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An integrated vegetation mapping approach for northern Alaska (1:4 M scale)

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Abstract. A six-step integrated vegetation mapping approach is described for making a small-scale (1:4 million) map of northern Alaska. The method uses two primary maps: (1) a Phytogeographic subzones and Floristic subprovinces Map (PFM) adjusted to Advanced Very High Resolution Radiometer false colour infrared (AVHRR CIR) imagery, and (2) an Integrated Vegetation-Complex Map (IVCM). The IVCM map-polygon boundaries are guided by information from a variety of remote-sensing data (AVHRR imagery, maximum greenness maps and classified images) and hard-copy source maps (surficial geology, bedrock geology, soils, percentage water cover). The map-polygon boundaries are integrated so that they conform to terrain features that are interpretable on the AVHRR CIR. The PFM and IVCM are overlaid in a geographic information system (GIS), and a series of derived maps is created through the use of look-up tables. Northern Alaska is a prototype area for the Circumpolar Arctic Vegetation Mapping (CAVM) project, which has a goal of producing a new vegetation map of the region north of the arctic tree line by the year 2001. The method could be modified and adapted to any region of the Arctic based on locally available information.

1. Introduction

The Circumpolar Arctic Vegetation Mapping (CAVM) project is a collaborative project involving vegetation scientists in all the circumpolar countries (Walker 1995, Walker *et al.* 1995, Walker and Markon 1996, Walker and Lillie 1997). The goal of the CAVM project is a 1:7.5 million scale vegetation map of the Arctic region north of the tree line with a consistent legend, similar to the 1:2.5 million-scale map of Europe (Bohn 1994). The map builds on the vegetation mapping heritage of Russia, where small-scale vegetation maps have been made by various authors for the Arctic region (e.g. Gribova *et al.* 1975, Shelkunova 1975, Isachenko and Lavrenko 1979, Andreev and Shcherbakov 1989). Vegetation maps of the Arctic vary greatly in their detail and quality. A new map is needed for a wide variety of scientific, educational

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and land-use planning uses. Currently, the CAVM project is developing a legend and method for making the maps that can be applied consistently across the whole Arctic. Prototype maps of relatively small areas in North America are being made to test various approaches. This paper presents a mapping approach that was developed for northern Alaska. It includes six steps with technical details and legends used for each step of the process. The method could be modified and adapted to any region of the Arctic based on available information.

Like many areas of the Arctic, northern Alaska has a small-scale vegetation map (Spetzman 1959), but the map is based on information collected before the vegetation was as well known as it is presently. The map portrays very broad categories of vegetation that in places are difficult to reconcile with modern vegetation maps based on satellite imagery (e.g. Walker *et al.* 1982, Jorgenson *et al.* 1994, Muller 1998). Some of the map unit boundaries are overly general and do not follow physiographic boundaries. The map also does not portray vegetation associated with different substrates that are evident on small-scale satellite imagery. For example, substrate pH defines the distribution of nonacidic plant communities, which have important ecosystem properties relevant for estimates of energy and trace-gas fluxes, wildlife habitat, and models linking climate to vegetation (Walker *et al.* 1998). It would be highly desirable to produce a vegetation map that combines all the available hard-copy-map information with satellite-derived information.

The integrated vegetation mapping approach is based on landscape-guided mapping espoused by the International Training Centre for Aerial Survey (ITC, now called the Institute for Aerospace Survey and Earth Sciences) in the Netherlands (Zonneveld 1988). A similar approach applied to geographic information system (GIS) technology has been described as the Integrated Terrain Unit Mapping (ITUM) approach (Dangermond and Harnden 1990). The approach uses the philosophy that soil and vegetation boundaries on maps are controlled principally by physiographic landscape features. In Arctic North America, this philosophy has been applied to geobotanical mapping (Walker *et al.* 1980). The integrated method described here requires that vegetation complexes first be defined and mapped based on a wide variety of sources, including remotely sensed images and hard-copy geology, soil, vegetation maps, and maps of vegetation greenness and satellite-derived land-cover classifications. Rather than aiming toward a single vegetation map, the goal of the integrated vegetation mapping approach described here is a vegetation database for deriving a variety of vegetation-related products and spatial information.

2. Methods

The method consists of six steps:

2.1. *Step 1, collect and reproduce source maps at 1:4 million scale (figure 1)*

The first step is to collect and evaluate all the relevant maps and literature for the region and then reproduce the source maps at a common 1:4 million scale. Map sources include remote sensing imagery described below (figure 1, maps 1–3; Fleming 1997a), a topography/hydrology map produced from the Digital Chart of the World (DCW; figure 1, map 4) and maps from literature sources (vegetation, surficial geology, bedrock geology, soils, percentage water cover, and phytogeographic subzones and floristic subprovinces) (figure 1, maps 5–10). The hard-copy maps that are useful for the project are photographically reproduced to 1:4 million scale to match the colour infrared (CIR) image. The following remote sensing and DCW

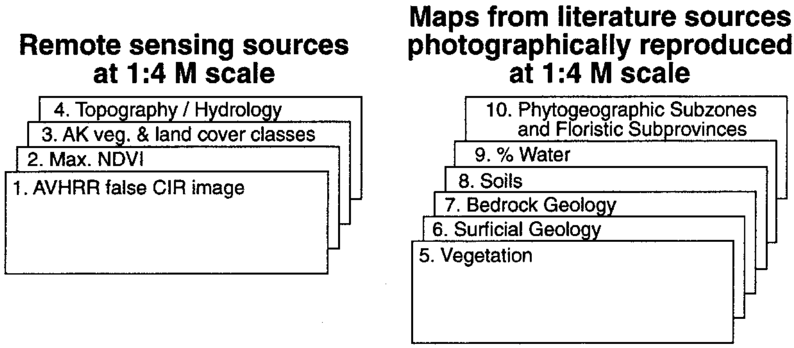

Figure 1. Source maps for the Alaskan portion of the CAVM.

products are used in the mapping process. Bold-face consecutive numbers of the paragraphs below refer to layer numbers in figures 1–6.

1. Advanced Very High Resolution Radiometer false colour infrared (AVHRR CIR) composite (1:4 M scale) (Fleming 1997b). This layer provides basic boundaries for the landscape units and is the base image to which all boundaries conform. It is the northern Alaska piece of an AVHRR false colour-infrared composite of the circumpolar region produced at 1:4 million-scale. It displays the maximum reflectance of the land surface for each 1×1-km pixel from a biweekly time series of AVHRR data obtained during the summer of 1992.

2. Maximum normalized difference vegetation index (Max NDVI) (Fleming 1997c). This layer is derived from the AVHRR data. NDVI is a measure of vegetation greenness and is defined by the equation $NDVI=(NIR-R)/(NIR+R)$, where NIR is the reflectance of the vegetation in near infrared portion of the spectrum and R is the reflectance in the red portion of the spectrum. Generally, the NDVI values are highest in vegetation with greater biomass. In tundra, Max NDVI is useful to define areas of sparse vegetation, such as barrens, or areas with high biomass such as shrublands. The Max NDVI image displays the maximum NDVI of the land surface for each 1×1-km pixel from a biweekly time series of AVHRR data obtained during the summer of 1992.

3. Alaska Vegetation/Landcover classes (Fleming 1997d). This layer was also prepared from the 1992 time series of AVHRR images. The classification contains 54 classes and is useful for helping to define boundaries on some vegetation classes.

4. Topography/hydrology map (Fleming 1997e). This layer is a polar projection of elevation and hydrological information in the Digital Chart of the World. This layer provides the coastal boundaries for the map and helps guide landscape-unit boundaries along rivers and major lakes and in the mountains.

2.2. *Step 2, simplify source maps and adjust boundaries to the AVHRR CIR image (figure 2)*

In Step 2 the source maps are *simplified to reflect only information that is relevant to the vegetation*, and the map polygon boundaries are adjusted to conform to the AVHRR CIR base map (figure 2, maps 5a–10a). Polygon boundaries are drawn on mylar overlays of the hard-copy source maps. Landsat or other finer-scale satellite images are also used to help delineate boundaries. Minimum polygon size is 3.5 mm except for river valleys and linear features, where a 2-mm minimum width is used.

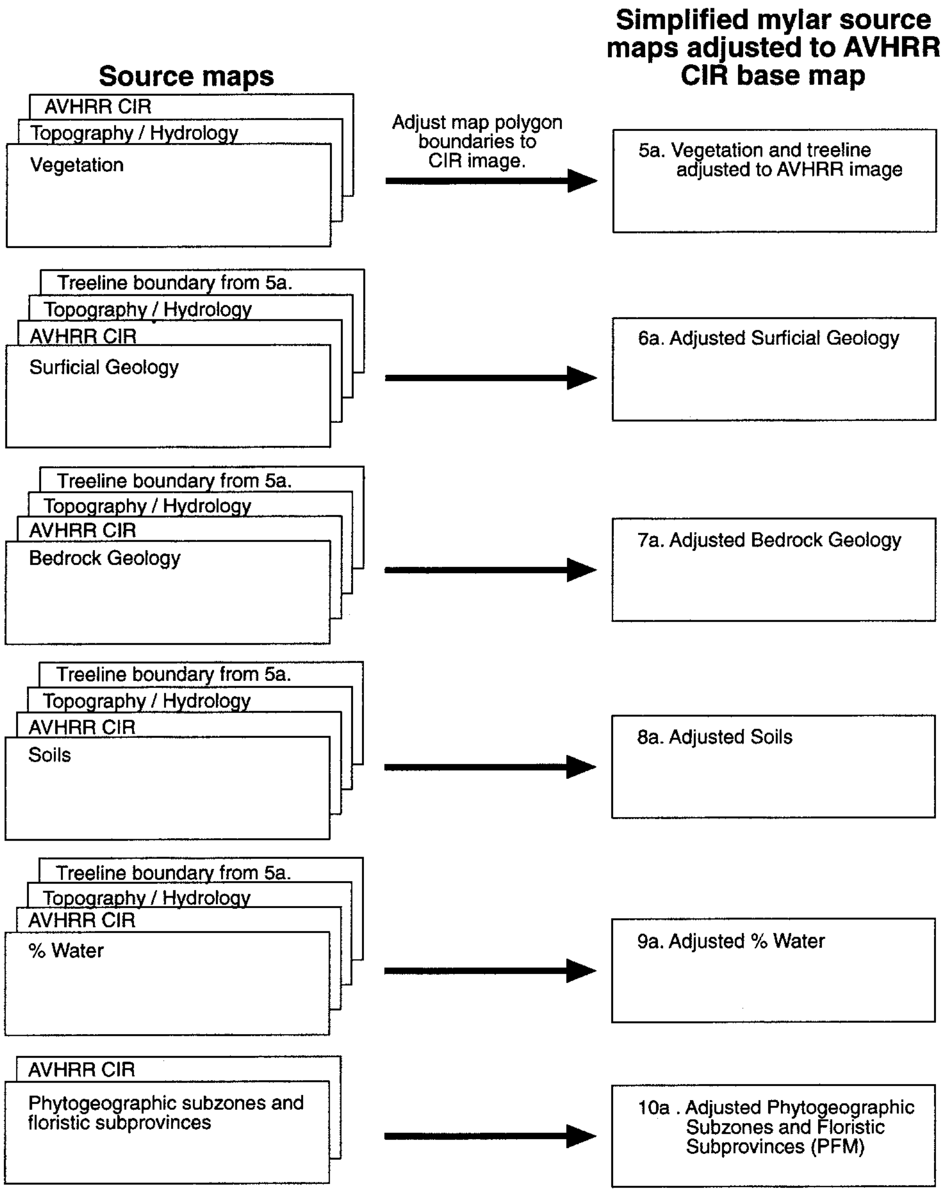

Figure 2. Creation of simplified source maps with boundaries adjusted to the AVHRR CIR base.

Map legends are also simplified to retain only information with known relevance to the vegetation. The simplified maps include:

5a. Vegetation. This layer is derived from the vegetation map of the Arctic Slope of Alaska (Spetzman 1959) and is used primarily for defining the treeline (southern boundary of the study area) and for some areas of alpine vegetation.

6a. Surficial geology. The differences in the vegetation on acidic and nonacidic substrates have not been previously mapped in northern Alaska, and it is necessary to use a combination of spectral information, soil and geological information to infer the location of these tundra types. This layer is derived from the Surficial Geology of Alaska (1:1 584 000 scale) (Karlstrom *et al.* 1964) and Surficial Geology Map of the National Petroleum Reserve, Alaska (Williams *et al.* 1977).

7a. Generalized bedrock geology. Bedrock composition is particularly important to plant communities in areas where bedrock is near the surface and not overlain by deep unconsolidated deposits. A variety of bedrock types are important to plants but, other than the contrasts between acidic and nonacidic bedrock (Cooper 1986), there is little literature regarding the relevance to Alaskan plant communities that could be mapped at 1:4 million scale. This layer is, therefore, greatly generalized from the Geologic map of Alaska (Beikman 1980). The units are generalized into groups that weather into acidic or nonacidic soils.

8a. Soil associations. Soil maps can help in defining the location of vegetation complexes associated with soils of different pH and texture. This is particularly useful in the foothills and coastal plain, where distinctive plant community complexes are associated with acidic sandy substrates, or nonacidic loamy substrates. The map is based on photointerpretation of AVHRR false CIR composite and several sources Hamilton and Porter 1975, Rieger *et al.* 1979, Gryc 1985, Hamilton 1986), and personal unpublished data from numerous surveys.

9a. Lake cover. Spectral variation within wetland complexes at the AVHRR scale is mainly a function of the size and density of lakes. In most cases, lakes have subpixel dimensions at the AVHRR scale (1×1-km pixels). The map boundaries were interpreted by reference to the more detailed Landsat images of the North Slope (USGS 1978, USGS EROS Data Center) and maps of the percentage cover of water on the Arctic Slope (Sellmann *et al.* 1975). Percentages reflect only lakes and do not include wetlands in marshes and drained lake basins.

10a. Phytogeographic subzones and Floristic subprovinces Map (PFM). This map shows the variation in north–south phytogeographic zonation due to temperature and east to west variation due to floristic variation. The map is based on information from Yurtsev's (1994) maps, which portray seven subzones and subzone variants (three of which occur in northern Alaska) and 21 subprovinces (two of which occur in northern Alaska). The boundaries of the units have been adjusted based on expert knowledge and interpretation of the AVHRR CIR image.

2.3. *Step 3, Integrated Landscape-Unit Map (ILUM) (figure 3)*

The ILUM (figure 3, map 11) includes all the geologic and terrain information relevant to the vegetation. The boundaries on this map are used to guide the boundaries on the Integrated Vegetation-Complex Map (IVCM) (next step). The map is based on photo interpretation of AVHRR CIR composite image 1:4 million (Fleming 1997a) and maps 6a–9a (surficial geology, bedrock geology, soils and

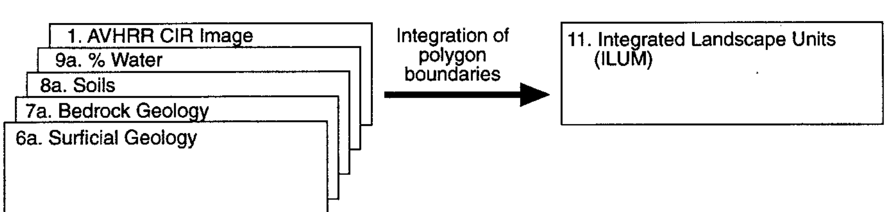

Figure 3. Procedure for making the Integrated Landscape-Unit Map (ILUM).

percentage cover of water). Landscape-unit boundaries are drawn on a mylar overlay of maps 6a–9a (surficial geology, bedrock geology, soils and percentage water) to create the ILUM. In some cases, the locations of mountain valleys and floodplains are difficult to delineate on the AVHRR CIR image, and the position of landscape unit boundaries is aided by reference to the standard false-colour controlled Landsat mosaic of mainland Alaska, Scale 1:1 million (USGS 1978) and other source maps.

The boundaries are reconciled to eliminate all unecessary polygons. The overlays are continuously shuffled to use the most relevant boundaries from the best source in different parts of the map and to minimize sliver polygons (narrow polygons that result from mismatched lines from different source maps). All boundaries are also reconciled to the AVHRR CIR base (figure 1, map 1). *Hard boundaries* are those associated with water boundaries, river corridors and major physiographic features, and are laid down first. *Soft boundaries* are those associated with features that vary across gradients, such as soils or percentage water cover, and are laid down second. The soft boundaries are adjusted to conform to hard boundaries wherever appropriate. A full explanation of the integrated mapping approach is contained in Dangermond and Harnden (1990). The method has been applied to terrain mapping at a wide variety of scales including entire continents. The advantages include: (a) use of common boundaries wherever possible for various geobotanical themes; (b) minimizing the total number of polygons stored in the GIS; (c) resolution of boundary inconsistencies between the various themes; and (d) smoothing of boundaries to eliminate unnecessary crenulations and sliver polygons. It allows information from a wide variety of sources to be compiled at a common scale with the same level of accuracy and registered to the same photo base. The following legend for the landscape units is modified slightly from that used for the maps shown in this paper and is recommended for future mapping.

11. Landscape units:

- Mountains
  1 Acidic mountain complex with coarse rubbly deposits, extensive bedrock
  2 Nonacidic mountain complex with coarse rubbly deposits, extensive bedrock
  3 Acidic plateau, basin or plain complex
  4 Nonacidic plateau, basin or plain complex
  5 Glaciated valley and moraine complex
- Hills
  6 Acidic hill complex with rare bedrock outcrops
  7 Acidic hill complex with occasional bedrock outcrops
  8 Nonacidic hill complex with rare bedrock outcrops
  9 Nonacidic hill complex with occasional bedrock outcrops
- Plains
  10 Acidic plains, $<25\%$ lakes
  11 Acidic plains, 25–75% lakes
  12 Nonacidic plains, $<25\%$ lakes
  13 Nonacidic plains 25–75% lakes
  14 Deltas and coastal wetlands (saline)
- Riparian areas
  15 River valley or alluvial complex

- Water and glaciers
  - 16 Water or lake complex (> 75% water cover)
  - 17 Glacier complex (> 75% glacier cover)

2.4. *Step 4, Integrated Vegetation-Complex Map (IVCM) (figure 4)*

At very small scales, it is not possible to map the details of plant communities, and it is necessary to map vegetation complexes related to terrain features. Vegetation complexes (figure 4, map 12) are created by adding vegetation information to the boundaries of the ILUM. For example, in northern Alaska, additional polygons were added from the vegetation map (map 5a, for some areas of alpine vegetation), maximum NDVI map (map 2, for areas of shrub tundra), and the classified AVHRR image (map 3, for better defining the boundary between moist acidic and moist nonacidic tundra). The boundaries of the new polygons are made to conform with existing boundaries wherever possible. The legend for the IVCM is given below.

An uncoded version of the IVCM, showing only the map polygon boundaries, is prepared for scan digitizing (map 13). This results in a raster-format file, which is then converted to a vector (or line) format using GIS software. Unique consecutive polygon identification (ID) labels are added to each polygon either automatically using GIS software or by manually creating centroids (dot in the centre) in each polygon and attaching the polygon ID number. A final polygon ID map is then produced that shows the polygon boundaries, centroids and polygon ID numbers.

12. Vegetation complexes.

- Mountains
  - 1 Acidic mountain complex with coarse rubbly deposits, extensive bedrock, and vertical zonation (vegetation zonation related to altitude)
  - 2 Nonacidic mountain complex with coarse rubbly deposits, extensive bedrock, and vertical zonation
  - 3 Acidic plateau, basin or plain complex
  - 4 Nonacidic plateau, basin or plain complex
  - 5 Glaciated valley and moraine complex

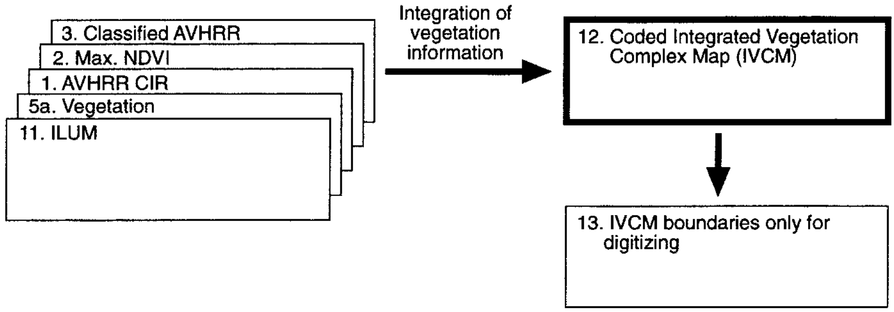

Figure 4. Procedure for making the Integrated Vegetation-Complex Map (IVCM) and version for digitizing.

- Hills
  - 6 Acidic hill complex with rare bedrock outcrops, no vertical zonation
  - 7 Acidic hill complex with occasional bedrock outcrops, no vertical zonation
  - 8 Nonacidic hill complex with rare bedrock outcrops, no vertical zonation
  - 9 Nonacidic hill complex with occasional bedrock outcrops, no vertical zonation
  - 10 Low- to high-shrub tundra complex on uplands
  - 11 Subalpine shrubland complex
  - 12 Mixed evergreen and deciduous forest on uplands (border area with Canada)
- Wetlands
  - 13 Acidic mire complex, < 25% lakes
  - 14 Acidic mire complex, 25–75% lakes
  - 15 Nonacidic mire complex, < 25% lakes
  - 16 Nonacidic mire complex, 25–75% lakes
  - 17 Coastal mire complex (saline)
- Riparian areas
  - 18 River floodplain complex
  - 19 Bottomland evergreen forest complex
  - 20 Bottomland deciduous forest complex
- Water and glaciers
  - 21 Water or lake complex (> 75% water cover)
  - 22 Glacier complex (> 75% glacier cover)

2.5. *Step 5, look-up tables (figure 5)*

The look-up tables relate the vegetation complexes to common plant communities and other vegetation information. The plant communities within the vegetation complexes vary according to the phytogeographic subzone and the floristic subprovince in which they occur (PFM, figure 5, map 10). A map showing the locations of all vegetation study locations (map 14) is overlaid on the PFM to find the relevant literature sources for each vegetation complex/subzone/subprovince combination.

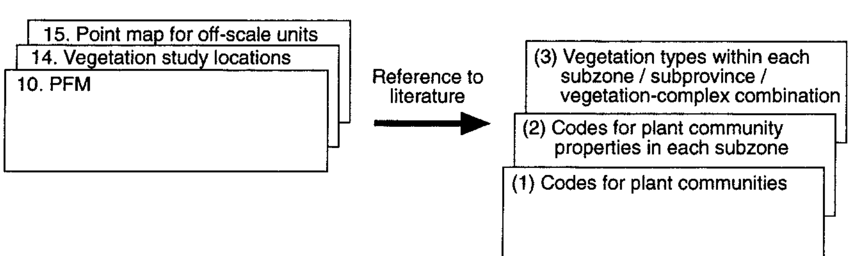

Figure 5. Derivation of look-up tables.

Plant communities and their characteristics (Braun–Blanquet class, community name, habitat, literature sources, dominant plant functional types (PFTs), horizontal structure, total biomass, net primary production (NPP)) within each subzone and subprovince are determined from the literature and expert knowledge. Codes giving the names and characteristics of the plant communities are listed in look-up tables 1 and 2. Look-up table 3 lists the dominant plant community codes for each vegetation complex/subzone/subprovince combination.

13. Polygon map with no labels. This map is the same as No. 12 except without labels or polygon codes so that the polygon boundaries can be scan digitized.

14. Locations of vegetation studies. This information is used to determine the dominant communities described in the literature for each vegetation complex/subzone/subprovince combination. These sites generally have detailed vegetation descriptions with complete species lists and/or vegetation maps derived from photo-interpretation. Information from these studies helps to create the information in the look-up tables.

Map code	Location	References
1	Barrow	(Webber 1978, Gersper *et al.* 1980, Webber *et al.* 1980, Elias *et al.* 1995)
2	Fish Creek	(Lawson *et al.* 1978)
3	Kuparuk Oil Field	(Everett and Walker 1982)
4	Prudhoe Bay Oil Field	(Everett and Parkinson 1977, Walker 1985, Walker and Acevedo 1987)
5	Barter Island	(Elias *et al.* 1995)
6	Meade River	(Everett 1980, Komárková and Webber 1980)
7	West Oumalik	(Ebersole 1985)
8	Umiat	(Bliss and Cantlon 1957, Chruchill 1955)
9	Sagwon Upland	(Walker *et al.* 1998)
10	Happy Valley	(Walker 1994)
11	Arctic National Wildlife Refuge	(Hettinger and Janz 1974, Walker *et al.* 1982, Jorgenson *et al.* 1994)
12	Cape Thompson	(Holowaychuk *et al.* 1966, Johnson *et al.* 1966)
13	Arrigetch Mountains	(Cooper 1986)
14	Toolik Lake	(Walker *et al.* 1994)
15	Imnavait Creek	(Walker *et al.* 1989, Walker and Walker 1996)
16	Kobuk River Valley	(Racine 1976)
17	Lake Peters	(Batten 1977)
18	Noatak River	(Young 1973)
19	Killik River	(Murray 1974)

2.5.1. *Look-up table 1. Codes for plant communities (table 1)*

Table 1 contains the plant-community names, habitats and literature sources:

Look-up table 1. Partial list of plant communities, habitats and literature sources.

Veg code	B–B class and plant community	Habitat	Source
01000	***Rhizocarpetea geographici***	**Acidic rock lichen communities**	
01010	*Cetraria nigricans-Rhizocarpon geographicum* comm.	Xeric, acidic, sandstone and conglomerate rocks	Walker *et al.* 1994
02000	***Carici rupestris-Kobresietea bellardii***	**Dry, often calcareous, tundra swards**	
02010	*Selaginello sibiricae-Dryadetum octopetalae*	Xeric, exposed, acidic, rocky slopes, mountains, foothills	Walker *et al.* 1994
02011	*Oxtropis bryophila* ssp. *pygmaeus-Dryas octopetala* comm.	Xeric, exposed, acidic, rocky slopes, Cape Thompson	Johnson *et al.* 1966
02012	*Dryas integrifolia-Oxytropis nigrescens* comm.	Xeric, exposed, calcareous sites, coastal plain	Walker and Everett 1991
02020	*Dryas integrifolia-Cassiope tetragona* comm.	Subxeric, well-drained, nonacidic, shallow snowbeds	Walker *et al.* 1994
03000	***Cetrario-Loiseleurietea***	**Dry acidic tundra**	
03010	*Salici phlebophyllae-Arctoetum alpinae*	Subxeric, moderately exposed, acidic, rocky sites, glacial till, foothills, sandstone	Walker *et al.* 1994
03020	*Hierochloë alpina-Betula nana* comm.	Subxeric, somewhat protected, acidic sites	Walker *et al.* 1994
03030	*Carici microchaetae-Cassiopetum tetragonae*	Subxeric, well drained, acidic shallow snowbeds	Walker *et al.* 1994
04000	**Salicetea herbaceae**	**Snow patch communities**	
04010	*Salix rotundifolia* comm.	Mesic, nonacidic, deep snowbeds	Walker *et al.* 1994
05000	***Oxycocco-Sphagnetea***	**Raised bogs, acidic tussock tundra**	
05010	*Sphagno-Eriophoretum vaginati* typicum	Mesic to subhygric, acidic, uplands, moderate snow	Walker *et al.* 1994, Churchhill 1955, Bliss 1956, Johnson *et al.* 1966
05011	*Eriophorum vaginatum-Cassiope tetragona* comm.	Coastal plain tussock tundra with short tussocks and few shrubs	Walker unpub.
05020	*Sphagno-Eriophoretum vaginati betuletosum nanae* subass. prov.	Dwarf-birch dominated, mesic margins of water tracks, high-centred polygons	Walker *et al.* 1994
05030	*Sphagnum lenense-Salix fuscescens* comm.	Subhygric, acidic fens	Walker *et al.* 1994
06000	***Scheuchzerio-Caricetea nigrae***	**Small sedge nonacidic mires and moist tundra**	
06010	*Dryado integrifoliae-Caricetum bigelowii*	Mesic to subhygric, non-acidic, uplands foothills	Walker *et al.* 1994
06011	*Eriophorum triste-Dryas integrifolia* comm.	Mesic to subhygric, non-acidic, uplands coastal plain	Walker 1985

06012	*Trichophorum caespitosum-Tomentypnum nitens* comm.	Subhygric hummocks in fens	Walker unpub.
06020	*Sphagnum orientale-Eriophorum scheuchzeri* comm.	Hygric, acidic, poor fens	Walker *et al.* 1994
06030	*Eriophorum angustifolium-Carex aquatilis* comm.	Hygric, non-acidic fens	Walker *et al.* 1994
06031	*Carex aquatilis-Saxifraga cernua* comm.	Mesic to subhygric acidic coastal uplands, Barrow	Elias *et al.* 1996
06032	*Eriophorum angustifolium-Carex aquatilis-Calliergon sarmentosum* comm.	Hygric, acidic, poor fens, coastal areas	Elias *et al.* 1996
06033	*Eriophorum angtustifolium-Carex aquatilis-Drepanocladus brevifolius* comm.	Hygric, non-acidic fens, coastal plain	Walker 1985, Elias *et al.* 1995
06040	*Carex aquatilis-Carex chordorrhiza* comm.	Subhygric to hygric, non-acidic fens	Walker *et al.* 1994
06050	*Hippuris vulgaris-Arctophila fulva* comm.	Hydric, marshes, pond margins	Walker *et al.* 1994
07000	***Potametea***	**Rooted water-plant communities**	
07010	*Hippuris vulgaris-Sparganium hyperboreum* comm.	Hydric, ponds and lake margins	Walker *et al.* 1994
08000	***Juncetea maritimi***	**Coastal shore shallow water communities**	
08010	*Caricetum subspathacea*	Hygric, saline, tidal areas	Hadac 1946, Walker *et al.* 1980
09000	***Betulo-Adenostyletea***	**Tall perennial herb and shrub communities**	
09010	*Salix alaxensis-Salix lanata* comm.	Riparian, calcareous shrublands	Walker *et al.* 1994
09011	*Epilobium latifolium-Artemisia arctica* comm.	Riparian, coastal, depauperate	Walker 1985
09020	*Eriophorum angustifolium-Salix planifolia* ssp. *pulchra* comm.	Riparian, noncalcareous shrublands	Walker *et al.* 1994
09030	*Alnus crispa*	Subalpine alder thickets	Racine 1976
09031	*Alnus crispa-Carex bigelowii*	Alder savannas	Racine 1976
10000	**Miscellaneous communities and other**		
10010	*Anthelia juratzkana-Juncus biglumis* comm.	Acidic nonsorted circles	Walker *et al.* 1994
10020	*Saxifraga oppositifolia-Juncus biglumis* comm.	Nonacidic nonsorted circles	Walker *et al.* unpub.
10030	*Picea glauca-Betula papyrifera*	Upland forests, Canadian border	
10040	*Picea glauca-Betula nana*	Valley forests, Noatak River	Young 1973
11000	Barren		
12000	Water		
13000	Ice		

Column 1, plant-community codes. The codes are standardized according to the following format: Each plant community is given a 5-digit code with the first two numbers corresponding to the Braun–Blanquet class (bold numbers and names, see column 2). The third and fourth numbers refer to the association or plant community, and fifth number corresponds to the subassociation.

Column 2, Braun–Blanquet class and plant-community name. The Braun–Blanquet approach is a standard hierarchical system of vegetation classification based on plant-community floristics used worldwide (Westhoff and van der Maarel 1978). Although the Arctic is still poorly studied according to the Braun–Blanquet approach, the method is applied wherever possible in order to provide a consistent framework of nomenclature (Walker *et al.* 1994, Daniels 1996). Several studies in northern Alaska have utilized the Braun–Blanquet approach (Cooper 1986, M.D. Walker *et al.* 1995, Schikoff in prep.). The plant communities in look-up table 1 are grouped according to Braun–Blanquet classes. The classes are broad groups of vegetation communities roughly corresponding to habitat categories. Published Braun–Blanquet association names are used wherever possible. These formal names, with an *-etum* suffix, permit a great deal of inferred information regarding species composition, geographic location and habitat. If no Braun–Blanquet association name is available, the best available plant-community description is selected as the reference plant community. The reference information should contain a complete species list for the community (vascular plants and cryptograms), preferably with a table showing the abundance of the species in multiple relevés or samples. Informal plant-community names that have not been published according to the Braun–Blanquet protocols should contain two species, the dominant plant species and a characteristic plant species, preferably one that is characteristic of the floristic subregion in which the community occurs. For subassociations, a third plant species characteristic of the subassociation is included in the name. The plant names are italicized and separated by a dash, and *comm.* is added at the end of the name to indicate a temporary or informal community name.

Column 3, habitat. Habitat information is given emphasizing site moisture, pH conditions, special habitat conditions and distribution of the plant community if it is restricted to a certain region.

Column 4, literature source. The author(s) of the article in which the community is described and the date of publication. A bibliography containing all the literature citations is also included.

2.5.2. *Look-up table 2. Plant-community properties in each subzone (table 2)*

Table 2 provides a description of vegetation properties (plant functional types, horizontal structure, biomass and net primary production). Other properties such as suitability for wildlife, resistance to disturbance, or trace-gas and energy fluxes could also be added for the derivation of the other maps.

Column 1. Plant-community codes (from look-up table 1); columns 2–4. Plant functional types (PFTs). The concept of plant functional types is being used to help reduce the complexity of the multitude of plant species to a smaller number of functional types that are more useful for modelling ecosystem processes (Smith *et al.* 1997). The following list of Arctic plant functional types was derived at a workshop to apply the BIOME model (Prentice *et al.* 1992) to the Arctic region. Secondary and tertiary PFTs are listed if they normally occupy $>30\%$ of the plant cover of the dominant plant community of a vegetation complex. Example plant species for each PFT are in parentheses.

Look-up table 2. Vegetation properties for each plant community in look-up table 1. Primary, secondary, and tertiary plant functional types refer to plant occupying at least 30% of the plant cover. Horizontal structure, biomass and NPP are allowed to vary across subzone boundaries.

	Plant functional types			Horizontal structure			Total biomass ($g\ m^{-2}$)			Net primary production ($g\ m^{-2}\ year^{-1}$)		
Veg code	1°	2°	3°	Sub-zone2	Sub-zone3	Sub-zone4	Sub-zone2	Sub-zone3	Sub-zone4	Sub-zone2	Sub-zone3	Sub-zone4
01000												
01010	18	17		2	2	2	1	1	1	1	1	1
02000												
02010	8	17	12	2	3	3	2	2	2	2	2	2
02011	8	17	12	2	3	3	2	2	2	2	2	2
02012	8	17	12	2	3	3	2	2	2	2	2	2
02020	6	18	8	4	4	4	3	3	3	2	2	2
03000												
03010	9	18	6	na	4	4	na	2	2	2	2	2
03020	7	18		na	na	3	na	na	3	na	na	3
03030	6	18	11	na	na	4	na		2	na	na	2
04000												
04010	9			4	4	4	2	2	2	2	2	2
05000												
05010	7	19	6	3	4	4	3	3	4	3	3	4
05011	19	6	7	3	4	na	3	3	na	3	3	na
05020	7	6	19	na	na	4	na	na	5	na	na	4
05030	10	16	7	na	4	4	na	3	3	na	4	5
06000												
06010	11	8	14	2	3	3	2	3	3	2	3	3
06011	11	8	14	2	na	na	2	na	na	3	na	na
06012	19	14	6	na	na	4	na	na	3	na	na	3
06020	10	16		na	na	3	na	na	2	na	na	3
06030	10	14		3	3	3	2	2	3	2	3	3
06031	10	14	13	3	na	na	2	na	na	2	na	na
06032	10	14		3	na	na	2	na	na	2	na	na
06033	10	14		3	3	4	2	3	3	2	3	3
06040	10	14		na	3	4	na	3	3	na	3	3
06050	10	20	14		2	2	2	3	3	2	3	3
07000												
07010	20	14		na	2	2	na	3	3	na	3	3
08000												
08010	10			3	3	3	2	2	2	2	2	2
09000												
09010	5	13		na	3	4	na	4	5	na	4	5
09011	13			2	2	2	1	1	2	1	1	2
09020	5	10	16	na	3	4	na	4	5	na	4	5
09030	5			na	na	4	na	na	6	na	na	6
09031	5	11	7	na	na	4	na	na	5	na	na	5
10000												
10010	17	11		1	1	1	1	1	2	1	2	2
10020	12	17	11	1	1	1	1	1	2	1	2	2
10030	1	5		na	na	4	na	na	6	na	na	5
10040												
11000				1	1	1	1	1	1	1	1	1
12000				1	1	1	1	1	1	1	1	1
01300				1	1	1	1	1	1	1	1	1

01 Evergreen needleleaf tree (*Picea glauca*)
02 Deciduous broadleaf tree (*Populus balsamifera*)
03 Deciduous needleaf tree (*Larix laricina*)
04 Low to tall evergreen shrub (> 50 cm) (*Pinus pumila*)
05 Low to tall deciduous shrub (> 50 cm) (*Alnus crispa*, *Betula*, *Salix*)
06 Dwarf evergreen shrub (3–50 cm) (*Cassiope*, *Ledum*, *Empetrum*, *Vaccinium vitis-idaea*
07 Dwarf deciduous shrub (3–50 cm) (*V. uliginosum*, many *Salix*, *Artemisia*)
08 Prostrate evergreen shrub (mat forming, < 3 cm) (*Dryas*, *Loiseleuria*)
09 Prostrate deciduous shrub (mat forming, < 3 cm) (*Salix arctica*, *Arctous alpina*, *S. polaris*, *S. ovalifolia*)
10 Wet graminoids (*Carex aquatilis*, *Eriophorum angustifolium*, *Arctophila*)
11 Dry graminoids (*Hierochloë alpina*, *Carex rupestris*, *Luzula confusa*)
12 Cushion and rosette forbs (*Saxifraga*, *Draba*, *Silene*, *Papaver*)
13 Other forbs (*Pedicularis* , *Astragalus*, *Eutrema*)
14 True mosses and liverworts (*Bryum*, *Dicranum*, *Tomentypnum*, *Calliergon*, *Ptilidium*)
16 *Sphagnum*
17 Crustose lichens and bryophytes (*Rhizocarpon*, *Lecanora*, *Lecidea*)
18 Foliose and fruticose lichens (*Thamnolia*, *Cladonia*, *Peltigera*)
19 Tussock graminoids (*Eriophorum vaginatum*, *Deschampsia caespitosa*)
20 Aquatic forbs (*Sparganium*, *Potomogeton* , *Menyanthes trifoliata*)

Columns 5–7. Horizontal structure for the plant community within each subzone. Horizontal structure refers to the openness of the plant canopy.

1 Barren, very limited, 0–5% cover of plants
2 Open patchy vegetation, scattered clusters of vegetation, 5–50% cover of plants
3 Interrupted closed vegetation, closed vegetation canopy with patches of bare soil, 50–80% cover of plants
4 Closed canopy, 80–100% cover of plants

Columns 8–10. Biomass classes (aboveground and belowground, g m^{-2}) (Bliss and Matveyeva 1992, Gilmanov 1997, Shaver *et al.* 1997). Examples of Arctic areas for each biomass class are in parentheses. Biomass of plant communities can vary across subzone boundaries, and separate columns are provided in look-up table 2 for biomass in each subzone.

1 0–100 (polar deserts)
2 100–500 (polar semidesert, high arctic mires)
3 500–750 (low arctic mires)
4 750–2000 (tussock tundra)
5 2000–4000 (low shrublands)
6 4000–10 000 (tall shrublands)

Columns 11–13. Net primary production (NPP) classes (aboveground and belowground, g m^{-2}) (Bliss and Matveyeva 1992, Gilmanov 1997, Shaver *et al.* 1997). Examples of Arctic areas for each NPP class are in parentheses. NPP of plant communities can vary across subzone boundaries, and separate columns are provided in look-up table 2 for NPP in each subzone.

1 0–20 (polar desert, barrens)
2 20–50 (dry tundra, polar semidesert)

3 50–150 (high arctic mires, northern tussock tundra, MNT)
4 150–250 (low arctic mires, southern tussock tundra)
5 250–1000 (low-shrub tundra)
6 > 1000 (tall shrublands, forest tundra)

2.5.3. *Look-up table 3. Primary, secondary, and tertiary plant communities within each subzone/subprovince vegetation-complex combination (table 3)*

Table 3 lists the common plant communities occurring in each vegetation complex with each subzone and subprovince. Veg1, Veg2 and Veg3 are primary, secondary and tertiary plant communities. Secondary and tertiary communities are listed if they normally cover more than 30% of a vegetation complex. Refer to look-up table 1, column 1 for the list of vegetation codes.

Column 1. Phytogeographic subzones. Based on Yurtsev (1994):

1 High Arctic Tundra (Rosette-forb, lichen, moss subzone)
2 Arctic Tundra (Prostrate shrub, herb subzone)
3 Northern Hypoarctic (Sedge, dwarf-shrub subzone)
4 Southern Hypoarctic (Low-shrub subzone)

Column 2. Floristic subprovinces (Yurtsev 1994):

1 Northern Alaska
2 Beringian Alaska

Column 3. Vegetation complex. Refer to Step 4, map 12. **Column 4–6. Plant communities.** These codes denote the dominant plant communities with the vegetation complex. Refer to look-up table 1 for the list of plant community codes. Secondary and tertiary types are listed if they usually cover more than 30% of the vegetation complex.

Look-up table 3 (excerpt). Common plant communities within each subzone/subprovince/vegetation-complex combination. Subdominant plant communities (Veg2 and Veg3) are listed if they normally occupy more than 30% of a vegetation complex. Code na means that no plant communities occur in that combination.

Subzone	Subprovince	Veg. Complex	Veg1	Veg2	Veg3
1	1	1	na	na	na
1	1	2	na	na	na
1	1	3	na	na	na
1	1	4	na	na	na
1	1	5	na	na	na
1	1	6	05011	10010	
1	1	7	na	na	na
1	1	8	06011	10020	
1	1	9	na	na	na
1	1	10	na	na	na
1	1	11	na	na	na
1	1	12	na	na	na
1	1	13	09011	06011	11000
1	1	14	na	na	na
1	1	15	na	na	na
1	1	16	06032	06031	

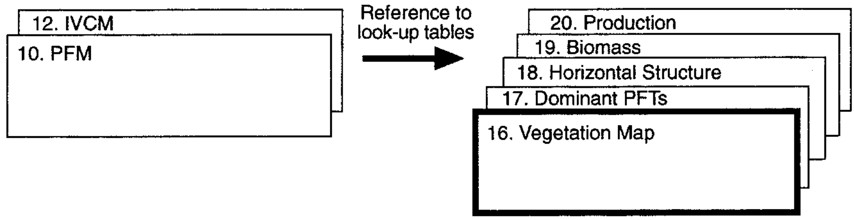

Figure 6. Making the final vegetation map and other derived maps.

2.6. *Step 6, derived maps (figure 6)*

The vegetation map (figure 7) is created by overlaying the IVCM (map 12) and PFM (map 10) in a GIS with reference to look-up table 3 to derive a vegetation (map 16, figure 6). Separate maps are also prepared for each theme (PFTs, horizontal structure, biomass and production), by reference to the look-up tables (maps 16–20 in figure 6, also figures 8–11).

Maps portraying the separate geobotanical attributes that went into the Integrated Vegetation-Complex Map (IVCM) can also be prepared (Walker *et al.* 1980). A coding sheet (not shown) is prepared with a list of all the polygon ID numbers, and columns corresponding to each geobotanical attribute (surficial geology, bedrock geology, soils, percentage water). The polygon ID map (map 13 except with polygon ID numbers) is overlaid on a given adjusted source map (e.g. surficial geology, map 6a) and the attribute code corresponding to each polygon on IVCM is entered on the data sheet. This procedure is repeated for all the geobotanical attributes. This information is then keypunched. This data file, in combination with the file containing the topological information for each polygon, makes up the GIS database. Separate maps can be prepared for any of the attributes, or models can be made utilizing information from several attributes. The maps should be checked against the original source information.

3. Concluding remarks

1. the integrated mapping method provides a new picture of the vegetation of northern Alaska. This preliminary map was prepared independently of the MSS-derived map of northern Alaska (Muller *et al.* 1999, this volume), and it is intended for reproduction at a much smaller scale than the Muller *et al.* map. The map will have to be revised to take advantage of new information from the MSS-derived map and other recent sources. The final map will be supplemented with diagrams showing vegetation-terrain (altitudinal zonation) relationships in well-known areas of the map.

2. Accuracy assessment of maps covering such large areas is impractical; however, some field checking of the map of northern Alaska is planned as part of the Arctic System Science Arctic Transitions in the Land–Atmosphere System (ATLAS) project (Weller *et al.* 1995) to confirm some of the patterns that have not appeared on previous maps.

3. Within northern Alaska, there is currently insufficient literature to determine differences in plant communities related to floristic subprovinces. This may be generally true throughout the Arctic, and it may be better to portray only the variation due to six floristic provinces instead of the 21 subprovinces of Yurtsev (1994).

4. The method for making the map could provide a standard framework for the CAVM. The integrated mapping method proposed here relies on a wide variety of

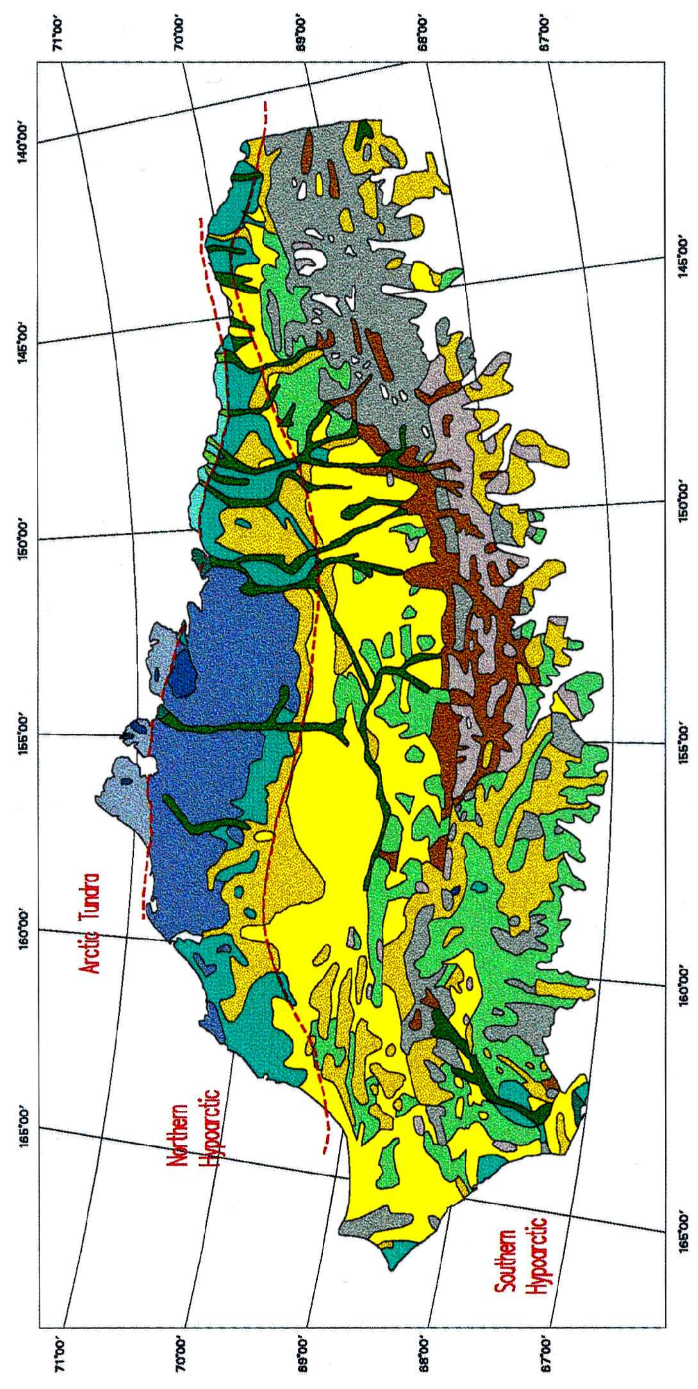

Figure 7. Vegetation map of northern Alaska derived from the integrated mapping approach.

Subzone	*Subprovince*	*Vegetation complex (GIS codes)*	*Common plant communities (primary, secondary, and tertiary)*
Arctic tundra (2)	Northern Alaska (1)	**Riparian areas:** River floodplain complex (13)	*Epilobium latifolium-Artemisia arctica* comm. (gravel bars), *Eriophorum triste-Dryas integrifolia* comm. (moist stable terraces), barrens (active channels)
		Wetlands: Acidic mire complex (16)	*Eriophorum angustifolium-Carex aquatilis-Calliergon sarmentosum* comm. (wet sites), *Carex aquatilis-Saxifraga cernua* comm. (moist sites)
		Nonacidic mire complex (18)	*Eriophorum angustifolium-Carex aquatilis-Drepanocladus brevifolium* comm. (wet sites), water *Eriophorum angustifolium-Carex aquatilis-Drepanocladus brevifolium* comm. (wet sites), *Carex aquatilis-Saxifraga cernua* comm. (moist sites) *Eriophorum angustifolium-Carex aquatilis-Drepanocladus brevifolium* comm. (wet sites), water (lakes), *Eriophorum triste-Dryas integrifolia* comm. (moist sites)
		Coastal mire complex (saline) (20)	*Caricetum subspathacea* (wet saline), water (lakes), barrens (coastal mud flats)
Northern hypoarctic tundra (3)	Northern Alaska and Beringian Alaska (1,2)	**Hills:** Acidic hill complex (6)	*Sphagno-Eriophoretum vaginati* typicum (moist sites), *Sphagno-Eriophoretum vaginati betuletosum nanae* subass. prov. (water tracks, raised areas in colluvial basins), *Sphagnum orientale-Eriophorum scheuchzeri* comm. (poor fens in colluvial basins)
		Nonacidic hill complex (8)	*Dryado integrifoliae-Caricetum bigelowii* (moist sites), *Saxifraga oppositifolia-Juncus biglumis* comm. (nonsorted circles)
		Riparian areas: River floodplain complex (13)	*Epilobio latifolii-Salicetum alaxensis* (river margins), *Salico glaucae-Salecetum lanatae* (upper terraces), barrens (active channels)
		Wetlands: Acidic mire complex (16)	*Carex aquatilis-Carex chordorrhiza* comm. (wet sites), *Sphagno-Eriophoretum vaginati* typicum (moist sites), water (lakes)
		Nonacidic mire complex (18)	*Eriophorum angustifolium-Carex aquatilis-Drepanocladus brevifolium* comm. (wet sites), *Eriophorum triste-Dryas integrifolia* comm., water (lakes)
		Coastal mire complex (saline) (20)	*Caricetum subspathacea* (wet saline), water (lakes), barrens (coastal mud flats)
Southern Hypoarctic (4)	Northern Alaska and Beringian Alaska (1,2)	**Mountains:** Acidic mountain complex with coarse rubbly deposits, extensive bedrock, and vertical zonation (1)	*Vaccinio uliginosi-Salicetum phlebophyllae* (ridgetops), barrens (bedrock and rubble), *Carici microchaetae-Cassiopetum tetragonae* (acidic snowbeds), *Carici microchaetes-Cladonietum stellaris* (high elevation lichen heaths)
		Nonacidic mountain complex with coarse rubbly deposits, extensive bedrock, and vertical zonation (2)	*Caricetum scirpolides-rupestris* (south-facing slopes), barrens (bedrock and rubble); *Boykinio richardsonii-Dryadetum alaskensis* (snowbeds)
		Glaciated valley and moraine complex (5)	*Dryado integrifoliae-Caricetum bigelowii* (mesic colluvium), *Salici phlebophyllae-Arctoetum alpinae* (moraine and kames crests), *Dryas integrifolia-Cassiope tetragona* comm. (snowbeds)
		Hills: Acidic hill complex (6)	*Sphagno-Eriophoretum vaginati* typicum (moist sites), *Sphagno-Eriophoretum vaginati betuletosum nanae* subass. prov. (water tracks, raised areas in colluvial basins), *Sphagnum orientale-Eriophorum scheuchzeri* comm. (poor fens in colluvial basins)
		Nonacidic hill complex (8)	*Dryado integrifoliae-Caricetum bigelowii* (moist sites), *Saxifraga oppositifolia-Juncus biglumis* comm. (nonsorted circles) *Dryado integrifoliae-Caricetum bigelowii* (moist sites), *Saxifraga oppositifolia-Juncus biglumis* comm. (nonsorted circles), *Selaginello sibiricae-Dryadetum octopetalae* (ridge tops and south facing slopes)
		Low- to high-shrub tundra complex on uplands and Subalpine shrublands (10)	*Sphagno-Eriophoretum vaginati betuletosum nanae* subass. prov. (shrub tundra), *Alnus crispa-Carex bigelowii* (alder savannas), *Eriophorum angustifolium-Salix planifolia* spp. *pulchra* comm. (water tracks), *Alnus crispa* (subalpine alder shrublands), barrens (active river channels)
		Riparian areas: River floodplain complex (13)	*Epilobio latifolii-Salicetum alaxensis* (river margins), *Salico glaucae-Salecetum lanatae* (upper terraces), barrens (active channels)
		Evergreen forest complex (14)	*Picea glauca-Betula nana* (moderately drained sites), *Sphagno-Eriophoretum vaginati betuletosum nanae* subass. prov. (shrub tundra), *Eriophorum angustifolium- Carex aquatilis* comm. (wetlands)
		Wetlands: Nonacidic mire complex (18)	*Eriophorum angustifolium-Carex aquatilis-Drepanocladus brevifolius* comm. (wet sites), *Dryado integrifoliae-Caricetum bigelowii* (moist sites) *Eriophorum angustifolium-Carex aquatilis-Drepanocladus brevifolius* comm. (wet sites), water (lakes), *Eriophorum triste-Dryas integrifolia* comm.
		Coastal mire complex (saline) (20)	*Caricetum subspathacea* (wet saline), water (lakes), barrens (coastal mud flats)
		Other: Water complex (>75% water cover) (21)	
		Glacier complex (>75% glacier cover) (22)	

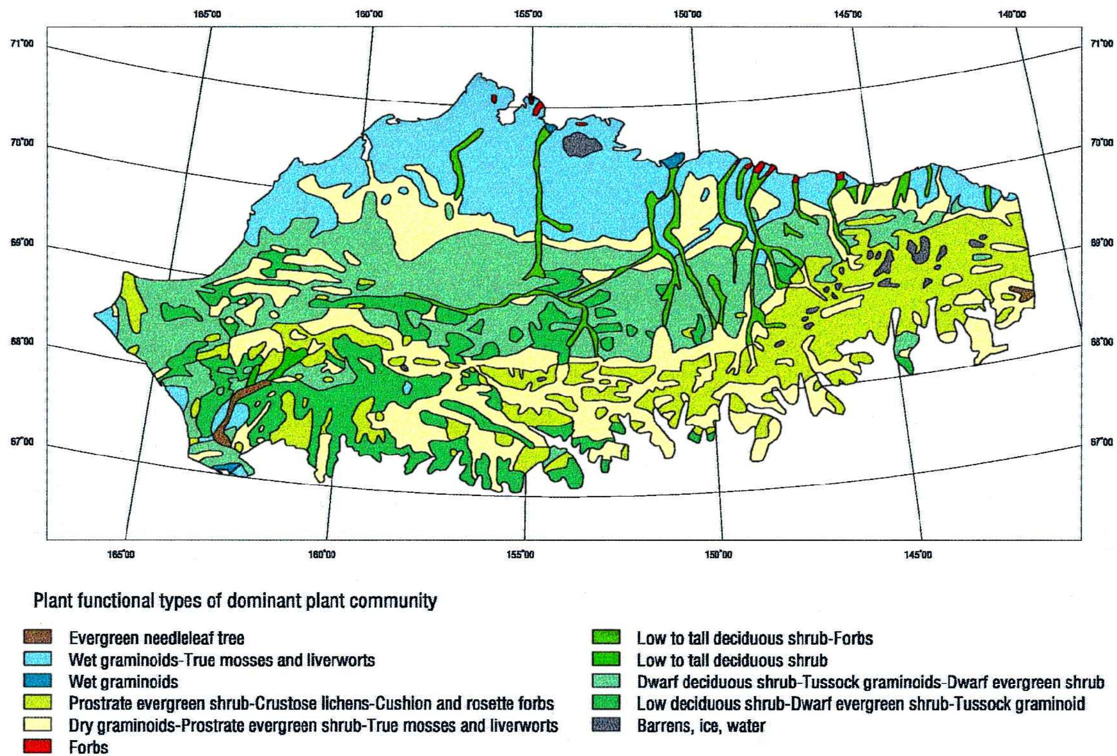

Figure 8. Dominant plant functional types in northern Alaska.

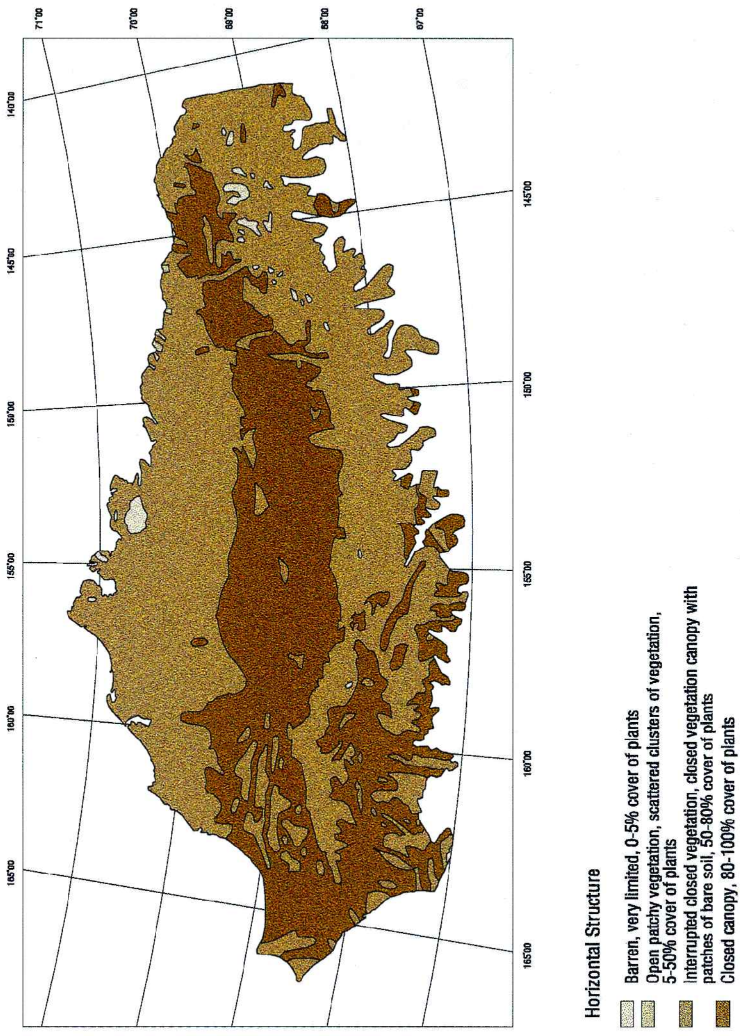

Figure 9. Horizontal structure of the vegetation canopy in northern Alaska.

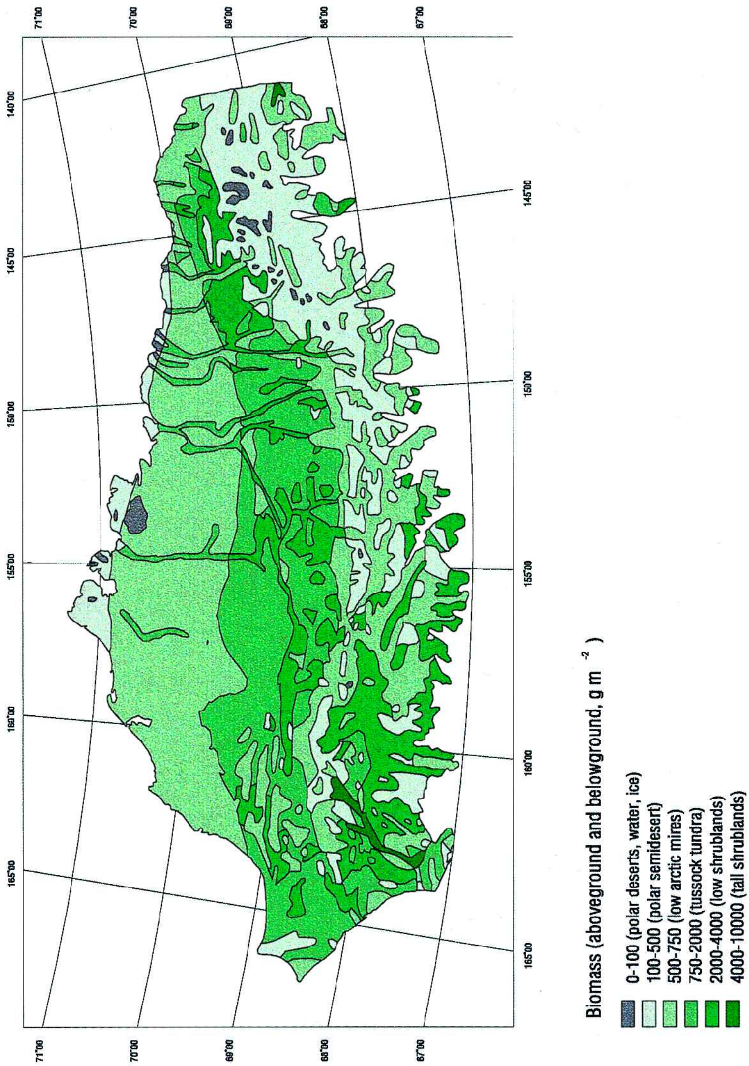

Figure 10. Biomass map of northern Alaska.

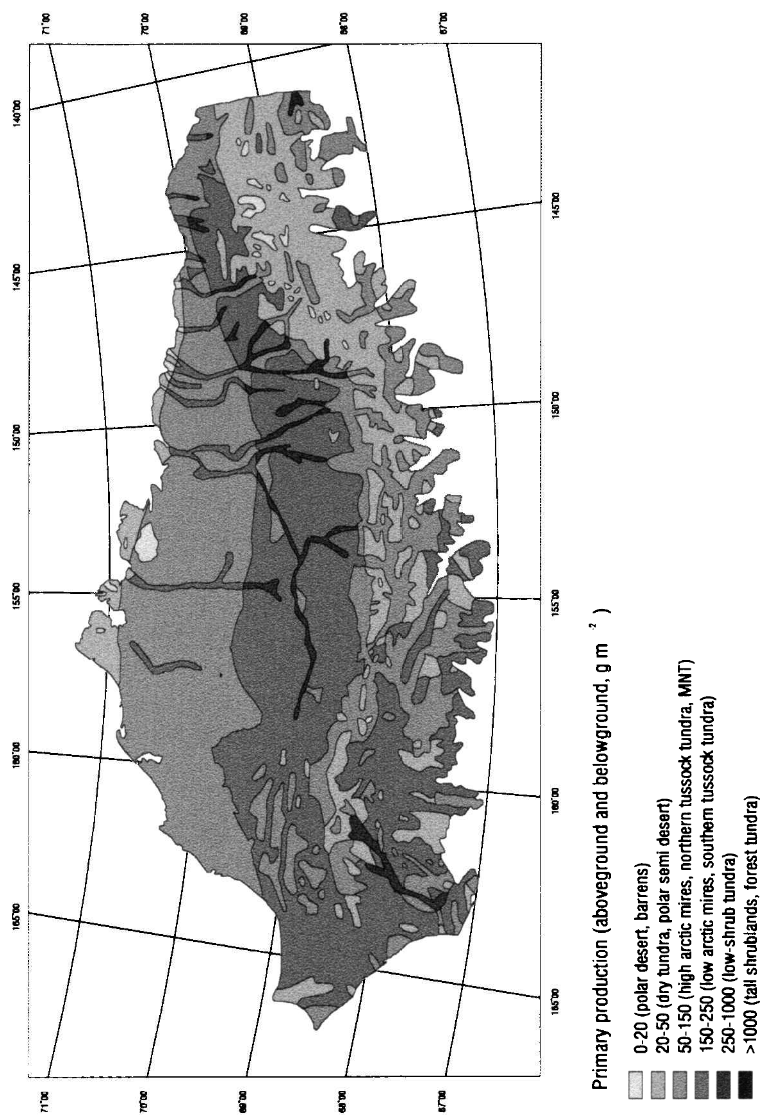

Figure 11. Net primary production in northern Alaska.

source maps including remotely sensed information and maps available in the literature. Not all of these resources are available to all the circumpolar countries, and the method would have to be adapted to the information that is available.

5. Although remote sensing and automated mapping methods are central to the method, it is not an automatic approach. It relies heavily on the ability of the vegetation mapper to integrate information from a variety of disciplines, and this requires local experts to help produce the map. This could prove to be a drawback in areas that are not as well known as northern Alaska. However, the integration of information from many sources allows the mapper to make educated guesses regarding the vegetation, which could not be done based solely on existing vegetation maps or aerial photographs. There are some potential pitfalls related to using GIS methods if mappers in some countries are not familiar with these techniques, but there are also large benefits including the ability to produce a wide variety of derived maps and the flexibility of the database for modelling purposes.

6. The inclusion of the phytogeographic-zone and floristic-subprovince boundaries allows easy modification of the maps as new information regarding these boundaries becomes available. It should be permissible to reduce the number of subzone/subprovince/vegetation-complex combinations by creative use of colours. It is recommended that the primary colour refers to the dominant vegetation of the vegetation complex and that shades of the colours represent variations related to north–south zonation. East–west variation related to floristic-province differences could be shown by patterns overlaid on the colours or with the use of letters.

7. For consistency, the CAVM project needs to agree on the basic set of landscape units and vegetation complexes that will be mapped. It should be expected that additional terrain units and vegetation complexes will be required in other geographic regions as the mapping proceeds.

8. This method should allow the CAVM project to begin work immediately without first finalizing the ultimate vegetation legend. By using the vegetation complexes and look-up tables, each country can proceed with mapping using their own local source maps. The properties of the vegetation, which is what most users will be interested in, are contained in the look-up tables.

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