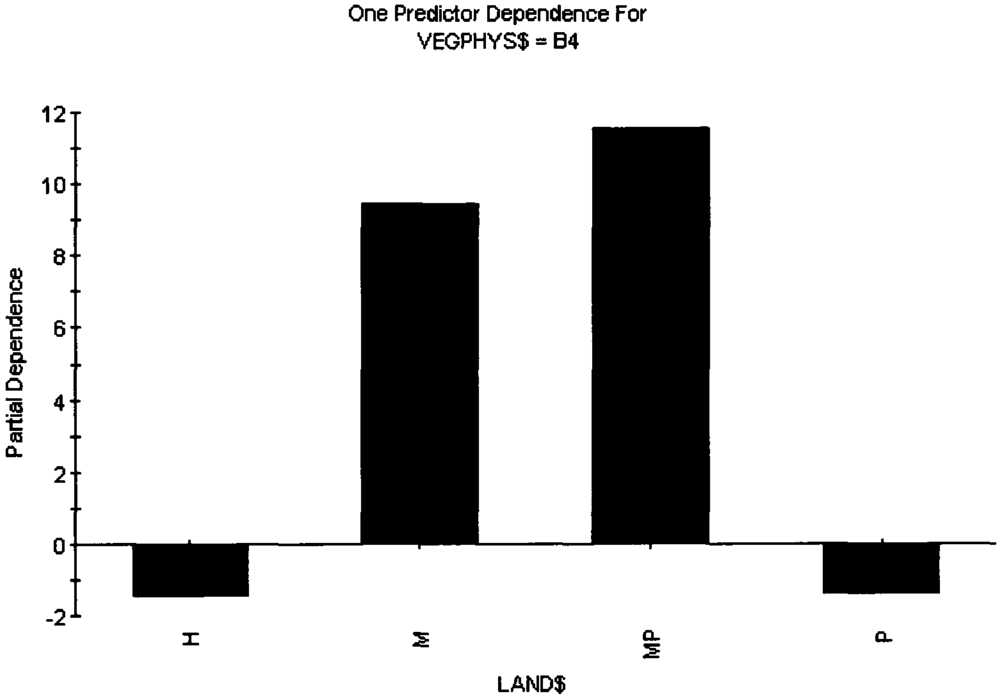


Figure A6.2j) Response curve for CAVM vegetation type B4 to landscape category (H-hill, M – mountain, MP – plateau, P – plain).

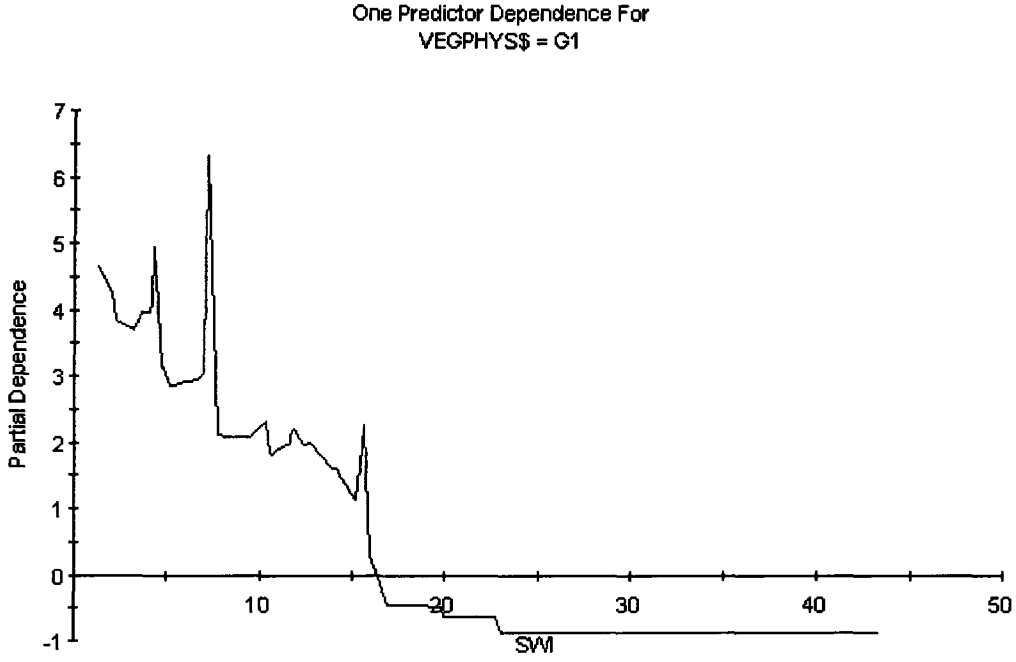


Figure A2k) Response curve for CAVM vegetation type G1 to summer warmth index (SWI, °C).

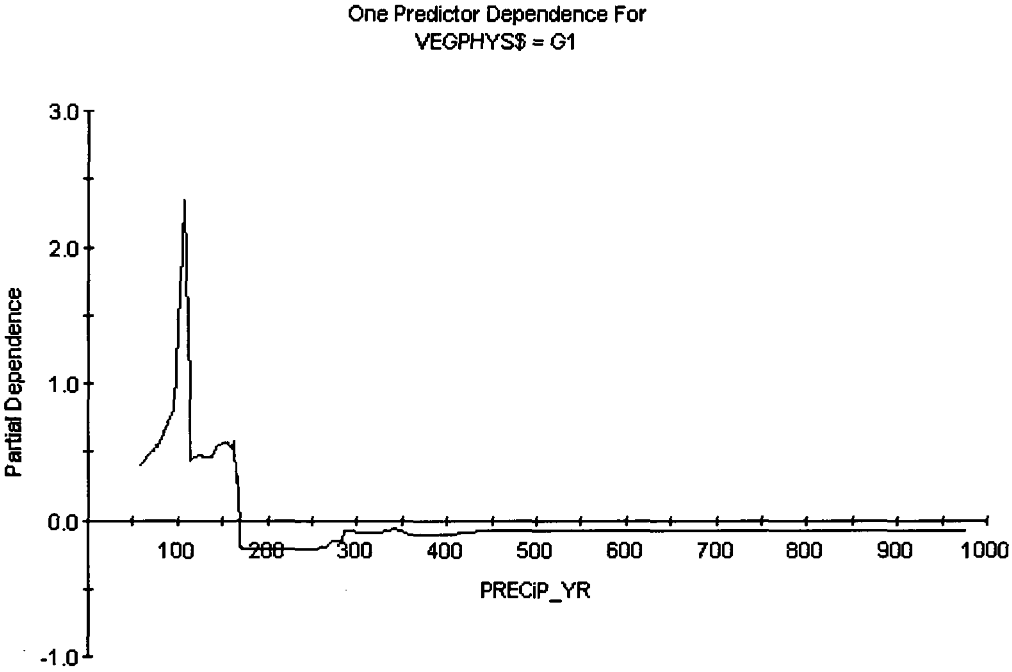


Figure A2l) Response curve for CAVM vegetation type G1 to annual precipitation (mm).

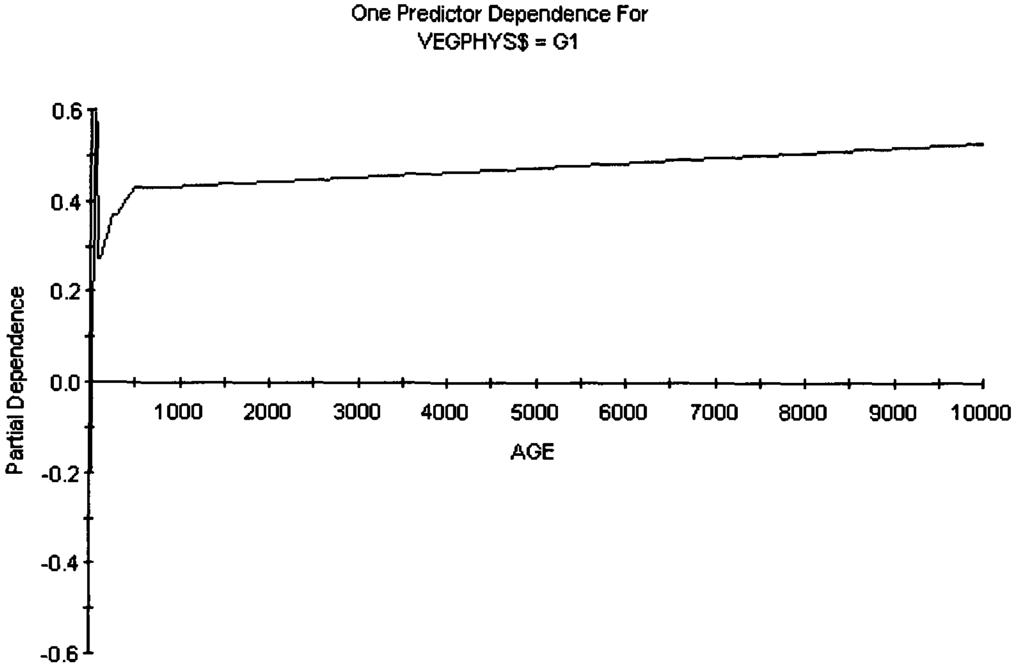


Figure A6.2m) Response curve for CAVM vegetation type G1 to landscape age (1000 years).

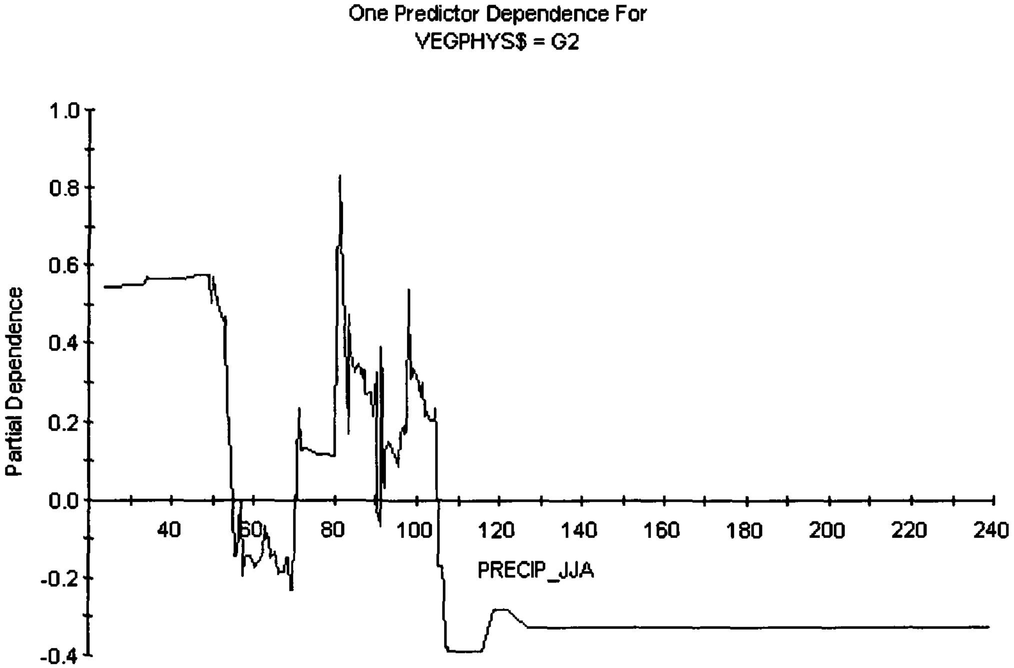


Figure A6.2n) Response curve for CAVM vegetation type G2 to summer precipitation (June - August).

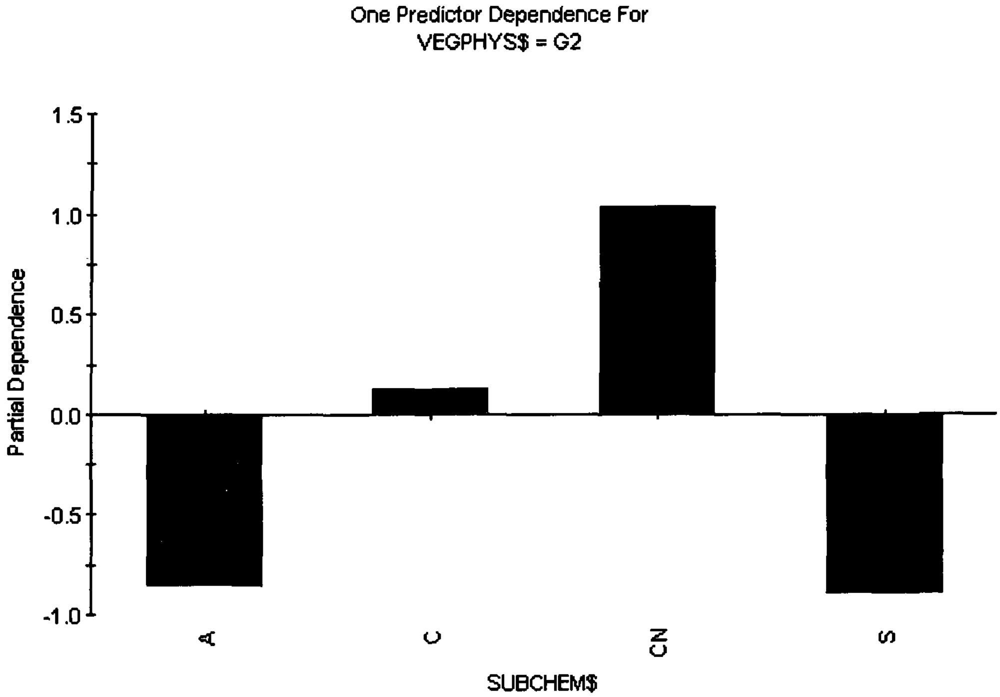


Figure A6.2o) Response curve for CAVM vegetation type G2 to substrate chemistry category (A – acidic, C – carbonate, CN – circumneutral, S – saline).

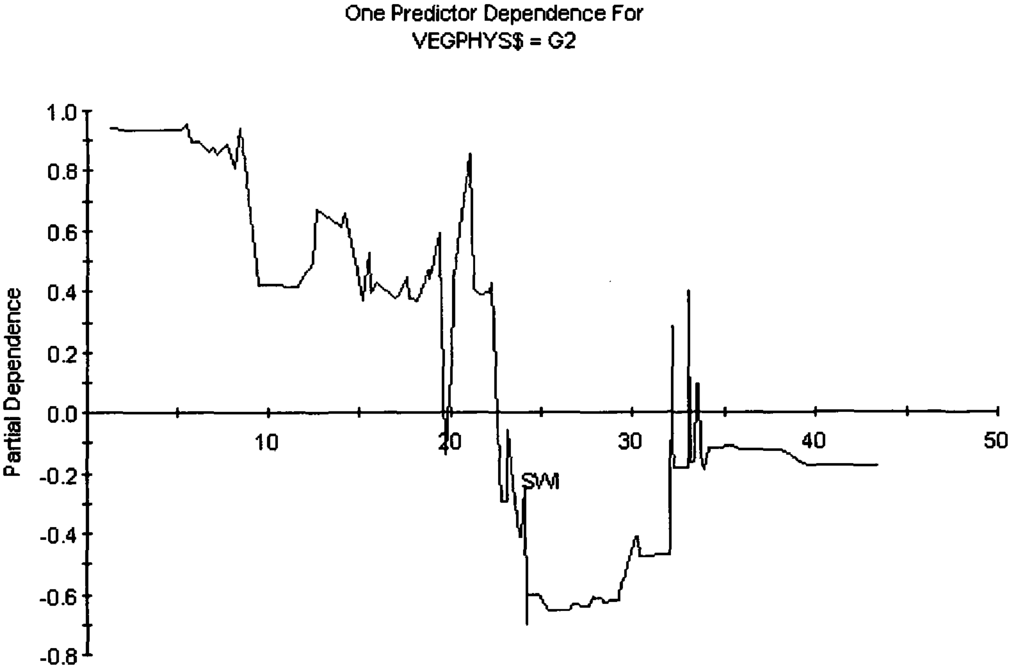


Figure A6.2p) Response curve for CAVM vegetation type G2 to summer warmth index (SWI, °C).

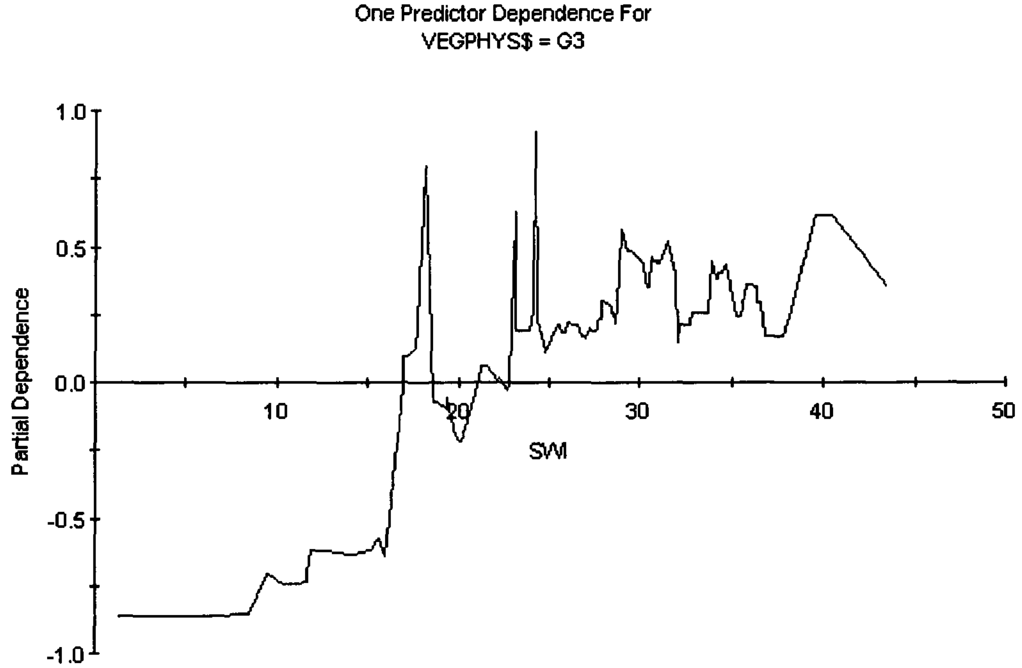


Figure A6.2q) Response curve for CAVM vegetation type G3 to summer warmth index (SWI, °C).

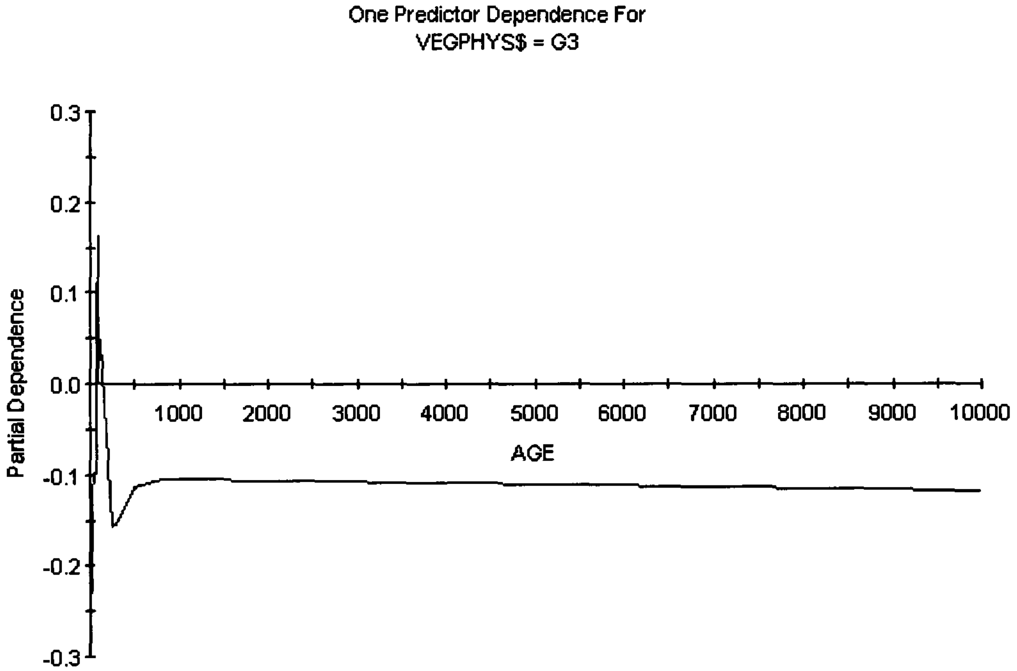


Figure A6.2r) Response curve for CAVM vegetation type G3 to landscape age (1000 years).

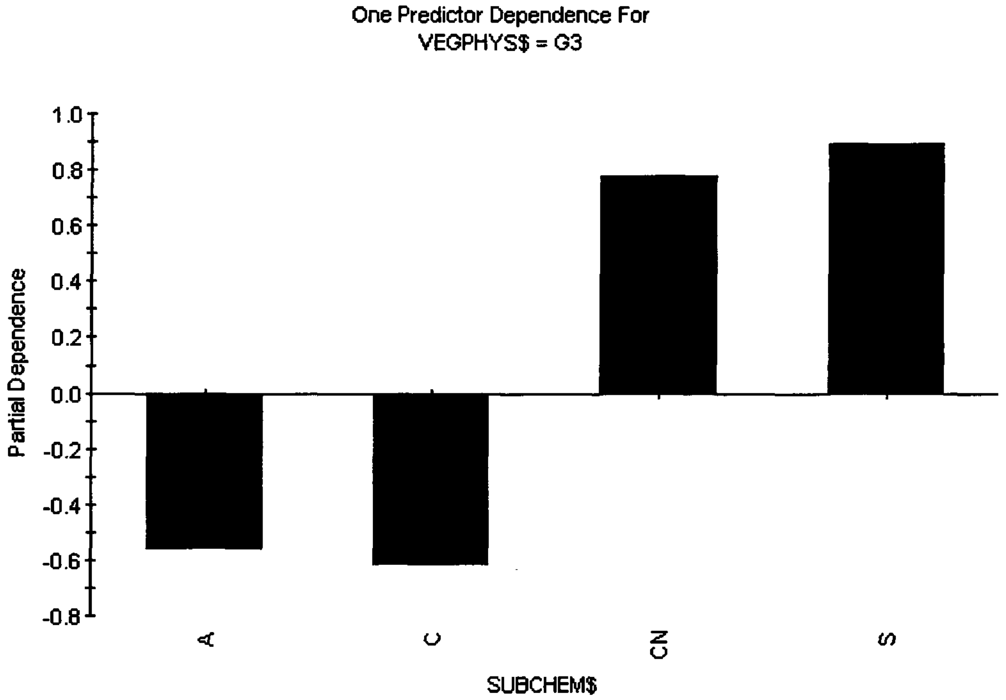


Figure A6.2s) Response curve for CAVM vegetation type G3 to substrate chemistry category (A – acidic, C – carbonate, CN – circumneutral, S – saline).

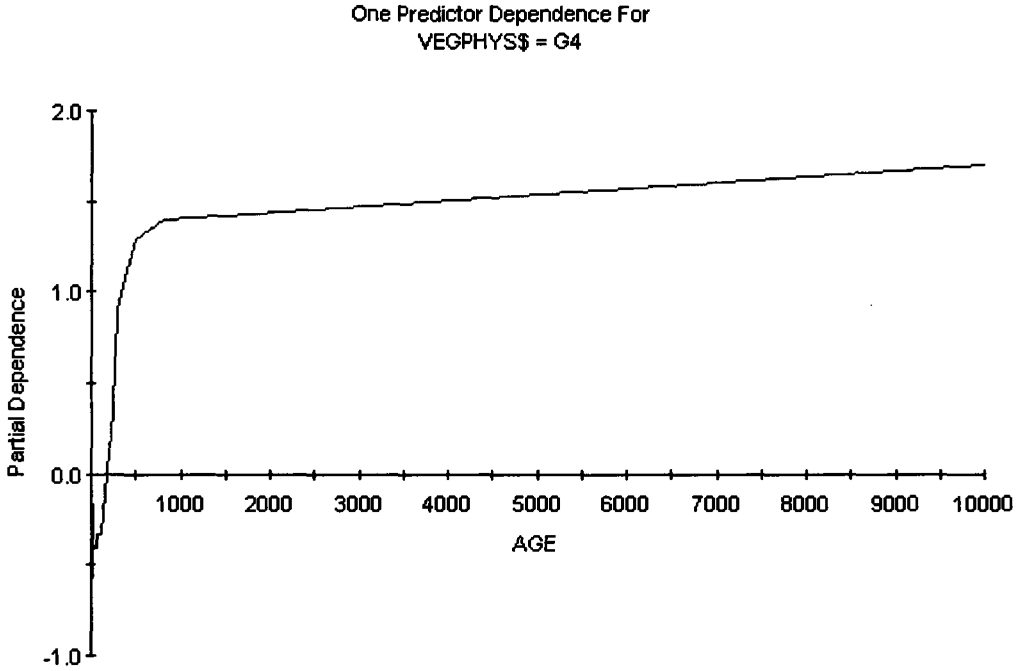


Figure A6.2t) Response curve for CAVM vegetation type G4 to landscape age (1000 years).

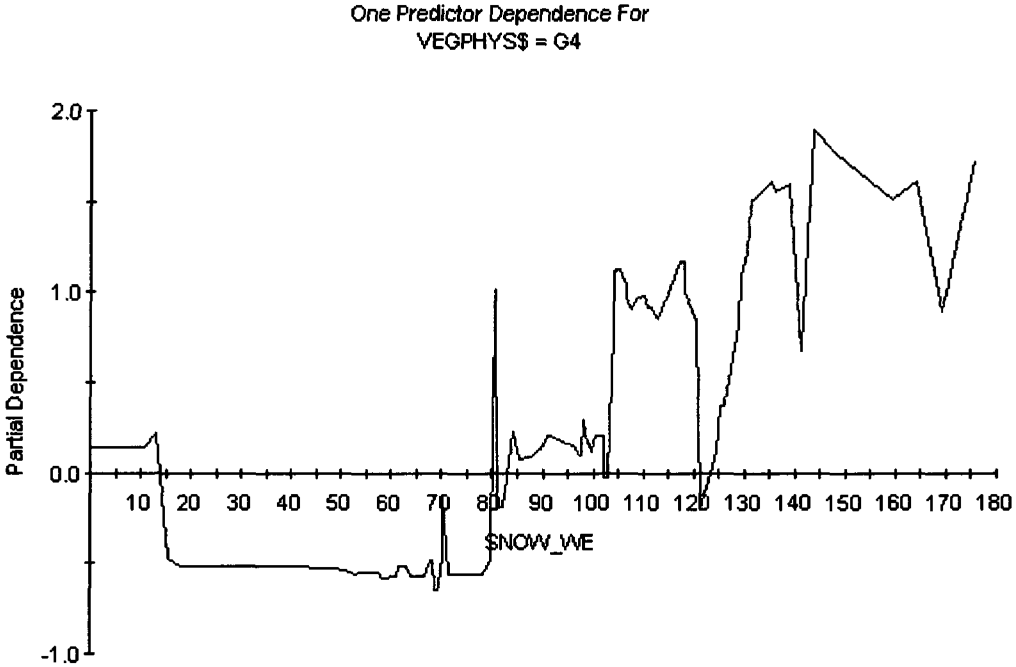


Figure A6.2u) Response curve for CAVM vegetation type G4 to snow-water-equivalent (mm).

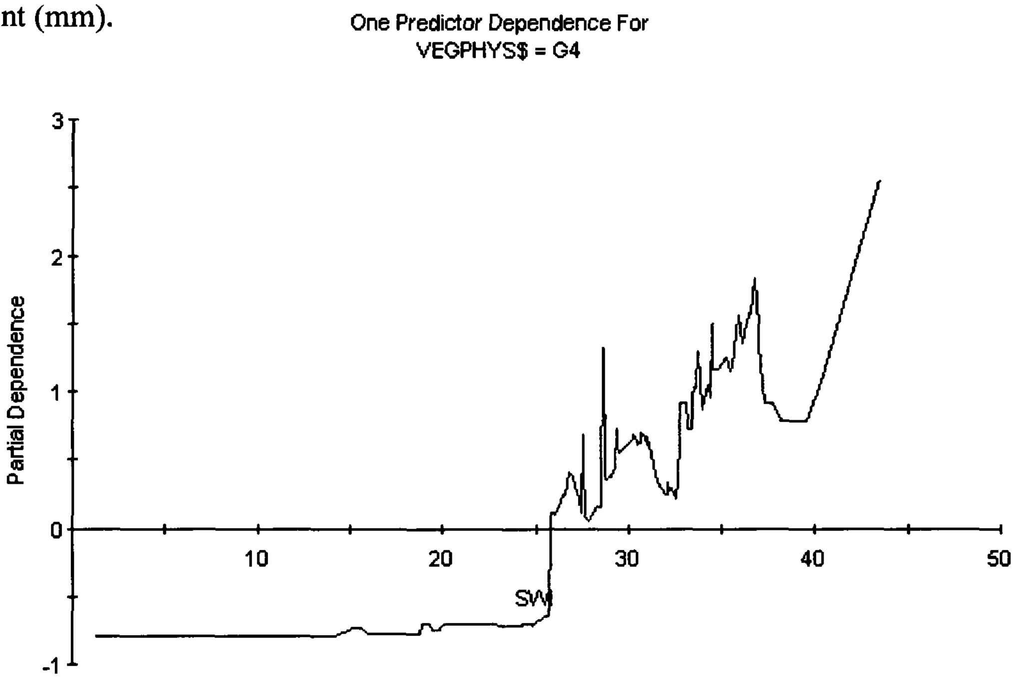


Figure A6.2v) Response curve for CAVM vegetation type G4 to summer warmth index (SWI, °C).

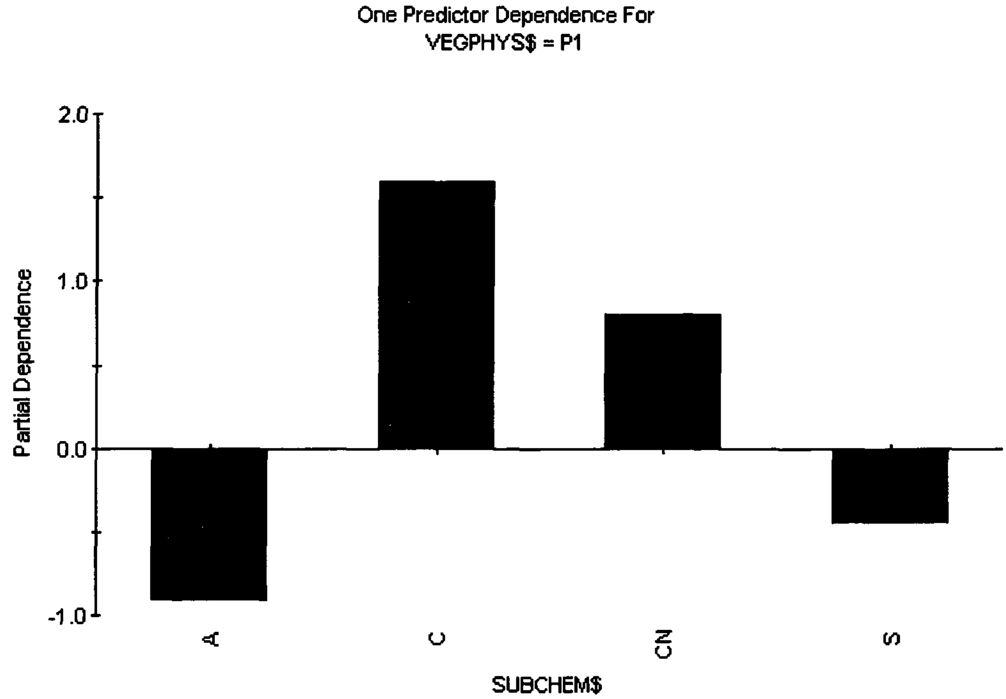


Figure A6.2w) Response curve for CAVM vegetation type P1 to substrate chemistry category (A – acidic, C – carbonate, CN – circumneutral, S – saline).

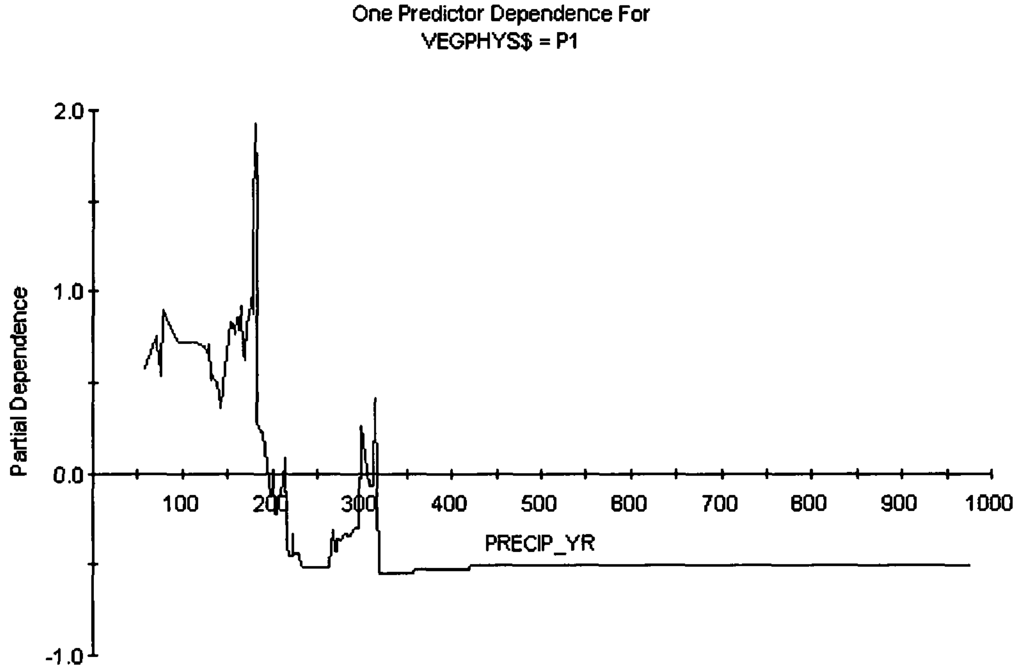


Figure A6.2x) Response curve for CAVM vegetation type P1 to annual precipitation (mm).

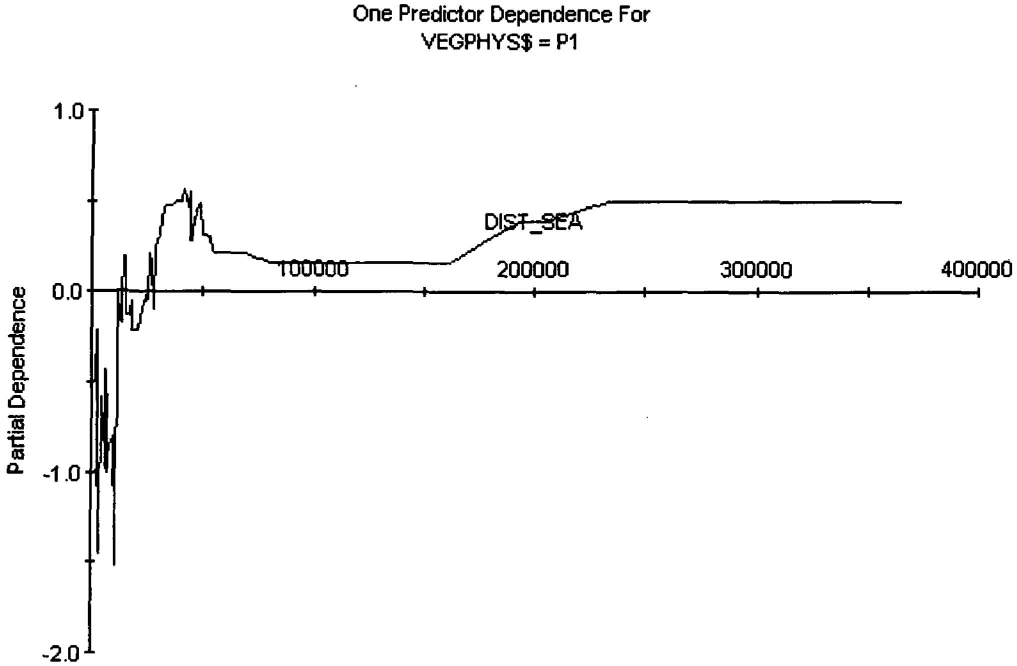


Figure A6.2y) Response curve for CAVM vegetation type P1 to distance to sea (m).

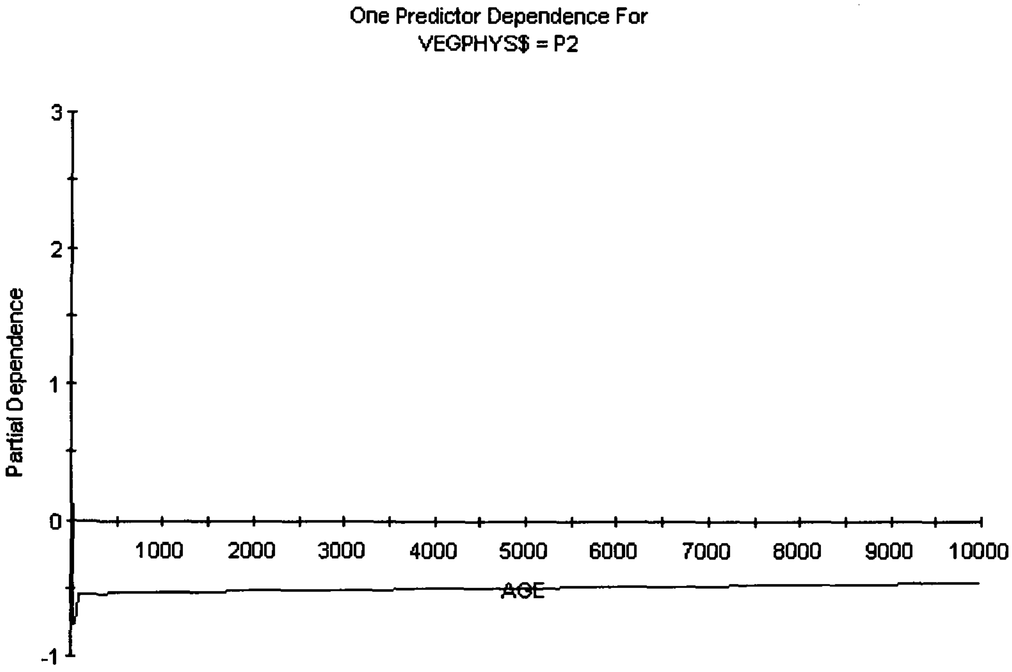


Figure A6.2z) Response curve for CAVM vegetation type P1 to landscape age (1000 years).

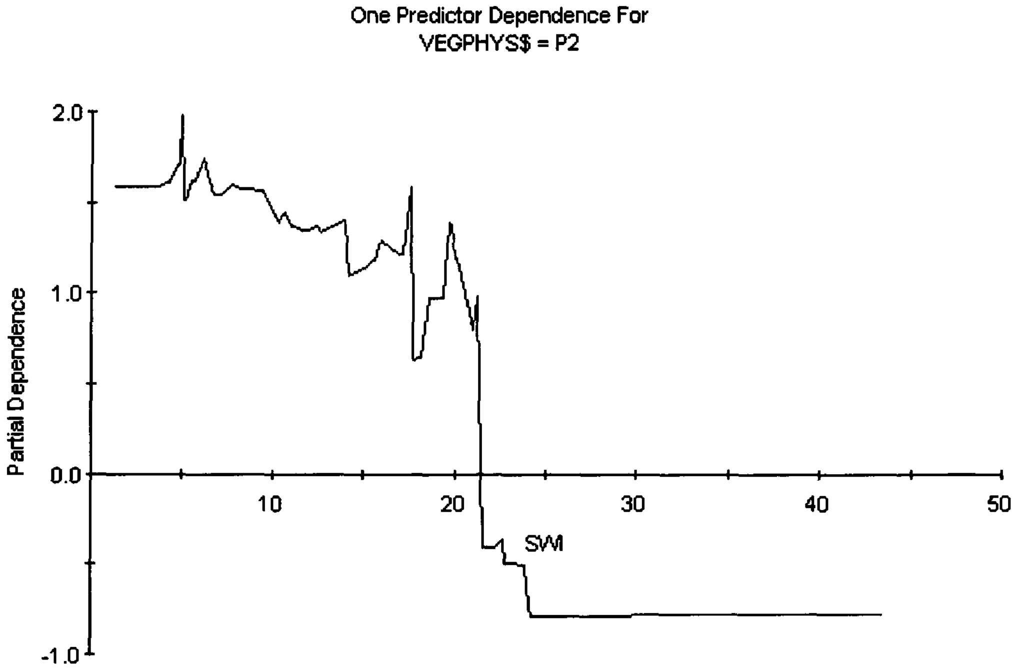


Figure A6.2aa) Response curve for CAVM vegetation type P2 to summer warmth index (SWI, °C).

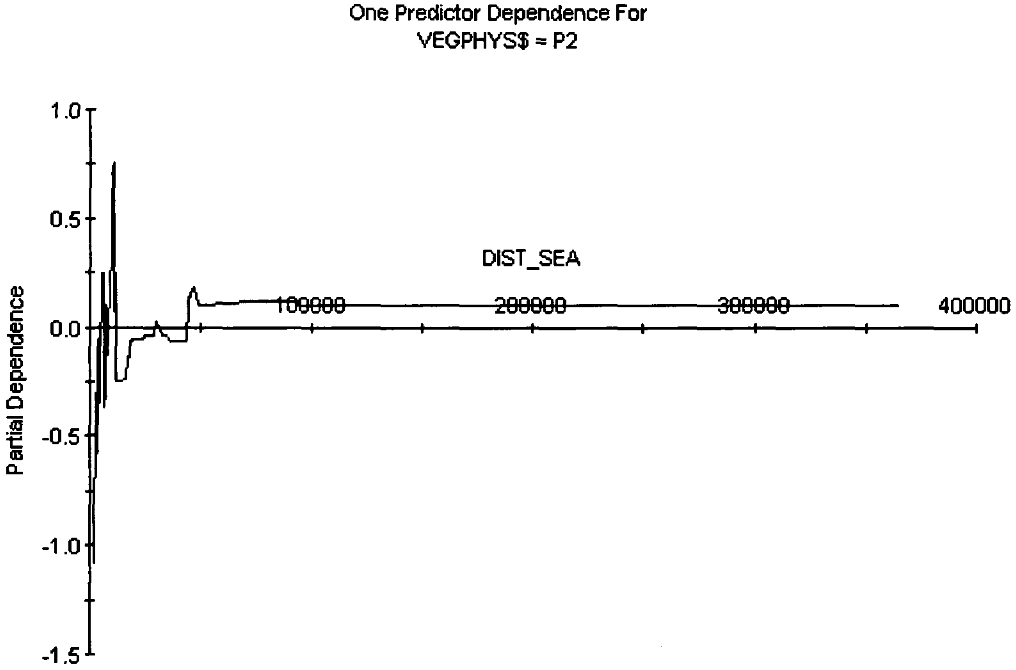


Figure A6.2ab) Response curve for CAVM vegetation type P2 to distance to sea (m).

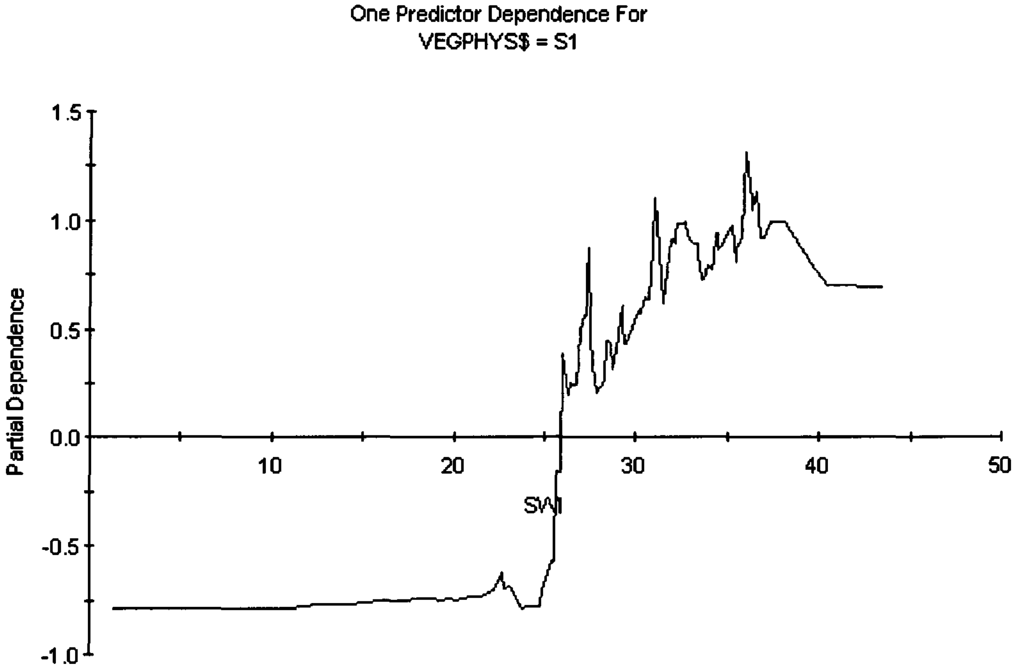


Figure A6.2ac) Response curve for CAVM vegetation type S1 to summer warmth index (SWI, ˚C).

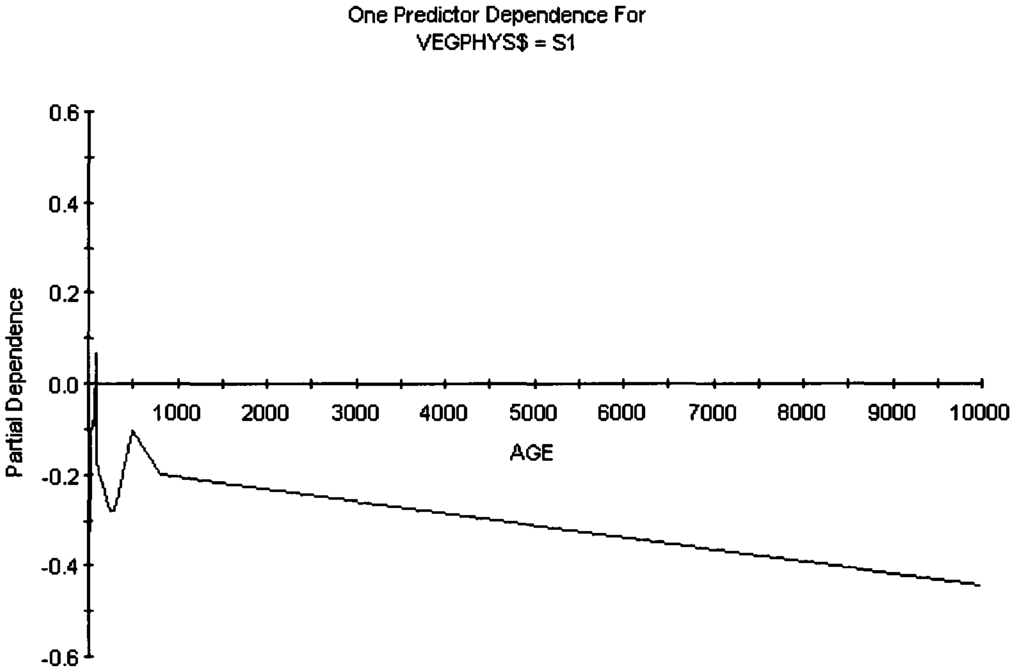


Figure A6.2ad) Response curve for CAVM vegetation type S1 to landscape age index (1000 years).

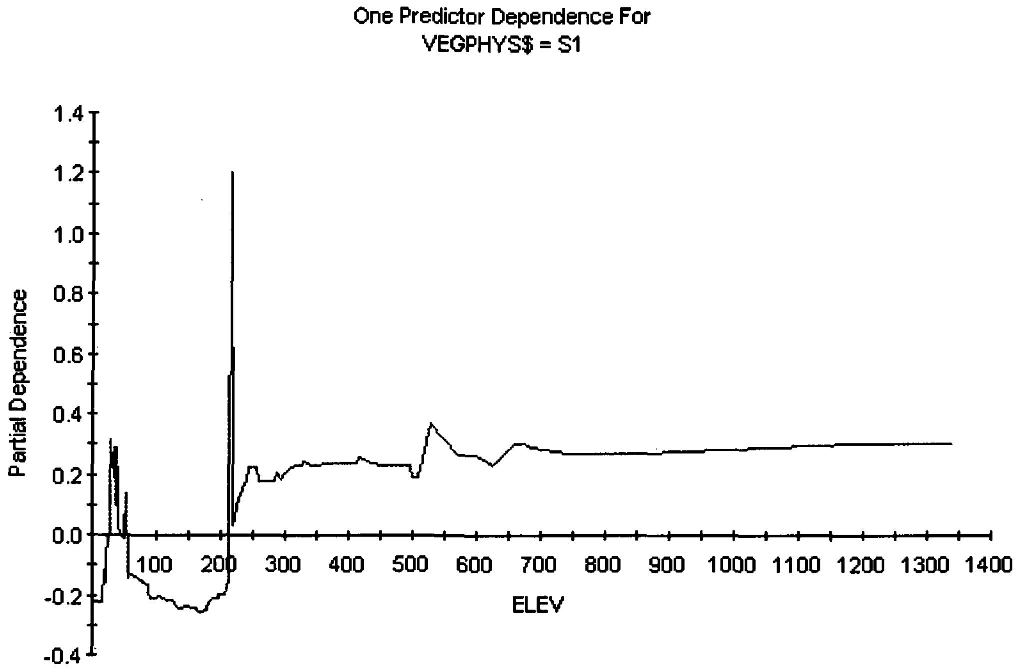


Figure A6.2ae) Response curve for CAVM vegetation type S1 to elevation (m).

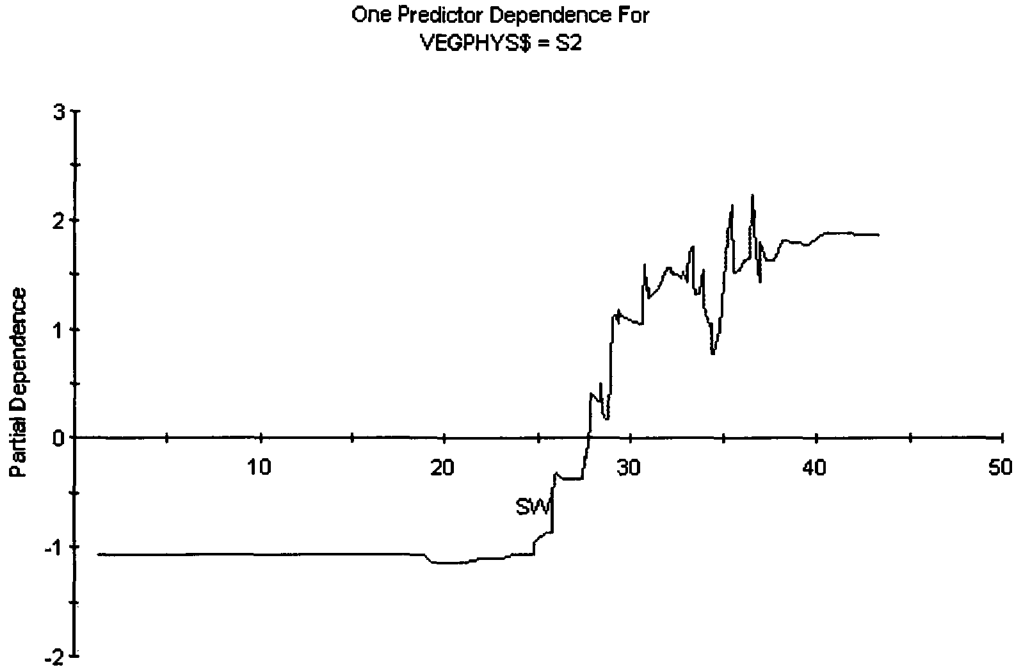


Figure A6.2af) Response curve for CAVM vegetation type S2 to summer warmth index (SWI, °C).

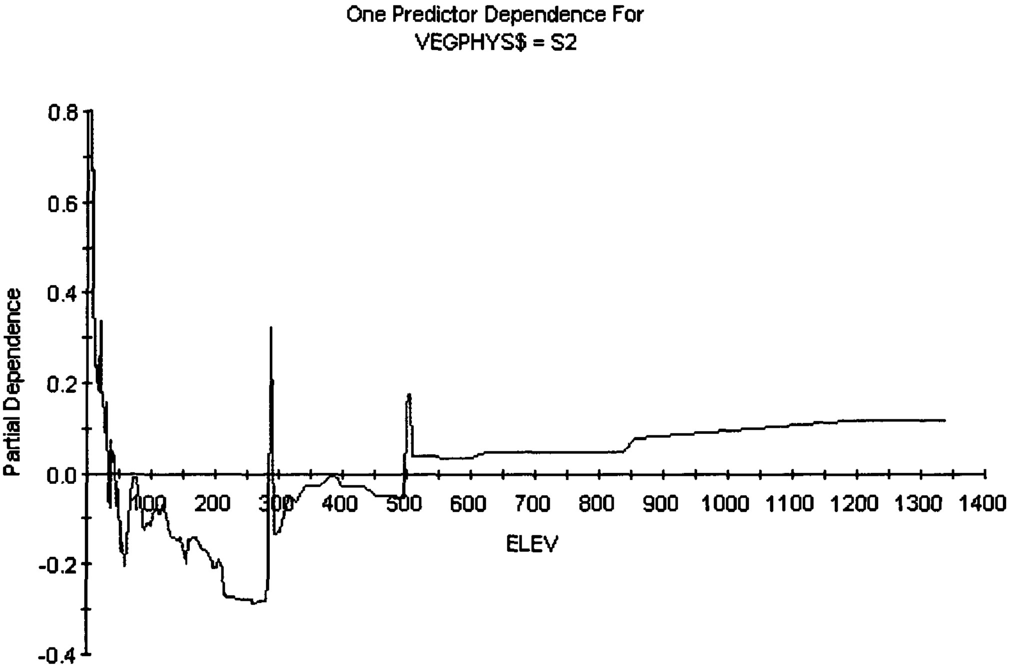


Figure A6.2ag) Response curve for CAVM vegetation type S2 to elevation (m).

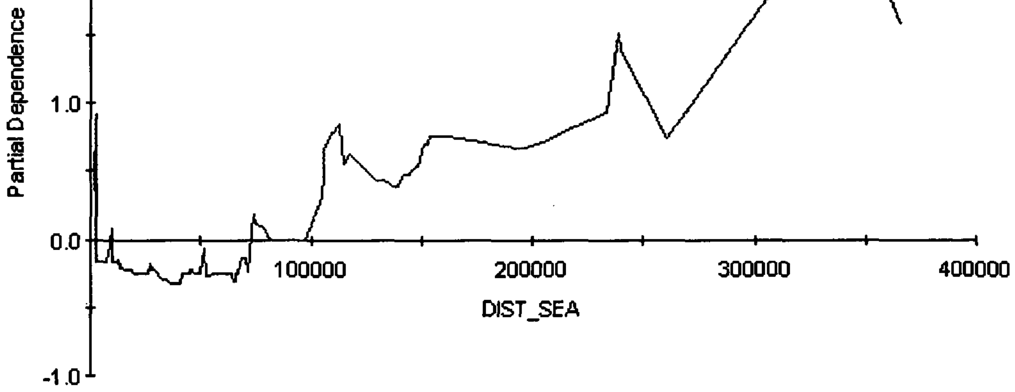


Figure A6.2ah) Response curve for CAVM vegetation type S2 to distance to sea (m).

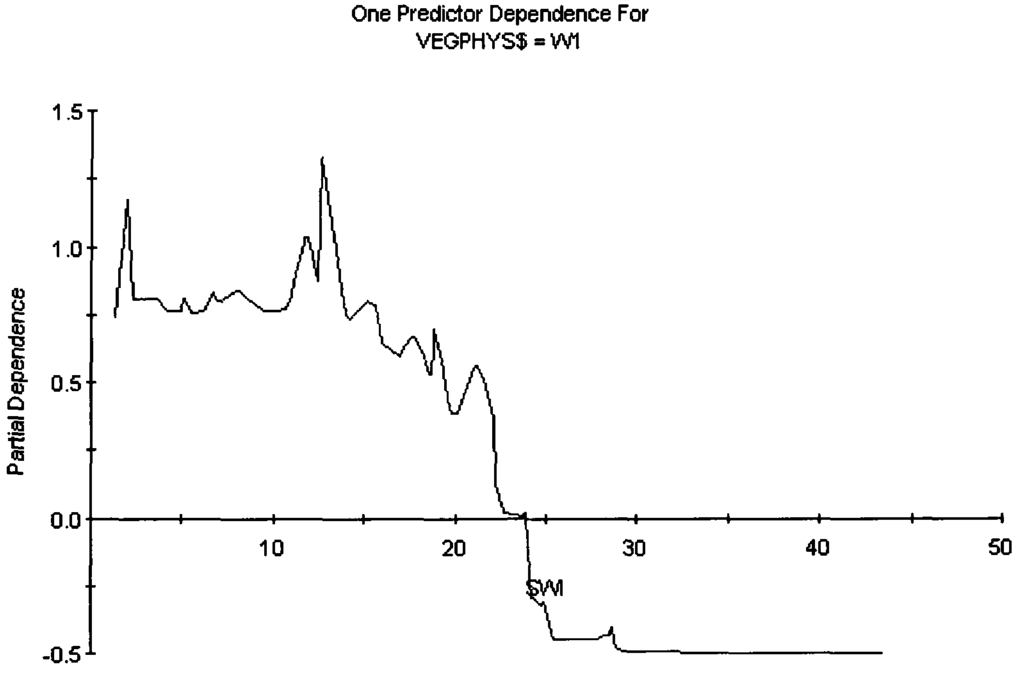
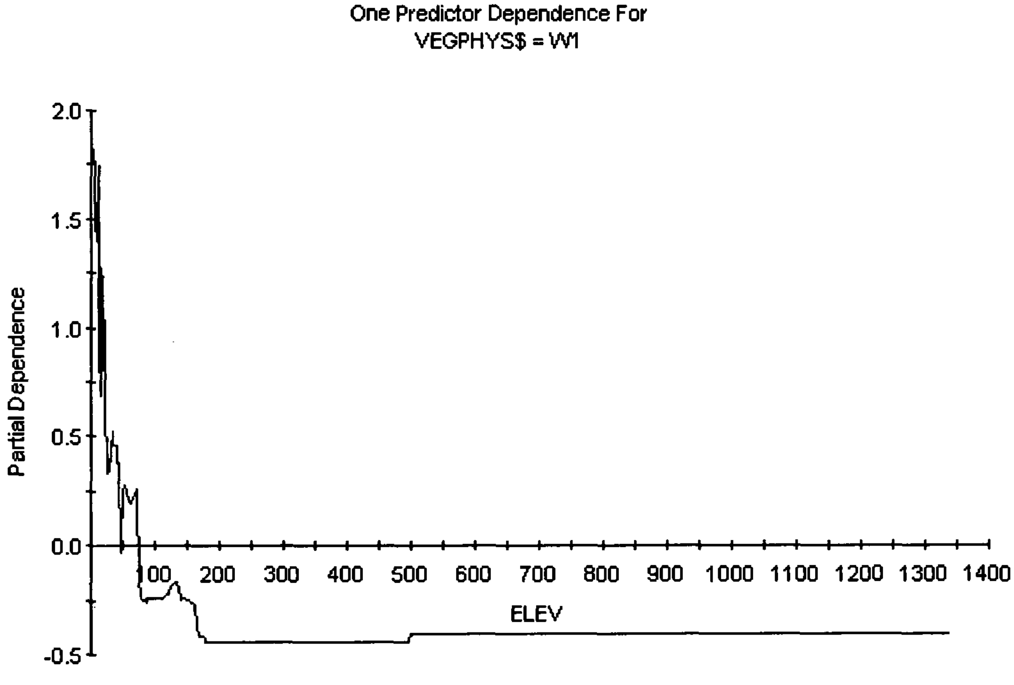


Figure A6.2ai) Response curve for CAVM vegetation type W1 to summer warmth index (SWI, °C).



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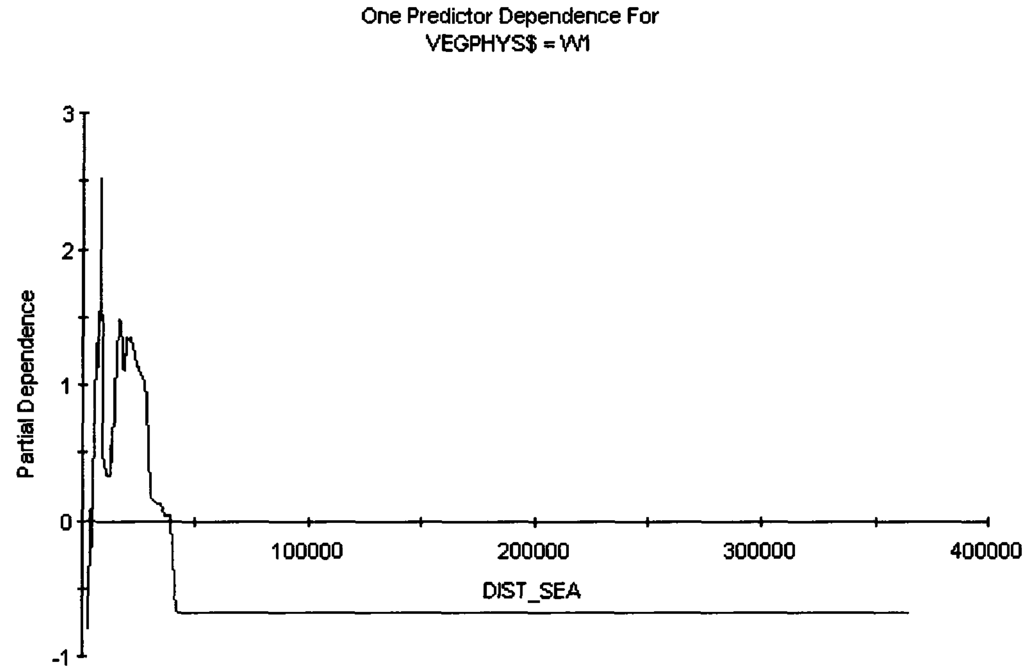

Figure A6.2ak) Response curve for CAVM vegetation type W1 to distance to sea (m).

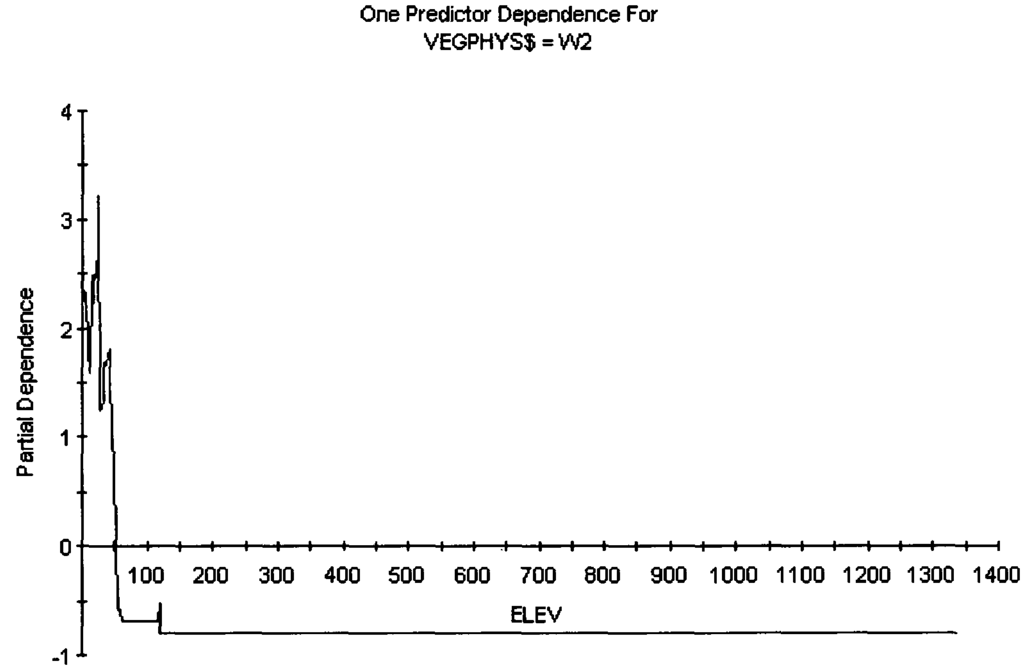

Figure A6.2al) Response curve for CAVM vegetation type S2 to elevation (m).

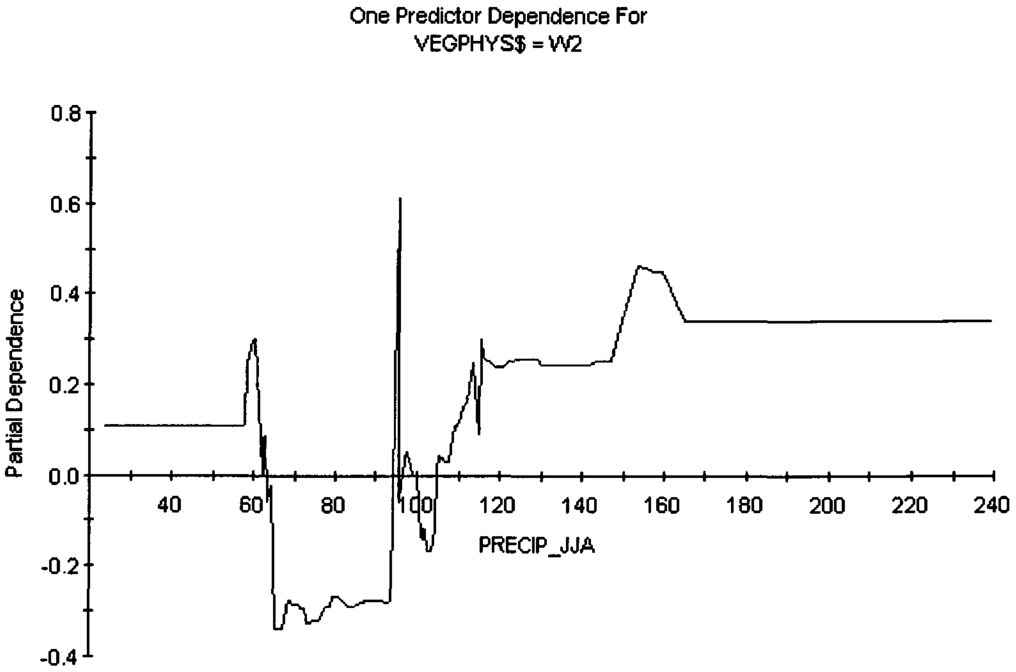

Figure A6.2am) Response curve for CAVM vegetation type W2 to summer precipitation (mm).

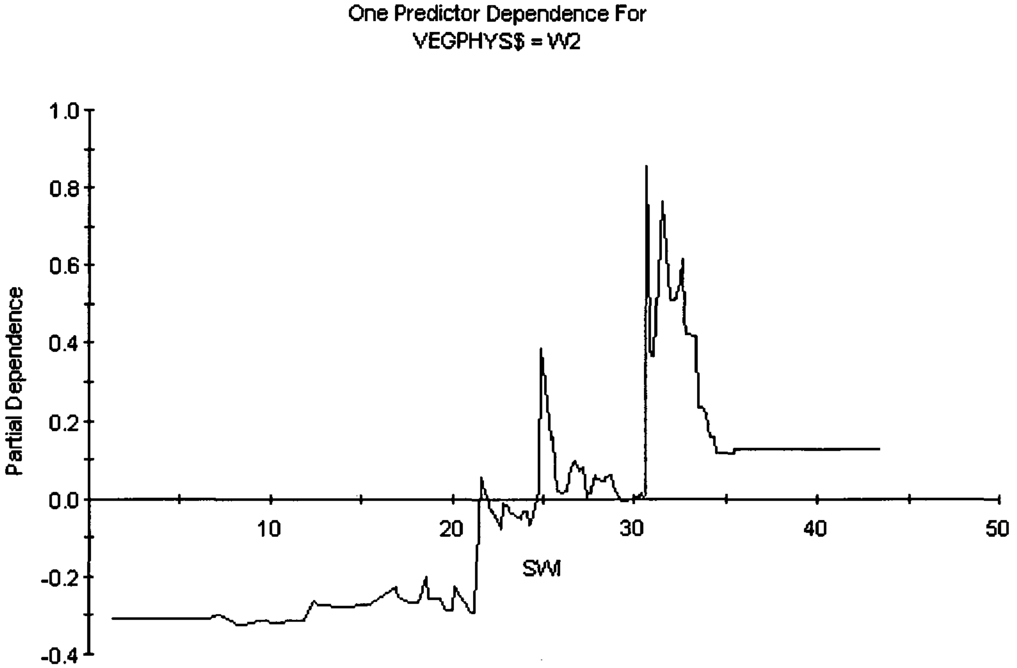

Figure A6.2an) Response curve for CAVM vegetation type W2 to summer warmth index (SWI, °C).

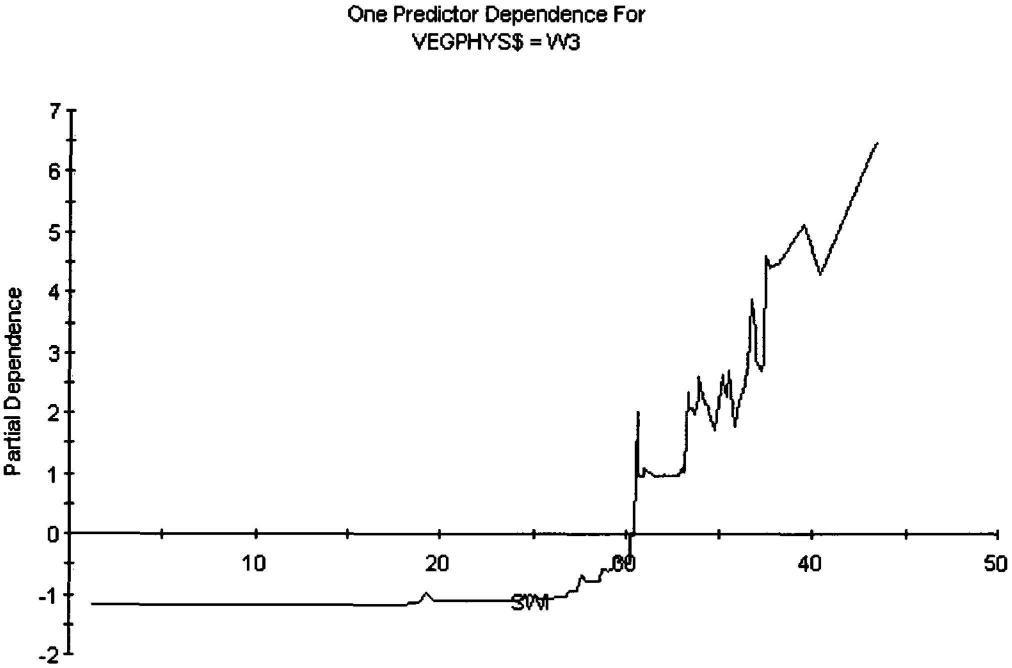

Figure A6.2ao) Response curve for CAVM vegetation type W3 to summer warmth index (SWI, °C).

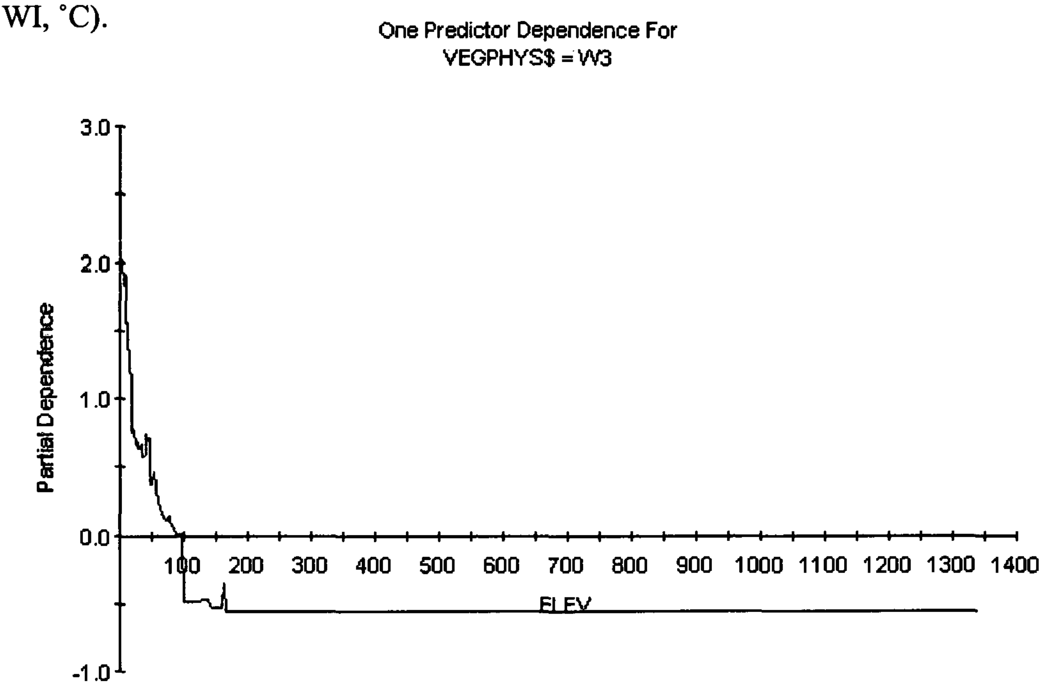

Figure A6.2ap) Response curve for CAVM vegetation type W3 to elevation (m).

Chapter 7 – Conclusion

This chapter briefly reviews what was known about the biogeography of arctic vegetation before I began this research. I then discuss how the information presented in this dissertation added to the knowledge of the spatial distribution of arctic vegetation. In the second section I review what was known about the response of arctic vegetation to climate change and discuss how my research has helped answer some important questions on that topic.

7.1 Biogeography of circumpolar arctic vegetation

7.1.1 Origin of arctic vegetation

The poles are the most climatically dynamic portions of the Earth. Swings from warm to cool climates through geologic time have been amplified in polar areas due to both the albedo feedback effects of snow and ice and atmospheric circulation patterns transferring heat to the poles (Bradley, 1999). The Arctic has gone through very warm times - it supported lush forests and dinosaurs 100 million years ago, and very cold times when it was mostly ice-covered (Ruddiman, 2001). For the last several million years, glacial climate cycles have been occurring every 100,000 years or more frequently (Ruddiman, 2001). These glacial cycles were extreme enough in the Arctic to completely change the vegetation, even in areas not directly affected by glacial ice (Lozhkin et al., 2007). Thus existing arctic plant communities are not stable, climax communities, but rather what we see now is one moment in a continually changing mix of arctic plants species. The arctic vegetation that we know today is the result of plant populations responding to climatic conditions that are fluctuating on many different time scales, including warming since the Last Glacial Maximum (21,000 years ago), warming since the Little Ice Age (400-200 years ago), and most recently, anthropogenically-induced warming.

On an evolutionary time scale, the arctic flora is a comparatively young derivative of the boreal flora (Bliss et al., 1980; Yurtsev, 2004). Conditions that we would recognize as arctic did not developed until 3-5 million years ago, when the Bering Strait first opened (Marincovich and Gladenkov, 2001). Plants that colonized the Arctic at that time were species and complexes that were pre-adapted to the climate, such as alpine plants. These plants grew in exposed, wind-swept, snowfree, usually stony sites or moist, concave snowbank sites and were adapted to short growing seasons (Yurtsev, 2004). Plants that were successful in arctic climates were low-growing enough to use the ground surface layer that is warmest in summer and usually snow-covered in winter. They also were slow-growing, stress tolerant, and able to grow under low-resource conditions (particularly cold summer temperatures). Many were evergreen and most had live and dead plant parts that persisted for many years (Yurtsev, 2004).

The circumpolar distribution of arctic plants was fragmented by repeated Quaternary glaciations (Love and Love, 1974). Some arctic plants retreated to more southern alpine areas, such as the Chukotka Mountains, the Urals, the Alps and the Rocky Mountains during glacial maxima. Unglaciated areas in Beringia also provided refugia during the Pleistocene glaciations. Northeastern Asia is the center of diversity for arctic plants. It is the origin for many species and has the greatest potential reserve for florogenesis and adaptive evolution in the Arctic and Subarctic (Yurtsev, 2004).

People had thought that because arctic plants grow and reproduce so slowly, existing arctic vegetation must have spread from "refugia", northern areas that persisted unglaciated throughout the LGM (Love and Love, 1974; Serebryanny and Tishkov, 1997). However, the perception that plant colonization and the formation of Arctic plant communities is slow, taking millennia, has proven to be false, with recent work showing that recolonization occurs fairly rapidly in the Arctic. In Svalbard, areas deglaciated in the last 150 years have almost complete vegetation cover (Hodkinson et al., 2003; Moreau et al., 2005). Succession continues rapidly, with measurable changes in species composition occurring over the last 30 years (Moreau et al., 2005). Examination of the fossil and genetic record of vascular plants in the North Atlantic supported distribution based on high migration rates and rapid recolonization rather than evidence of refugia (Brochmann et al., 2003). Genetic evidence shows that Svalbard, despite its remote location, has been repeatedly colonized by plants from several source regions (Alsos et al., 2007).

So the current view of arctic vegetation is of a dynamic group of plant species, well-adapted to dispersing and colonizing cold regions.

7.1.2 Categorization of arctic vegetation

The first broad divisions of arctic vegetation in the 1800's were based on the height and cover of the plants (Aleksandrova, 1980). Later this was refined by Russian geobotanists into subdivisions of the Arctic based on climate and the corresponding plant growth forms (e.g. Sochava, 1934). The division into 2-6 latitudinal bioclimate subzones (5 for the Circumpolar Arctic Vegetation Map; CAVM Team, 2003) has been found to be a useful construct for grouping circumpolar arctic vegetation.

In addition to the north-south gradient caused by temperatures, there is also east-west variation in the Arctic. This is the result of the varying effects of glaciations, mountainous barriers to dispersion, and geologic bedrock chemistry. For example, prostrate willows are common in Tundra Bioclimate Subzones B and C, but species vary from *S. nummularia* in the Yamal to *S. sphenophylla* in Yakutia, *S. glauca* on Wrangel Island, *S. phlebophylla* and *S. rotundifolia* in Beringia, and *S. arctica* in Canada (Yurtsev, 2004). In Russia, a system of floristic provinces was described, based on variation in the local flora (Aleksandrova, 1980). This system was then expanded to a circumpolar scope, capturing distinctions such as the Beringian flora (Elvebakk et al., 1999; Yurtsev, 1994).

On the other end of the spatial spectrum, botanists have been exploring the Arctic, collecting species and describing local plants communities for centuries. The development of the European science of phytosociology in the early 1900s gave researchers the tools to group species into sets of interacting plants that form recognizable, repeating communities (Braun-Blanquet, 1928). The process of defining communities on the tundra is challenging due to its heterogeneity. Interactions between the soil, water and cold temperatures often create cryogenic patterning, varying in scale from large polygons (> 30 m diameter) to small hummocks (as small as 10 cm).

Vegetation varies with surface microtopography, such that on the Taimyr Peninsula 8 different communities could be distinguished on hummocks and 4 within troughs (Matveyeva, 2008). While it is valuable to describe and sample plant communities at this level of detail to research chemical and physical processes, it is possible to distinguish larger-scale discrete, repeating units that can be described as complexes of Braun-Blanquet associations (Matveyeva, 2008). These recognizable units, with a sampling size of 4 - 400 m^2, are at a scale that is useful for mapping and describing ecosystem functions. They can be described for a typical landscape toposequence, including ridges, slopes, snowbeds, wetlands and riparian areas. The zonal vegetation found on gentle slopes typifies the response of the available plant species to the prevailing climatic conditions.

The first map of circumpolar arctic vegetation to use this zonal approach was the CAVM. The 15 vegetation types were differentiated by the physiognomy of the zonal plant community and described based on plant functional types and constituent plant communities (Walker et al., 2005). This is an ecologically useful approach for modeling and other analyses, as the vegetation type can be characterized by plant species composition, vertical and horizontal plant structure, dominant plant growth forms, and estimates of phytomass and annual net primary production (CAVM Team, 2003; Walker et al., 2005).

The scale of the analysis presented in this dissertation is at the circumpolar level, using the CAVM vegetation types. While this level of resolution is appropriate for a circumpolar analysis of arctic vegetation, it is important to keep in mind that the vegetation types describe the dominant zonal vegetation of an area at a scale of 1:7.5 million. Each polygon has inclusions of other types, varies along toposequences, and is a heterogeneous mix of plant communities at scales down to less than 1 m. The advantage of the CAVM vegetation types is that they combine areas with broadly similar environmental and floristic characteristics, to allow a circumpolar perspective of the distribution of arctic vegetation.

In addition to the categorized vegetation types, I also used a continuous vegetation index to analyze arctic vegetation distribution. This 1-km resolution satellite data from the early 1990's showed the distribution of the normalized difference vegetation index (NDVI) (CAVM Team, 2003).

7.1.3 Environmental controls of arctic vegetation types

One of the main goals of the research presented in this dissertation was to gain a better understanding of the different environmental factors that affect the distribution of arctic vegetation. The concept was that plant assemblages are generated through the response of available plants to climate and substrate, and that an analysis of the spatial distribution of these environmental data would provide insight to factors controlling arctic vegetation and the likely response of that vegetation to climate change. Important original products of this research include the digital map and summaries of summer warmth index (SWI, sum of monthly means > 0 °C, Figure 3.2) and landscape age (Figure 5.2).

The CAVM was based on an integrated mapping approach (Walker, 1999), so it included data on bioclimate subzone, floristic province, elevation, landscape type, and substrate chemistry (acidity & salinity) (CAVM Team, 2003). During the course of this research additional data were acquired from other sources and formatted to be compatible with the CAVM data. These layers included land-surface temperature, permafrost type, landscape age, precipitation, and snow water-equivalent. Environmental variables were analyzed individually (Chapters 2-5) and a statistical analysis approach was used to analyze them jointly (Chapter 6). This boosted regression tree analysis (Salford Systems, 2005) described a unique set of environmental characteristics important for each of the vegetation types. The analysis helped define the ecological niches of the CAVM vegetation types and provided some quantification of the differences between types. If portions of the CAVM were mapped at a larger scale, the data layers and models developed by this research could be used to verify and adjust the boundaries between types.

7.1.4 Environmental controls of NDVI

The dominant trend in the analysis of maximum NDVI was an increase from north to south, from Subzone A to Subzone E (Chapter 2). NDVI increased with increases in summer warmth index (SWI), with an R^2 value of 0.5814 (Chapter 3). In a boosted regression tree model analysis of NDVI and environmental variables, SWI was one of the two most important variables (along with landscape age) that explained the circumpolar variation in NDVI (Chapter 6).

The positive effect of temperature on NDVI was expected, but some areas of the Arctic had more or less NDVI than would be expected from that relationship. A map of regression residuals showed negative values throughout the Canadian Shield and other recently glaciated areas (Chapter 3). NDVI increased with landscape age for all but the coldest parts of the Arctic (Subzone A) (Chapter 5). Although deglaciated areas in the coldest parts of the Arctic are quickly recolonized (Moreau et al., 2005), their NDVI values never rise very high because of the large proportion of bare ground and the limited flora (Chapter 2). After the initial rise in NDVI for newly colonized areas, NDVI stayed relatively constant for 2,000 - 20,000 year-old landscapes. These areas tend to have high ice-content permafrost and lower NDVI values (Chapter 4). Landscapes older than 20,000 years had higher NDVI levels (Chapter 5), being old enough for soil development (Birkeland, 1978) and lake infilling (Campbell et al., 1997).

Lake cover, extreme soil chemistry and elevation all had negative effects on NDVI (Chapter 2). Areas with carbonate and saline soils had strongly negative NDVI~SWI regression residuals (Chapter 3). For areas above 100 m in elevation, NDVI decreased with elevation (Chapter 6), except for the coldest bioclimate subzones, where there was no response with elevation (Chapter 2). NDVI decreased with increasing lake cover because of the low NDVI value of water, as shown by negative regression residuals for all areas with >2% lake cover (Chapter 3) and a negative boosted regression tree response curve (Chapter 6). NDVI increased with depth of the snow pack, as measured by maximum monthly snow-water-equivalent (Chapter 6). A threshold response showed higher NDVI for areas with > 75 mm of snow-water-equivalent (approximately 28 cm snow depth), a height at which erect dwarf shrubs become an important component of the vegetation.

A map of areas with high NDVI~SWI residuals showed areas with optimal conditions for vegetative growth (Chapter 3). These productive areas included areas unglaciated during the Last Glacial Maximum (northern Alaska, southern and western Taimyr Peninsula,Yakutia) and areas with high precipitation (Western Siberia, Kuskokwim Mountains) (Chapter 5). The highest NDVI values in the Arctic were found in shrub tundra in European Russia, the southern Taimyr Peninsula, northwestern Alaska and the Yukon-Kuskowim Delta, in areas with the warmest summer temperatures where permafrost is not continuous, on low-elevation non-carbonate substrates that were not glaciated within the last 20,000 years (Chapter 2-5).

One of the most interesting results of the analysis of NDVI was that the scale of response of NDVI to temperature from this spatial analysis was similar to the response seen over the satellite record. In the twenty years between 1981 and 2001, SWI calculated from northern Alaska climate station data increased 3.2–6.8 °C while the annual maximum NDVI increased 0.078±0.026 (Jia et al., 2003). According to the analysis presented in Chapter 3, a 5 °C increase in SWI (the mid-point of Jia et al.'s range) correlated to an increase of 0.069 in NDVI. Analysis of North America and Eurasia from 1982-1999 found a similar relationship (+0.055 NDVI/+5 °C; Kaufmann et al., 2003). This corroboration of the temporal response of NDVI to warming with the spatial relationship shows that the trend seen in the satellite data is in the range expected by the biological response of arctic vegetation to temperature. This strengthens the conclusion that the satellite trend is likely due to real changes in the vegetation and not just an artifact of the satellite data, as some researches have questioned (Fung, 1997; Kaufmann et al., 2000).

NDVI is also useful as an indicator of arctic vegetation biomass (Walker et al., 2003a). The relationship between biomass and NDVI was calculated from biomass sample plots in a wide variety of sites in arctic North America. Regression analysis revealed an asymptotic curve relationship between biomass and maximum annual AVHRR NDVI, with biomass rising rapidly as NDVI saturates at levels > 0.6 (Walker et al., 2003a). This relationship was used to estimate total arctic biomass from the arctic AVHRR NDVI data at 2.5×10^{15} g (Chapter 2). This estimate matches well with extrapolations based on biomass samples from plots along a transect across the North American Arctic, calculated without using NDVI (Walker et al., 2008). Biomass values for plots what were typical of each tundra bioclimate subzones were multiplied by the area of each subzone, producing an estimate of 2.4×10^{15} g of arctic vegetation biomass (Raynolds et al., 2008). Most of the Arctic's biomass is found in the warmest subzone, below 333 m elevation, on acidic substrates, and most is found in the Russian Arctic, which has large areas that meet these conditions.

7.2 Response of arctic vegetation to climate change

As shown above, both NDVI and vegetation types are affected by climate. We know arctic vegetation has changed often in the past and there is great interest in understanding how arctic vegetation is likely to respond to predicted climate changes. Some clues are available from physiological studies and experiments, and the research presented in this dissertation provides additional information, particularly a spatial context.

7.2.1 Results of studies of plant physiology and experiments

Arctic plants are well adapted to growing in cold conditions. Their photosynthesis and respiration rates are similar to temperate plants, but occur at lower temperatures. They have more chloroplasts and mitochondria per cell, which allows more photosynthesis at low temperatures, but also requires high maintenance respiration rates (Semikhatova et al., 1992). Similarly, high protein flexibility allows the enzymes of arctic plants to work at low temperatures, but this is achieved at the cost of high protein turnover, which increases maintenance respiration (Semikhatova 1992). Although arctic plants have low optimum temperatures for photosynthesis, during more that half the growing season air temperatures are significantly lower than optimum (Semikhatova et al., 1992). Thus, even for low-temperature adapted arctic plants, photosynthesis is still temperature-limited most of the time.

Increases in rates of photosynthesis due to increased temperature have not been found to persist or result in continued higher productivity in arctic plants (Chapin et al., 1995). Photosynthesis usually becomes sink-limited due to limited nutrient availability. Though photosynthesis allows the plant to produce more carbohydrates, without the nitrogen and phosphorus to convert these products into plant parts, high carbohydrate level in leaves can damage chloroplasts. Plants respond by down-regulating photosynthesis through shutting down stomata and by regulating Rubisco & Rubisco-activase (Lambers et al. 1998), or burning off excess carbohydrates using alternative pathway respiration (APR) (Crawford 1997). Warming experiments show that tundra plants respond to increased temperature by increased growth, but that these responses are short-term and that nutrients limit production more than any other factor (Chapin et al., 1995; van Wijk et al., 2003). Cold soil temperatures, which persist despite atmospheric warming due to the insulative effect of tundra vegetation, limit decomposition and nutrient availability (Chapin et al., 1995).

At the community level, changes in vegetation composition are the results of interactions of different species as they respond to warming temperature. Within genetic limitations, plants can reduce energy allocation to cold-protective mechanisms such as leaf hairiness and relax protective limitations that minimize plant height and flower and seed production. Responses vary by species and growth form. For example, evergreen shrubs can only increase their height slowly, as they invest more energy in their leaves than deciduous plants. ITEX experiments have shown that warming increased height and cover of deciduous shrubs and graminoids, decreased cover of mosses and lichens, and decreased species diversity and evenness (Walker et al. 2006).

The response of arctic vegetation to changes in precipitation is less well studied than temperature response. Changes in precipitation affect soil moisture, resulting in changes in water available to plants, decomposition rates, and nutrient availability (Wahren et al., 2005). Results presented in this research demonstrate the importance of precipitation and snow depth in determining vegetation type and NDVI (Chapter 6). However, experiments in the Arctic show little response of vegetation to water addition (Dormann and Woodin, 2002). Studies in Greenland have found plant productivity to be strongly positively correlated with precipitation (Heide-Jorgensen and Johnsen, 1998), despite the fact that increases in precipitation are usually accompanied by increases in cloudiness. Studies in Northern Alaska during an 8-year period that spanned a 28% increase in summer precipitation, showed an increase in shrub cover (Wahren et al., 2005). Reports of local conditions in Canada describe poor growth in eastern regions associated with warmer summers and less rain, but increased growth in western regions with warmer, longer, wetter summers (Callaghan, 2005). A study of North American graminoid-dominated systems showed that increases in precipitation increased productivity of shrub-dominated areas more than graminoid dominated areas (Knapp et al., 2008). The general consensus of these studies is that the increased precipitation predicted for the Arctic in most climate models (Bates et al., 2008) may cause small increases in shrubbiness and NDVI (Dormann and Woodin, 2002).

7.2.2 Documented changes in arctic vegetation

The paleo-record is full of evidence of dramatic changes in arctic vegetation (e.g. Bigelow et al., 2003). Climate cycles at many scales are continuing right now and the resultant temperature and moisture conditions affect arctic plants at many scales – from minute-to-minute internal regulation to long-term species evolution (Fig. 5.7). The questions that raise the most concern relate to the response of arctic vegetation to anthropogenic warming on the decadal time scale. Climate changes over the next century are predicted to be comparable to the full swing between glacial and interglacial cycles, to occur more rapidly than any changes in the last 20,000 years, and to likely reach warmer conditions than seen in the last million years (Callaghan, 2005).

Despite long-term records in pollen and other fossil data, we do not have detailed data on changes that occurred in the Arctic in the last several hundred years to compare with recent changes, which would allow us to distinguish an anthropogenic signal. Some of the longest-term historical documentation of change comes from studies of tree cores. Treeline advances in Alaska have been correlated to warming that has occurred since the early to mid 1800s (Hamm, 2007; Lloyd, 2005), though studies of individual trees found both increased and decreased growth responses to warming in white spruce (*Picea glauca*) (Wilmking et al., 2004). Treeline studies in northwestern Canada found that stand density and elevation increases during the early to mid-1900's were correlated to increased summer temperatures (Danby and Hik, 2007), and that warm temperature were required for up to 50 years for recruitment and survival (Szeicz and MacDonald, 1995). Studies of treeline in the Ungava Peninsula, east of Hudson Bay found that white spruce expanded its range beginning around 1880 (Payette and Filion, 1984). A 50-year comparison of air-photos taken on the North Slope of Alaska showed an increase in alder shrub cover occurred that was estimated to have begun in the mid-1800's (Tape et al., 2006). The evidence indicates recent acceleration of vegetation changes that began in response to pre-industrialization climate warming.

Recent responses to climate change have been documented using the 25+-year satellite record, with many studies reporting increases of arctic NDVI (e.g. Jia et al., 2007). However, aside from the shrub and treeline studies, there is a lack of ground studies documenting changes of tundra vegetation in response to climate warming. Long-term studies of arctic vegetation cover are difficult to design, expensive to carry out, and hard to get funded. Tundra vegetation is very heterogeneous, and the relationship between plot-scale sampling and satellite pixels is complex and not easily quantified (Laidler et al., 2008).

The likely effect of anthropogenic climate change on tundra vegetation will be to accelerate on-going change. On the decadal time scale the response of arctic vegetation to climate change will not be dramatic, except in places where disturbance has increased. Disturbance, due to fire, thermal erosion of permafrost, insects, or disease outbreak, is likely to increase and have much larger effects on species composition and productivity than climate change alone (Lantz, 2008).

There are many buffering effects that minimize the response of arctic vegetation to warming. Adaptations of plants to arctic environments, such as slow growth and dependence on vegetative reproduction, will limit changes in species ranges (Callaghan, 2005). On the southern boundaries of the Arctic where vegetation cover is continuous and moss layers are often thick, the soil is insulated from summer warming (Kade et al., 2006). This results in cold soils, with shallow thaw depth above permafrost. The permafrost restricts soil drainage, keeping the soils close to saturation. These conditions in turn favor the growth of mosses, which acidify the soils (Walker et al., 2003b). The cold, saturated, acidic soils and the lack of bare ground, make it hard for colonization by new species to occur. Paleoecological studies and models of treeline advance found that colonization by tree species lagged climate change by > 200-500 years (Epstein et al., 2007; Lloyd, 2005). However, as Callaghan (2005) pointed out, "The latitudinal temperature gradient within tundra is steeper than for any other biome, and outlier populations of more southerly species frequently exist in favorable microenvironments far to the north of their centers of distribution. Consequently, migration of southerly taxa is very likely to occur more rapidly in the Arctic than in other biomes."

7.2.3 Relationship of spatial patterns to climate response

A circumpolar spatial perspective on the response of arctic vegetation to climate change can inform decisions as to where to expect the largest changes, where to look for changes on the ground, and how to include spatial variability in regional and global modeling efforts. Epstein et al. (2004) emphasized the importance of spatial information in evaluating changes in the Arctic and suggested that "vegetation will respond most rapidly to climatic change when (i) the vegetation transition correlates more strongly with climate than with other variables, (ii) dominant species exhibit gradual changes in abundance across spatial transitions, and/or (iii) the dominant species have demographic properties that allow rapid increases in abundance following climatic shifts." This dissertation presented information relevant to all three of these points.

In the coldest subzone (A), NDVI and phytomass values are not much affected by changes in elevation or substrate and are similar in all regions of the Arctic. In this subzone there is a limited vascular flora and all species are at the coldest extreme of their growing range. Since these plants are so constrained by climate, there is little variation in NDVI due to factors other than temperature. In the intermediate subzones (B-D), factors such as elevation, substrate and regional characteristics begin to exert a stronger influence. Increased plant diversity and a wider range of habitable conditions allow more competition and specialization of plant communities, resulting in a larger range in NDVI values. In the warmest subzone (E), much of the variation in NDVI and phytomass is due to variation in substrate and geologic history. Mountain building and erosion, glaciations, sea-level fluctuations, and sediment deposition in wetlands and deltas all affect how long soils have had to develop and how long plants have had to colonize and evolve into communities (Chapters 2 and 5).

Examination of the effect of temperature on NDVI showed areas where response to climate is limited by substrate factors (Fig. 3.5). Those areas with negative NDVI~SWI regression residuals, such as recently glaciated areas or calcareous areas, are least likely to respond to increases in temperature with increases in NDVI. The slope of the response of NDVI to increases in SWI varied by vegetation type (Table 6.3). The largest responses were seen in mountainous and High Arctic partially-vegetated types (B4, G1, B3, W1, G2). This result was confirmed by boosted regression tree analysis of NDVI (Chapter 6), which showed the least response in NDVI to increased temperature in vegetation types that typically have complete plant cover (G3, G4, S1, S2, W2, W3). Predicted increases in precipitation and increased snow depths

(Bates et al., 2008) are most likely to affect shrub vegetation types (Sturm et al., 2001), particularly those types with partial cover of dwarf shrubs (Chapter 6).

7.3 Limitations of prediction of changes in arctic vegetation

There are serious limits to our ability to predict vegetation changes in the tundra. To start with, we cannot accurately predict climate – there are large uncertainties with long time scales or small spatial scales. We know that most of the Arctic is warming, but the change is heterogeneous in space and time. The climate in turn affects tundra ecosystems functions at many levels, from the cellular to the landscape scale. In addition, the interactions between the climate, ocean, soil and vegetation systems are very complex. Only by looking at the range of responses of arctic plant species and existing ecosystems to a range of environmental conditions do we have any basis for prediction, and are able to get some idea of what changes might be expected. Once climate conditions change to the point where there are no present-day analogies, prediction becomes even more difficult.

Predictions of changes in arctic vegetation are at best hypotheses to be tested. We need to continue to increase our understanding of the major influences on arctic vegetation and to monitor the tundra with ground studies and remote sensing. By applying these new data to our hypotheses, we will be able to adjust them as circumstances change and the inadequacies of our theories and models are revealed.

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