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The Circumpolar Arctic Vegetation Map: AVHRR-derived base maps, environmental controls, and integrated mapping procedures

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Abstract. A new false-colour-infrared image derived from biweekly 1993 and 1995 Advanced Very High Resolution Radiometer (AVHRR) data provides a snow-free and cloud-free base image for the interpretation of vegetation as part of a 1:7.5 M-scale Circumpolar Arctic Vegetation Map (CAVM). A maximum-NDVI (Normalized Difference Vegetation Index) image prepared from the same data provides a circumpolar view of vegetation green-biomass density across the Arctic. This paper describes the remote sensing products, the environmental factors that control the principal vegetation patterns at this small scale, and the integrated geographic information-system (GIS) methods used in making the CAVM.

1. Introduction

Remote sensing products from Earth-orbiting satellites provide the image base to make the first detailed vegetation map of an entire global biome, the arctic tundra. A new vegetation map of the Arctic is needed for numerous international efforts, including global-change and conservation studies, land-use planning, large-scale resource development, and education. The Circumpolar Arctic Vegetation Map (CAVM) will be based on current knowledge of arctic plant communities and their environmental controls. During the past six years, the CAVM participants have defined the project organization and methods in a series of workshops (Walker 1995, D. A. Walker *et al.* 1995, Walker and Markon 1996, Walker and Lillie 1997, Markon and Walker 1999, Walker 2000, Raynolds and Markon 2002). Six groups of collaborators are now working on regional maps of Alaska, Canada, Greenland, Iceland, Svalbard, and Russia. This paper presents two new AVHRR-derived images of the circumpolar Arctic, the key environmental variables used for interpreting the vegetation, and the GIS framework for the mapping methods.

2. Remote-sensing products

2.1. *AVHRR-derived base map*

A high-resolution false colour-infrared (CIR) image of the circumpolar region representing the vegetation at maximum greenness is an essential element of the

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mapping method (figure 1). This image is derived from Advanced Very-High Resolution Radiometer (AVHRR) data that were obtained from the US Geological Survey (USGS) Alaska Geographical Science Office. It is composed of 1 km × 1 km picture elements (pixels). The image is a composite of pixels, where each pixel was selected by using the date with highest Normalized Difference Vegetation Index (NDVI) for that pixel among biweekly images taken during the periods from 1 April to 31 October in 1993 and 1995. These periods cover the vegetation green-up-to-senescence period during two relatively warm years when summer-snow cover was at minimum in the Arctic. This permitted the construction of an image with minimum snow and cloud cover. The white areas are glaciers that were masked out using information from the Digital Chart of the World. The ocean ice was masked out using the coastlines from the Digital Chart of the World. The southern border of the CIR image is clipped to tree line, which was derived from the best available

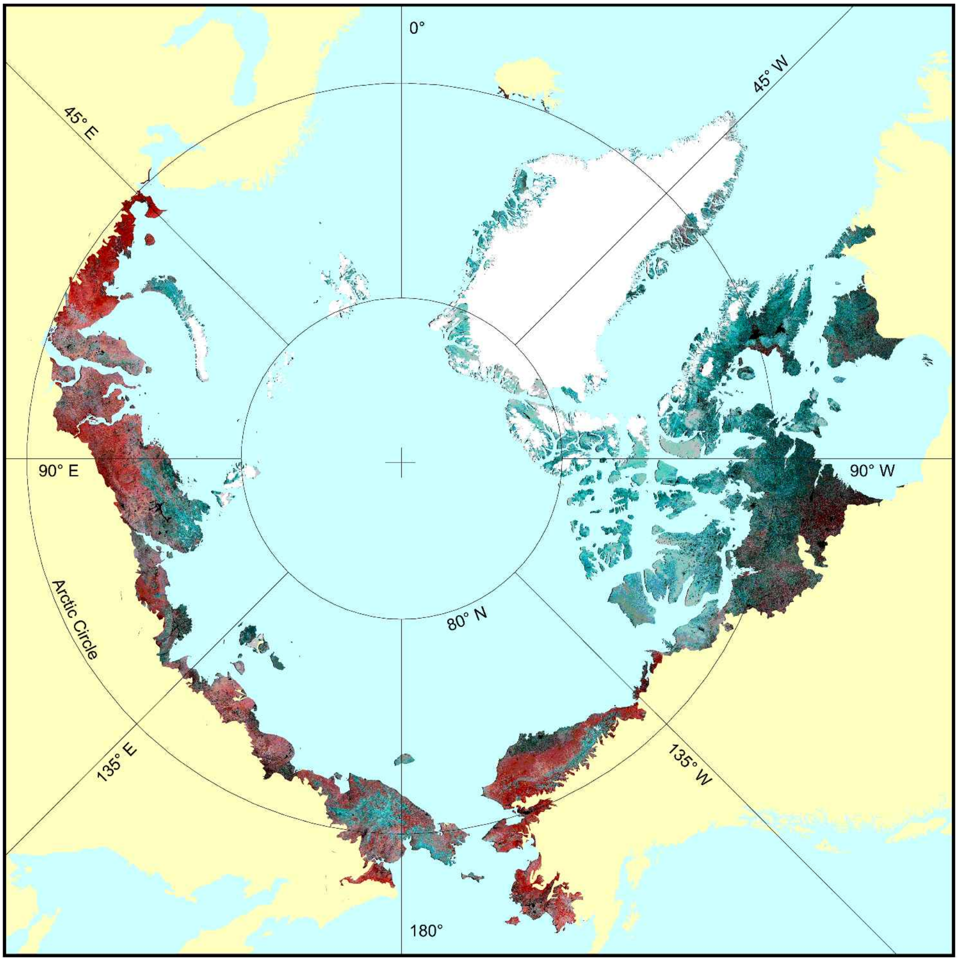

Figure 1. AVHRR-derived false colour-infrared image of the circumpolar Arctic. The image is derived from the pixels with highest NDVI among biweekly images from 1993 and 1995. The southern border of the CIR image is clipped to treeline, which was derived from the best available vegetation maps.

vegetation maps and the most recent information (Raynolds and Markon 2002). The image is used as a base for drawing vegetation map polygons. Most boundaries on the vegetation map correspond to features that can be seen on the AVHRR image (see §4).

2.2. *Maximum-NDVI image*

An image portraying maximum NDVI (figure 2) is used to delineate areas of high and low vegetation biomass. This image was created from the same data as the false CIR image (figure 1). $NDVI=(NIR–IR)/(NIR+IR)$, where IR is the spectral reflectance in the AVHRR near-infrared channel (0.725–1.1 μm), where light-reflectance from the plant canopy is dominant, and R is the reflectance in the red channel (0.5–0.68 μm), the portion of the spectrum where chlorophyll absorbs maximally. The NDVI values were grouped into eight classes that meaningfully separate the vegetation according to biomass. Red and orange areas in figure 2 are areas of shrubby vegetation with high biomass, and blue and purple areas are areas with low biomass.

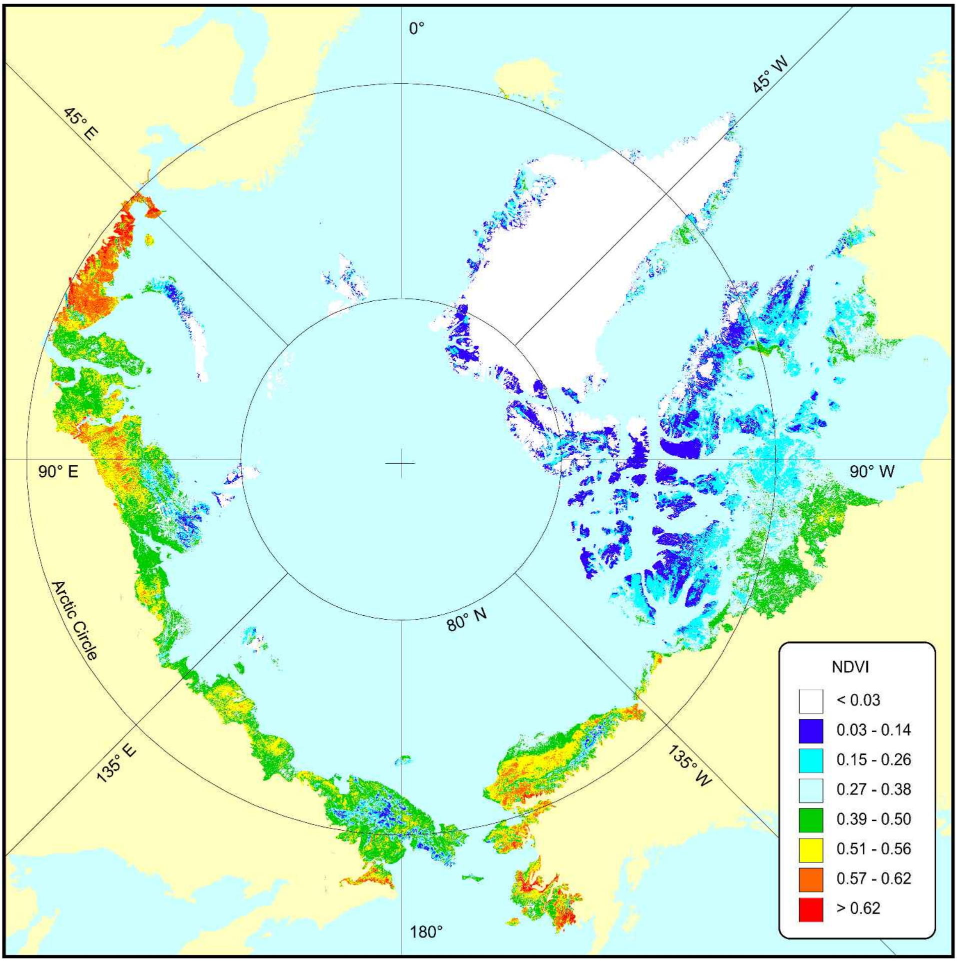

Figure 2. Maximum NDVI for the circumpolar Arctic derived from the same data as figure 5.

3. Environmental controls of vegetation at 1:7.5 M scale

The approach used for making the CAVM is based on manual 'photo-interpretation' of the AVHRR satellite image. A map based purely on automated remote sensing procedures could not portray the details of plant communities for the entire circumpolar region because there is large variability of tundra vegetation with similar spectral properties. Due to the small scale of the map and lack of previous vegetation maps for much of the Arctic, vegetation information must be inferred from expert knowledge of the plant communities in relation to principal landforms and other terrain features that are visible on small-scale satellite imagery. In the Arctic, vegetation of a given landscape can be predicted on the basis of summer temperature regime (bioclimatic subzones), available plants in the regional flora (floristic sectors), soil chemistry, and prevailing drainage conditions (Walker 2000).

3.1. *Bioclimatic zonation*

A fundamental problem for the CAVM is how to characterize the transitions in vegetation that occur across the roughly 10°C mean July temperature gradient from the tree line to the coldest parts of the Arctic. The important role of summer temperature has been noted with respect to a wide variety of ecological phenomena, including phenology (Sorensen 1941), species diversity (Young 1971, Rannie 1986), plant community composition (Matveyeva 1998), biomass (Bliss and Matveyeva 1992, Bazilevich *et al.* 1997), and invertebrate and vertebrate diversity (Chernov and Matveyeva 1997). Various authors, working with different geobotanical traditions, have divided the Arctic into bioclimatic regions using a variety of terminologies (table 1). The origins of these different terms and approaches have been reviewed for the Panarctic Flora (PAF) initiative (Elvebakk 1999). The PAF and CAVM have accepted a five-subzone version of the Russian zonal approach (figure 3). The subzone boundaries are somewhat modified from the phytogeographic subzones of Yurtsev (1994) based on recent information from a variety of sources (Raynolds and Markon 2002). A brief description of each subzone follows:

3.1.1. *Subzone A: Herb subzone*

Subzone A includes mostly fog-shrouded islands within the permanent arctic ice pack where July mean temperatures are less than about 2–3°C, such as Ellef Ringnes, Amund Ringnes, King Christian, northern Prince Patrick and nearby islands in the northwest corner of the Canadian Archipelago. It also includes the coastal fringe of northernmost Greenland and northern Ellesmere and northern Axel Heiberg islands, the northeastern portion of Svalbard, Franz Josef Land, Severnaya Zemlya, the northern tips of the Taimyr Peninsula, and northern tip of Novaya Zemlya. The summer temperatures in these areas are near freezing all summer due to a combination of nearly continuous cloud and fog cover, which limits solar radiation, and the close proximity to the ice-covered ocean (Bay 1997, Razzhivin 1999). More continental inland areas of the larger islands are often considerably warmer. Permanent ice covers large areas of the land. Major parts of the nonglacial land surfaces are largely barren, often with $<5\%$ cover of vascular plants, however, meadow-like plant communities are not uncommon on mesic fine-grained soils, where there is sufficient moisture provided by the cold humid oceanic climate.

Woody plants are absent on *zonal* sites. Zonal sites are flat or gently sloping, moderately drained sites with fine-grained soils that are not influenced by extremes of soil moisture, snow, soil chemistry, or disturbance and which fully express the influence of the prevailing regional climate. Lichens, bryophytes, cyanobacteria, and scattered forbs (e.g. *Papaver*, *Draba*, *Saxifraga* and *Stellaria*) are the dominant plants. Many of the forbs, lichens and mosses have a compact cushion growth form. In midsummer, the arctic poppy, *Papaver radicatum*, is the most conspicuous plant over large portions of this subzone. Other important low-growing cushion-forb genera include *Minuartia* and *Cerastium*. Soil lichens, mosses, and liverworts can cover a high percentage of the surface, particularly in more maritime areas such as Novaya Zemlya (Alexandrova 1980). Rushes (*Luzula* and *Juncus*) and grasses (*Alopecurus*, *Puccinellia*, *Phippsia*, and *Dupontia*) are the main graminoid groups. Sedges (Cyperaceae) are rare, and wetlands lack organic peat layers. There is little contrast in the composition of vegetation on mesic sites, streamside sites, and snowbeds. The vascular plant flora is extremely depauperate, consisting of only about 50–60 species (Young 1971). On fine grained soils, the extremely cold temperatures and the thin sparse plant canopy induce intense frost activity, which forms networks of small (<50 cm diameter) nonsorted hummocks and polygons, and plants are confined mainly to the depressions between the hummocks (Chernov and Matveyeva 1997).

3.1.2. *Subzone B: Prostrate dwarf-shrub subzone*

Subzone B includes parts of the southern Queen Elizabeth Islands, the eastern fringe of Ellesmere Island, much of Peary Land in Greenland, the eastern portion of Svalbard, central Novaya Zemlya, the northern coast of the Taimyr Peninsula, and the New Siberian Islands. Because of its small size and weakly defined distinguishing characteristics, Subzone B could be characterized as a transition zone to Subzone C. Several treatments of arctic zonation include subzones B and C in a single subzone (Matveyeva 1998, Yurtsev 1994). The mean July temperature at the southern boundary of Subzone B is approximately 5°C. This subzone has scattered prostrate (creeping) dwarf shrubs on zonal soils. Erect shrubby vegetation is lacking. Mesic, low-elevation surfaces with fine-grained soils generally have open, patchy plant cover, generally with 5–25% cover of vascular plants. Well-differentiated snowbed and riparian plant communities are lacking. Nonsorted circles, stripes, and ice-wedge polygons are common. Vascular plant vegetation is often confined to cracks and depressions in the polygonal network, and areas irrigated by runoff from snow patches. The dominant growth forms on mesic sites are prostrate dwarf shrubs (e.g. *Dryas*, *Salix arctica* and *S. polaris)*, forbs (e.g. *Draba*, *Saxifraga*, *Minuartia*, *Cerastium* and *Papaver*), graminoids, (e.g. *Carex stans*, *Carex rupestris*, *Alopecurus alpinus*, *Deschampsia borealis* and *Luzula confusa*), mosses and lichens. Rushes (*Luzula*) are also an important component of many mesic vegetation types. Sedges (*Carex*, *Eriophorum*) often are dominant in wet areas.

3.1.3. *Subzone C: Hemiprostrate dwarf-shrub subzone*

Subzone C includes northern Banks Island, northern Victoria Island, Devon Island, Prince of Wales Island, Somerset Island, northern Baffin Island, most of Ellesmere Island, Axel Heiberg Islands, the west coast of Greenland, and inner fiord regions of northeast Greenland, southern Novaya Zemlya, some coastal areas of Yakutia and Chukotka, and the northernmost coast of Alaska (Yurtsev 1994). The mean July temperature at the southern boundary of Subzone C is about 7°C. Mesic zonal surfaces in this subzone have more luxuriant plant growth than that in Subzone B. Zonal sites are generally well vegetated, but vascular-plant cover is still open, and

Table 1. Approximate equivalent subdivisions of the Arctic Zone in Russia, North America, and Fennoscandia.

	Russia			North America				Fennoscandia	
Subzone	Yurtsev (1994)	Alexandrova (1980)	Matveyeva (1998)	Walker (2000)	Polunin (1951, 1960)	Edlund and Alt (1989) Edlund (1996)	Bliss (1997)	Tuhkanen (1986)	Elvebakk (1999)
A	High arctic tundra	Northern polar desert Southern polar desert	Polar desert (1.5–2°C)[1]	Cushion-forb subzone (2–3°C)[2]	High arctic[3]	Herbaceous and cryptogam (1–3°C, 50–150 TDD)[4]	High arctic	Inner polar zone (C = 0.0°)[5] Outer polar zone (C = 0.5°)	Arctic polar desert zone
B	Arctic tundra–northern variant	Northern arctic tundra	Arctic tundra	Prostrate dwarf-shrub subzone		Herb-prostrate shrub transition (3–4°C, 150–250 TDD) Prostrate shrub (4–6°C, 250–350 TDD)		Northern arctic zone (C = 1.0°)	Northern arctic tundra zone
C	Arctic tundra–southern variant	Southern arctic tundra	(5–6°C)	(7°C)	Middle arctic	Dwarf and prostrate shrub (5–7°C, > 350 TDD)		Middle arctic zone (C = 1.75°)	Middle arctic tundra zone
D	Northern hypoarctic tundra	Northern subarctic tundra Middle subarctic tundra	Typical tundra (8–10°C)	Erect dwarf-shrub subzone (9°C)	Low arctic	Low erect shrub	Low arctic	Southern arctic zone	Southern arctic tundra zone
E	Southern hypoarctic tundra	Southern subarctic tundra	Southern tundra (10–12°C)	Low-shrub subzone (10–12°C)		(7–10°C)		(C = 2.5°)	Arctic shrub tundra zone

interrupted by frost scars and other periglacial features. The main features distinguishing Subzone C from Subzone B are the presence of the hemiprostrate shrub *Cassiope tetragona* and well-differentiated plant communities in mires, snowbeds and creek sides. *Cassiope* covers large areas on mesic sites in areas with acidic parent material, such as on Svalbard, Baffin Island, and interior portions of Greenland. However, *Cassiope* is lacking on mesic alkaline surfaces in the western Canadian Islands. In these areas, *Cassiope* is generally confined to snow accumulation areas. Subzone C has much greater species diversity than Subzone B. Sedges, such as *Kobresia myosuroides*, *Carex bigelowii* and *Carex rupestris*, are common on upland surfaces, and numerous forbs, such as members of the Fabaceae (e.g. *Oxytropis*, *Astragalus*) are important in nonacidic regions. Communities in intrazonal habitats (snowbeds and creek sides) are well developed. Wetland communities are much better developed than in Subzone B. Creek sides have distinctive *Epilobium latifolium* communities.

3.1.4. *Subzone D: Erect dwarf-shrub subzone*

Subzone D covers the southern parts of Banks Island and Victoria Island, much of Keewatin, southern Baffin Island, most of southern Greenland, and a broad band across Siberia and Chukotka. Climatically, Subzone D periodically receives relatively temperate air from the south during the summer while Subzone C receives predominately arctic air masses. The mean July temperature at the southern boundary of Subzone D is about 9°C. The boundary between subzones C and D is considered of highest rank because it separates the northern drier tundras on mineral soils from the southern relatively moist tundras with moss carpets and peaty soils (Alexandrova 1980). This is approximately equivalent to the boundary between Bliss' High and Low Arctic (Bliss 1997). The major difference in pedology causes dramatic changes to the vegetation. The plants in Subzone D have strong hypoarctic (boreal forest) affinities (Yurtsev *et al.* 1978). Important hypoarctic species such as birch (e.g. *Betula nana*), alder (*Alnus*), willow (*Salix*) and heath plants (Ericaceae and Empetraceae) extend their ranges from the lower layer of subarctic woodlands, but are not dominant as they are in Subzone E. Low shrubs (>40 cm tall) occur along streams. Overall, the role of shrublands is much less prominent than in Subzone E. The plant canopy is usually interrupted by patches of bare soil caused by nonsorted circles, stripes, and a variety of other periglacial features ('spotty tundra' in the Russian literature). Vascular plants generally cover about 50–80% of the surface. Zonal vegetation on gently sloping upland surfaces consists of sedges (e.g. *Carex bigelowii*, *Carex membranacea*, *Eriophorum triste*, *E. vaginatum* and *Kobresia myosuroides)*, prostrate and erect dwarf (<40 cm tall) shrubs (e.g. *Salix planifolia*, *S. lanata* ssp. *richardsonii*,

Footnote to Table 1.

[1]Mateveyeva (1998): Range of mean July temperature at southern boundary of subzone.

[2]Walker (2000): Approximate mean July temperature at the southern boundary of the subzone.

[3]Polunin (1951): Zones based roughly on openness of ground cover. High arctic, very sparsely vegetated; middle arctic, open vegetation carpet; low arctic, closed vegetation carpet.

[4]Edlund and Alt (1989): Zones defined on the bases of mean July temperature and sum of mean temperature of days exceeding 0°C (thawing degree days, TDD).

[5]Tuhkanen (1986): Southern boundary of zones defined by Holdridge biotemperature as the sum of mean monthly temperatures >0°C divided by 12.

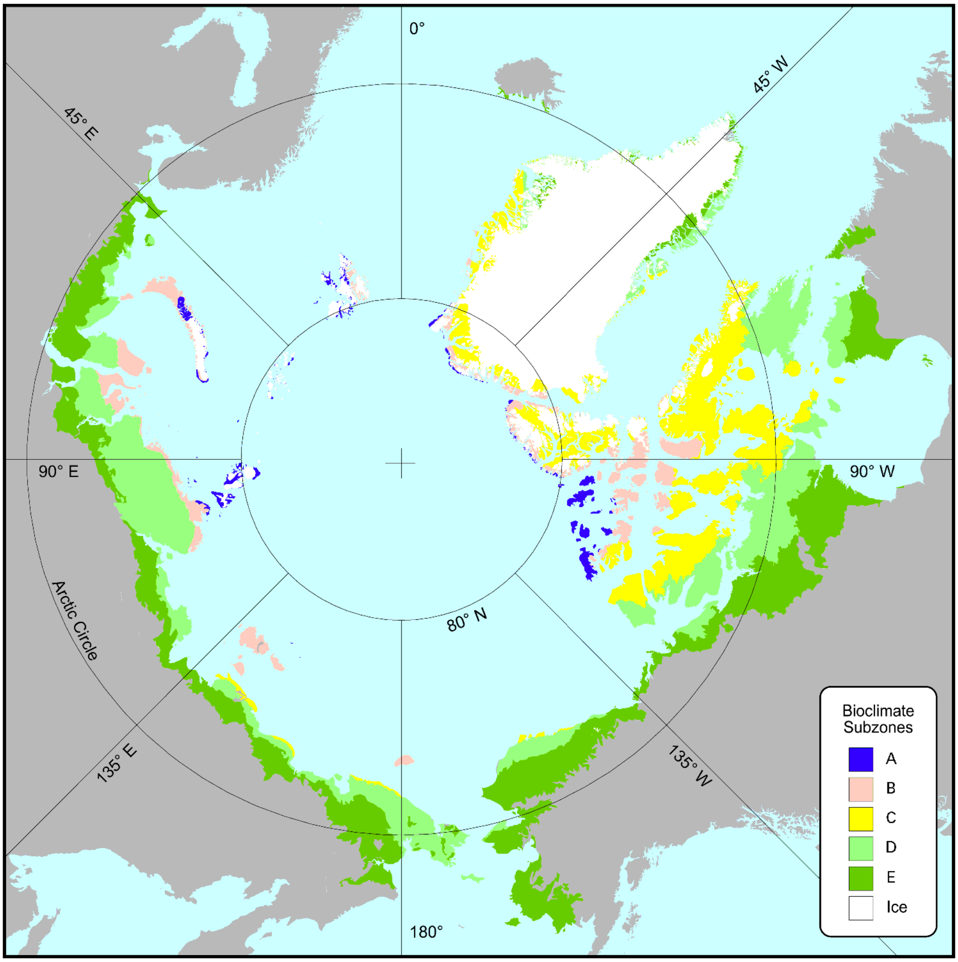

Figure 3. Bioclimatic subzones in the Arctic. Modified from Elvebakk *et al.* (1999).

S. reticulata, *S. arctica*, *Betula exilis* and *Dryas integrifolia*) and mosses. Prostrate-dwarf-shrub communities, which were common on zonal surfaces in Subzone C, are confined mainly to wind-swept sites. The moss layer, consisting primarily of *Tomentypnum*, *Hylocomium*, *Aulacomnium* and *Sphagnum*, contributes to the development of organic soil horizons on fine-grained soils. Soils in Subzone D have thin peaty horizons, and fine-grained soils are often nonacidic, whereas soils in Subzone E are usually acidic regardless of texture.

There is more regional variation in the zonal vegetation than in subzones A, B, and C. Tussock tundra consisting of cottongrass tussocks (*Eriophorum vaginatum*) and dwarf shrubs is common on fine-grained acidic soils over much of northeastern Siberia and northern Alaska (Walker *et al.* 1994), particularly in areas that were unglaciated during the last part of the Pleistocene. In transitional areas to Subzone C and on nonacidic loess, *Dryas* spp. and *Cassiope tetragona* are important (Walker and Everett 1991). Some continental areas of Russia have dry steppe tundras that are relicts of cold dry Pleistocene vegetation (Yurtsev 1982).

3.1.5. *Subzone E: Low-shrub subzone*

Subzone E is the warmest part of the Arctic Tundra Zone with mean July temperatures of 10–12°C. In Subzone E, the zonal vegetation is dominated by hypo-arctic low shrubs that are often greater than 40 cm tall (e.g., *Betula nana*, *B. exilis*, *B. glandulosa*, *Salix glauca*, *S. phylicifolia*, *S. planifolia*, *S. richardsonii* and *Alnus* spp.). True shrub tundra with dense canopies of birch, willows, and sometimes alder (*Alnus*) occur in many areas. Birch or willow thickets 80 to 200 cm tall occur on zonal sites in some moister areas such as west Siberia and northwest Alaska. In more continental areas and areas with less snow cover, the shrubs are shorter and form a more open canopy. Tussock tundra is common in northern Alaska and eastern Siberia and contains more shrubs than in Subzone D (Alexandrova 1980). Low and tall (> 2 m) shrubs are abundant in most watercourses. Toward the southern part of Subzone E, in flat areas that are continuous with the boreal forest, patches of open forest penetrate into this area along riparian corridors. These woodlands consist of a variety of species of spruce (*Picea*), pine (*Pinus*), cottonwood (*Populus*), and larch (*Larix*) and tree birches (*Betula*). Peat plateaus (palsas) up to 1.5 m tall occur in lowland areas.

3.1.6. *Altitudinal zonation*

Adiabatic cooling of air masses at higher elevations causes altitudinal zonation. For continental areas, the environmental adiabatic lapse rate is about 6°C per 1000 m (Barry 1981). This is equivalent to a shift in bioclimatic subzone for about every 333-m elevation gain. A topographic map was made with elevation isolines at 333, 667, 1000, 1333, 1667, and 2000 m (figure 4). These show roughly where altitudinal zonation shifts can be expected.

3.2. *Floristic variation within the zones*

Russian geobotanists have described longitudinal subdivisions within the subzones, which are based primarily on floristic differences (Alexandrova 1980, Yurtsev 1994). These divisions are useful for characterizing the considerable east–west floristic variation within the subzones, particularly in subzones C, D, and E. In the more northern two subzones, the Arctic has a relatively consistent core of circumpolar arctic plant species that occur around the circumpolar region. Further south, local east-west variation is related to a variety of factors, including different paleo-histories and the greater climatic heterogeneity. Large north-south trending mountain ranges, primarily in Asia, have also restricted the exchange of species between parts of the Arctic (Alexandrova 1980). Yurtsev (1994) delineated six floristic provinces and 22 subprovinces and has discussed their characteristics. These have recently been revised by the Panarctic Flora Project (figure 5) (Elvebakk *et al.* 1999). The Northern Alaska subprovince is used below in an example for a framework for a circumpolar arctic vegetation map (see table 2). This area covers the region north of the Brooks Range, from the Mackenzie River westward to about Point Lay.

3.3. *The role of parent material*

Vegetation patterns related to parent material differences are extensive and therefore important to global and regional scale modelling efforts. There is a rich literature describing the peculiarities of floras and vegetation on carbonate and ultramafic rocks, saline soils, and fine vs. coarse textured soils in the Arctic (Edlund 1982, Elvebakk 1982, Cooper 1986, Walker *et al.* 1998). These differences in parent material

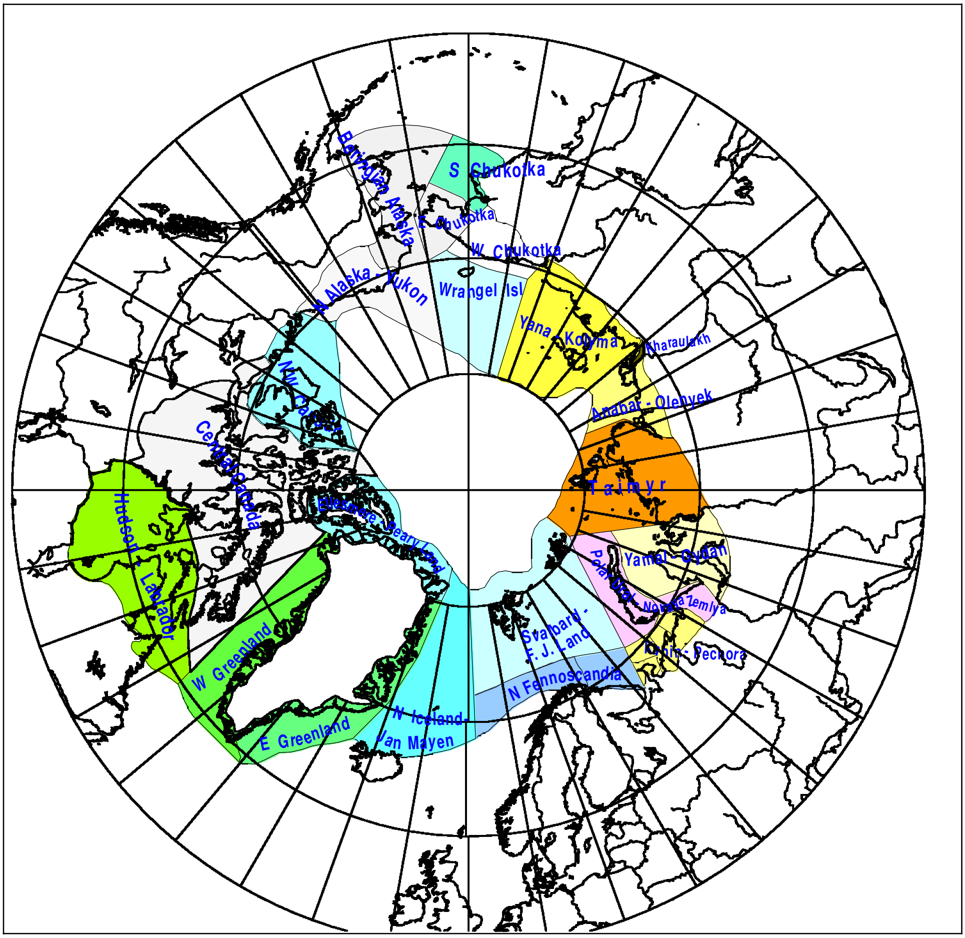

Figure 4. Floristic sectors within the Arctic. From Elvebakk *et al.* (1999).

have important effects on ecosystem patterns and processes. Some of the most important vegetation effects are related to substrate pH. Sylvia Edlund's diagram in figure 6 illustrates well differences in plant communities on alkaline and acidic substrates across zonal boundaries in the Canadian High Arctic. Similar patterns have been described on Svalbard (Elvebakk 1985) and northern Alaska (Walker *et al*. 1994). Vegetation on nonacidic and acidic parent materials can be determined for most regions of the Arctic using available soil and surficial-geology maps in a GIS context. Extensive saline areas occur in parts of the Russian arctic. Other parent material subdivisions could be made for global mapping if they were found to be regionally extensive and important to ecosystem processes.

3.4. *The role of topography*

At landscape scales (1–100 km^2), topography strongly influences soil moisture, which is an important control of patterns of tundra plant communities and tundra ecosystem processes (Webber 1978). The effect of topography can be portrayed along hill-slopes as a mesotopographic gradient (figure 7 and Billings 1973). Generally,

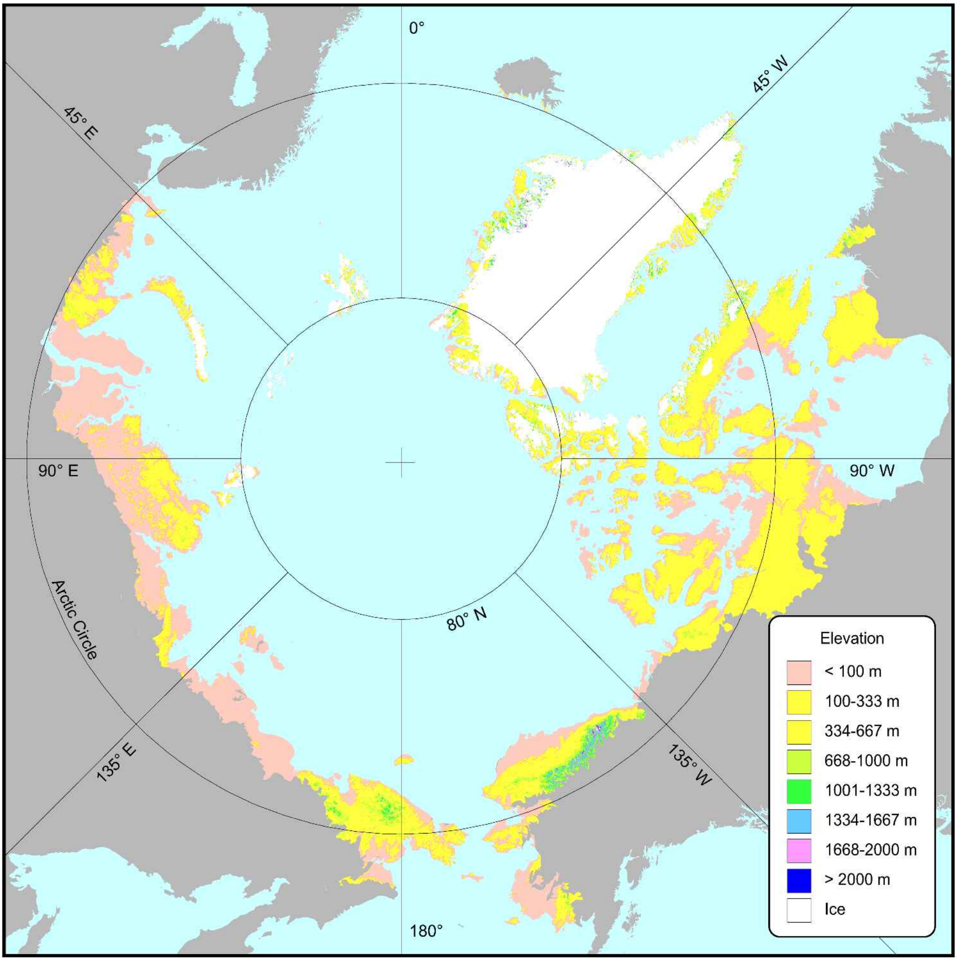

Figure 5. Topography of the circumpolar Arctic showing colour breaks corresponding to approximate altitudinal zonation boundaries. The environmental adiabatic lapse rate of 6°C per 1000 m creates a shift in equivalent bioclimatic subzone about every 333-m elevation gain.

only extensive wetlands and dry mountainous areas are large enough to be displayed at the 1:7.5 M scale. Plant communities in snowbeds and along streams are usually too small to map, but are important components of regional vegetation mosaics and are used to help differentiate the vegetation in different landscape units and complexes of plant communities in different bioclimate subzones.

3.5. *Hierarchical tables summarizing regional plant communities*

The plant community summary table and associated look-up tables are the foundation of vegetation knowledge for the CAVM. Separate tables have been compiled for each floristic province. An example from northern Alaska is shown in table 2. The major columns of the tables are the subzones, and the subcolumns are the various parent material types. The rows are the major habitats along the mesotopographic gradient. Plant communities are listed with a unique identification (ID)

Table 2. Summary table for plant communities in the North Alaska Subprovince (part of Alaska floristic region). Dominant plant communities occurring in major habitats along the mesotopographic gradient on acidic and nonacidic substrates[1] in Subzones C, D and E. Subzones A and B are missing in Northern Alaska. The break between acidic and nonacidic soils is approximately pH 5.5. Data are missing for the Beringian Alaska Subprovince and are assumed to be similar to northern Alaska.

Habitat along mesotopographic gradient	Subzone C		Subzone D		Subzone E	
	Acidic substrates (Barrow)	*Nonacidic substrates (Prudhoe Bay, coast)*	*Acidic substrates (Atqasuk)*	*Nonacidic substrates (Prudoe Bay, inland)*	*Acidic substrates (Imnavait Creek)*	*Nonacidic substrates (Toolik Lake)*
Dry exposed sites	I. *Spaerophorus globosus–Luzula confusa* subtype *Salix rotundifolia* comm. (Elias *et al.* (1996)= Nodum II, Webber (1978)) (Dry beach and river terraces)	8. *Oxytropis bryophila-Dryas integrifolia* comm. (=Walker (1985). Type B12; =Unit 18 this table) (Dry nonacidic gravelly sites)	13. *Diapensia lapponica-Salix phlebophylla* comm. (=Komárková and Webber (1980), Map 2, Unit 6) (Dry sandy sites)	18. *Oxytropis bryophila-Dryas integrifolia* comm. (=Walker (1985) Type B1; =Unit 8 this table; also M. D. Walker (1990)) (Dry nonacidic gravelly sites)	26. *Selaginello sibiricae–Dryadetum octopetalae* (Walker *et al.* (1994)) (Dry gravelly soils) 27. *Salici phlebophyllae–Arctoetum alpinae* (Walker *et al.* (1994)) (Dry acidic organic soils)	38. *Selaginello sibiricae–Dryadetum octopetalae* (Walker *et al.* 1994), same as Unit 26, this table (Dry gravelly soils)
Mesic zonal sites	2. *Sphaerophorus globosus–Lusula confusa* subtype *Saxifraga foliolosa* comm. (Elias *et al.* (1996)= Nodum 1. Webber (1978) Type 5, Walker (1977)) (Mesic high-centered polygons) 3. *Saxifraga cernua–Carex aquatilis* comm. (Elias *et al.* (1996)= Nodum IV, Webber (1978) Type 6 and 7, Walker (1977)) (Moist, acidic fine-grained soils)	9. *Dryas integrifolia–carex aquatilis* comm. [=Type U12. Walker 1985] (Mesic calcareous coastal meadows)	14. *Ledum decumbens–Eriophorum vaginatum* comm. (=Map 2, Unit 8, Komárková and Webber (1980)) (Mesic stabilizied sands)	19. *Dryas integrifolia–Eriophorum triste* (=Stand Type U3. Walker (1985)) (Mesic nonacidic loess)	28. *Sphagno–Eriophoretum vaginati* (Walker *et al.* (1994)) (Tussock tundra on acidic fine grained soils) 29. *Sphagno–Eriophoretum vaginati betulosum nanae* (Walker *et al.* (1994)) (Shrub tundra in warmer mesoclimatic oases of the foothills, also along water tracks and in basins) 30. *Climaceum dendroides–Alnus viridis* comm. (Walker *et al.* (1997), same as Unit 45, this table) (Open alder shrub savannas in warmer mesoclimatic oases of the foothills)	39. *Dryado integrifolia Caricum bigelowi* (Walker *et al.* (1994) (moist calcareous (tundra)

Table 2. (*Continued*).

Habitat along mesotopographic gradient	Subzone C		Subzone D		Subzone E	
	Acidic substrates (Barrow)	*Nonacidic substrates (Prudhoe Bay, coast)*	*Acidic substrates (Atqasuk)*	*Nonacidic substrates (Prudoe Bay, inland)*	*Acidic substrates (Imnavait Creek)*	*Nonacidic substrates (Toolik Lake)*
Wet sites	4. *Calliergon sarmentosum–Carex aquatilis* comm. (=Noda V and VI, Webber (1978), Type 9, 10, 12 and 13. Walker (1977); *Eriophorum angustifolium–Carex aquatilis* comm. Elias *et al.* (1996)) (Wet acidic sites without standing water)	10. *Drepanocladus brevifolius-Carex aquatilis* comm. (=Type M10, Walker (1985)) (Wet calcareous coastal meadows)	15. *Eriophorum angustifolium–Carex aquatilis* comm. (=Map 2, Unit 16, Komárková and Webber (1980)) (Wet marshes)	20. *Drepanocladus brevifolius–Carex aquatalis* comm. J=stand Type M2, Walker (1985) (Wet calcareous meadows, ice-wedge polygon centers, lake margins).	31. *Sphagnum orientale–Eriophorum scheuchzeri* comm. (Walker and Walker 1996) (Wet microsites in wet acidic tundra in foothills) 32. *Spagnum lenense–Salix fuscenscens* comm. (Walker and Walker 1996) (Raised microsites in acidic wetlands)	40. *Eriophorum angustifolium–Carex aquatilis* comm. (M. D. Walker *et al.* 1996) (Nonacidic marshes)
Snow beds	5. *Salix rotundifolia–Cetraria delesii*, comm. (Elias *et al.* (1996)) (Early-melting snow beds near the coast) 6. *Phippsia algida–Saxifraga rivularis* comm. (=Nodum VIII. Webber (1978); Type 15, Walker (1977)) (Late-melting snow beds near the coast)	11. No data. Probably similar to Unit 21, this table	16. *Boykinia richardsonii–Cassiope tetragona* comm. (=Map 2, Unit 11, Komárková and Webber (1980)) (Early-melting snow beds; similar to Unit 33, this table)	21. *Dryas integrifolia–Cassiope tetagona* comm. (=Stand Type U6, Walker (1985); Stand type *Cassiope tetradona-Dryas integrifolia*, M. D. Walker (1990)) (Early melting nonacidic snowbeds) 22. *Eriophorum triste–Salix rotundifolia* comm. (=Stand Type U7, Walker (1985); *Salix rotundifolia–Eriophorum triste*, M. D. Walker (1990)) (Late melting nonacidic snowbeds)	33. *Carici microchaetae–Cassiope tetragona* comm. (Walker *et al.* 1994) (Early-melting acidic snowbeds) 34. *Saxifraga nivalis–Salix rotundifolia* comm. (=M. D. Walker *et al.* (1989); similar to Unit 22 this table)) (Late-melting snow beds)	41. *Dryas integrifolia–Cassiope tetragona* comm. (M. D. Walker *et al.* (1994)) (Early-melting nonacidic snow beds) 42. *Salix rotundifolia–Saxrifaga rivalis* comm. (=M. D. Walker *et al.* (1989) (similar to Unit 22 this table) (Late melting snow beds)

Table 2. (*Continued*).

Habitat along mesotopographic gradient	Subzone C		Subzone D		Subzone E	
	Acidic substrates (Barrow)	*Nonacidic substrates (Prudhoe Bay, coast)*	*Acidic substrates (Atqasuk)*	*Nonacidic substrates (Prudoe Bay, inland)*	*Acidic substrates (Imnavait Creek)*	*Nonacidic substrates (Toolik Lake)*
Streamsides	7. *Phippsia algida–Cochlearia officinalis* (=Nodum VIII, Webber (1978); Type 15, Walker (1977), possibly equal to Unit 7, this table) (Unstable stream margins at coast)	12. *Epilobium latifolium–Artemsia arctica* (Possibly=*Epilobio latifolia–Salicetum alaxensis* ass. prov. Schikoff in prep. (Active nonacidic floodplains near coast)	17. *Salix lanata–Salix alaxensis* (=Map 2, Unit 17, Komárková and Webber (1980)) (streambank shrublands; probably equal to Unit 23, this table)	23. *Epilobio latifolii–Salicetum alaxensis* ass. prov. [Schikoff in press] (active nonacidic floodplains) 24. Low shrub version of *Salicetum glauco–richardsonii* (Ass. prov. Schikoff in press; =Stand Type U8) Walker (1985) (Willow shrublands on stable floodplains) 25. *Dryas integrifolia–Lupinis arctica* comm. (Walker *et al.* (1997)) (Dry river terraces)	35. *Valeriano capitatae–Salicetum planifoliae* (Ass. prov., Schikoff. In press;=*Eriophorum angustifolium—Salix purlchra* comm. (Walker *et al.* (1994)) (Acidic to circumneutral water tracks, streamsides) 36. Low shrub version of *Salicetum glauco–richardsonii* (Ass. prov. Schikoff in press) (Willow shrublands on stable floodplains) 37. *Climaceum dendroides–Almus viridis* comm. (Walker *et al.* 1997) (Alder shrublands floodplains)	43. *Epilobio latifolii-Salicetum alaxensis* (Ass. prov. Schikoff in press) (Active floodplains) 44. Tall shrub version of *Salicetum glauco–richardsonii* (Ass. prov Schikoff in press) (Willow shrublands on stable floodplains) 45. *Cllimaceum dendroides–Alnus viridis* comm. (Walker *et al.* (1997)) (Alder shrublands floodplains) 46. *Dryas integrifolia–Lupinus arctica* comm. (Walker *et al.* (1997)) (Dry river terraces)

[1]Surface deposits at the representative sites: Barrow—acidic marine sands and gravels; Predhoe Bay, coast—calcareous glacial outwash; Atqasuk—acidic colian sands; Prudhoe Bay island—calcareous loess; Immavait Creek—acidic mid-Pleistocene glacial tilt; Toolik Lake—calcareous lake-Pleistocene glacial tilt.

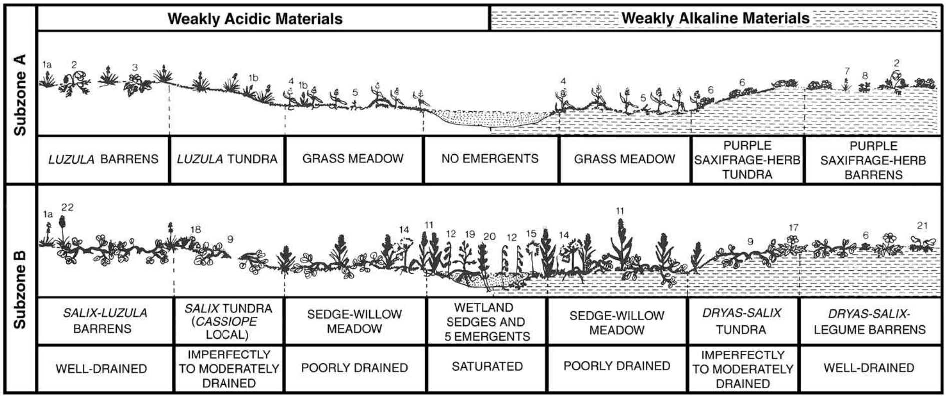

Figure 6. Vegetation on acidic and alkaline substrates in subzones A and B. Modified from Edlund and Alt (1989). Species shown are: 1, *Luzula confusa*; 1b, *L. arctica*; 2, *Papaver radicatum*; 3, *Potentilla hyparctica*; 4, *Alopecurus alpinus*; 5, *Phippsia algida*; 6, *Saxifraga oppositifolia*; 7, *Poa abbreviata*; 8, *Draba* sp.; 11, *Carex aquatilis var. stans*; 12, *Pleuropogon sabinei*; 14, *Eriophorum triste*; 15, *E. scheuchzeri*; 17, *Dryas integrifolia*; 18, *Cassiope tetragona*; 19, *Arctophila fulva*; 20, *Hippuris vulgaris*; 21, *Oxytropis arctobia*; 22, *Hierochloe alpina.*

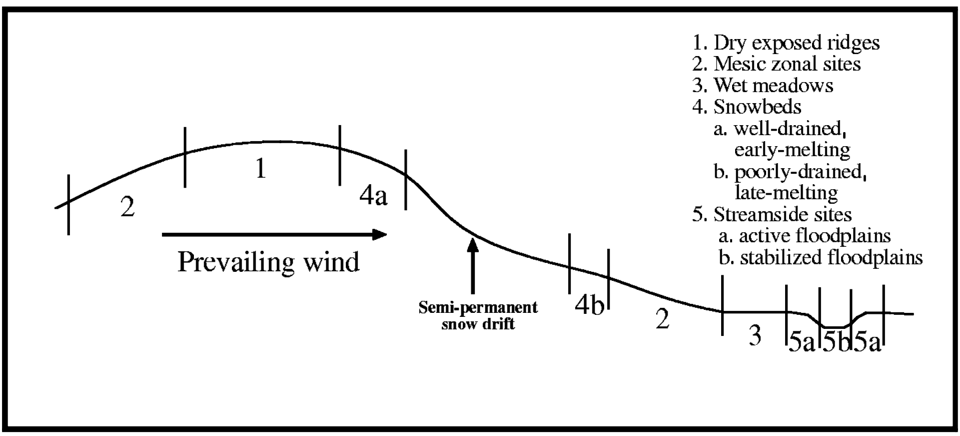

Figure 7. Conceptual mesotopographic gradient for arctic landscapes.

number, a two-species plant community name, and the publication where the community is described. Plant communities that are only described locally are given 'plant community type' (comm.) designations. Those that have 'association' (suffix -*etum*) names have been compared globally to types described from other areas and have been incorporated into the Braun–Blanquet syntaxonomic nomenclature system (Westhoff and van der Maarel 1978). This European phytosociological approach has many advantages as an international classification system at the plant community level because of its well-established procedures, long history, and wide application throughout the Arctic (Daniels 1994, Elvebakk 1994, Dierssen 1996, M. D. Walker *et al.* 1995, Matveyeva 1998). An example table is shown for the Alaska floristic province (table 1).

More detailed information for the plant communities is contained in separate look-up tables that are linked to this table via the plant community identification (ID) number. The linked tables contain information such as dominant plant growth forms, plant species, horizontal structure, vertical structure, primary production, and biomass (see look-up table 2 in Walker 1999).

4. Integrated mapping methods

Vegetation is interpreted on the basis of 'integrated vegetation complexes' (IVC). These IVCs are derived from a combination of information on satellite-derived images and information from existing source maps, such as bedrock geology, surficial geology, soils, hydrology, and previous vegetation maps. The procedures for defining these complexes are summarized in figure 7 and described briefly below. Supplementary information can be found in Walker (1999).

First level geological features (mountains, hills, plains, tablelands) are first interpreted directly from the AVHRR image (see step 1, and layer 1 in figure 8).

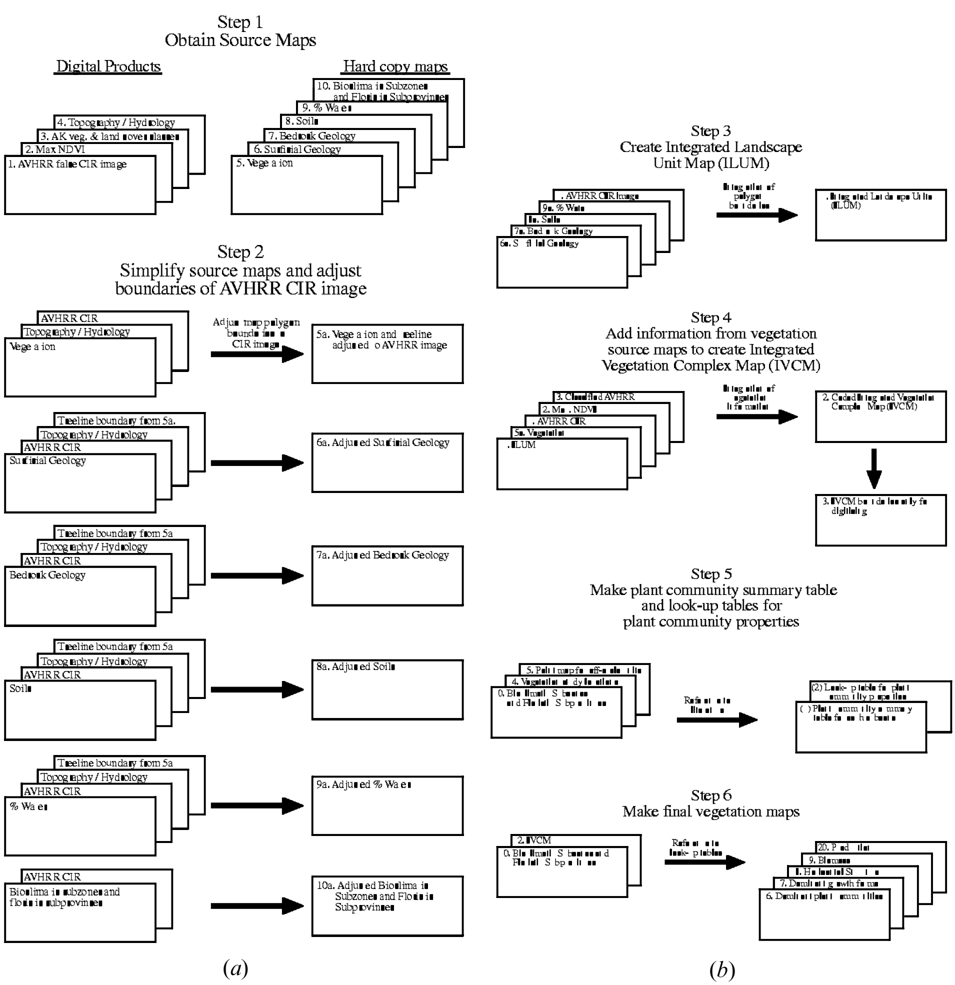

Figure 8. Six-step procedure for making the CAVM. See text for brief synopsis of each step. Summarized from Walker (1999).

Information from other simplified source maps, such as bedrock geology, surficial geology, per cent water cover, and soils, are used to create additional map boundaries (steps 2 and 3 in figure 8). These procedures are based on the principle that geomorphic features are the primary controls of vegetation boundaries. This process considers water and landform boundaries as unalterable (hard) boundaries. Boundaries controlling variables such as soils, and vegetation, which change across ecotones or gradients, are considered soft boundaries, which are made to conform to landscape boundaries wherever possible. The number of additional polygons is minimized through the integrated mapping procedures. The result is the 'integrated land-unit map' (ILUM). This map has all the essential terrain information.

At the next step vegetation information from a variety of sources is used to create additional vegetation boundaries on the integrated map (step 4, figure 8). The NDVI map (figure 2) and other vegetation maps are used to help delineate other features that may be visible on the AVHRR imagery. Where possible the polygon boundaries are made to conform to those of the ILUM. This new map is called the 'integrated vegetation complex' map (IVCM). The names of the complexes generally correspond to landscape features such as 'acidic mountain complex', 'acidic mire complex with less than 25% lakes', 'nonacidic plateau, basin or plain complex', 'nunatak complex', 'island complex' or 'large river floodplain complex'. The IVCM is the only map that needs to be digitized in the mapping procedures. Each polygon on the map is given a unique ID number. An attribute table contains each polygon ID number, followed by a series of codes that describe the polygon's attributes (vegetation complex, bedrock geology, surficial geology, per cent water cover, etc.).

Step 5 of the mapping procedures has already been described in the creation of the plant community summary table (see table 2), which contains the basic plant-community information for a given floristic region. A look-up table contains detailed information for each community (plant species, growth forms, production, biomass, etc.). This table is not shown here, but an example can be found in table 3 of Walker (1999). The creation of the final maps assumes that similar vegetation complexes within a given combination of floristic region and bioclimatic subzone will all have the same suite of plant communities. If there are known exceptions that do not conform to this logic, these map polygons can be selected out and recoded. Primary, secondary and tertiary (dominant and subdominant) plant communities are listed for each combination of subzone, floristic region, and vegetation complex. At step 6, a wide variety of vegetation-related maps can be created by reference to the linked tables that list growth forms, production and dominant species (Walker 1999).

5. Conclusion

Circumpolar AVHRR-derived false (CIR) and maximum NDVI images are the first products from the Circumpolar Arctic Vegetation Mapping project. They provide the key means of making an image-interpreted vegetation map of the arctic tundra biome. The CAVM is essentially a GIS database that uses expert knowledge of the relationship of plant communities to climate, parent material and topographic factors, to predict vegetation within landscape units that can be delineated on 1:7.5M scale AVHRR images. The database will be a source for creating a wide variety of map products that will be useful for many aspects of arctic research and education. The first draft of the CAVM is expected in 2002. The methods outlined in this paper could be applied to vegetation maps of other biomes. The images in this paper are available through the UCAR/Joint Office for Science Support, Boulder, CO, USA; e-mail: jmoore@ucar.edu.

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