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NDVI patterns and phytomass distribution in the circumpolar Arctic

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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 2.5×10^{12} kg, with most of this in the warmest subzone, at the lowest elevations, and on acidic substrates.

Keywords: NDVI; Phytomass; Plant biomass; Arctic; Arctic vegetation; Tundra; Circumpolar; Circumpolar Arctic vegetation map; Bioclimate zones; Substrate pH; Elevation

1. 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 (Comiso, 2003; Hassol, 2004). 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. Methods

2.1. 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

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(Walker et al., 2005). The total area of the arctic tundra as mapped by the CAVM was 7.11×10^6 km^2.

2.2. 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: $\mathrm{NDVI} = (\mathrm{NIR} - R)/(\mathrm{NIR} + R)$, 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. 1a).

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 1990s.

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

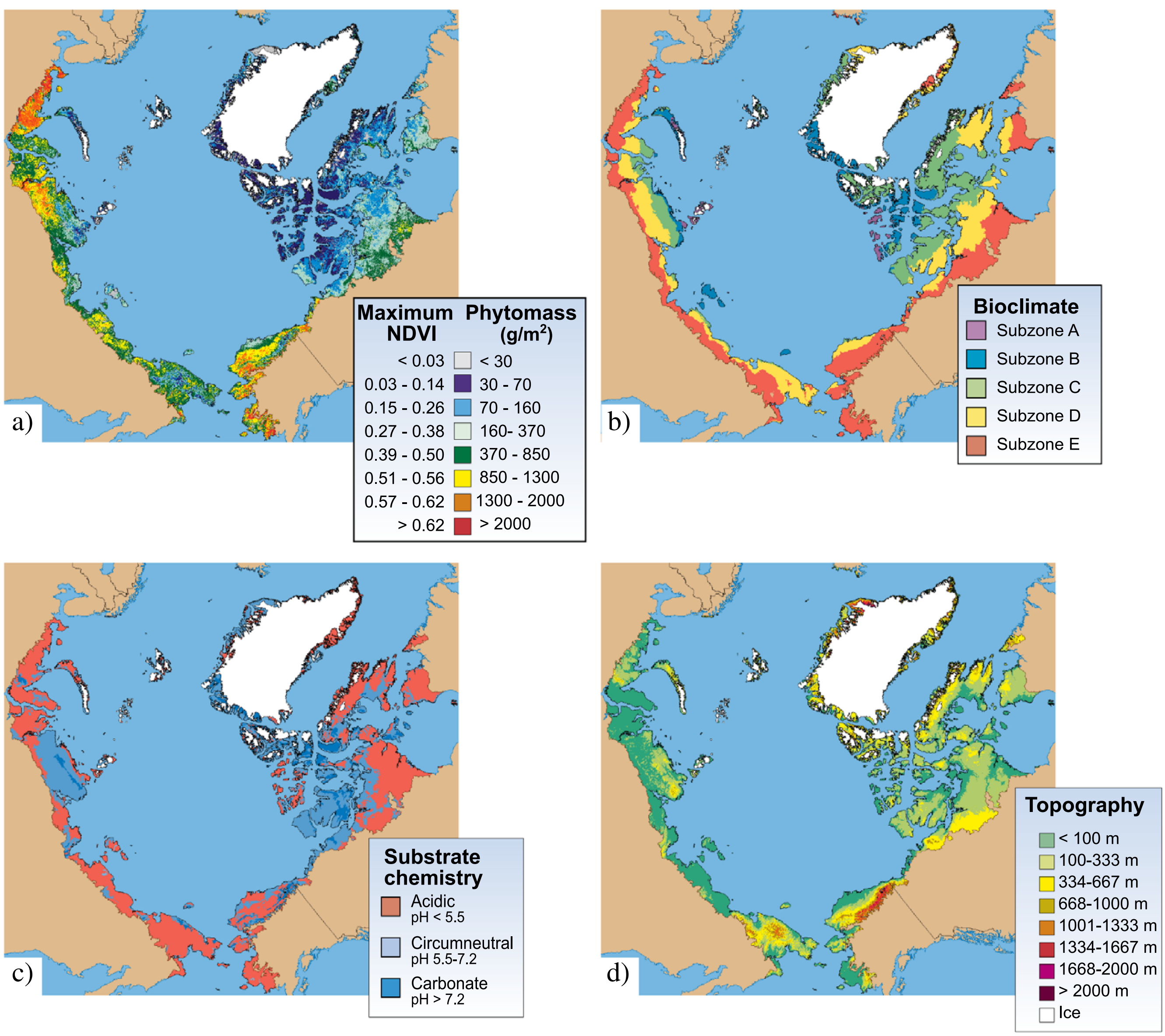

Fig. 1. Small-scale versions of CAVM ancillary maps: (a) NDVI/phytomass, (b) bioclimate subzones, (c) substrate chemistry, (d) elevation (CAVM Team, 2003).

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. 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. 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. 1b). The primary factors defining these subzones were approximate 2 °C differences in mean-July temperature, and the stature of woody vegetation (Fig. 2) (Walker et al., 2005). Substrate types were divided into three major pH categories based on their effect on plant nutrient availability (Fig. 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. 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. 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).

2.4. 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 7.11×10^6 to 4.98×10^6 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

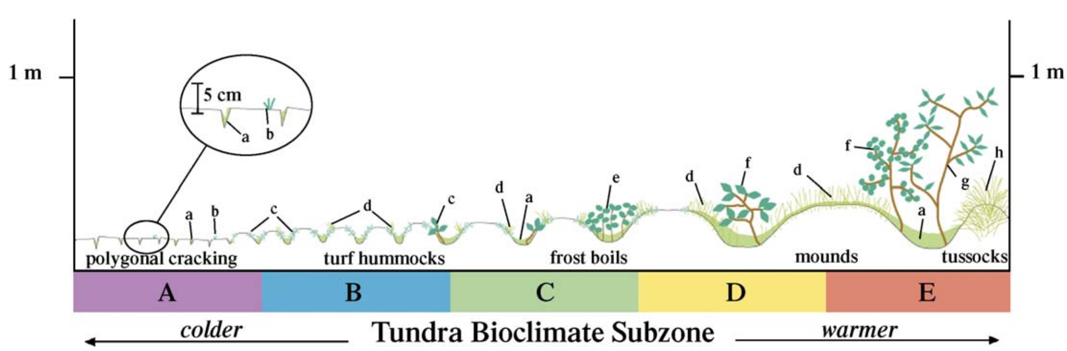

Fig. 2. Plant physiognomy occurring in different Tundra Bioclimate Subzones: A — mosses, liverworts and lichens, B — forbs, C — prostrate dwarf-shrubs, D — non-tussock graminoids, ehemiprostrate dwarf-shrubs, F — erect dwarf-shrubs, G — low shrubs, H — tussock graminoids.

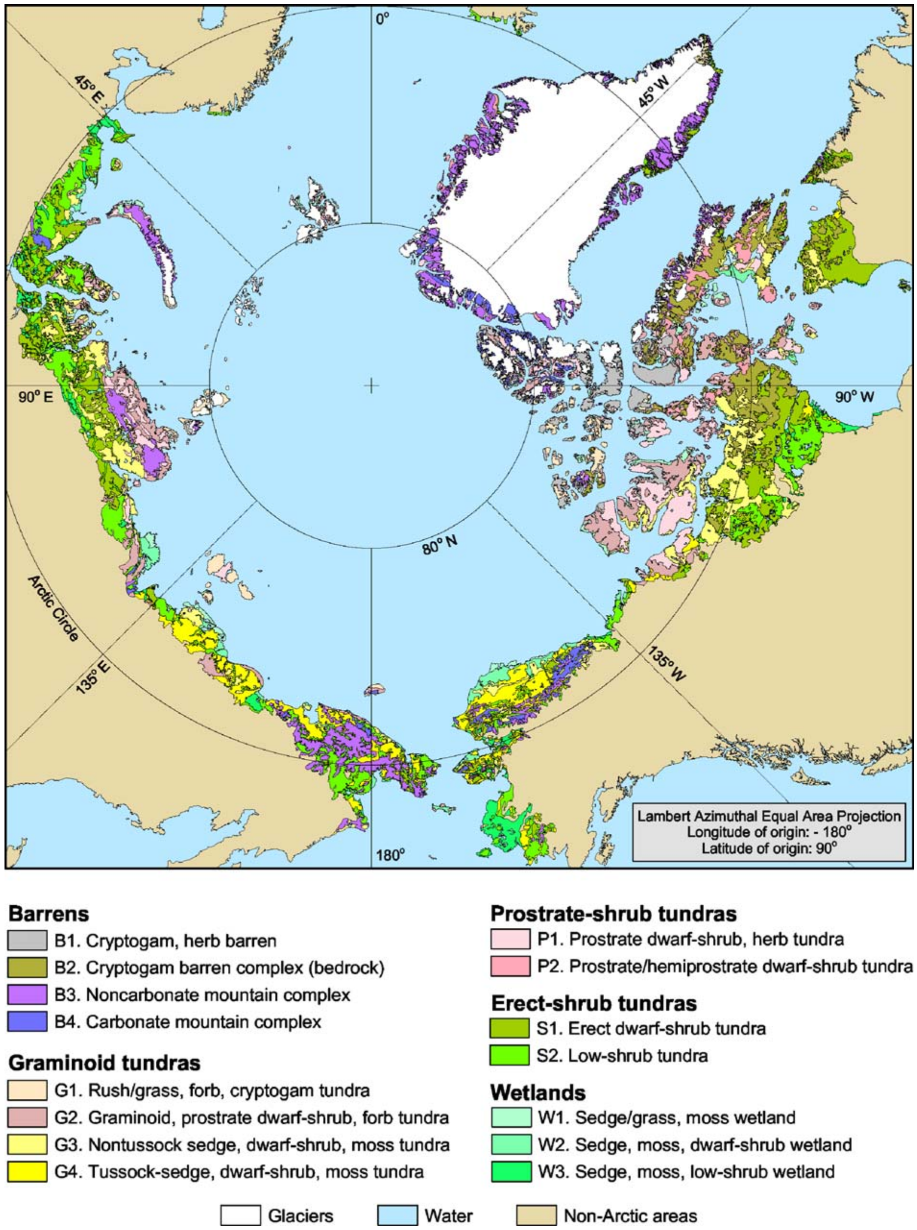

Fig. 3. Small-scale version of the Circumpolar Arctic Vegetation Map (Walker et al., 2005).

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).

2.5. 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 from 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. 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.

Several researchers have shown linear relationships between NDVI and phytomass within arctic vegetation types (Boelman et al., 2005, 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 NDVI value, using the relationship shown in Fig. 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.

3. Results

3.1. 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. = .038). NDVI in the Arctic increased from colder to warmer bioclimate subzones (Fig. 5), from 0.07 (s.d. = 0.005) in Subzone A to 0.44 (s.d. = 0.042) in Subzone E.

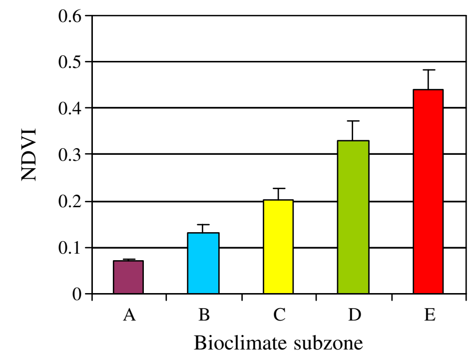

Fig. 5. Mean NDVI of tundra bioclimate subzones, lines represent standard deviation of pixel values.

NDVI also decreased as elevation increased (Fig. 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).

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. 7 (a–e). In Subzone A both NDVI values and elevation values were low, with little correlation (R^2 = 0.01) (Fig. 7a). In Subzones B through D, NDVI values decreased with elevation, though there were also many low elevation pixels with low NDVI (Fig. 7b–d). Regression 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. 7e). NDVI in Canada showed no relationship with elevation, while both Russia and the United States showed decreases in NDVI after 300 and 600 m

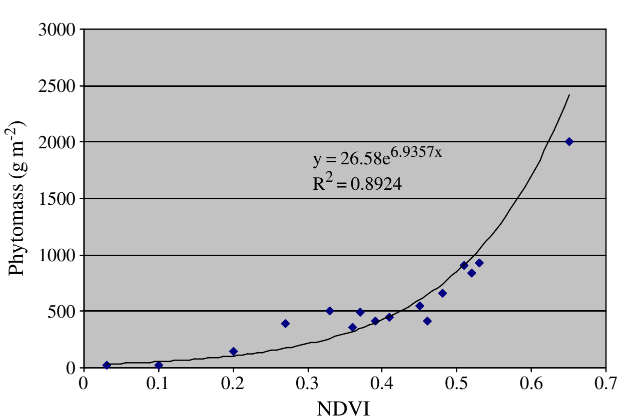

Fig. 4. Regression relationship between aboveground plant biomass (phytomass) and NDVI (Walker et al., 2003).

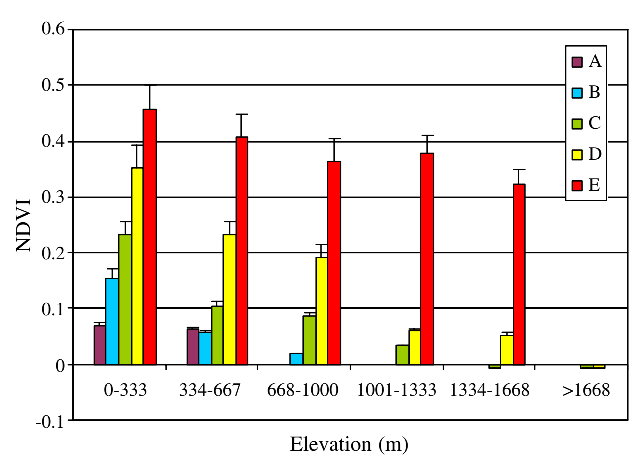

Fig. 6. Mean NDVI of elevation classes divided by subzone, lines represent standard deviation of pixel values.

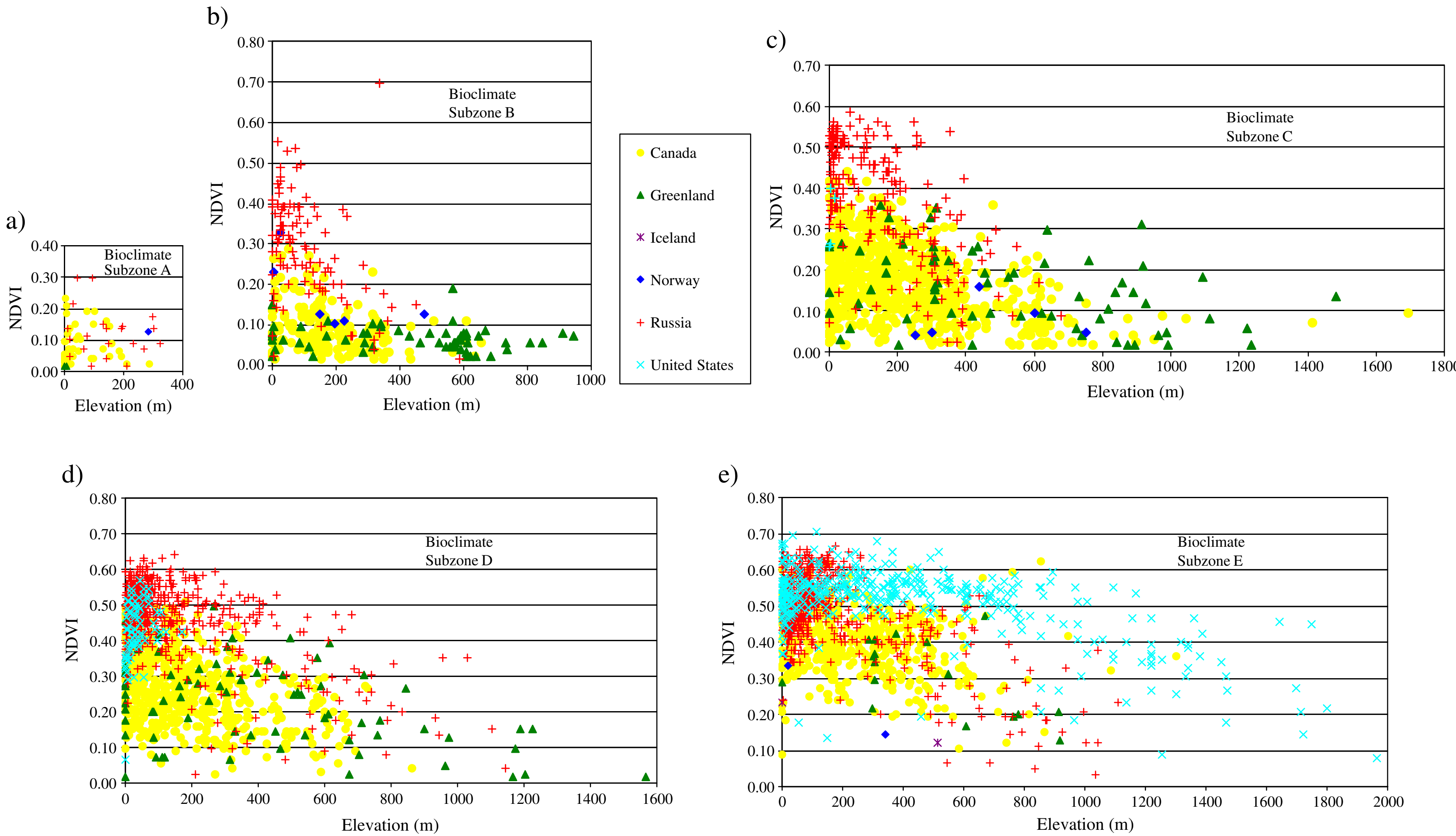

Fig. 7. Mean NDVI value of CAVM polygons by elevation for Bioclimate Subzones a–e.

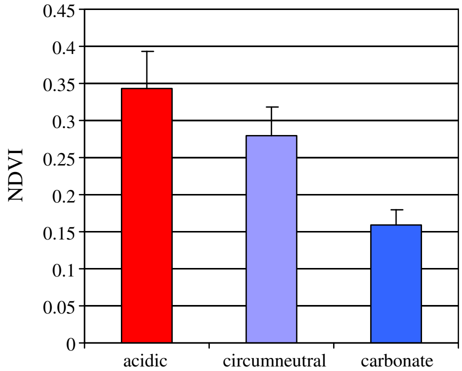

Fig. 8. Mean NDVI of arctic substrate chemistry classes, lines represent standard deviation of pixel values.

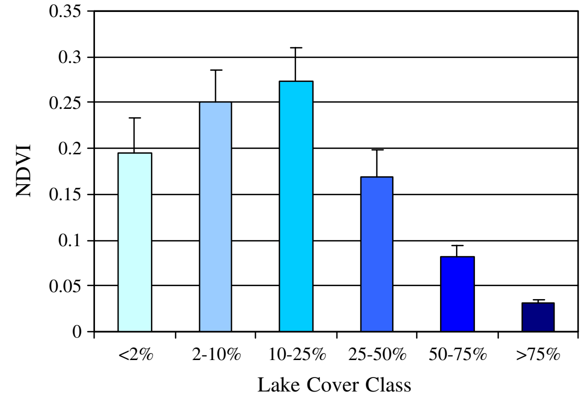

Fig. 10. Mean NDVI of arctic lake cover classes, lines represent standard deviation of pixel values.

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. 8). The effect of changes in substrate on vegetation can be quite obvious on the ground (Fig. 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.

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. 10). Polygons with the most lake cover (>75%) had the lowest NDVI.

NDVI varied considerably between physiognomic vegetation units (Fig. 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 1).

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).

3.2. Phytomass

Estimated total aboveground plant biomass (phytomass) of the Arctic was 2.5×10^{12} kg (Table 2). The combination of

Fig. 9. Variation in phytomass due to substrate chemistry, with more phytomass on the acidic substrate on the left, and less on the carbonate area to the right (Council, Alaska, photo by D. A. Walker).

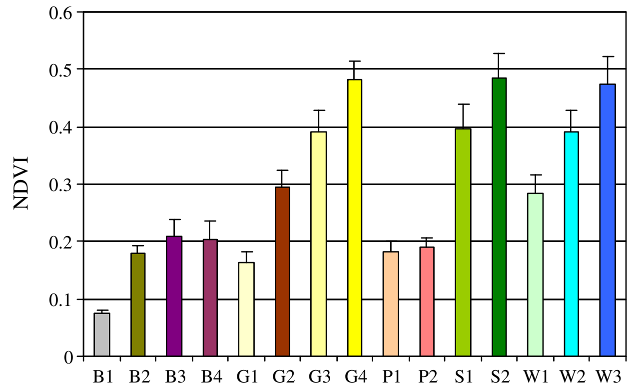

Fig. 11. Mean NDVI of CAVM vegetation types, lines represent standard deviation of pixel values. B = barren, G = graminoid, P = prostrate shrub, S = erect shrub, W = wetland. For legend of vegetation units, see Fig. 3.

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.

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 3). As shown in Fig. 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.

Acidic substrates cover more area than circumneutral and carbonate areas together (Table 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 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 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

Table 2
Area and phytomass of arctic tundra bioclimate subzones

Tundra bio-climate subzone	Area 1000 km^2	Phytomass $kg \times 10^9$ (%)
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)

4. Discussion

4.1. 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 (Subzones 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

Table 3
Arctic area and phytomass of elevation classes

Elevation class	Area 1000 km^2	Phytomass $kg \times 10^9$ (%)
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)

Table 4
Arctic area and phytomass of substrate chemistry classes

Substrate chemistry class	Area 1000 km^2	Total phytomass kg × 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)

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

Table 5
Arctic area and phytomass of countries

Country	Arctic area 1000 km^2	Total phytomass kg × 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)

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 Fig. 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.

4.2. 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.

5. 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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