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Canadian Arctic vegetation mapping

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Abstract. During the next few decades the Arctic is expected to experience unprecedented changes in climate and resource development. All of these will potentially affect land use and vegetation cover. There is a need for a comprehensive and consistent circumpolar map of arctic vegetation that will be useful for modelling vegetation change in the circumpolar region. The Canadian arctic vegetation map is part of the Circumpolar Arctic Vegetation Mapping project (CAVM) which was initiated to fulfil this need. The CAVM is an effort by an international group of arctic vegetation scientists to create a map and GIS database of circumpolar vegetation at the 1:7 500 000 scale. The Canadian vegetation map and ultimate circumpolar map will be useful for the study of arctic vegetation, modelling vegetation change at the continental and circumpolar scale, interpreting patterns of wildlife distribution and migration, land management, and educational purposes.

The mapping effort combines information on soils, bedrock and surficial geology, hydrology, remotely-sensed vegetation characteristics, previous vegetation studies and regional expertise of mapping scientists. Map units are drawn using photo-interpretation of a 1:4 000 000 scale AHVRR false colour infrared image basemap. Mapped polygons represent homogeneous landscape terrain units (e.g. hills, plains, plateaus, mountains and valleys). A GIS database contains ancillary information for each polygon and vegetation is defined through a series of lookup tables with information on dominant climatic, parent material chemistry and topographic characteristics.

We present the mapping methods, a vegetation map of the Canadian Arctic, and ancillary maps developed in the mapping process. Twenty land cover classes are presented on the map, including 17 vegetation classes that are defined by dominant physiognomy (growth form), dominant moisture regime, characteristic plant communities and characteristic degree of vegetation cover. Ancillary data presented include the AVHRR CIR basemap and landscape unit polygons, a maximum NDVI image, bioclimatic and elevational zones, and a map of parent material pH.

1. Introduction

Climatic models and observations indicate that significant climatic changes can be expected in the Arctic over the next century and these changes will likely affect

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Arctic vegetation patterns (Chapin *et al.* 1992, Oechel *et al.* 1997). Changing vegetation patterns will have impacts on wildlife, human activity and (through feedback loops) climate (Chapin *et al.* 1992, Levis *et al.* 1999, Walker *et al.* 2001). Modelling and monitoring these vegetation changes at the continental and circumpolar scale is an important research goal for a variety of research communities and requires small-scale maps of sufficient detail and accuracy to be effective (Walker, D. *et al.* 1995).

Current small-scale vegetation maps of the Arctic fall into two categories: recent satellite-based maps that portray Arctic regions with few land cover types (DeFries and Townshend 1994, Cihlar and Beaubien 1998); and older small-scale maps that are not based on current understanding of vegetation patterns or lack the perspective given by satellite imagery analysis (e.g. Spetzman 1959, Shelkunova 1975, Bliss 1977, Andreev and Scherbakov 1989). At a meeting on circumpolar Arctic vegetation in 1992 (Walker, M. *et al.* 1995), the realization that significant climate change is expected in the Arctic and that current maps do not adequately reflect the variation in vegetation within the Arctic led to the organization of the Circumpolar Arctic Vegetation Mapping (CAVM) project (Walker, D. *et al.* 1995).

The CAVM project began as a series of international workshops (Walker, D. *et al.* 1995, Walker and Markon 1996, Walker and Lillie 1997, Markon and Walker 1999, Raynolds and Markon 2001), and led to the development of a set of common goals and methods to be used in the creation of a circumpolar vegetation map and associated products. It is an effort to create a vegetation map sufficient scope and detail to monitor vegetation change and serve as input to models examining vegetation change on a circumpolar scale (McGuire *et al.* 2000). Output of the CAVM project will include regional vegetation descriptions and maps at the 1:4 000 000 scale, circumpolar maps of dominant vegetation physiognomy and derived vegetation characteristics, and a final vegetation map at the 1:7 500 000 scale indicating dominant plant communities. The Canadian Arctic vegetation map presented here is a component of the CAVM project (Walker and Lillie 1997, Walker 1999).

Variation in vegetation within the Canadian Arctic is primarily influenced by climate, substrate, and topography (Bliss and Matveyeva 1992, Walker 2000). The climatic influence on vegetation in the Arctic is manifest as a distinct pattern of bioclimatic zones from north to south (Bliss and Matveyeva 1992, Yurtsev 1994, Elvebakk 1999). This zonation can be recognized by shifts in dominance of growth form, amount of vegetation cover, diversity of species and plant communities and associated ecological properties (Chernov and Matveyeva 1997, Walker 2000). The substrate influence is primarily reflected in differing species composition on the acidic and non-acidic substrates of the Canadian Shield of the mainland and the limestone and marine sediments of the Arctic Archipelago. Topographic control is manifest as variation in dominant moisture regimes among differing landscape terrain units. The goal of the Canadian Arctic vegetation map is to show the variation in vegetation influenced by this climatic and landscape variation.

The aim of this article is to present the methods and important ancillary data layers used in producing the Canadian Arctic vegetation map, and to present a vegetation map and legend indicating variation in dominant growth forms and plant communities along the major climatic, substrate and topographic gradients of the region. This is one of the first efforts to map the vegetation of the entire Canadian Arctic using remotely-sensed satellite imagery in combination with a wide array of ancillary information on arctic vegetation, hydrology and substrate characteristics.

The Canadian Arctic Vegetation Map (figure 1) encompasses the area north of the treeline and captures variation in vegetation related to climate (figure 2), elevation (figure 3), substrate (i.e. parent material pH) (figure 4) and vegetation cover (figure 5) in landscape units (e.g.hills, plains, plateaus, mountains, valleys) visible in AVHRR false colour infrared imagery (figure 6). The map links large-scale phytogeographic patterns with landscape units and the ecological attributes of the dominant plant communities associated with these units.

2. Methods

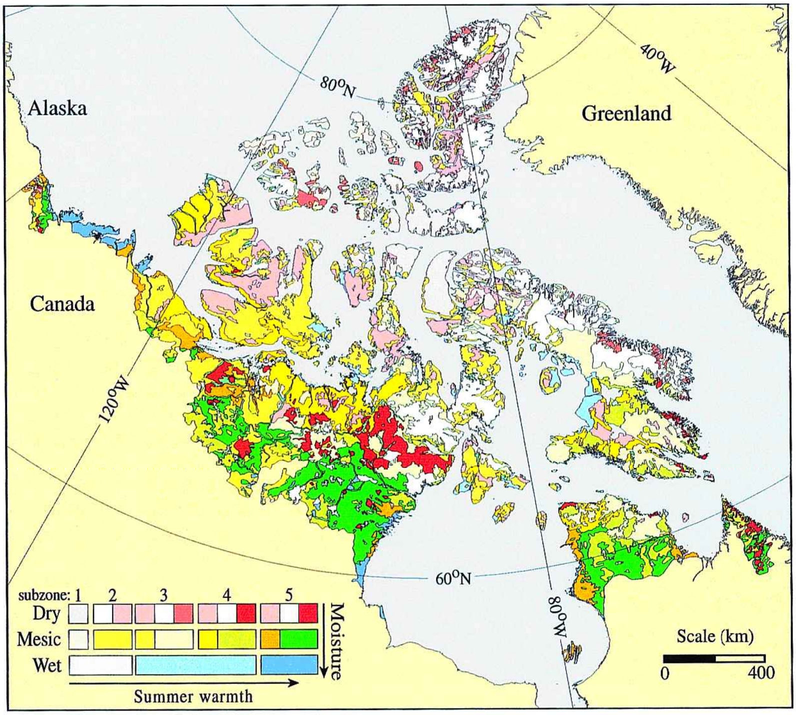
The CAVM project includes mapping work in Canada, Norway, Greenland, Russia, Iceland, Germany and the USA. This circumpolar work shares a common set of mapping methods (Walker 1999). These methods combine information on soils, bedrock and surficial geology, hydrology, remotely-sensed vegetation classifications, normalized difference of vegetation index (NDVI), previous vegetation studies and regional expertise of the mapping scientists. The information is used to define polygons drawn using photo-interpretation of a 1:4 000 000 scale AVHRR CIR image basemap.

The basemap is a key element in providing continuity for the circumpolar effort. It was created using NOAA-AVHRR data from the summers of 1993 and 1995, relatively warm years with minimum cloud and snow cover. The 1 km AVHRR data was downloaded from the USGS Eros data center as 10-day composites and multi-year composites of bands 1 and 2 were created by selecting pixels from these bands from which the highest NDVI values could be obtained. Ten-day composites were acquired between 11 July and 31 August for 1993 and 1995, with the exception of the 21–31 July period in 1995, which had uncorrectable data problems. Composite bands 1 and 2 were then used to create the false colour infrared image used as a basemap, plotted at the 1:4 000 000 scale, Lambert's Azimuthal projection, for Canada and the other circumpolar regions (figure 6). Polygons were hand-drawn on acetate overlays by photo-interpretation of variation in the AVHRR basemap and interpretation of ancillary data.

Important ancillary data sources include hydrology, shorelines and topography from the Digital Chart of the World (DMA 1992) as well as large-scale topographic maps; surficial geology derived from Surficial Materials of Canada map, 1:5 000 000 (Fulton 1995); bedrock geology derived from Geological Map of Canada, Map 1860A, 1:5 000 000 scale (Wheeler *et al.* 1996); soil associations and parent material chemistry derived from several sources including Tedrow and Douglas (1964), Tedrow (1977), Schut (1996), and Tarnocai and Lacelle (1996); floristic and phytogeographic provinces derived from Yurtsev (1994) and Elvebakk (1999); and previous vegetation maps (Edlund 1976, 1990, Gould 2000).

Hand-drawn polygons reflect the following characteristics:

1. They are greater than a minimal polygon size of 3.5 mm (14 km on the ground) for circular polygons and 2 mm (8 km on the ground) for linear polygons.
2. They consist of a relatively homogeneous landscape unit (either plains, hills, plateaus, mountains, valleys, lakes or glaciers) with boundaries visible on AVHRR imagery.
3. They consist of relatively homogeneous substrate chemistry (non-acidic, acidic, or saline substrates).



Canadian Arctic Vegetation

Dry

Cryptogam barrens. *Hierochloë alpina-Rhizocarpon geographicum* comm. (Gould and Walker 1999), *Cetraria nigricans- Rhizocarpon geographicum* comm. (Walker *et al.* 1994). < 5% cover.

Cushion-forb barrens. *Papaveretum dahlianae* (Dierssen 1996) with *Papaver dahliana* and *Saxifraga oppositifolia*. < 5% cover.

Prostrate dwarf-shrub tundra (nonacidic). *Carici-Dryadetum integrifoliae* (Daniëls 1982) with *Dryas integrifolia* and *Carex rupestris*. 5-50% cover.

Prostrate dwarf-shrub-lichen tundra (acidic). *Salix arctica-Dryas integrifolia* comm. 5-50% cover.

Hemiprostrate dwarf shrub-lichen tundra (acidic). *Vaccinium vitis-idaea-Ledum decumbens* comm. with *Betula glandulosa*. 5-50% cover.

Mesic

Graminoid-forb tundra. *Papaveretum dahlianae* (Dierssen 1996) with *Papaver dahliana* and *Luzula confusa*. 5-80% cover.

Prostrate dwarf-shrub-graminoid tundra (nonacidic). *Carici-Dryadetum integrifoliae* (Daniëls 1982) with *Carex misandra*. 5-80 % cover.

Hemiprostrate dwarf-shrub tundra (acidic). *Vaccinium uliginosum-Cassiope tetragona* comm. with *Salix arctica*. 50-80% cover.

Erect dwarf-shrub-graminoid tundra (nonacidic). *Carex atrofusca-Salix lanata ssp. richardsonii, Equisetum arvense-Salix lanata ssp. richardsonii* comms. (Gould and Walker 1999) with *Oxytropis* spp. 80-100% cover.

Erect dwarf-shrub tundra (acidic). *Betulo-ledetum decumbentis* (Lambert 1968). 80-100% cover.

Low shrub-graminoid tundra. *Dryado integrifoliae-Caricetum bigelowii, Sphagno-Eriophoretum vaginati* (Walker *et al.* 1994), *Saussuria angustifolia-Dryas integrifolia* comm. (Gould and Walker 1999). Nonacidic and tussock tundra. 100% cover.

Low shrub tundra. *Hierochloë alpina-Betula glandulosa* comm. (Gould and Walker 1998). 100% cover.

Wet

Grass-moss tundra. *Alopecuris alpinus-Campylium arcticum* comm. 5-50% cover.

Sedge-moss tundra. *Carex aquatilis* var. *stans-Drepanocladus revolutum* comm. 80-100% cover.

Low shrub-sedge-moss tundra. *Carex aquatilis* var. *stans-Drepanocladus revolutum* comm. with *Salix* spp., *Carex aquatilis-C. chordorrhiza* comm. (Gould and Walker 1999). 100% cover.

Riparian

Forb-graminoid barrens. *Cerastium regelii-Papaver dahliana* comm. with *Alopecuris alpinus*. < 5% cover.

Low shrub-graminoid-forb complex. *Epilobium latifolium-Salix alaxensis* and *Salix pulchra-Carex aquatilis* comms. (Gould and Walker 1999) 5-100% cover.

Water

> 75% lake cover.

Glaciers

> 75% ice cover.

Nunatak complex.

Figure 1. Vegetation map of the Canadian Arctic. Derived from photo-interpretation of an AVHRR false colour infrared composite image and interpretation of ancillary information on soils, bedrock and surficial geology, parent material chemistry, hydrology, maximum NDVI signal and existing vegetation maps and studies.

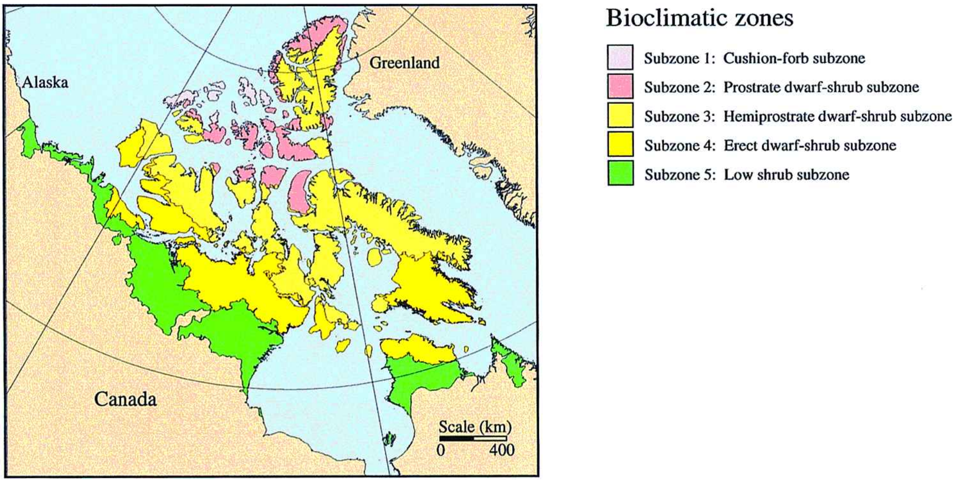


Figure 2. Bioclimatic zonation patterns indicating five arctic subzones within the Arctic Tundra Zone (Yurtsev 1994, Elvebakk 1999, Walker 2000). Vegetation patterns are strongly controlled by summer warmth (Young 1971, Rannie 1986).

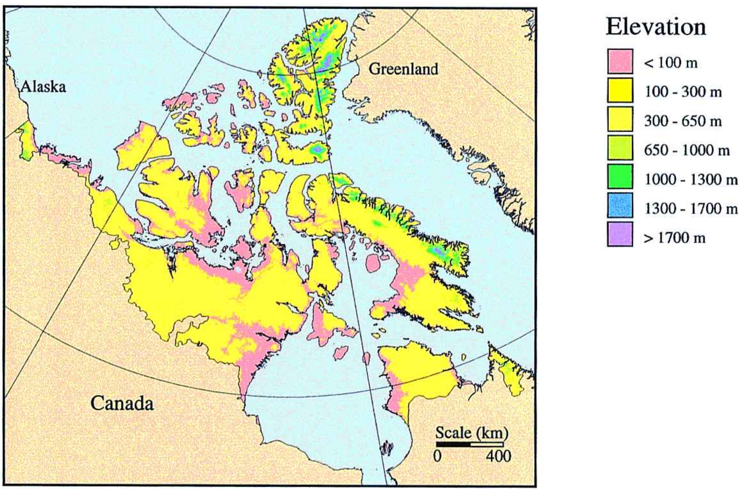


Figure 3. Seven elevational bands are shown, six of which roughly corresponding with 300 m shifts in elevation and a 3°C shifts in mean July temperatures. The 100 m elevation is shown and it was useful in delineating lowlands. Elevation patterns influence vegetation as summer warmth decreases with elevation (Walker 2000). Additionally, lowlands are typically dominated by wet and mesic vegetation, uplands are typically dominated by mesic and dry vegetation and mountains are typically dominated by dry vegetation.

These polygons make up what we call the Integrated Vegetation Complex Map (IVCM), shown overlain on the basemap in figure 6. Determining vegetation within polygons in the IVCM is a process of: (1) identifying landscape units (which combine information on soils, bedrock and surficial geology, hydrology and elevation); (2) compiling information from previous vegetation studies and satellite measures of NDVI (Walker 1999); and (3) determining the location of units with climatic

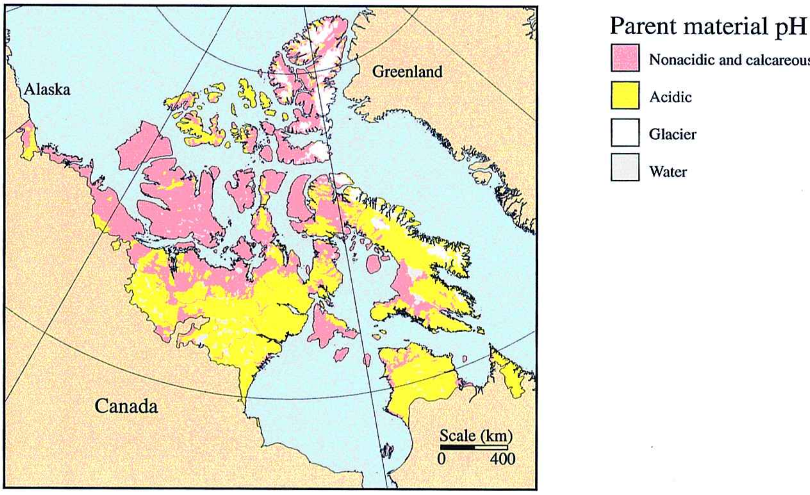


Figure 4. Patterns of parent material chemistry indicating acidic (e.g.Canadian Shield granites and gneiss, acidic till) and non-acidic (e.g.sedimentary bedrock, uplifted marine sediments, loess dominated areas) substrates. Substrate pH strongly affects plant species composition and vegetation patterns.

subzones. A set of 25 vegetation complex units in the ICVM are simplified to a set of 19 landcover classes in the vegetation map and legend presented here.

The southern boundary of the map is the northern treeline, defined as the northern limit of trees. It is derived from the work of Timoney *et al.* (1992) and Payette (1983).

2.1. *Important ancillary data*

Bioclimatic zones (figure 2, modified from Yurtsev 1994, Elvebakk 1999, Walker 2000) indicate the northern limit of low shrubs (including *Alnus* and many *Salix* species) (subzone 4–5 boundary), the northern limit of erect shrubs (including *Betula glandulosa*) (subzone 3–4 boundary), the northern limit of hemiprostrate shrubs (including *Cassiope tetragona*) (subzone 2–3 boundary), and the northern limit of woody species (including *Salix arctica* and *Dryas integrifolia*) (subzone 1–2 boundary). This zonation pattern was used to determine potential vegetation on wet, moist, dry, or riparian dominated landscape units visible on the AVHRR imagery (figure 6).

The following landscape attributes were used in conjunction with the bioclimatic zones to predict the probable dominant vegetation on landscape units:

2.1.1. *Elevation*

Variation in climate related to elevation affects vegetation patterns. As elevation increases approximately 330 m within a particular zone, the vegetation should shift to that expressed in a cooler bioclimatic zone. Digital elevations from the Digital Chart of the World (DMA 1992) (figure 3) were used to determine whether vegetation within a particular polygon would likely be zonal or azonal.

2.1.2. *Parent material chemistry*

Bedrock (Wheeler *et al.* 1996) and surficial geology (Fulton 1995) were simplified to reflect the most extensive controls on species composition at this scale, i.e. whether parent material is acidic or non-acidic (figure 4). This information was used to define

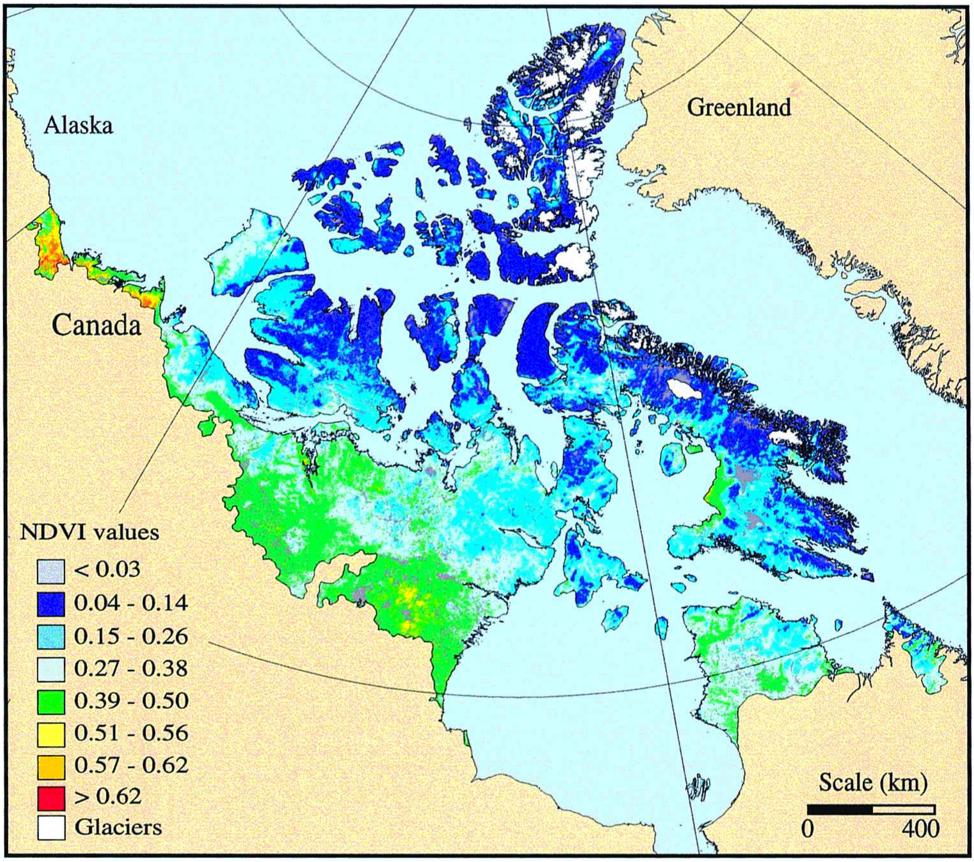


Figure 5. Nine classes of maximum normalized difference of vegetation index (NDVI) values for the Canadian Arctic derived from NOAA-AVHRR data by classifying pixels with highest NDVI among 10-day composite images from 1993 and 1995. Classes include NDVI values <0.03, 0.04–0.14, 0.15–0.26, 0.27–0.38, 0.39–0.50, 0.51–0.56, 0.57–0.62, >0.62 and ice cover.

polygons in terms of parent material pH, e.g. a polygon could be defined as either an acidic or non-acidic mesic plain, and the corresponding vegetation would reflect that substrate influence. Information used to create the parent material map comes from the following.

2.1.3. *Maximum greenness*

Maximum NDVI values were calculated from 1993 and 1995 composite AVHRR data and grouped into nine classes (figure 5). These were used to evaluate the relative amounts of bare ground and shrub cover of mapped polygons.

3. Results

The vegetation units depicted by this map (figure 1) encompass a wide range of habitats and plant communities. Vegetation has been characterized in the legend by the dominant growth forms and plant communities occurring on the dominant moisture regime within each vegetation unit. The map depicts the gradient from south to north in decreasing shrub heights, decreasing vegetation cover and increasing

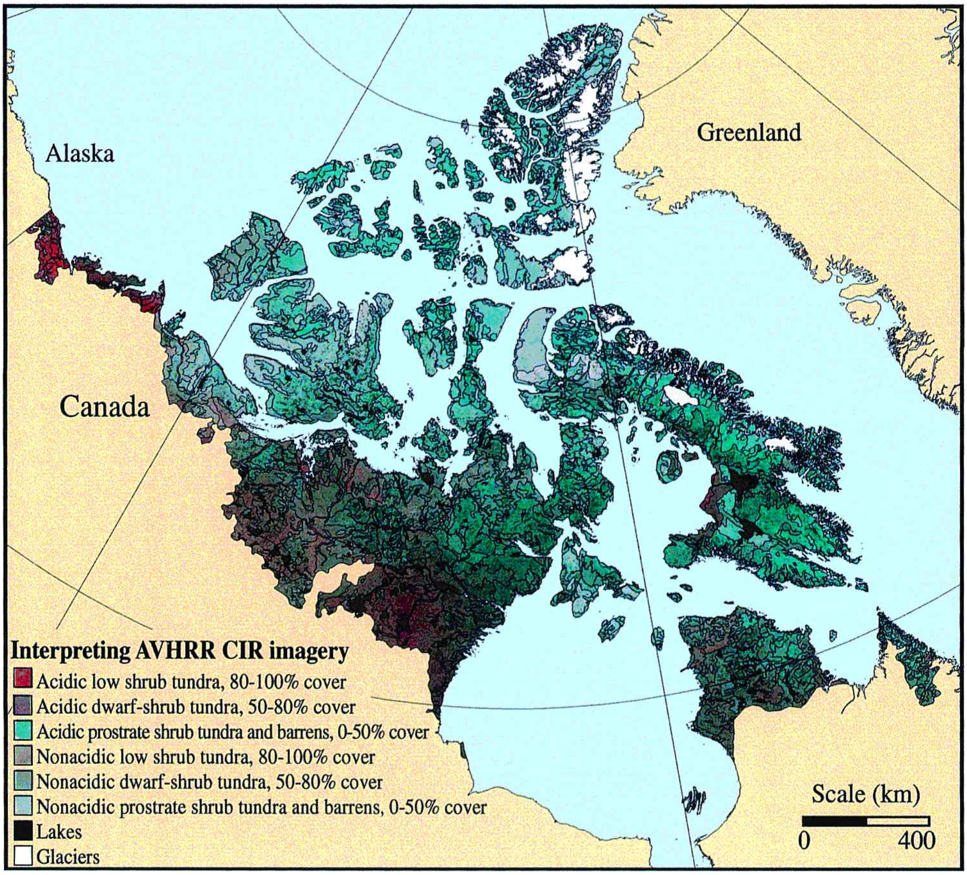


Figure 6. Map showing integrated vegetation complex (IVCM) polygons created by photo-interpretation of AVHRR colour infrared satellite imagery with ancillary information on soils, topography, substrate chemistry, maximum NDVI signal, previous vegetation maps and studies and expert knowledge.

similarity in vegetation in all habitats. The map shows the gradient in dry to wet vegetation within each bioclimatic zone, with dry vegetation dominant on uplands and steep slopes, mesic vegetation dominant on plains and gentle slopes, and wet vegetation dominant on coastal lowlands. Finally, the map shows the influence of parent material chemistry with differences in species composition occurring on acidic and non-acidic substrates apparent at this scale.

3.1. *Bioclimatic zonation*

Five distinct subzones of the Arctic tundra zone are recognizable in the Canadian Arctic (figure 2). They can be distinguished by dominant growth form and floristic composition on the mesic or zonal habitats and by differences in the less extensive intrazonal habitats such as snowbeds, wetlands and riparian areas.

The five subzones along the climatic gradient from north to south include: (1) cushion-forb; (2) prostrate dwarf-shrub; (3) hemiprostrate dwarf-shrub; (4) erect dwarf-shrub; and (5) low shrub subzones (figure 2). Prostrate dwarf-shrub species do not have an erect growth form and include *Salix arctica* and *Dryas integrifolia.*

Hemiprostrate dwarf-shrubs include *Cassiope tetragona* and *Empetrum nigrum*. Erect shrubs species may be dwarf (<20 cm), low (20–50 cm), or tall (50–200 cm). *Betula* and several *Salix* species can be found at a variety of heights depending on climate. *Alnus* is typically found as a low or tall shrub.

3.1.1. *Subzone 1: cushion-forb*

Subzone 1 is characterized by the absence of woody plants and sedges and the dominance of herbaceous dicots, grasses, rushes and bryophytes. It is equivalent to the Russian polar desert region (Chernov and Matveyeva 1997). It is restricted to the low-lying northern Queen Elizabeth Islands and the northern and western most edges of Ellesmere and Axel Hieberg Islands. This region is primarily within the permanent polar ice pack and has frequent summer fogs, reducing insolation and summer temperatures. Average vegetation cover is <5% but regions with suitable fine-grained, neutral substrates can have up to 100% cover. Mean July temperature ranges from 0–3°C.

3.1.2. *Subzone 2: prostrate dwarf-shrub*

Subzone 2 is restricted to the Arctic Islands and characterized by prostrate dwarf-shrub vegetation including *Salix arctic* on more acidic sites and *S. arctica* and *Dryas integrifolia* (Braun-Blanquet association: *Carici-Dyradetum integrifoliae*, Daniëls 1982) on non-acidic sites. There are large areas with scant vegetation cover on the strongly calcareous substrates of Cornwallis, Devon, Somerset and parts of Boothia Peninsula. The sedge *Carex aquatilis* var. *stans* occurs in wet areas. The mesic-zonal vegetation is similar throughout both subzone 2 and 3 on the strongly calcareous substrates found in the Canadian Arctic but variation does occur in the wet, riparian and snowbed habitats. Vegetation cover averages 5–50%. Mean July temperature ranges from 3–5°C.

3.1.3. *Subzone 3: hemiprostrate dwarf-shrub*

Subzone 3 occurs on the Arctic Islands in eastern and western Canada and on the mainland west of the Foxe Basin. It is characterized by the presence of dwarf-shrub heath vegetation with *Cassiope tetragona* on mesic acidic substrates, *Salix arctica* and *Dryas integrifolia* (*Carici-Dyradetum integrifoliae*, Daniëls 1982) on non-acidic zonal sites with *Salicetio-Cassiopetum tetragonae* (Daniëls and Fredskild in Fredskild 1998) dominated snowbeds on non-acidic substrates, a higher diversity of sedges in the wetlands than in subzone 2 and increased presence of *Epilobium latifolium* communities in the riparian areas. Vegetation cover averages 50–80% and mean July temperature ranges from 5–7°C.

3.1.4. *Subzone 4: erect dwarf-shrub*

Subzone 4 occurs on the Arctic islands in the west and on the mainland of eastern Canada. Dry sites on nonacidic coarse textured soils in subzone 4 are dominated by *Salix arctica* and *Dryas integrifolia*. Mesic (zonal) sites in this subzone are characterized by the presence of *Salix lanata* ssp. *richardsonii*. Zonal vegetation on the more acidic mainland is dominated by *Ledum decumbens* and *Betula glandulosa*. Low shrub vegetation can be found along sheltered streambanks. Vegetation cover is continuous on mesic and wet sites and discontinuous on knolls and ridges. Mean July temperature ranges from 7–9°C.

3.1.5. *Subzone 5: low-shrub*

Subzone 5 is restricted to the mainland in Canada and characterized by low-shrub vegetation on the zonal sites, primarily *Betula glandulosa* on acidic sites and

Salix glauca on nonacidic sites. *Eriophorum vaginatum* tussock tundra can be dominant on acidic substrates in the western portion of this subzone in Canada. Boreal floristic elements are common (Yurtsev 1994). A variety of tall shrubs are found in riparian and sheltered areas. Wetlands show considerable peat development. Vegetation cover is continuous except on exposed ridges and areas of the Canadian Shield with minimal surficial deposits. Mean July temperature ranges from 9–12°C.

4. Discussion

The vegetation map presented here is the result of combining the capability of satellite imagery to display the spatial extent and current state of landcover attributes with expert knowledge and interpretation of ancillary data and published vegetation descriptions. By creating a composite using AVHRR data over two exceptionally warm and dry growing seasons, we created a snow-free and cloud-free image of the Canadian Arctic useful for depicting maximum greenness and for photo-interpretation and delineation of landscape units. Variation in the AVHRR CIR image allowed the differentiation of landscape units by degree of vegetation cover, by the degree of shrub versus graminoid cover and by the variation in bedrock when it is at the surface e.g. calcareous limestones have a lighter tone than the darker granitic bedrock (figure 6). In the Arctic, these landscape units typically have a dominant vegetation that can be determined by examination of the CIR imagery and knowledge of the climate, substrate chemistry and topography of each unit. This approach may be less feasible in areas where disturbance or land-use history can also strongly influence vegetation cover.

The map (figure 1) represents a new view of Canadian Arctic vegetation, with more detail and spatial precision than available from older maps (Bliss 1977) and more tundra land cover classes than available from recent satellite classifications of Canada (Cihlar and Beaubien 1998). The map can be seen as a starting point for generating and testing hypotheses on landcover and vegetation distribution and for summarizing vegetation attributes for the Canadian Arctic (Gould *et al.* 2001).

Information created in the development and interpretation of the landscape unit polygons for the Canadian vegetation map has been incorporated in a geobotanical GIS database developed at the 1:4 000 000 scale. Two advantages to linking both vegetation and ancillary data to a single set of landscape unit polygons are that these can be updated and vegetation cover or associated properties can be re-evaluated as new information is available through field work and/or publication and that this database can be made publicly available for web-based inquiry. A future expanded legend will take advantage of the geobotanical database generated in creating the vegetation map and contain information on dominant and subdominant communities on dry, mesic, wet, snowbed and riparian habitats within each mapped landscape unit. Additionally, a series of maps utilizing the database will be produced depicting ecological characteristics of each unit e.g. biomass, horizontal or vertical vegetation structure and primary productivity (Gould *et al.* 2001).

5. Conclusion

The mapping approach combining photo-interpretation of satellite imagery and interpretation of ancillary data and published vegetation description in order to map dominant growth forms and plant communities provides a new map product useful in the study of Arctic landscapes. Potential improvements include the addition of new field descriptions from previously undescribed sites and the incorporation of information from an automated classification of the satellite image using the same AVHRR data set. The compatibility of this analysis and map with the final CAVM circumpolar vegetation map and GIS database will increase the utility of the map and vegetation information.

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