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The Circumpolar Arctic vegetation map

Errata:

1) Page 276, the first sentence in the caption for Table 4 should read:
   Area of vegetation mapping units ($x10^3 km^2$)

2) Page 277, the first sentence in the caption for Table 5 should read:
   Area of subzones ($x10^3 km^2$)

3) Page 278, the first sentence in the caption for Table 6 should read:
   Area of mapping units ($x10^3 km^2$)

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The Circumpolar Arctic vegetation map

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Abstract

Question: What are the major vegetation units in the Arctic, what is their composition, and how are they distributed among major bioclimate subzones and countries?

Location: The Arctic tundra region, north of the tree line.

Methods: A photo-interpretive approach was used to delineate the vegetation onto an Advanced Very High Resolution Radiometer (AVHRR) base image. Mapping experts within nine Arctic regions prepared draft maps using geographic information technology (ArcInfo) of their portion of the Arctic, and these were later synthesized to make the final map. Area analysis of the map was done according to bioclimate subzones, and country. The integrated mapping procedures resulted in other maps of vegetation, topography, soils, landscapes, lake cover, substrate pH, and above-ground biomass.

Results: The final map was published at 1:7 500 000 scale map. Within the Arctic (total area = 7.11 × 106 km^2), about 5.05×10^6 km^2 is vegetated. The remainder is ice covered. The map legend generally portrays the zonal vegetation within each map polygon. About 26% of the vegetated area is erect shrublands, 18% peaty graminoid tundras, 13% mountain complexes, 12% barrens, 11% mineral graminoid tundras, 11% prostrate-shrub tundras, and 7% wetlands. Canada has by far the most terrain in the High Arctic mostly associated with abundant barren types and prostrate dwarf-shrub tundra, whereas Russia has the largest area in the Low Arctic, predominantly low-shrub tundra.

Conclusions: The CAVM is the first vegetation map of an entire global biome at a comparable resolution. The consistent treatment of the vegetation across the circumpolar Arctic, abundant ancillary material, and digital database should promote the application to numerous land-use, and climate-change applications and will make updating the map relatively easy.

Keywords: AVHRR; Bioclimate zone; Geographic information system; Plant functional type; Radiometer; Tundra.

Nomenclature: US Department of Agriculture Plants Database (USDA-NRCS 2004) for all plant names. Nomenclature of syntaxa is in accordance with Weber (2000).

Abbreviations: AVHRR = Advanced Very High Resolution Radiometer; CAVM = Circumpolar Arctic Vegetation Map; CIR = False colour-infrared; DCW = Digital Chart of the World; PAF = Panarctic Flora initiative.

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Introduction

The Circumpolar Arctic Vegetation Map (CAVM) began in 1992 at the First Circumpolar Arctic Vegetation Mapping Workshop in Boulder, Colorado (Walker 1995; Walker et al. 1994). The participants noted that the Arctic is increasingly recognized as a single geo-ecosystem with a common set of cultural, political, economic, and ecological issues. Previous vegetation maps of the circumpolar Arctic depicted a few broad arctic land-cover categories (Prentice et al. 1992; Steffen et al. 1996); however, it was noted that much more detail was needed for a variety of conservation studies, land-use planning, and education. In addition, changes associated with global warming and rapid land-use changes in the Arctic (Nelleman et al. 2001) added urgency to the creation of a new map.

Arctic vegetation is particularly sensitive to climate change, especially changes in summer temperature. With mean July temperatures close to freezing, a few-degree shift in summer air temperatures can cause a several-fold change in the total amount of warmth available for plant growth, resulting in major changes to vegetation structure, plant productivity, phytomass, species diversity, and shifts in altitudinal and zonal vegetation boundaries. Changes in vegetation biomass will have important consequences to many components of the arctic system including status of the permafrost, hydrological cycles, wildlife, and human occupation. There will also be important feedbacks to climate through changes in albedo and carbon fluxes (Anon. 2004a). Documenting the current distribution of Arctic vegetation is a first step toward monitoring these long-term changes.

In the ten years following the Boulder meeting, thirty-four vegetation scientists and mapping experts representing all six Arctic nations collaborated to produce the Circumpolar Arctic Vegetation Map. International CAVM workshops were held in Lakta, Russia, in 1994 (Walker & Markon 1996); Arendal, Norway, in 1996; Anchorage, Alaska, in 1997 (Walker & Lillie 1997); the Canadian Arctic in 1999 (Gonzalez et al. 2000); Moscow, Russia, in 2001 (Raynolds & Markon 2001), and Tromsø, Norway in 2004 (Daniëls et al. in press). The participants first reviewed the status of Arctic vegetation mapping in each country (Walker et al. 1995) and then agreed to a set of terminology and protocols for making the map in each country (Walker 1999; Walker et al. 2002). This information was then synthesized, first separately for North America and Eurasia, and then as one map for the whole Arctic (CAVM Team 2003).

Methods

Delimitation of the Arctic and common terminology

The first step was to define the spatial domain of the map. We followed the approach of the Panarctic Flora (PAF) initiative (Elvebakk et al. 1999), which considered the *Arctic* to be equivalent to the Arctic Bioclimate Zone, the area of the Earth with tundra vegetation (see definition of tundra below), an Arctic climate and Arctic flora, with the tree line defining the southern limit. It excludes tundra regions that lack an Arctic flora, such as the boreal oceanic areas of Iceland, the Aleutian Islands, and alpine-tundra regions south of the latitudinal tree line. The tree line for the CAVM was based on a variety of sources. In Alaska, we used the Ecoregions map of Alaska (Joint Federal State Land Use Planning Commission for Alaska 1973). In Canada, we used maps of tree line (Timoney et al. 1992) and the extensive personal experience of S. Zoltai, who had studied the Canadian boreal forest for several decades. In Russia, we relied on several vegetation maps at 1:2.5 million and 1:4 million scales and the personal communication of Natalia Moskalenko (Earth Cryosphere Institute) and Alexei Polezhaev (Zonal Research Institute of North-east Agriculture, Magadan).

Some terms commonly used on maps of Arctic vegetation have different meanings to those involved in map compilation; hence a glossary of terms is provided on the map for clarification. We adopted a definition of tundra from the *Glossary of Landscape and Vegetation Ecology for Alaska* (Gabriel & Talbot 1984): "Low-growing vegetation beyond the cold limit of tree growth, both at high elevation (alpine tundra) and at high latitude (arctic tundra)." This broad definition allowed us to use this physiognomic term for nearly all Arctic vegetation composed of various combinations of herbaceous plants, shrubs, mosses, and lichens. This is similar to the approach of Yurtsev, who considered the Arctic zone to be equivalent to the tundra zone; the Yurtsev floristic and phytogeographic subdivisions of the Arctic are the primary underlying framework for the map (Yurtsev 1994a, b). In naming the bioclimate subdivisions of the Arctic, we adopted the alphabetic designations (subzones A through E) in conformance with the approach used by PAF (Elvebakk et al. 1999).

Base map

The base map was a 1:4-million-scale false colour-infrared (CIR) image derived from the Advanced Very High Resolution Radiometer (AVHRR), a sensor on board the National Oceanic and Atmospheric Administration (NOAA) satellites (Fig. 1). The satellite

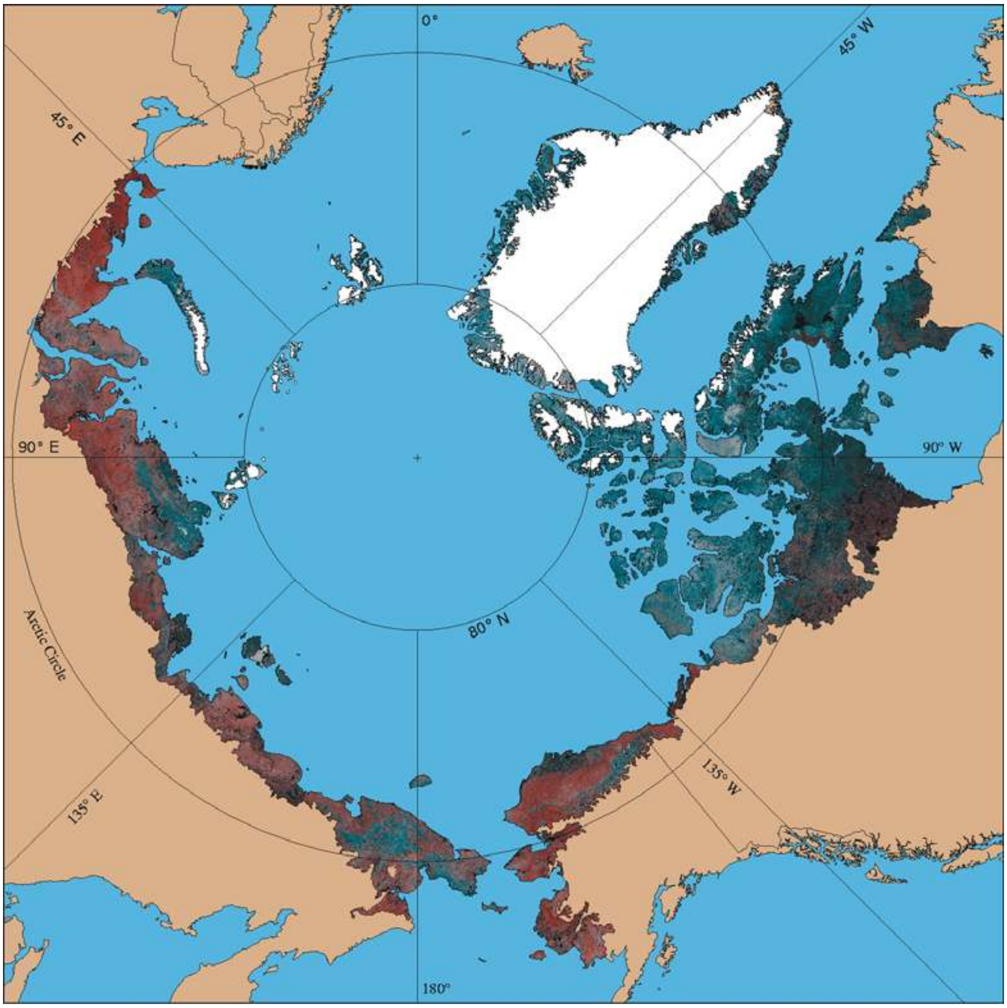


Fig. 1. False-colour infrared image of the circumpolar Arctic. Red areas represent greater amounts of green vegetation; blue and gray areas represent sparse vegetation; black areas represent fresh water, and white areas represent ice. Most boundaries on the vegetation map correspond to features that can be seen on the image when it was enlarged to 1:4 million scale. (Walker et al. 2002, with permission of Taylor and Francis Ltd.)

data were obtained and processed by the U.S. Geological Survey, Alaska Geographic Science Office, Anchorage, AK. The image is composed of 1 km × 1 km picture elements (pixels). Each pixel portrays the vegetation at the maximum greenness during two years of 10-day composite data (Anon. 2004b) between 11.07 and 30.08 in 1993 and 1995, which were two relatively warm years when summer-snow cover was at a minimum in the Arctic. Shorelines were adapted from the Digital Chart of the World (DCW), which is a 1:1 000 000-scale geographic data base developed for the U.S. Defense Mapping Agency (Anon. 1993). Small islands less than 49 km^2 were deleted from the DCW files, and the coastlines were simplified by removing arc vertices that were closer together than 5000 m. Glaciers, oceans and sea ice were masked out of the image using information from the DCW. The final image shows the Arctic at maximum greenness with minimum snow and cloud cover. This allowed delineation of areas that are predominantly covered by green vegetation (reddish areas in the false CIR image) as opposed to areas of sparse vegetation and barrens (blue or gray areas), wetlands and water (dark gray or black areas), or ice (white areas).

Source information

The task of making the map was assigned to different groups based in nine geopolitical regions (Canada, Greenland, Iceland, Norway including Svalbard, European Russia, West Siberia, East Siberia, Chukotka and Alaska). Local vegetation mapping experts in each region mapped their respective regions.

The first step was to collect and evaluate all the

Table 1. Vegetation properties in each bioclimate subzone. Modified from CAVM Team (2003). 1: Subzone; 2: Mean July temperatures based on Edlund (1996) and Matveyeva (1998). 3: Sum of mean monthly temperatures greater than 0°C, modified from Young (1971). 4, 5: Vertical and horizontal vegetation structure based on Chernov & Matveyeva (1997). 6: Codes for plant functional types: b = barren; c = cryptogam; cf = cushion or rosette forb; deds = deciduous erect dwarf shrub; dls = deciduous low shrub; dpds = deciduous prostrate dwarf shrub; g = grass; ehds = evergreen hemiprostrate dwarf shrub; nb = nonsphagnoid bryophyte; neds = nondeciduous erect dwarf shrub; npds = nondeciduous prostrate dwarf shrub; ns = nontussock sedge; of = other forb; ol = other lichen; r = rush; rl = reindeer lichen; sb = sphagnoid bryophyte; ts = tussock sedge. Underlined plant functional types are dominant. 7: Dominant vegetation unit (for species composition, see detailed unit descriptions in App. 2). 8: Total phytomass based on Bazilevich et al. (1997): above-ground + below-ground, live + dead. 9: Total phytomass and annual production based on Bazilevich et al. (1997): above-ground + below-ground. 10: Number of vascular species in local floras based mainly on Young (1971).

1.Subzone	2.Mean July Temp[1] (°C)	3.Summer warmth index (Thawing °C mo)	4.Vertical structure of plant cover	5.Horizontal structure of plant cover	6.Major plant plant functional types	7.Dominant vegetation unit (see detailed vegetation descriptions for species)	8.Total phyto-mass ($t\ ha^{-1}$)	9.Net annual production ($t\ ha^{-1}\ yr^{-1}$)	10.Number of vascular plant species in local floras
A	1-3	<6	Mostly barren. In favorable microsites, 1 lichen or moss layer <2 cm tall, very scattered vascular plants hardly exceeding the moss layer.	<5% cover of vascular plants, up to 40% cover by mosses and lichens.	b, g, r, cf, of, ol, c	Units 1 and 2	<3	<0.3	<50
B	4-5	6-9	2 layers, moss layer 1-3 cm thick and herbaceous layer, 5-10 cm tall, prostrate dwarf shrubs <5 cm tall.	5-25% cover of vascular plants, up to 60% cover of cryptogams.	npds, dpds, b, ns, cf, of, ol	Unit 4	5-20	0.2-1.9	50-100
C	6-7	9-12	2 layers, moss layer 3-5 cm thick and herbaceous layer 5-10 cm tall, prostrate and hemi-prostrate dwarf shrubs <15 cm tall.	5-50% cover of vascular plants, open patchy vegetation.	npds, dpds, b, ns, cf, of, ol, ehds* * in acidic areas	Unit 5	10-30	1.7-2.9	75-150
D	8-9	12-20	2 layers, moss layer 5-10 cm thick and herbaceous and dwarf-shrub layer 10-40 cm tall.	50-80% cover of vascular plants, interrupted closed vegetation.	ns, nb, npds, dpds, deds, neds, cf, of, ol, b	Units 7 and 9	30-60	2.7-3.9	125-250
E	10-12	20-35	2-3 layers, moss layer 5-10 cm thick, herbaceous/ dwarf-shrub layer 20-50 cm tall, sometimes with low-shrub layer to 80 cm.	80-100% cover of vascular plants, closed canopy.	dls, ts*, ns, deds, neds, sb, nb, rl, ol *in Beringia	Units 8 and 10	50-100	3.3-4.3	200 to 500

relevant maps and literature for the region (Walker et al. 1995). Map sources included remote sensing imagery, topography, hydrology, vegetation, surficial geology, bedrock geology, soils, percentage water cover, bioclimate subzones, and floristic provinces. All hard copy maps that were deemed useful for helping to define vegetation boundaries were then photographically reproduced to the 1:4 M scale of the base map, and the boundaries adjusted to match the AVHRR CIR image.

Bioclimate subzones. A fundamental problem was how to characterize the transitions in vegetation that occur across the Arctic's roughly 10 °C difference in mean July temperature (Table 1). Summer temperature plays a primary role in determining the dominant plant functional types, phytomass, production, and number of plants in regional floras, as well as the dominant vegetation that grows on a particular arctic landscape (Chernov & Matveyeva 1997). Different geobotanical traditions have divided the Arctic into bioclimatic regions using a variety of terminologies (Table 2). The CAVM adopted with some modification the approach used by the PAF initiative (Elvebakk et al. 1999). This approach divides the Arctic into five bioclimate subzones based on a combination of summer temperature and vegetation (Fig. 2a). Subzone A is the coldest and most barren subzone, and Subzone E is the warmest and most lushly vegetated. In North America, the Arctic has traditionally been subdivided into the High and Low Arctic (Bliss 1997). On the CAVM, subzones A, B, C compose the High Arctic with its open very low-statute vegetation mainly on mineral soils; subzones D and E compose the Low Arctic with generally closed vegetation on peat-rich soils. More full descriptions of the changes of vegetation along the bioclimate gradient are presented in several references (Alexandrova 1980; Bazilevich et al. 1997; Chernov & Matveyeva 1997; Edlund & Alt 1989; Elvebakk 1999; Matveyeva 1998; Walker 2000; Young 1971).

Floristic provinces. The Arctic has a relatively consistent core of plant species that occur around the circumpolar region, but there is also considerable east to west variation in the regional floras, particularly in subzones C, D,

Table 2. Other Arctic bioclimate zonation approaches. Modified from CAVM Team (2003).

	Russia			North America					Fennoscandia	
CAVM subzone	**Alexandrova (1980)**	**Yurtsev (1994)**	**Matveyeva (1998)**	**Polunin (1951)**	**Edlund (1990) Edlund & Alt (1989)**	**Bliss (1997)**	**Daniels et al. (2000)**	**Walker et al. (2002)**	**Tuhkanen (1986)**	**Elvebakk (1999)**
A	Northern polar desert Southern polar desert	High Arctic tundra	Polar desert	High Arctic	Herbaceous and cryptogam	High Arctic	Arctic herb	Cushion forb	Inner polar Outer polar	Arctic polar desert
B	Northern Arctic tundra	Arctic tundra: northern variant	Arctic tundra	Middle Arctic	Herb-prostrate shrub transition Prostrate shrub		Northern Arctic dwarf shrub	Prostrate dwarf shrub	Northern Arctic	Northern Arctic tundra
C	Middle Arctic tundra Southern Arctic tundra	Arctic tundra: southern variant	Typical tundra		Dwarf and prostrate shrub		Middle Arctic dwarf shrub	Hemi-prostrate dwarf shrub	Middle Arctic	Middle Arctic tundra
D	Northern sub-Arctic tundra Middle sub-Arctic tundra	Northern hypo-Arctic tundra		Low Arctic	Low erect shrub	Low Arctic	Southern Arctic dwarf shrub	Erect dwarf shrub	Southern Arctic	Southern Arctic tundra
E	Southern sub-Arctic tundra	Southern hypo-Arctic tundra	Southern tundra				Arctic shrub	Low shrub		Arctic shrub-tundra

and E. This variation is due to a number of factors, including different histories related to glaciations, land bridges, and north-south trending mountain ranges, primarily in Asia. These influences have restricted the exchange of species between parts of the Arctic. Russian geobotanists have described a set of floristic subdivisions based primarily on these floristic differences (Yurtsev 1994a). The map in Fig. 2b was adapted from the PAF project (Elvebakk et al. 1999) based largely on Yurtsev's approach.

Topography and landscapes. Elevation of landscapes and their physiographic character (mountains, hills, plains) are useful in determining the dominant vegetation. A topographic map was used to help develop a landscape map that showed broad physiographic regions. The topographic map was derived from the Digital Chart of the World (Anon. 1993). Colours on the topographic map in Fig. 2c correspond to broad 333-m elevation belts, which are equivalent to mean-July-temperature intervals of about 2 ˚C, or about the same temperature interval that separates the Arctic bioclimate subzones. The relationship between elevation and temperature corresponds to the ecological adiabatic lapse rate of – 6 ˚C per 1000 m elevation (Barry & Chorley 1987). An additional < 100-m belt delineates the extensive low flat plains of the Arctic. The landscape map (Fig. 2d) was derived from visual interpretation of the AVHRR false-CIR image supplemented with the topographic data and regional physiographic maps to show areas with plains, hills and mountains.

Lake Cover. Lake cover strongly affects the albedo, or reflectance, of the land surface over large areas of the Arctic and is useful for delineating extensive wetlands. Lake cover was based on the number of AVHRR water pixels in each mapped polygon, divided by the total number of pixels in the polygon (Fig. 2e). Since the imagery has a pixel size of 1 km^2, lake cover is underestimated for areas with many small lakes. No pixels were sampled within two pixels (2 km) of the coastline to avoid including ocean pixels.

Substrate pH. Differences in substrate chemistry have important effects on dominant plant communities and ecosystem properties. Some of the most important effects are related to soil pH, which governs the availability of essential plant nutrients and creates distinctive plant communities (Edlund 1982; Elvebakk 1982; Walker et al. 1998). Soils in the circumneutral range (pH 5.5-7.2) are generally mineral rich, 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). The latter often have unique assemblages of endemic plant species. There are no circumpolar base maps that show this essential difference in substrate chemistry, so the map in Fig. 2f was derived from a wide variety of available sources including soil, surface-geology, and bedrock-geology maps, and from spectral patterns that could be recognized on the AVHRR base image. For example, limestone mountains are usually barren and have a white colour on the image, whereas most other bedrock types have dark-coloured minerals

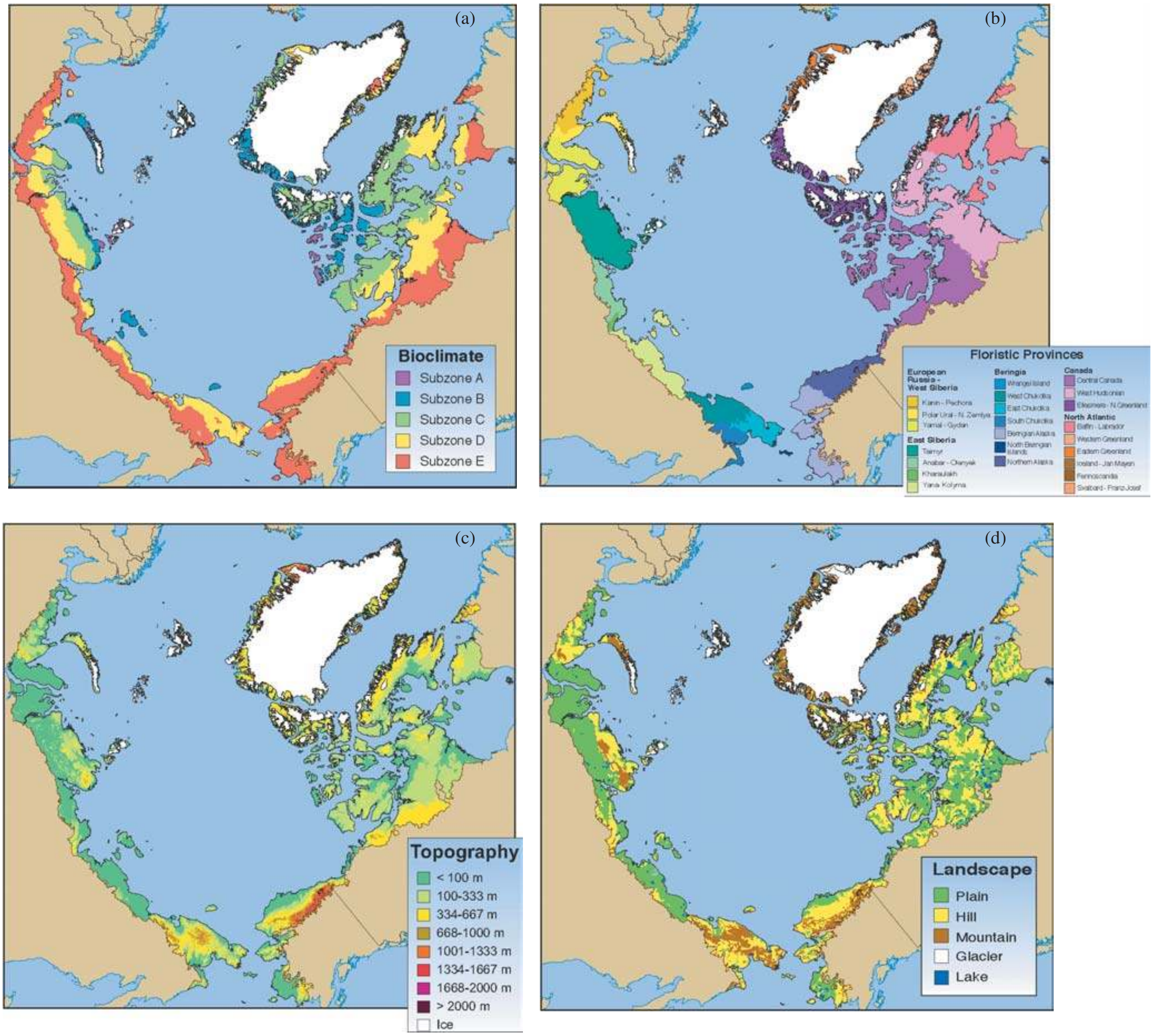
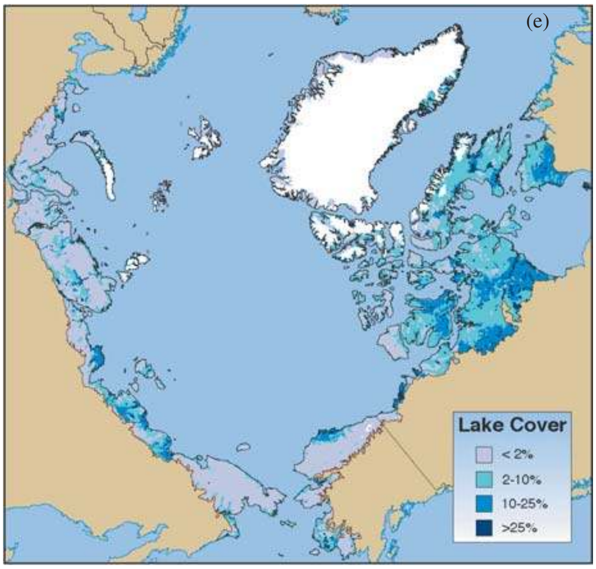


Fig. 2. Maps of geobotanical variables in the CAVM GIS database. **a.** Arctic bioclimate subzones. Based on Yurtsev (1994a) and Elvebakk (1999) with modification. **b.** Floristic provinces and subprovinces (based on Yurtsev 1994a with modification). **c.** Topography of the Arctic; 333-m elevation intervals to show approximate 2˚C temperature shifts in the mountainous areas. Areas below 100 m are separated to show low elevation plains. Data are at approximately 1-km spacing, taken from the GTOPO30 global digital elevation model (DEM) (CAVM Team 1993). **d.** Landscapes of the Arctic. **e.** Lake cover in the Arctic. **f.** Substrate pH in the Arctic. **g.** Maximum NDVI for the Arctic. Calculation of NDVI is discussed in the text. The NDVI values were grouped into eight classes that meaningfully separate the vegetation according to biomass. Red and orange areas in the NDVI map on the left are areas of shrubby vegetation with high biomass, and blue and purple areas are areas with low biomass. (Modified from CAVM Team 2003.)

and/or extensive lichen cover. Spectral differences have also been noted on plains and hills, where the vegetation on acidic or non-acidic soils have distinctive reflectance characteristics (Walker et al. 1995).

NDVI map. An NDVI map was prepared from the baseline AVHRR imagery and was used to delineate areas with high shrub cover, primarily in subzones D and E (Walker et al. 2003) (Fig. 2g). The NDVI, an index of vegetation greenness, is calculated by the equation: *NDVI = (NIR – IR)/(NIR + IR),* where *R* is the spectral reflectance in channel 1 (red band, 0.58 to 0.68 μm) where chlorophyll absorbs maximally, and *NIR* is the reflectance in channel 2 (near-infrared band, 0.73-1.1 μm)



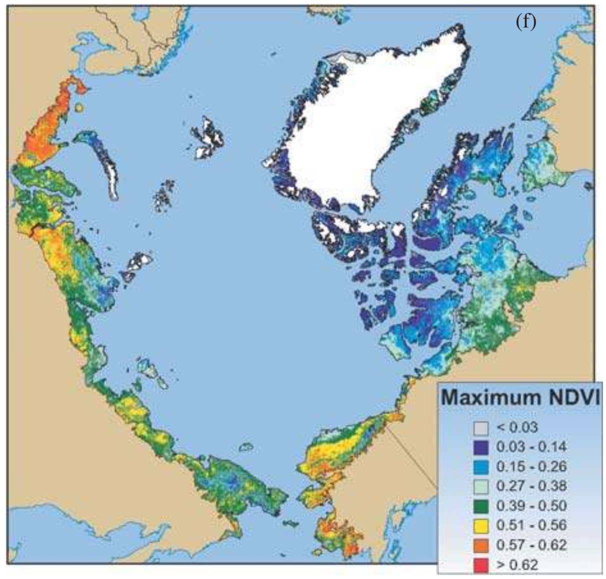
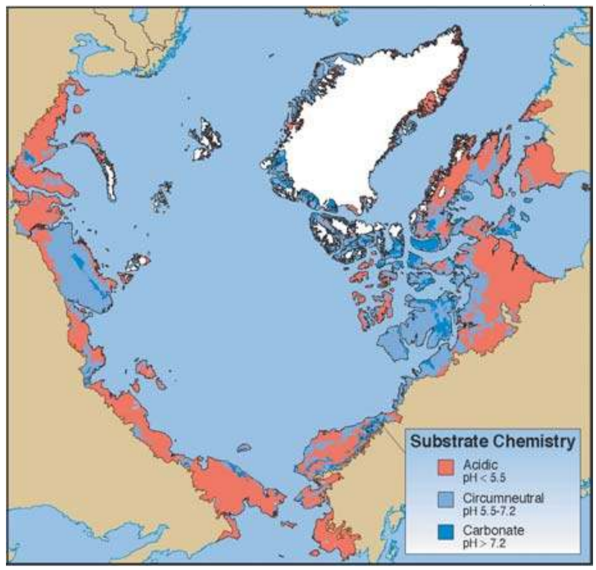


Fig. 2, cont.



where reflectance from the plant canopy is dominant (Markon et al. 1995). Tundra areas with NDVI values exceeding 0.57 usually indicated the presence of dense shrub cover.

Mapping procedure

An integrated mapping procedure based on image interpretation was used for drawing the map polygons. An automated remote-sensing classification procedure was considered; however, many mapping units had similar spectral properties, and often the spectral properties of single classes varied depending on their geographic and ecological setting. Hence, our approach relied mostly on literature, expert knowledge, and close examination of the spaced-based image (Walker 1995). Previous studies had shown that in most regions the dominant vegetation of large arctic landscapes can be predicted based on multi-spectral satellite imagery, and knowledge of other factors, including summer temperature regime (bioclimate subzone), the regional flora, bedrock geology, soil chemistry, and prevailing drainage conditions (Walker 2000). The actual method combined elements of several landscape-guided mapping techniques (Dangermond & Harnden 1990; Melnikov 1998; Walker et al. 1980; Zonneveld 1988).

The mapping was done by drawing polygon boundaries on frosted mylar sheets overlaid on the AVHRR imagery. Boundaries were drawn around areas of homogeneous colour and texture, guided by boundaries from the other source maps. Most boundaries on the map follow physiographic boundaries, such as glacial boundaries, or the boundary between hills and plains, or floodplains and uplands.

Several areas of the Arctic had good vegetation maps at the start of this mapping effort, including much of Russia, Svalbard, and Iceland; for these areas, map boundaries were adjusted to fit features on the AVHRR imagery.

The minimum map polygon size was defined as 3.5 mm on a side or 2 mm across for linear features at 1: 4 M scale. This translated to 14 km on a side or 196 km^2, and 8 km across for linear features. In practice however, smaller polygons occurred in some areas of small islands, fjords and glaciers.

The final result was a single ARC/INFO coverage, where each polygon was coded with the following attributes: dominant vegetation, bioclimate subzone, floristic subprovince, landscape type, lake cover, and substrate chemistry. Elevation and maximum NDVI were in separate raster coverages at 1-km pixel size.

Summary tables of dominant plant communities

Vegetation for most of the Arctic, particularly Canada, Greenland, and Chukotka, had not been mapped at the 1: 4 M scale previously, so vegetation information had to be inferred from known relationships between plant communities and terrain features that were visible on the small-scale satellite-derived image. The dominant plant community type was derived from a look-up table that listed the expected plant communities for each combination of floristic subprovince, bioclimate subzone, soil reaction class, and topographic position. Tables of dominant plant community types were made for most regions of the map based on the vegetation literature from each region. Studies based on the Braun-Blanquet

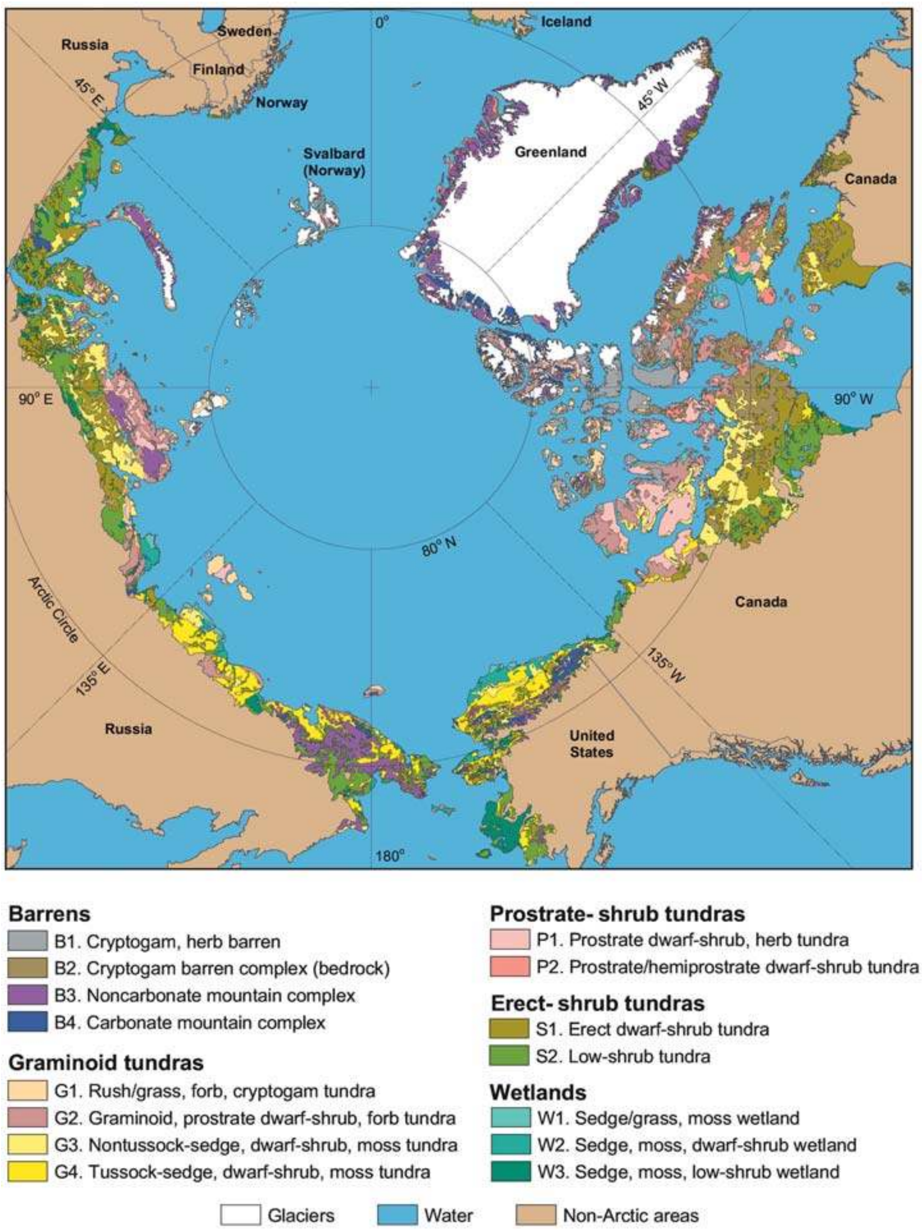


Fig. 3. Circumpolar Arctic vegetation. This is a generalized version of the CAVM (CAVM Team 2003). The published map has more detail in the mountainous areas and contains an expanded legend (see App. 2). The map is available in the on-line version of this paper.

approach (Weber et al. 2000) were most valuable for these tables, but were not available for all areas of the Arctic, so a variety of nomenclature formats for plant communities appear in the tables. Separate tables were made for each floristic subprovince within a given region. The columns of the tables contained the plant communities on acidic and non-acidic substrates within each bioclimate subzone. The rows of the table contained the plant communities in each of five topographic situations (dry exposed sites, mesic zonal sites, wet sites, snow beds, and stream sides). Also listed in the tables were literature sources for each plant community type. These tables are the underlying foundation for the map. Our original intent was to show the dominant plant communities on the map; however, it soon became clear that the resulting map would be far too complex; i.e., over 400 plant community types were assembled in the tables. Furthermore, not all areas of the map had the same level of plant-community information; consequently, the communities were grouped into the 15 physiognomic-level categories based on dominant plant functional types. The summary tables can be used to derive more detailed plant-association-level maps for each of the Arctic regions as has been done for Arctic Alaska (Raynolds et al. in press). See App. 1 for an example summary table from the Northern Alaska Floristic Province, Subzone C.

The final map

The final map was published at 1:7.5 M scale by the US Fish and Wildlife Service and the Circumpolar Arctic Flora and Fauna (CAFF) project (Fig. 3) (CAVM Team 2003). The map is 36 × 48 inches (91 × 121 cm), printed on both sides. The front side of the map displays the main vegetation map with an abbreviated legend, glossary, and photographs of the mapping units. The back has detailed vegetation descriptions and nine supplementary maps (CIR image, bioclimate subzones, elevation, landscapes, substrate pH, floristic provinces, lake cover, NDVI, and phytomass), supplementary tables and literature cited. The map is available on either glossy paper or YUPO synthetic paper and can be ordered (Anon. (Alaska Geobotany Center) 2005). A full-sized PDF file can be downloaded from the *JVS* on-line version of this paper.

Mapping units

Mapped polygons at 1:7.5 million scale contain many vegetation types. The map often portrays the dominant *zonal* vegetation within each mapped polygon. Zonal sites are areas where the vegetation develops under the prevailing climate, uninfluenced by extremes of soil moisture, snow, soil chemistry, or disturbance, and are generally flat or gently sloping, moderately drained sites, with fine-grained soils (Vysotsky 1927). Large areas of azonal vegetation that are dependent on specific soil or hydrological conditions, such as mountain ranges and large wetlands were also mapped.

The legend contains five broad physiognomic categories: B = barrens; G = graminoid-dominated tundras; P = prostrate-shrub-dominated tundras; S = erect-shrub-dominated tundras; W = wetlands. These are subdivided into 15 vegetation mapping units with numeric codes added to the alphabetic codes. The mapping units are named according to dominant *plant functional types* except in the mountains where complexes of vegetation are named according to the dominant bedrock (Carbonate and Noncarbonate Mountain Complexes). The plant functional types are based on a variety of criteria including growth form (e.g. graminoids, shrubs), size (e.g. dwarf and low shrubs), and taxonomical status (e.g. sedges, rushes, grasses). The legend takes into special consideration the stature of woody shrubs, which is a major diagnostic feature of zonal vegetation in the Arctic (Edlund & Alt 1989; Walker et al. 2002; Yurtsev 1994b).

Very steep bioclimate gradients occur in mountains, so these areas are mapped as complexes of elevation belts. Mountainous areas of the map are shown with *hachures;* the background colour indicates the nature of the bedrock, and the colour of the hachures indicate the bioclimate subzone at the base of the mountains. A more full description of the map legend protocols and complete descriptions of the vegetation units, including photographs, locations of the units, dominant plant taxa, and representative syntaxa are provided in App. 2. An example of the level of information in the legend descriptions is provided in Table 3.

Area analysis of the map

Area analysis of the map was performed using ARC/INFO software. The total area of the Arctic as delineated on the CAVM is 7.11×10^6 km^2. This is comparable to the area reported by Bliss & Matveyeva (1992) (i.e. 7.57×10^6 km^2), who included several areas that are not part of the Arctic Bioclimate Zone, such as the Aleutian Islands, the southern part of Iceland, and the northern Kola Peninsula. Glaciers, including areas with nunataks (non-vegetated mountain peaks rising above the surrounding glaciers), cover 29% of the Arctic zone, mainly in Greenland, leaving about 5.05×10^6 km^2 of the Arctic that is vegetated (Table 4). Of the vegetated portion of the Arctic, ca. 26% is dominated by erect-shrub

Table 3. Example mapping unit description from the CAVM. A modified version of the full legend is in App. 2.

Barrens (B)

B1. Cryptogam, herb barren (Fig. App. 2.3a, see photos of mapping units in on-line supplement to this article).

This unit occurs in dry to wet barren desert-like landscapes mainly in Subzone A and on some coarse-grained, often calcareous sediments in subzones B and C. It is characterized by sparse (2-40%) horizontal plant cover and very low vertical structure (generally < 2 cm tall) with a single layer of plants where they occur. Dry herb barrens composed of few scattered vascular plants are present over much of the landscape. Snow-flush communities are often a conspicuous component forming dark streaks on the otherwise barren lands, composed largely of bryophytes and cryptogamic crusts. In upland areas, vascular plant cover is generally very sparse (< 2%), consisting mainly of scattered individual plants often in crevices between stones or small (< 50 cm diameter) cryoturbated polygons. Sedges (Cyperaceae), dwarf shrubs, and peaty mires are normally absent.

Dominant plants: (Note superscripts denote plants more or less restricted to acidic (a) or nonacidic (n) substrates.) The most common vascular plants are cushion forbs (*Papaver dahlianum* ssp. *polare*, *Draba* spp., *Potentilla hyparctica*[a], *Saxifraga oppositifolia*[n]) and graminoids (*Alopecurus alpinus*, *Deschampsia borealis/brevifolia*, *Poa abbreviata*, *Puccinellia angustata*, *Phippsia algida*, *Luzula nivalis*[a], *L. confusa*[a]), lichens (*Caloplaca*, *Lecanora*, *Ochrolechia*, *Pertusaria*, *Mycobilimbia*, *Collema*, *Thamnolia*, *Cetraria*, *Flavocetraria*, *Cetrariella*, *Stereocaulon*), mosses (*Racomitrium*, *Schistidium*, *Orthothecium*[n], *Ditrichum*[n], *Distichium*[n], *Encalypta*, *Pohlia*, *Bryum*, *Polytrichum*), liverworts (e.g. *Gymnomitrion*, *Cephaloziella*), and cyanobacteria.

Representative syntaxa: Communities of the classes *Thlaspietea rotundifolii* (e.g. *Papaveretum dahliani*) and *Salicetea herbaceae* (e.g. *Phippsietum algidae-concinnae*).

tundras (units S1 and S2); 18% is peaty graminoid tundras (units G3 and G4); 13% is mountain complexes (Units B3 and B4); 12% is barrens (units B1 and B2); 11% is graminoid tundras on mineral soils (units G1 and G2); 11% is prostrate-shrub tundras (units P1 and P2); and 7% is wetlands (units W1, W2, W3, and lakes).

Subzone analysis

The subzones cover progressively more area as one moves south. Subzone A covers the smallest area (2% of the non-glacier Arctic), and Subzone E is the largest (36%) (Table 4). The major trends toward the south are less barrens and glaciers, and more wetlands, lakes, and vegetation types with taller shrubs and dense moss mats, particularly in subzones D and E.

Subzone A is predominantly glaciers, including glacier areas with nunataks (48% of the subzone). Cryptogam, forb barrens (B1), cover 24%, and there are also relatively large well-vegetated areas with rush/grass cryptogam tundra (G1, 19%).

Subzone B also has a large cryptogam, forb barren component (B1, 24%) and is the most mountainous subzone (24% barren mountain complexes, 12% glaciers). Vegetated areas of Subzone B have a mixture of rush/grass cryptogam tundra (G1, 17%), prostrate dwarf-shrub, herb tundra (P1, 11%), and graminoid, prostrate dwarf-shrub, forb tundra (G2, 9%).

Table 4. Area of vegetation mapping units ($\times 10^6$ km^2) within the bioclimate subzones, the Greenland ice sheet, and the whole Arctic. The Greenland ice sheet was not placed in a subzone, except for portions of the glacier that had numerous nunataks (mountain peaks that rise above the surrounding glacier). Bolded values are the designated zonal types within each subzone. In subzones D and E, there are two zonal types. In this treatment, G3 and G4 were considered zonal in loess areas with ice-rich permafrost, whereas S1 and S2 were zonal in areas with better drained soils.

	Subzone A		Subzone B		Subzone C		Subzone D		Subzone E		Grnlnd Ice sheet		TOTAL		
Map Unit	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	% Arctic	% Nonglac. Arctic
B1	48	24	122	24	55	4							225	3.2	4.5
B2			1	0.2	181	14	164	10	26	1			372	5.2	7.4
B3	13	7	69	13	146	11	165	11	146	8			539	7.6	10.7
B4			51	10	19	1	5	1.0	58	3			132	1.9	2.6
G1	**37**	**19**	89	17	15	1		0					141	2.0	2.8
G2			45	9	**300**	**23**	19	1	65	4			429	6.0	8.5
G3					35	3	**399**	**25**	134	7			569	8.0	11.3
G4							100	6	**236**	**13**			336	4.7	6.7
P1	0.3	0.2	**56**	**11**	213	16	129	8	1	0.3			399	5.6	7.9
P2					108	8	31	2					140	2.0	2.8
S1					3	0.7	**257**	**16**	429	23			689	9.7	13.7
S2					2	0.5	62	4	**548**	**30**			613	8.6	12.1
W1	2	1	15	3	81	6	3	0.5					101	1.4	2.0
W2							135	9	1	0.3			136	1.9	2.7
W3									159	9			159	2.2	3.2
Glacier areas with nunataks	14	7	2	0.3	12	1	62	4					89	1.3	0.0
Other glaciers	80	41	61	12	122	9	12	1	2	0.3	1787	100	1975	27.8	0.0
Lakes			1	0.2	8	1	26	2	32	2			67	0.9	1.3
TOTAL	195	100	511	100	1301	101	1570	101	1837	101	1787	100	7110	100.0	100.0
% of the Arctic	2.7		7.2		18.3		22.1		25.8						
% of nonglacier Arctic	2.0		8.9		23.1		29.6		36.4						
Total nonglacier area	5046														

In Subzone C, graminoid, prostrate dwarf-shrub, forb tundra (G2, 23%) is most abundant, followed by prostrate dwarf-shrub, herb tundra (P1, 16%), cryptogam barren complexes of the shield areas (B2, 14%), mountain complexes (B3 and B4, 12%), glaciers (10%), prostrate/ hemiprostrate dwarf-shrub tundra (P2, 8%), and wetlands (W1, 6%).

Subzone D is much more vegetated than subzones A, B, or C, with large areas of non-tussock sedge, dwarf-shrub, moss tundra (G3, 25%). Erect dwarf-shrub tundras (S1) cover 16%, mountain complexes (B3 and B4) 12%, wetlands (W2 and lakes) 11.5%, and barren shield areas (B2) 10%.

Subzone E is the most densely vegetated subzone with over half of the subzone covered by erect shrub vegetation (S1 23%, and S2 30%). Tussock-sedge, dwarf-shrub, moss tundra (G4) covers 13%, wetlands (W3 and lakes) 11.3%, and mountain complexes (B3 and B4) 11%.

Mapping units designated in the legend as zonal vegetation (bold numbers in Table 4) are not always the most abundant mapping units within their respective subzones. For example, in the High Arctic, mapping unit G1, rush/grass, forb, cryptogam tundra, is the designated zonal vegetation in Subzone A, and mapping unit P1, prostrate dwarf-shrub, herb tundra, is the zonal vegetation in Subzone B. Mapping unit G1 is the second most abundant type in Subzone A with 19% cover, and mapping unit P1 is only the fourth most abundant type in Subzone B with 11% cover. Extremely barren habitats (mapping unit is B1, cryptogam, herb barrens) are abundant in both subzones, covering 24% of the non-glacier portion of both subzones. There is, in fact, considerable debate regarding just what are the zonal types in these subzones. Yurtsev (1994) argued that the more mesic sites should be considered the zonal situation, but it could also be argued that the barren wind-swept areas are the typical zonal habitats within both subzones, and that the more mesic sites are somewhat protected and therefore azonal.

Another zonal controversy involves the vegetation occurring on acidic versus non-acidic bedrock. For example, mapping unit P1, prostrate dwarf-shrub tundra, herb tundra, is dominant over much of the High Arctic in areas with circum-neutral to alkaline soils; whereas, mapping unit P2, prostrate/hemi-prostrate dwarf-shrub tundra (dominated by *Cassiope tetragona*), is dominant in circum-neutral to acidic areas with granite or gneiss bedrock, such as much of the shield areas of Canada and much of Greenland and Svalbard (Edlund 1982; Elvebakk 1982; Walker 2000). At present, it is not clear which of these types should be considered the zonal vegetation in Subzones B and C. Some authors argue that soil and vegetation developing on different bedrock types will have their own zonal patterns (Razzhivin 1999; Sokolov et al. 1994).

Yet another zonal issue involves vegetation on ice-rich permafrost. In subzones D and E, two zonal types are designated in each subzone. The dominant vegetation in much of northeastern Russia and Alaska is a result of wet soil moisture conditions that result from near-surface permafrost. Mapping units G3 (non-tussock-sedge, dwarf-shrub, moss tundra) and G4 (tussock-sedge, dwarf-shrub, moss tundra (tussock tundra)) are considered zonal in areas of subzones D and E with fine-grained loess-derived soils and ice-rich permafrost; whereas mapping units S1, erect dwarf-shrub tundra, and S2, low-shrub tundra, are zonal in other areas of the circumpolar region. Some authors argue that these wet soils of tussock tundra are azonal and one needs to look elsewhere in the landscape to find zonal vegetation (e.g., gentle slopes without near-surface ice-rich permafrost) (Razzhivin 1999). The CAVM Team was unable to resolve all these issues in a fully consistent manner, but the map has helped vegetation scientists in Eurasia and North America to recognize and resolve major terminology conflicts and problems in defining zonal conditions within different parts of the Arctic.

Country analysis

Table 5 shows the amount of each subzone within each country. The total areas (including glaciers) are listed separately from the portion that is not glacier-covered (i.e. the vegetated part). The amount of each mapping unit within each country is presented in Table 6.

Canada contains the largest portion of the Arctic (36%), followed by Greenland (30%), Russia (26%),

Table 5. Area of subzones (× 10^6 km^2) within the Arctic countries. Area summaries are for total area in the Arctic portion of each country (including glaciers) and the nonglacier part (the terrestrial vegetated portion).

	CANADA				GREENLAND				ICELAND				NORWAY				RUSSIA				UNITED STATES				TOTAL			
	Total		Nonglac. Part		Total		Nonglac. Part		Total		Nonglac. Part		Total		Nonglac. Part		Total		Nonglac. Part		Total		Nonglac. Part		Total		Nonglac. Part	
Subzone	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%
A	53	2	51	2	4.5	0.2	4	1.3					44	69	6	23	93	5	39	2			0		195	3	100	2
B	246	10	209	9	126	6	100	29.7					8	13	8	33	130	7	130	7			0		511	7	447	9
C	955	37	828	35	97	5	90	26.7					9	14	9	34	234	13	234	13	7	1	7	1	1301	18	1167	23
D	689	27	686	29	184	9	113	33.8							0	0	622	33	622	34	76	16	76	16	1570	22	1496	30
E	610	24	610	26	28	1	28	8.5	6.8	100.0	6	100.0	3	4	3	11	787	42	787	43	405	83	403	83	1839	26	1837	36
Greenland Ice Cap					1697	79																			1697	24		
TOTAL	2553	100	2384	100	2137	100	335	100.0	6.8	100	6	100.0	63	100	26	100	1866	100	1811	100	487	100	486	100	7113	100	5048	100

Table 6. Area of mapping units ($\times$ 106 km^2) within the Arctic countries and the total Arctic.

Mapping Unit	CANADA		GREENLAND		ICELAND		NORWAY		RUSSIA		USA		TOTAL	
	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%
B1	207	8	3	0.1			6	10	9	0.5			225	3.2
B2	371	15											371	5.2
B3	46	2	224	10					233	12	36	7	539	7.6
B4	36	1	33	2					20	1	43	9	132	1.9
G1	80	3					2	4	58	3			141	2.0
G2	269	11					0.4	0.6	158	8	1	0.1	429	6.0
G3	309	12							223	12	37	8	569	8.0
G4	29	1							177	9	131	27	336	4.7
P1	288	11	21	1			3	5	87	5			399	5.6
P2	107	4	22	1			6	9	3	0.2	1	0.3	140	2.0
S1	351	14	27	1					263	14	49	10	689	9.7
S2	150	6	3	0.1	6	89	3	4	393	21	58	12	613	8.6
W1	50	2					5	8	39	2	7	1.4	101	1.4
W2	27	1							65	3	45	9	136	1.9
W3	19	1							68	4	72	15	159	2.2
Glac. w/nunataks	16	1	59	3			14	23					89	1.3
Other glaciers	153	6	1742	81	1	9	23	37	55	3	1	0.2	1975	27.8
Lakes	47	2	2	0.1					14	0.8	4	0.8	67	0.9
TOTAL	2553	100	2137	100	7	97	63	100	1866	100	485	99	7110	100.0
% of Arctic		36		30		0.1		1		26		7	100	

Alaska (7%), Norway (1%), and Iceland (0.1%) (Table 6). Canada also has by far the largest amount of terrain in the High Arctic (subzones A, B, and C) with 1.25 $\times$ 10^6 km^2 or about 63% of the total circumpolar High Arctic. Canada has 1.3 $\times$ 10^6 km^2 in the Low Arctic (subzones D and E), second only to that of Russia, which has 1.4 $\times$ 10^6 km^2. The most abundant vegetation types in the Canadian Arctic are the barren types B1, B2, B3, and B4, which make up a total of 26% of arctic Canada. The barren complexes of the Canadian Shield (B2) cover 15% of the Canadian Arctic, whereas mountains (B3 and B4) cover only 3%. Graminoid types are split about equally between the types on mineral soils (G1 and G2, 14%) and those on peaty soils (G3 and G4, 13%). Prostrate shrub tundras (P1 and P2) cover 15%, erect shrublands (S1 and S2) cover 20%, and wetlands (W1, W2, W3, and lakes) cover 7% of arctic Canada.

Greenland is predominantly glaciers (84%), with the central ice sheet covering 79% of the island. Mountain complexes (B3 and B4) cover 12%, and the non-glacier portion of Greenland is about equally divided between the Low and High Arctic. The most abundant non-mountainous mapping units in Greenland are prostrate dwarf-shrub tundras (P1 and P2) and erect dwarf-shrub tundra (S1), each covering about 1% of the country.

Only the northernmost part of Iceland is within the Arctic (Subzone E), and is dominated by low-shrub tundra (89%).

Norway has two distinctly different components of the Arctic; the islands of Svalbard are entirely in the High Arctic, whereas the coastal strip of northern Norway is entirely in the Low Arctic. Svalbard is in subzones A, B, and C, and is dominated by glaciers (60%). Vegetation in the non-glacier areas is a mix of prostrate dwarf-shrub tundras (P1 and P2, 14%), cryptogam, forb barrens (B1, 10%), and wetlands (W1, 8%). The northern strip of continental Norway is predominantly low-shrub tundra (S2).

Russia's large arctic landmass is nearly as diverse as Canada's, but unlike Canada, 75% is in the Low Arctic (subzones D and E) and much of this is dominated by shrub tundra (S1 and S2, 35%). Russia has 64% of the total low-shrub tundra in the Arctic, much of it concentrated in European Russia and the *Pinus pumila* stlaniks of southern Chukotka. Other abundant vegetation types in Russia include mountain complexes concentrated in Chukotka, northern Taimyr Peninsula, and Novaya Zemlya (B3 and B4, 13%); non-tussock-graminoid, dwarf-shrub, moss tundra concentrated in Taimyr Peninsula (G3, 12%); wetlands (W1, W2, W3, and lakes, 9.8%); and tussock-sedge, dwarf-shrub, moss tundra (G4, 9%).

Most of arctic Alaska, except for a narrow strip along the northern coast, is in the Low Arctic (subzones D and E). The most abundant vegetation types in Alaska are wetlands concentrated in the Yukon-Kuskokwim River delta and the Arctic Coastal Plain (W1, W2, W3, and lakes, 26.2% of arctic Alaska). Alaska has 31% of the total Arctic wetlands, excluding lakes. Other large mapping units in Alaska include tussock-sedge, dwarf-shrub, moss tundra concentrated in the Arctic Foothills of northern Alaska and the central portion of the Seward Peninsula (G4, 24%) and mountain complexes concentrated in the Brooks Range of northern Alaska (B3 and B4, 16%).

Discussion

Comparison with other vegetation maps of the Arctic

Previous maps showing the vegetation of the Arctic have generally shown only a few broad vegetation zones (Alexandrova 1980). The only other map of the entire Arctic at a comparable scale is the vegetation map in the Russian *Arctic Atlas* (1:10 000 000 scale) (Gribova & Tichomirov 1985). The legend of that map is hierarchically arranged with four major zones (high arctic tundras, arctic tundras, northern tundras, and southern tundras). Below the zones are 29 arctic mapping units described with a combination of dominant plants and geographic location. A similar approach was followed for the arctic portion of the recent *Map of the natural vegetation of Europe* at 1: 2.5 M scale (Bohn et al. 2000), which divides the Arctic into five distinct zonal mapping units: arctic polar deserts, northern arctic tundras, middle arctic tundras, southern arctic tundras, and arctic shrub tundras. These are further subdivided into geographic units that identify specific dominant plant communities in major floristic sectors. The European map has a total of two arctic polar desert community types and 33 arctic tundra community types.

The CAVM departs from these previous efforts by naming the units at the highest level according to the physiognomic structure. Basing the names and colors of the mapping units on dominant plant functional types and not on bioclimatic boundaries provides more insight to the composition of these units, and gives a better impression of the mosaic of major structural types within the subzones. The information regarding details of the structure and plant-growth-form composition of the vegetation units within the subzones (Table 1) should aid in modelling response to climate change. More details regarding the composition of the typical plant communities in each bioclimate subzone of each floristic province is organized in look-up tables and can be used to make more detailed plant-community-level maps, as has been done recently for Arctic Alaska (Raynolds et al. in press). The digital map files can be easily updated as new information becomes available from the less studied areas of the Arctic.

Zonal vegetation within the subzones

The map has already generated a reassessment of the concept of zonal vegetation within the Arctic. One major issue is the accuracy of the bioclimate subzone boundaries (Fig. 2). The boundaries are based on very sparse climate data from the Arctic. The High Arctic has especially few climate data points, nearly all of which are coastal. More accurate maps of land-surface temperatures that portray maritime-continental influences and elevation would help to more accurately delineate the boundaries of the bioclimate subzones.

It is also often not clear exactly what the zonal vegetation in a given subzone should be. As noted above, in subzones A and B it is not obvious if the zonal situation is represented by extremely barren areas (mapping unit B1) or more mesic sites (mapping unit G1). In the Low Arctic, other issues arise as a result of fine-grained soils with ice-rich permafrost (Razzhivin 1999). Precipitation is also important. For example, dense thickets of tall-shrub tundra are common in the European Russia portion of Subzone E and in the Yukon-Kuskokwim (Y-K) delta of Alaska (note the high NDVI of the tundra in the western portion of the Russian Arctic and the Y-K delta in Fig. 2g). This could be due to greater summer precipitation or less ice-rich permafrost in these areas or both. Substrate chemistry (discussed earlier) (Elvebakk 1982) and the age of landscapes are particularly important factors affecting arctic vegetation. Landscape evolution proceeds very slowly in the Arctic, and different aged glacial surfaces within the same climate regime often have distinctly different vegetation (Walker et al. 1995). This is a particularly important issue in mapping northern Canada. The combined effects of these variations and others are often subtle and at present are not fully understood. The map presented here is the first attempt to integrate all these factors in a map for the whole Arctic, and the map will undoubtedly change as more field information becomes available and our ecological understanding improves.

Relevance to global change research

Over the past two decades, the Arctic has seen the largest temperature increases on the globe, varying from 0.33 °C per decade over the sea ice to 1.06 °C per decade over North America (Comiso 2003). Not all of the Arctic, however, is warming; higher elevations of the Greenland ice sheet, northern Novaya Zemlya, Severnaya Zemlya, and the New Siberian Islands, cooled over the same period. Predictions of vegetation change will need to combine these climatic differences with geobotanical information from maps such as the CAVM. The effects on land must also be linked to changes over the oceans. Terrestrial areas of the Arctic could be strongly influenced by interdecadal cyclical patterns of sea-ice extent (Proshutinsky & Johnson 1997; Thompson & Wallace 1998). It will be important to consider the transient nature and spatial heterogeneity of sea ice as it melts over the next 100 years or so. Our map also highlights the vulnerability of some areas of the Arctic to global change. For example, Subzone A is already quite small, covering 2% of the non-glacier Arctic, and located primarily on islands at the cold end of the climate gradient. If the climate warms, the current vegetation distribution could change, limiting Subzone A to new land exposed by melting glaciers.

It is also likely that the Arctic will see large changes in land use over the next several decades (Nelleman et al. 2001). Although the scale of the map presented here is not an appropriate baseline for detailed analysis of local changes associated with development, it will serve as a baseline against which to measure changes over large areas such as major transportation corridors, or to examine the regional context of large construction projects.

Conclusions

The map presented here is the first vegetation map of an entire global biome at a comparable resolution. The map provides a broad view of the vegetation of the whole Arctic through legend descriptions, photographs, lists of major syntaxonomic groups, and supplementary maps. The consistent treatment of the vegetation across the circumpolar Arctic makes it appropriate for numerous land-use management, and climate-change applications. It has already helped vegetation scientists in Eurasia and North America to recognize and resolve major terminology conflicts between the two regions. The map is a step in developing an international approach to describing and mapping vegetation. Adoption of an international approach to vegetation classification, such as the Braun-Blanquet approach, by all countries would greatly aid in the development of future global maps.

The geographic information system used to compile, generate, and analyse the map provides great insight regarding the underlying ecological relationships. Overlying the concentric arrangement of the bioclimate subzones are complex patterns of topography, geology, hydrology, and historical factors that control the vegetation distribution across the Arctic. One unanticipated result of this database was the AVHRR-derived NDVI (Normalized Difference Vegetation Index) map, which permitted a circumpolar analysis of biomass patterns in relationship to the CAVM vegetation units (Raynolds et al. in press.; Walker et al. 2003). If replicated in a time series, circumpolar NDVI maps could provide more insights regarding how the Arctic is responding to global temperature changes.

The map covers many areas of the Arctic where there were no available field data. Consequently, the accuracy of the map undoubtedly varies from area to area depending on the quality of the information available. In total 34 regional experts were involved in producing the map and another 17 helped in the review of specific areas of the map, but many areas are still insufficiently known, so the map should be viewed as a hypothesis that still requires some estimate of its spatially explicit accuracy before it can be used as a baseline for arctic global change studies. As new information becomes available, the digital database makes updating the map relatively easy.

The original intent of the authors was to produce a map showing dominant plant communities across the Arctic. This proved to be very difficult because no consensus could be reached regarding the legend for such a map, which would have been voluminous. The map presented here condenses over 400 known plant communities into 15 physiognomic mapping units, which is a fairly radical departure from earlier maps of the Arctic which placed the bioclimate subzones at the highest level in the legend. The plant community data are in tables for each floristic subprovince. Maps of dominant plant communities can be constructed by adding a decimal suffix to the existing physiognomic codes. Such a map has been constructed for Arctic Alaska (Raynolds et al. in press), and this could also be done for the entire Arctic from the existing tables.

One criticism of the map is that it is restricted to the arctic tundra region. Very few questions relevant to the Arctic stop at the tree line. For example, most rivers flowing into the Arctic Ocean have their origins far to the south of the map boundary. Climate and vegetation-change models, analysis of animal migrations, roads and industrial developments, and arctic-human interactions all require maps that include the boreal forest and biomes even further south. It would be highly desirable to use similar methods to extend the map further south, possibly using the boundary of the Arctic watershed as the southern limit.

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