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LETTER

Circumpolar Arctic vegetation: a hierarchic review and roadmap toward an internationally consistent approach to survey, archive and classify tundra plot data

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Abstract

Satellite-derived remote-sensing products are providing a modern circumpolar perspective of Arctic vegetation and its changes, but this new view is dependent on a long heritage of ground-based observations in the Arctic. Several products of the Conservation of Arctic Flora and Fauna are key to our current understanding. We review aspects of the PanArctic Flora, the Circumpolar Arctic Vegetation Map, the Arctic Biodiversity Assessment, and the Arctic Vegetation Archive (AVA) as they relate to efforts to describe and map the vegetation, plant biomass, and biodiversity of the Arctic at circumpolar, regional, landscape and plot scales. Cornerstones for all these tools are ground-based plant-species and plant-community surveys. The AVA is in progress and will store plot-based vegetation observations in a public-accessible database for vegetation classification, modeling, diversity studies, and other applications. We present the current status of the Alaska Arctic Vegetation Archive (AVA-AK), as a regional example for the panarctic archive, and with a roadmap for a coordinated international approach to survey, archive and classify Arctic vegetation. We note the need for more consistent standards of plot-based observations, and make several recommendations to improve the linkage between plot-based observations biodiversity studies and satellite-based observations of Arctic vegetation.

1. Introduction

Accurate and consistent approaches for documenting the composition and structure of Arctic vegetation and its relationships to the environment are essential to ground-based and remote-sensing studies that attempt to understand Arctic biodiversity and the causes of circumpolar vegetation change (Bunn and Goetz 2006, Bhatt *et al* 2010, Elmendorf *et al* 2012, 2015, Meltofte *et al* 2013, Myers-Smith *et al* 2015b). The International Biological Program (IBP) Tundra Biome stimulated Arctic vegetation research between 1967 and 1974 (Brown *et al* 1980, Bliss 1981, Bliss *et al* 1981), which led to numerous syntheses in the 1990s (Chapin *et al* 1992, Oechel *et al* 1997, Wielgolaski 1997). More recently the Flora Group within the Conservation of Arctic Flora and Fauna (CAFF) made major progress toward an integrated circumpolar view of Arctic vegetation. CAFF is the biodiversity working-group of the Arctic Council, which is an intergovernmental forum promoting international cooperation, coordination and interaction among the eight Arctic Nations.

The *Annotated PanArctic Flora* (*PAF*) *Checklist* (Elven *et al* 2011) was first proposed at the 1975 International Botanical Congress in Leningrad as a means to assess panarctic plant diversity (Murray and Yurtsev 1999). The PAF was completed under the leadership of Reidar Elven and colleagues at the University of Oslo, and is now a living updatable online annotated checklist that provides a consensus of the names for all Arctic vascular plants. A new Arctic Vegetation Archive (AVA) initiative, described later in this paper, relies heavily on the PAF for standardized plant names. The Circumpolar Arctic Vegetation Map (CAVM), which was first proposed at the 1992 International Arctic Workshop on Classification of Arctic Vegetation in Boulder, CO (Walker *et al* 1994), and the map was completed in 2003 (CAVM Team 2003, Walker *et al* 2005). The CAVM provided a framework for the Arctic Biodiversity Assessment (ABA) (Meltofte *et al* 2013), which included three circumpolar vegetation-related syntheses devoted to plants (Daniëls *et al* 2013), fungi (Dahlberg *et al* 2013), and terrestrial ecosystems (Ims *et al* 2013). In sections 2, 3 and 4 of this review, we use several products from the ABA, along with other sources, to describe our current hierarchical understanding of Arctic vegetation at circumpolar, regional, and land-scape levels. In section 5 we focus at the plot level. We describe an example plot archive from Arctic Alaska, and make several recommendations that provide the beginning of a roadmap for more consistent international approaches to surveying, archiving, and classifying Arctic plot data.

2. Circumpolar patterns: the north–south influence of zonal climate and sea ice

The Arctic bioclimate zone occupies the land area beyond the northern climatic limit of forests. The zone has cold winters (mean January temperatures well below freezing) and cool summers (mean July temperatures below about 10 °C–12 °C). The Arctic zone covers 7.1×10^6 km^2, or about 4.8% of the land area of the Earth. Of this, glaciers cover about 29%; the remaining area constitutes the Arctic Tundra Biome, which has an Arctic flora, and tundra vegetation composed mostly of various combinations of herbaceous plants, small shrubs, mosses, and lichens (Walker *et al* 2005).

The Arctic Tundra Biome is essentially a long narrow ecological transition zone between the boreal forest and the Arctic Ocean. Eighty percent of the entire lowland portion of the Arctic zone lies within 100 km of the cooling influence of seasonally ice-covered seas with roughly 177 000 km of highly dissected coastline. This narrow circumpolar ribbon of tundra is divided into five Arctic bioclimate subzones (figure 1, inset map). The subzone boundaries are based primarily on the Arctic phytogeographic zones of Boris Yurtsev (Yurtsev 1994) and are defined according to summer temperatures and dominant growth forms of plants in the zonal vegetation types. The subzones as delineated by geobotanists are generally closely aligned with land-surface summer-warmth index classes (figure 1, main map) that were derived from the Advanced Very High Resolution Radiometer satellite data (Raynolds *et al* 2008a). The map also shows areas where some adjustments in the subzone boundaries are needed, particularly along steep coastal temperature gradients, on islands, and in mountainous areas.

The growth forms and diversity of plant species that comprise tundra plant canopies are related to the available summer warmth along latitudinal and altitudinal gradients. For example, the vertical structure of zonal vegetation varies from very small plants (<2 cm tall) in a single discontinuous layer in subzone A to complex plant canopies with two to three layers in subzone E, which can include shrubs that exceed 80 cm tall (Walker *et al* 2005). Species richness in the five Arctic subzones increases twenty-fold from north to south, but the number of endemics increases only about a three-fold (Daniëls *et al* 2013). Within Arctic mountain ranges, floristic richness in altitudinal bioclimatic belts is similar to the richness in latitudinal bioclimate subzones with similar summer temperature regimes, but strongly modified by the effects of slope and duration of snow cover (Sieg *et al* 2006).

Subzone A is the coldest (mean July temperatures less than 3 °C), smallest (approximately 2% of the area of the Arctic) and most unique subzone, with tundra unlike that elsewhere in the Arctic. The subzone lacks dwarf shrubs, all woody plants, sedges, bog mosses (*Sphagnum*), and peat in wetlands, all of which are among the dominant characteristics of tundra vegetation in subzones further south. A new class of vegetation, the *Drabo corymbosae-Papaveretea dahliani* (Daniëls *et al* 2016), has been described recently to characterize the zonal vegetation of subzone A. Subzone A is also the most threatened subzone. It is restricted to parts of the Arctic that, until recently, were generally surrounded by summer coastal sea ice all summer. Melting of the summer ice will result in higher summer temperatures on the adjacent land areas. Only a 1 °C to 2 °C increase in July mean temperatures in subzone A would permit the establishment of woody dwarf shrubs, sedges, and a large group of species that are generally currently missing in subzone A (Walker *et al* 2008).

A circumpolar map of Arctic aboveground phytomass on zonal sites (figure 2(a)) is based on the strong

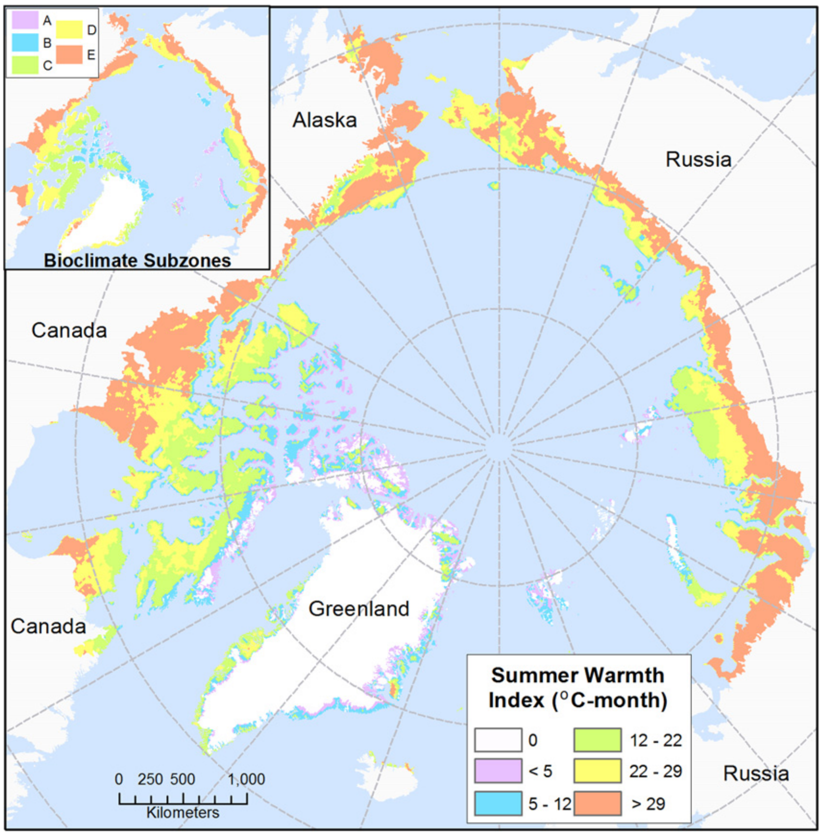

Figure 1. Map of the 22 year (1982–2003) mean of the summer warmth index (SWI = sum of monthly mean temperature above freezing) of arctic tundra, based on AVHRR land surface temperature data. Compare to inset map showing Arctic bioclimate subzones according to the CAVM Team (2003). The AVHRR-derived temperature is the land-surface radiant temperature, which characterizes the environment of low growing tundra plants within the surface boundary layer better than climate station temperature data, which are measured 2 m above the ground. On a monthly basis, Arctic mid-summer land-surface temperatures are warmer than air temperatures by about 2 °C, but vary considerably under different summer climate regimes. Adapted from Raynolds *et al* (2008a).

correlation between phytomass and the Normalized Difference Vegetation Index (NDVI) (figure 2(a), inset regression curve). The NDVI is a 'greenness index' derived from spectral-reflectance data. NDVI values are calculated from a variety of optical sensors aboard Earth-orbiting satellites, and are used for monitoring vegetation biomass, productivity, and related properties (Tucker and Sellers 1986) (see legend of figure 2 for how the index is calculated). In the Arctic, NDVI is often well correlated with ground measurements of phytomass, the leaf-area index (LAI), carbon dioxide flux and other measures of tundra photosynthetic activity (Stow *et al* 2004). The phytomass values reported in figure 2(b) were obtained from plots of zonal vegetation along two latitudinal transects in North America and Eurasia that cross all five Arctic bioclimate subzones (Raynolds *et al* 2012).

Temporal changes in tundra greenness are monitored annually using the NDVI (Bhatt *et al* 2010, Epstein *et al* 2014). The maximum NDVI (MaxNDVI) is an index of the peak greenness and the peak phytomass reached in a given summer. A general increase in MaxNDVI occurred from 1982 to 2013 in most of the Arctic (figure 3) (Bhatt *et al* 2013). This is generally attributed to increased growth of warmth-adapted plants, particularly deciduous shrubs (Myers-Smith *et al* 2015a), but there is considerable spatial and temporal variation. Some areas, particularly much of Arctic Russia and southwest Alaska, show recent (1999–2011) declines in midsummer temperatures and MaxNDVI, which suggests decreased productivity is linked to documented increased midsummer cloudiness and cooler midsummer temperatures (Bhatt *et al* 2013).

3. Regional patterns

3.1. The east-west influences of geography, geology, and history

Much of the regional variation in Arctic productivity (figure 2) and biodiversity (figure 4) can be attributed to historical patterns of glaciation, changes to the positions of the Arctic coastlines, and differences in parent material. For example, the amount of time since deglaciation accounts for about 34% of the variation in circumpolar aboveground phytomass and NDVI patterns (Raynolds and Walker 2009).

Global cooling over the past ~50 million years (MY) led to particularly dramatic changes in the environment of the Arctic. The cooling was linked to a

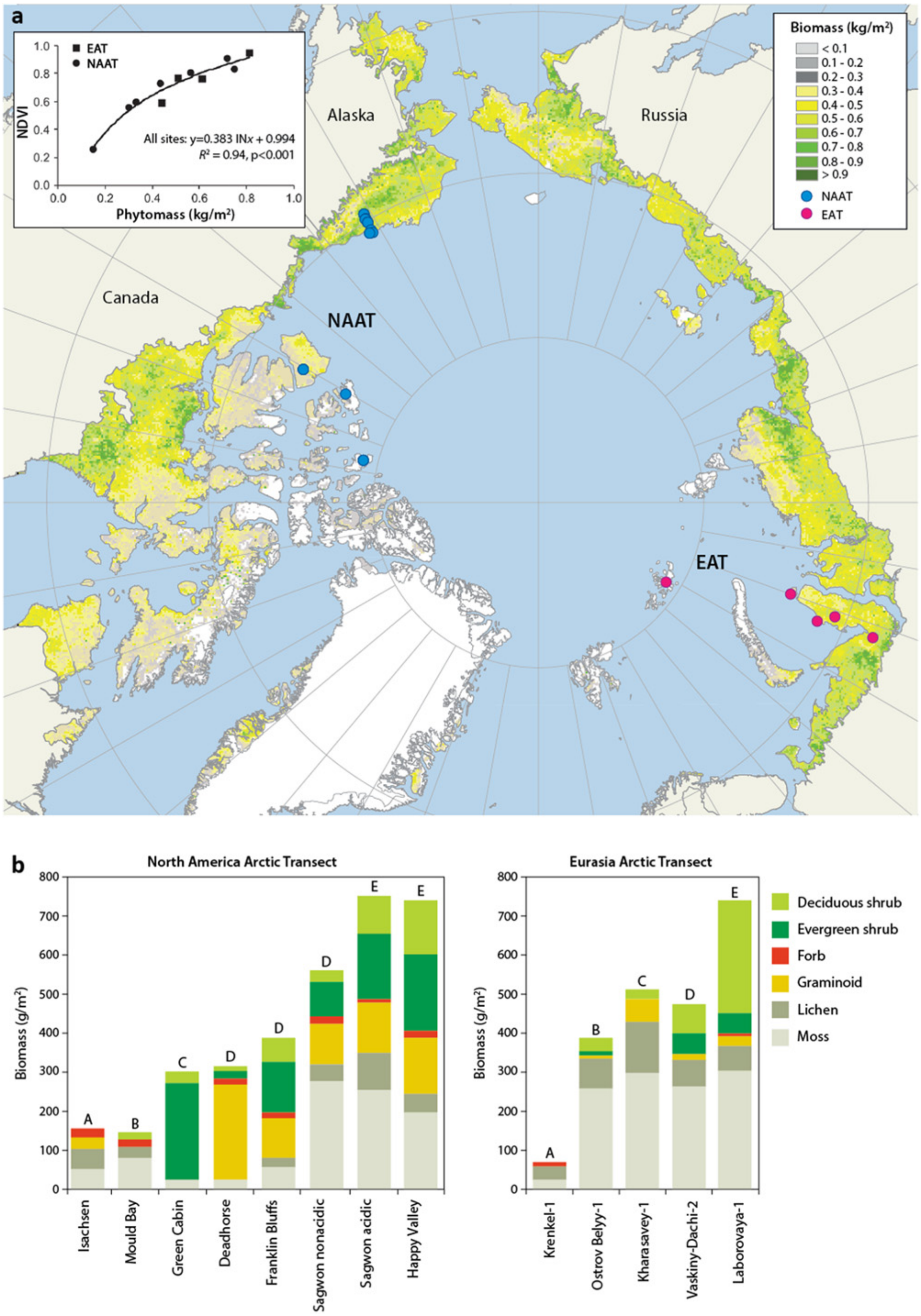

Figure 2. Aboveground zonal phytomass in the Arctic. (a) Zonal phytomass map based on NDVI-phytomass regression (inset graph, upper left). NDVI (normalized difference vegetation index) is interpreted as the photosynthetic capacity of the vegetation and is calculated by the formula NDVI $= (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R})$, where NIR is the near-infrared band of the spectrum and R is the red band of the spectrum. The relation was calculated using GIMMS3g AVHRR maximum NDVI 8 km data for years during which the phytomass was collected (2003–2010). The bioclimate subzone of each location is indicated by the letter above each bar. (b) Clip-harvest samples of zonal vegetation were made along pan-Arctic transects in North America (NAAT, blue dots) and Eurasia (EAT, red dots) summarized for each location along the NAAT and EAT by plant functional type. Adapted from Raynolds *et al* (2012) for the Arctic Biodiversity Assessment (Meltofte *et al* 2013) and reprinted by permission of CAFF.

drop in levels of atmospheric greenhouse gases and to continental drift, which altered ocean currents and patterns of global heat transport. The fossil record indicates that over much of this period climates were temperate, and lower-elevation terrain within the present-day Arctic was forested (Miller *et al* 2010). Between 2 and 3 MY ago, a major climatic transition featuring growth of sea ice and cooling of the Arctic Ocean led to forest retreat, the development of tundra vegetation, and permafrost expansion. The past ~2 MY have seen repeated advance and retreat of ice sheets (the Quaternary glaciations), but these have been geographically asymmetric. Ice repeatedly spread across large areas of Canada, Greenland, northern Europe and northwestern Russia, whereas Beringia, which extends from northeast Siberia to far northwest

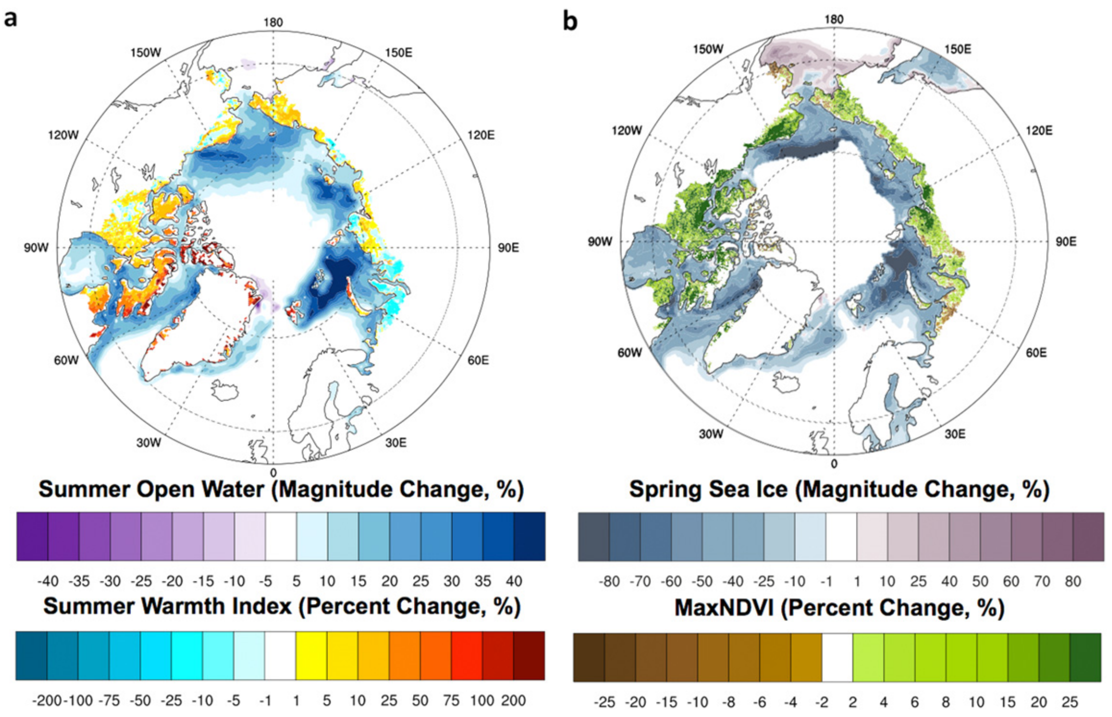

Figure 3. (a) Circumpolar changes in summer open water and the summer warmth index (SWI); and (b) the extent of spring sea ice and maximum NDVI (MaxNDVI). Changes in summer open water were determined during May–August SWI is the annual sum of the mean monthly temperatures exceeding freezing. The changes of sea-ice breakup are represented by 50% sea ice concentration. The annual maximum NDVI is usually reached in early August. The sea ice concentration and open water data were derived from SMMR and SSM/I passive microwave records. NDVI and land surface temperatures (SWI) information were derived from AVHRR data and the NDVI is from the Global Inventory, Modeling and Mapping Studies (GIMMS) dataset. (Adapted from Bhatt *et al* 2010, updated to 2013).

Canada, experienced only local mountain glaciations. During periods of lowered sea level, Beringia included the large land bridge that became exposed in the area of the present-day Bering Strait. The glaciated regions were subject to large-scale processes of erosion and deposition that eliminated the vegetation, though the extent of the ice varied spatially and temporally during the Quaternary period (Edwards *et al* 2000). During glacial periods, the climate over most of Beringia was cold and dry, which limited woody vegetation. The fossil record indicates the vegetation was dominated by graminoid species and forbs that have tundra and steppe affinities today (Anderson *et al* 2004). Nevertheless, the heterogeneity of Beringian landscapes almost certainly afforded local refugia for a range of woody plants (Brubaker *et al* 2005). In relatively warm, interglacial periods, such as the current Holocene (the past ~11 000 years), the dry herbaceous vegetation switched to mesic communities featuring a greater dominance of shrubs (Anderson *et al* 2004).

The Arctic is presently divided into floristic provinces and subprovinces that reflect the geographic history described above (Yurtsev 1994). The most recent iteration of these divisions has five phytogeographic provinces and 21 subprovinces (figure 4, legend upper left). There are 2218 recognized vascular plant species in the Arctic, distributed in 430 genera and 91 families (Elven *et al* 2011). Floristic diversity is low compared to other biomes and is less than 1% of the world flora. Thirty-six percent of the species belong to only four families: Asteraceae (254), Poaceae (224), Brassicaceae (133) and Cyperaceae (190) (Daniëls *et al* 2013). Floristic diversity varies widely across the phytogeographic provinces, largely a consequence of the varied glacial histories. The Beringian group of provinces has relatively high floristic diversity (315–825 species; average 621 species), which reflects its vast unglaciated areas, whereas the heavily glaciated North Atlantic group has relatively low diversity (215–649; average 449) (figure 4). Of the 106 Arctic endemics, the Beringian provinces have 39; whereas, European Russia-West Siberia provinces have only three (Daniëls *et al* 2013).

3.2. Genetic diversity

Genetic diversity within species is essential to long-term persistence of floristic diversity because it provides the opportunity for species to adaptively respond to changing climate. Similar to the patterns of floristic diversity, the highest levels of genetic diversity and most local genetic markers are found in Beringia with lower numbers in the North Atlantic region (Eidesen *et al* 2013). While Beringia has generally been inferred as a long-term refugium for Arctic plants (see above), there has been intense debate about the history of the plants in the repeatedly and heavily glaciated amphi-Atlantic region (Brochmann *et al* 2003). Genetic evidence indicates that a few species may have been

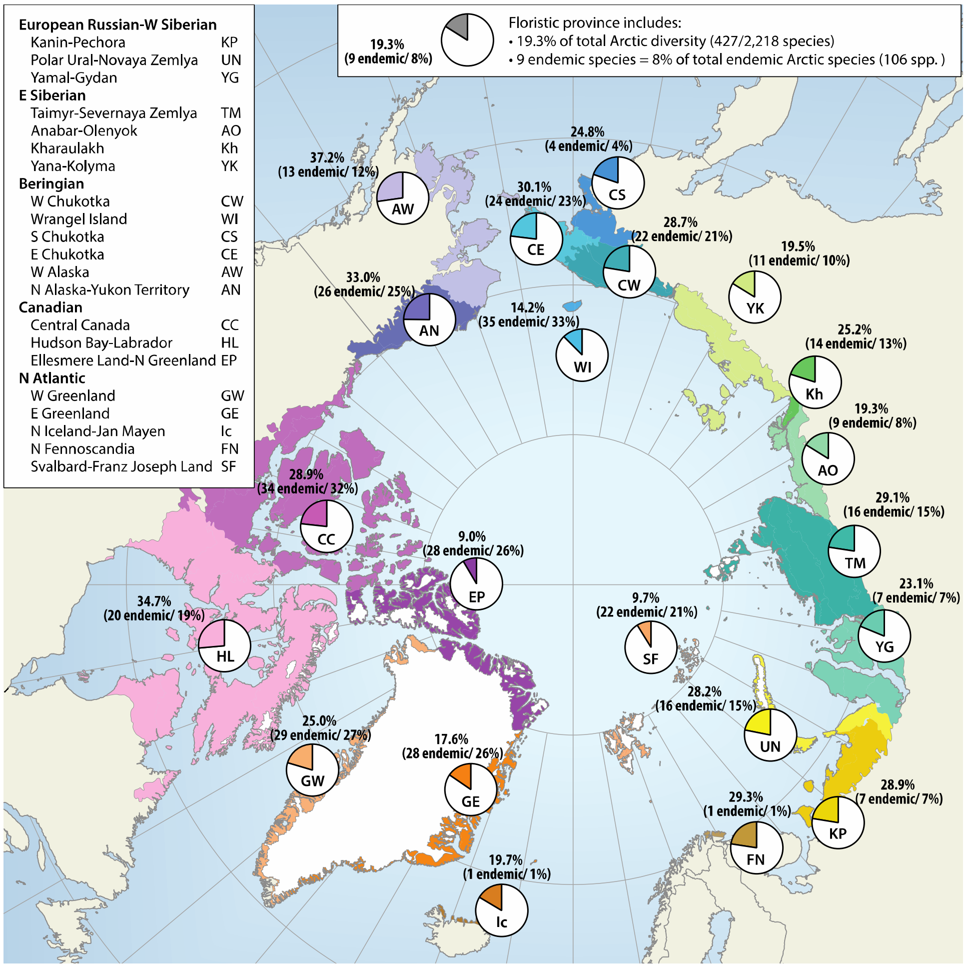

Figure 4. Vascular-plant species richness within each phytogeographic province (colors and codes on the background map) as a percentage of the total Arctic species richness (2218 species). The number of endemic species is shown in parentheses with percentage of the total arctic endemic species (106). From Daniëls *et al* (2013). Floristic provinces are according to Elven *et al* (2011) (reprinted by permission of the CAFF).

able to survive *in situ* during the last glacial maximum (Westergaard *et al* 2011), whereas the majority of species colonized post-glacially (Alsos *et al* 2015). This is reflected in the low number of Arctic endemic species (figure 4), the very few species endemic to any of the floristic provinces and the overall low levels of genetic diversity (Eidesen *et al* 2013). Genetic studies of 1200 populations of 27 northern vascular plant species combined with distribution modeling predict that most northern plant species will lose ranges at a higher rate than temperate species. The predicted loss of genetic diversity is overall less than range loss, but varies with species traits, such as adaptation to dispersal and growth form (Alsos *et al* 2012).

3.3. Productivity and diversity hotspots

No Arctic region is considered a global-scale hotspot of biodiversity (Vane-Wright *et al* 1991, Myers *et al* 2000, Meltofte *et al* 2013), but unglaciated regions, particularly in Beringia, have relatively high floristic diversity compared to the rest of the Arctic. Relatively large areas (100–1000 km^2) with locally high productivity and diversity also occur in association with unique physiographic features that influence local climate. These include the Arctic 'oasis' along the 70 km long Lake Hazen, near the northern limit of land (81.8° N) on Ellesmere Island (Svoboda and Freedman 1994), and the coastal plain of the Arctic National Wildlife Refuge in northeastern Alaska, where the eastern Brooks Range makes a turn toward the Arctic coast and compresses three Arctic bioclimate subzones to within 50 km of the Arctic Ocean.

The concept of hotspots needs to distinguish areas containing many endemic Arctic species with high conservation priority from local thermal hotspots with high biological productivity. The presence of anomalously tall shrubs or trees is an indicator of thermal hot spots in the Low Arctic (Forbes *et al* 2010, Lantz *et al* 2010, Tape *et al* 2012), but not necessarily hot spots of diversity. An area of particularly lush shrub and poplar growth in northern Alaska is the north-flowing Chandler River in the central part of the Arctic Foothills (Tape *et al* 2011). The presence of balsam poplar (*Populus balsamifera*) is another good indicator of local thermal hot spots because these trees often form small boreal enclaves that occur on thermally warm valleys and south-facing slopes of the Brooks Range, often near springs associated with limestone bedrock areas. Summer-warmth-index maps derived from satellite data indicate that about 40% of the balsam poplar stands in northern Alaska occur in sites with relatively high summer ground-surface temperatures (Breen 2014).

Remote sensing can be a useful tool to help identify potential hot spots of diversity and high productivity. In the Bathurst Inlet area of northern Canada, areas of relatively high species diversity correspond to areas with high diversity of spectral-signatures on Landsat images (Gould and Walker 1997, 1999). In Svalbard, a combination of remote sensing tools, digital elevation models, and detailed ground-based surveys were used to verify the presence of locally rare thermophiles in this High Arctic environment (Karlsen and Elvebakk 2003), and have recently been used to develop habitat suitability and species distribution models (Nilsen *et al* 2013). However, as shown in the discussion of subzone A, it is the *lack* of species from the south that give the extreme High Arctic areas their special character and conservation value.

4. Landscape-scale patterns

Major landscape-scale differences in productivity and species diversity can be attributed to underlying geology and topography, and resulting differences in soil, snow and wetland distribution. Successional patterns related to streams, lakes, fire, coastal flooding and humans are additional landscape-level factors. The effect of soil pH on Arctic vegetation is a particularly important factor that has been described in numerous studies (Edlund 1982, Elvebakk 1997, Walker *et al* 1998). For example, a striking substrate pH boundary stretches 800 km across the northern front of the Arctic Foothills in northern Alaska (figure 5). The boundary is thought to be caused by different ages of loess deposits on either side of the boundary, possibly enhanced by a regional climate boundary that coincides with the northern front of the Arctic Foothills (Zhang *et al* 1996). Differences in soil pH across the boundary affect the composition and structure of plant communities, and a wide variety of ecosystem properties and processes, including soil temperature, active-layer thickness, photosynthesis, respiration, decomposition, and fluxes of trace gases energy and water (Walker *et al* 1998). Similar patterns are seen in mountain ranges and other terrain with adjacent areas of carbonate-rich and acidic bedrock (Edlund 1982, Cooper 1986, Elvebakk 1994). Older landscapes generally have more leached soils with lower soil pH than younger surfaces. For example, the area near Toolik Lake, Alaska, has been subjected to repeated glaciations during the Pleistocene, leaving several glaciated landscapes of different age that span over a MY of glacial history within about 100 km north of the Brooks Range. Each different-aged glacial surface can be recognized by characteristic suites of landforms, periglacial features, soils and vegetation that are legacies of its geomorphic history (Hamilton 1986). Difference in productivity on the different-age surfaces can be inferred from NDVI patterns and corresponding biomass data (Walker *et al* 1995).

Landscape-scale maps at fine scales (approximately 1:5000 scale and finer) can display transitions in plant communities along mesoscale hill slopes (toposequences), riparian areas, snowbeds, and wetlands. Variation related to patterned-ground features is especially common in the Arctic (Washburn 1980). A study of non-sorted circles along the Arctic climate gradient found that major differences in soil moisture, soil temperature, and site stability occur within spatial distances of a few centimeters, and that the vegetation biomass and thickness of the plant layer on the patterned-ground features affect the soil thermal, hydrological, and nutrient properties (Kade *et al* 2005, Walker *et al* 2011, Frost *et al* 2013). Maps of patterned-ground landscapes ranging in size from about 4 m^2 to 1 ha are sometimes made at very fine scales (1:500 scale or finer) (Chernov and Matveyeva 1997, Raynolds *et al* 2008b).

Animals are also a major factor affecting landscape-level vegetation and productivity patterns. Rich habitats are often associated with areas of high animal use such as the south-facing gravelly slopes of pingos (Walker 1990), bird cliffs (Williams and Dowdeswell 1998), and archeological sites near polynyas in the central and High Arctic (Schledermann 1980, McCartney and Helmer 1989, Murray 2005). Animals can have both negative and positive effects on productivity. Resampling vegetation within herbivore exclosures at Barrow, Alaska, in the 1950s and 1970s found that lemmings and other herbivores outside the exclosures had reduced the relative cover of lichens and graminoids while the relative cover of deciduous shrubs increased; consequently, a wide variety of ecosystem properties, including thaw depth, soil moisture, albedo, NDVI, net ecosystem CO_2 exchange, and methane efflux were affected (Johnson *et al* 2011). Outbreaks of insect defoliators have also been shown to dramatically impact deciduous shrubs in low-arctic Greenland (Post and Pedersen 2008) and at the forest-tundra interface in Northern Fennoscandia (Jepsen *et al* 2013). These pulses of defoliation lead to changed nutrient cycling, and increased understory vegetation and indirectly affect herbivore community composition. Abundant semi-domestic reindeer populations, in combination with cyclic vole populations, appear to be able to counteract the climate-driven increase in shrub growth in some areas of the Low Arctic (Ravolainen *et al* 2014). One of the most dramatic examples of herbivore overabundance is the case of snow geese, which permanently transformed and partially destroyed large areas of salt-Marsh vegetation along the Hudson Bay in Canada (Jefferies *et al* 2006).

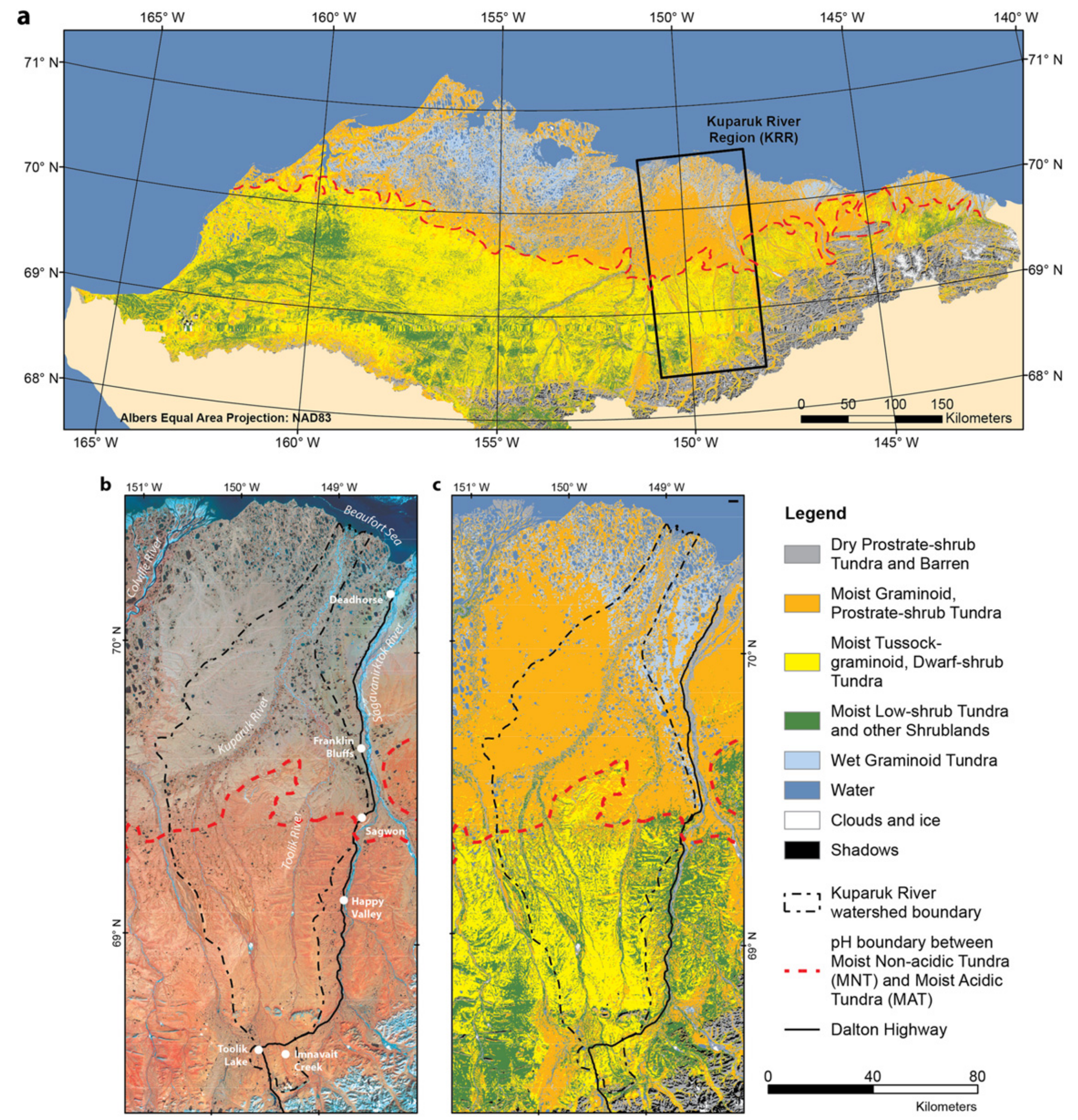

Figure 5. (a) Land-cover map of northern Alaska (adapted from Muller *et al* 1999). The map shows the distribution of major physiognomic groups of tundra types. The red dashed line separates mainly graminoid and prostrate-shrub-dominated tundras (orange) on in the northern part of the map from shrubbier tussock tundra (yellow) and low-shrub tundra (green) in the southern part. Wet tundra (light blue) also occurs on flat landscapes of northern coastal plain. The black rectangle contains the Kuparuk River region, an intensively studied Arctic watershed. (b) Landsat MSS false-color infrared mosaic of the Kuparuk River watershed (dashed black line). In this region, the gray area north of the red dashed line has predominantly moist nonacidic tundra (MNT). Redder areas south of the boundary have mainly moist acidic tundra (MAT). The redder tones of MAT are due mostly to more dwarf and low shrubs (e.g., *Betula nana, Ledum palustre* ssp. *decumbens*, and *Salix pulchra*). MNT vegetation has fewer shrubs, more erect dead sedge leaves, and more exposed soil patches due to a greater abundance of non-sorted circles. (c) Land-cover map of the Kuparuk River Region derived from the Landsat data (Muller *et al* 1998). Landsat data are courtesy of the US Geological Survey Alaska Data Center.

5. Plot-level observations: a panarctic vegetation plot archive

A conceptual diagram summarizes the four levels of observation of circumpolar Arctic vegetation and typical research topics described above, along with, monitoring, integration and modeling tools that can be applied across scales (figure 6).

Our knowledge of Arctic floristic (plant-species) and vegetation (plant-community) response to environmental gradients at all these scales relies on rather sparse ground-based plot data collected during expeditions and at Arctic observatories since the late 1800s. Vegetation data are usually collected from small plots that describe the structure, composition, and site factors of the plant canopy in common vegetation habitat types (figure 7).

5.1. Arctic vegetation plot databases

Plot based survey data are increasingly gathered and stored in large vegetation databases (Schaminée *et al* 2011). The Arctic Vegetation Archive (AVA) is an effort to assemble historic Arctic vegetation plot data into a single publically accessible database and to apply it to northern issues, including a much needed circumpolar Arctic vegetation classification (Walker

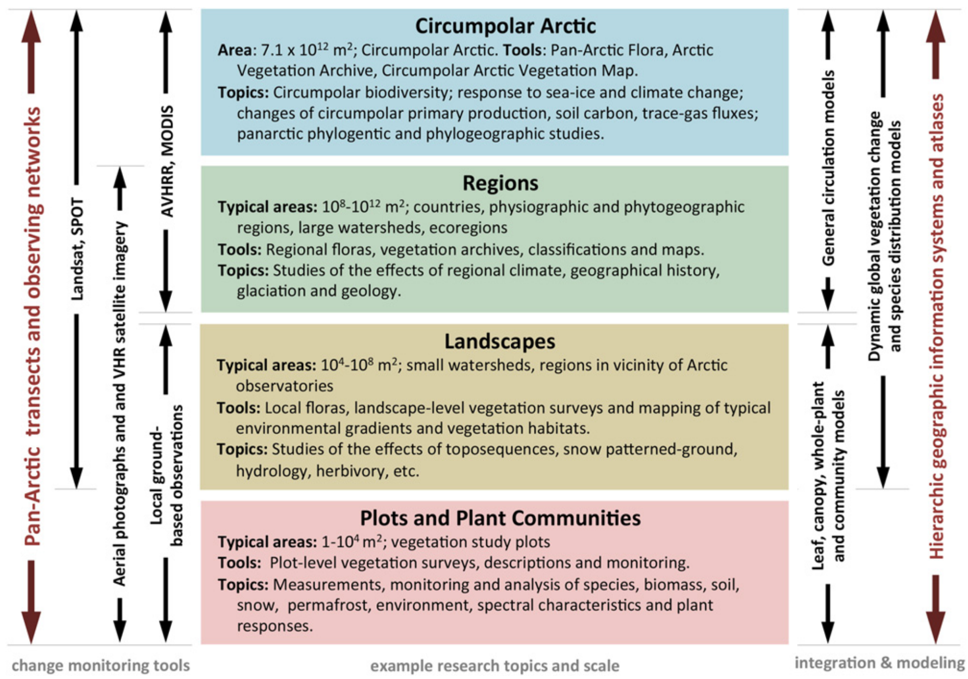

Figure 6. Hierarchy of levels of observation of Arctic vegetation. Left-hand vertical arrows show examples of monitoring tools that are effective across levels; right-hand bar shows corresponding examples of integration and modeling tools. Red highlighted monitoring and integration tools indicate methods used to examine vegetation at the full range of scales.

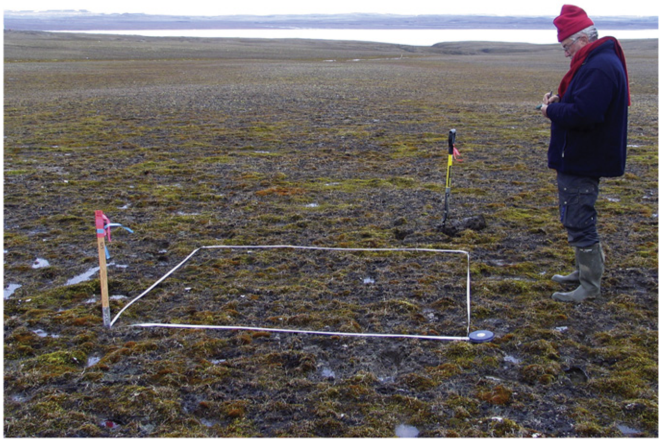

Figure 7. A vegetation survey being conducted in a wet vegetation plot located near Isachsen, Ellef Ringnes Island, Nunuvut, Canada, 78° 47′N, 103° 35′W, part of the North America Arctic Transect (blue dots on figure 3), using the Braun-Blanquet approach (Westhoff and van der Maarel 1978). This simple survey method is used widely across the Arctic.

and Raynolds 2011, Walker 2014). Prototype databases for the AVA are under development for Greenland (AVA-GL) (Bültmann and Daniëls 2013) and Arctic Alaska (AVA-AK) (Walker *et al* 2013). The AVA-AK is nearest to completion and currently contains species and environmental data from approximately 3000 vegetation plots in 24 datasets in northern Alaska (Walker *et al* 2016). The archive is accessible through the Alaska Arctic Geoecological Atlas (figure 8), a web-based portal at the University of Alaska. Each dataset has a 'Catalog' record with a detailed description of the dataset. Downloads or links to plot photographs, maps of plot locations, soil and environmental data, biomass and spectral data information and key data reports and publications are also provided wherever available.

The raw and standardized plot data are stored in .csv files, and a Turboveg database contains the species data from all AVA-AK datasets with consistent plant nomenclature and header data (a standardized set of key environmental variables). Turboveg is the most widely used software program specifically designed for

Figure 8. Home page for the plot archive within the Alaska Arctic Geoecological Atlas, showing locations of 38 currently known Arctic tundra plot datasets. Twenty four of these (dark and light green points) are in the AVA-AK Turboveg database; 17 (dark green) have complete catalog data records; the gray datasets are still being evaluated for inclusion. Clicking on a point or dataset name leads to a large scale image that shows individual plot locations and a Catalog data record which explains the data and provides links to the species data, plot photos, and other ancillary information if available.

the storage, selection, and export of vegetation plot data (Hennekens and Schaminée 2001). Plot data stored in Turboveg can be exported for further analysis by other spreadsheet and database tools (e.g., Microsoft Excel and Access, Twinspan, Canoco, PC-ORD, and JUICE). A key aspect of the AVA is a PanArctic Species List (PASL), which standardizes species names across datasets in the Turboveg database (Raynolds *et al* 2013). The AVA-AK Turboveg database follows as closely as possible the database protocols being developed for the European Vegetation Archive (Chytrý *et al* 2016). The data are also being exported to the VegBank plot database, which is used for the US National Vegetation Classification (USNVC) (Peet *et al* 2012). The AVA-AK is registered in the Global Index of Vegetation-plot Databases (Dengler *et al* 2011).

A preliminary cluster analysis of the first 16 datasets (1568 plots) produced a dendrogram with 17 clusters with sensible ecological organization, mainly along a complex soil-moisture/ soil-pH gradient. The diagnostic, constant, and dominant taxa in these clusters appear to show strong correspondence to previously described Br.-Bl. classes and alliances described elsewhere in the Arctic (Walker *et al* 2016).

5.2. Toward a coordinated international approach to survey and archive plot data

Although the AVA-AK database is a significant step toward developing a classification for Arctic Alaska and the circumpolar region, the datasets in the archive show considerable variability in quality. The data were collected during a period of over 65 years using a wide variety of survey methods. *Incompatible methods* included: (1) project-specific sampling protocols that made it difficult to compare datasets from different locations; (2) data that were collected from plots with obviously heterogeneous vegetation; (3) doubtful or incomplete taxonomic determinations. *Missing information* included: (4) data that were published only in summary form for vegetation types but not for the individual plot samples; (5) missing important ancillary information, such as plot coordinates, photographs of the vegetation, nature of the soils, or positions along slope, soil moisture, or snow gradients; (6) loss of the original data and/or critical metadata due to the death of the author(s); and (7) datasets that were unavailable because they were obtained for private industry and considered proprietary information.

Considerable progress toward a roadmap for international vegetation surveys has been made and summarized in a recent review (De Cáceres *et al* 2015). This framework is not reviewed here, but is an essential starting point for new vegetation surveys. Below, we provide some specific suggestions for future surveys in the Arctic. In most respects, these suggestions follow the 'analytic research phase' of the Braun-Blanquet (Br.-Bl.) approach described by Westhoff and Van der Maarel (1978) with rather minor adjustments specific for Arctic situations. We add some additional suggestions, such as collection of biomass and soil data, which greatly increase the value of plot data for remote-sensing and other applications.

5.2.1. Choice of area for a vegetation survey
The Arctic is remote and under-sampled. New surveys should focus in areas that have good logistical support, such as the existing network of Arctic Observatories, where researchers can spend the time necessary to produce high-quality datasets and where there is a likelihood that the plots will be revisited in the future for comparative monitoring studies. Special efforts should also be made to identify 'hotspots' of productivity, diversity, and endemism that are not represented at the main Arctic observatories. Remote sensing, local knowledge, and gaps in the existing plot network can aid in identifying these areas. Field camps should be considered to examine vegetation variation in ecological situations that are not adequately represented at the Arctic observatories or in the existing AVA.

5.2.2. Local floras
It is best to conduct vegetation surveys in conjunction with taxonomists who can devote the time necessary to make professional herbarium voucher collections and produce floristic surveys that include complete vascular-plant, bryophyte, and lichen species lists from a full suite of habitat types at each station. A standardized method of making local floras has been applied to approximately 500 locations in Russia (Tolmachev 1931, Yurtsev *et al* 2004, Balandin 2008, Khitun *et al* 2016). The Russian approach to making local floras should be considered and modified if necessary for other Arctic countries. The Pan-Arctic Flora and Pan Arctic Species List will need to be regularly updated as new floristic information is gained. There is also a critical need for a new generation of Arctic vegetation scientists with strong taxonomic training to make these floristic surveys.

5.2.3. Selection of plant communities in representative habitat types
Considerable debate surrounds the topic of plot selection, particularly whether to select sample sites preferentially based on expert knowledge, often in relation to typical habitats, as in the Br.-Bl. approach (Mueller-Dombois and Ellenberg 1974), or to use random approaches, including stratified random sampling, which better meet statistical assumptions required for ecological studies, but which undersample rare habitat types. In practice, a compromise is often necessary to meet the realities imposed by budgets, available time, and other logistic constraints, while at the same time avoiding the circular reasoning of only documenting preconceived vegetation types (De Cáceres *et al* 2015). An in-depth field reconnaissance guided by fine-scale aerial imagery of the study area should precede the formal survey to assess the habitat variation within the local region. Most of the Arctic is still in a natural state, so a good approach is to focus on the natural habitats and prioritize the sampling according the most- to least-common habitat types within a local landscape. First target the most abundant stable zonal sites, where the vegetation is mainly a product of long-term adaptation to the local climate. Then sample other common plant communities that are apparent at landscape scales including vegetation along toposequences, snow gradients, chronosequences associated with stream terraces and lake succession, different bedrock and soil types, and finally in small-scale special habitats associated with such features as rocky talus slopes and blockfields, frost boils, perennial springs, dunes, and zoogenic communities. Another approach that yields high-quality data is to sample a given habitat type across a broad regional gradient. Examples include sampling zonal sites along climate (Matveyeva 1998) or elevation (Sieg *et al* 2006) gradients. Other examples have focused on snowbeds (de Molenaar 1976), pingos (Walker 1990), riparian habitats (Schickhoff *et al* 2002), poplar groves associated with springs and warm habitats (Breen 2014) and anthropogenically disturbed areas (Sumina 2012).

5.2.4. Centralized-replicate sampling approach
Within a given a representative habitat type, a relatively small sample plot should be placed within a larger visually homogenous area of vegetation with relatively homogeneous plant-species composition, canopy structure, and local environmental factors, so as to avoid obvious transitions or boundaries between plant communities (Mueller-Dombois and Ellenberg 1974). The specific sites for plots generally should be at least partially subjectively chosen (rather than randomly located) to avoid obvious transitions between plant communities. This is a particularly important consideration in Arctic patterned-ground landscapes, where considerable habitat variation may be unnoticed on aerial photographs and can occur within a few centimeters. Make replicate samples (5–10) in areas of the same habitat type. Sampling along disturbance gradients or chronosequences can be done in a similar way by choosing sample sites in

plant communities that occur in multiple areas of the landscape. This sampling approach is good for classification but may not be compatible with experimental studies that require a purely random sampling design for making statistical inferences. In these cases, a statistician should be consulted to help design a sampling approach (De Cáceres *et al* 2015).

5.2.5. 'Minimum-area' plots

Ideally, the plots should be of the same size to compare the species diversity within them, and should contain a high percentage (90%–95%) of the total number of species in the plant community, but also be as small as possible so as to avoid sampling several plant communities in the same plot. Methods of determining the minimum area are described in the literature (Westhoff and van der Maarel 1978) but are sometimes difficult to apply to surveys that include many vegetation types with widely divergent vertical structure, or that are in areas of complex microtopography, such as areas of permafrost-related patterned-ground. A rough rule of thumb is that the plot size in m^2 should roughly equal the height of the vegetation in decimeters (Barkman 1989). Chytrý and Otýpková (2003) recommend 16 m^2 for most grassland, heathland and other herbaceous vegetation, 50 m^2 or low-shrub vegetation types and 200 m^2 for woodlands.

5.2.6. Permanent plot markers and photographs

The corners of the plot should be permanently marked and labeled in a manner that will be still be visible or at least locatable (e.g. with metal detectors) many years in the future. Plot documentation should include high-resolution GPS coordinates of the plot corner markers, and photographs of the vegetation landscape and soil with the plot number clearly visible. Visits to the plots in winter to collect snow data will require marking the plots with long vertical poles to aid in locating the plots in snow-covered landscapes.

5.2.7. Description of the sample site

Include habitat type, geographic coordinates, elevation, photos, slope, aspect, soil moisture regime, snow regime, pH, landform, parent material, geological setting, surface geomorphology, active-layer thickness, disturbance types and degree, animal sign, and stability of the soil. A standardized data form with codes or standard names for the various factors should be used so that this is part of the record for the plot. A list of required and recommended fields used for the AVA-AK are in Walker *et al* (2016).

5.2.8. Cover estimates for all vascular plants, lichens, and bryophytes

It is highly advisable to collect small samples of all species encountered in a plot to avoid misidentification. Expert taxonomists in various plant groups will probably be needed, especially for the mosses, liverworts, lichens, grasses, sedges, and willows. Cover estimates can use direct percentage cover estimates or classes, such as Br.-Bl. cover-abundance scores (Westhoff and van der Maarel 1978).

5.2.9. Characterize the soil

At a minimum photograph the soil profile, make a brief description, and collect soil samples from the plant rooting zone and the top mineral horizon for later physical and chemical analysis. Preferably, work with a soil scientist experienced in Arctic soils.

5.2.10. Biomass and spectral data

Biomass data and ground-based spectral data are necessary for linking remote-sensing spectral information to actual plant production. The methods for harvesting, sorting, and categorizing biomass samples can strongly impact the reported biomass values and need to be standardized to make the data comparable between datasets. This was attempted during the IBP in the late 1960s and 1970s (Wielgolaski *et al* 1981) with some success, but the methods need to be revisited and a manual developed that incorporates new knowledge and better serves the remote-sensing community. Standardized procedures are also required for collecting LAI and spectral-radiometric data for use in calculating vegetation indices, such as the NDVI. The use of spectral data in phytosociological studies is relatively new and sampling should be developed with the advice of a remote-sensing specialist.

5.2.11. Other data

Every attempt should be made to make the data as widely useful as possible. Vegetation scientists should return to their plots in other seasons, other years, and with experts in a variety of disciplines, for example, soils, remote sensing, snow ecology, and animal ecology, to help interpret the causes of the spatial and temporal patterns. The information is also essential to interpret changes to such things as active layer depths and trace-gas fluxes. However, care must be taken to protect the plots and surrounding vegetation from trampling during the revisits because these sites are extremely valuable and should be protected.

5.2.12. Publication of plot data

In the past, many journals would only publish synoptic or summary tables for vegetation types because of limited space, but recent wide acceptance of supplemental data files for on-line publications now make publishing the complete plot data a standard practice. We also highly recommend formal data reports for each survey that provide full methods, photographs, and all the ancillary data collected from the plots.

5.3. Toward an Arctic-wide vegetation classification

In polar regions of Canada, Greenland, Iceland, Svalbard, Russia, and the United States, the Br.-Bl. approach (Braun-Blanquet 1932, Westhoff and van der Maarel 1978, Dengler *et al* 2008) has historically been the most commonly used vegetation-survey method. This has resulted in compatible preliminary structured syntaxonomical and nomenclature surveys that can serve as a foundation for future sampling and a coherent consistent classification system across the Arctic (Bültmann and Daniëls 2013, Daniëls and Thannheiser 2013, Nilsen and Thannheiser 2013). Of 16 datasets in a preliminary analysis of the AVA-AK, thirteen followed the Br.-Bl. approach for sampling and five of these followed the International Code of Phytosociological Nomenclature (ICPN) for naming plant communities (Walker *et al* 2016).

The Br.-Bl. approach is primarily a floristic-based approach at all levels of its hierarchical framework, which consists of four primary vertical levels of organization (class, order, alliance, and association). At the lowest level, an association is a floristically defined plant-community type with a set of diagnostic species. The methods of naming new units is strictly defined by the ICPN (Weber *et al* 2000), and acceptance of new units requires formal publication according to the code. The approach is described in several textbooks although none incorporates the latest computer-based approaches for using the method. Arctic countries outside of North America will likely continue to use the Br.-Bl. approach for vegetation surveys and classification in the near future.

In North America, a relatively new EcoVeg vegetation classification approach has developed in the last 40+ years (Jennings *et al* 2009, Faber-Langendoen *et al* 2014). The method is an eight-level physiognomic-floristic-ecological classification approach (Class, Subclass, Formation, Division, Macrogroup, Grpoup, Alliance, and Association). The highest level in the EcoVeg approach is the formation class, which is a broad combination of dominant plant growth forms adapted to certain environmental conditions. The methods of field surveys, classification, and naming communities are described in several publications (FGDC Vegetation Subcommittee 2008, Jennings *et al* 2009, Faber-Langendoen *et al* 2014). The approach was adopted by North American land-management agencies as the vegetation standard for the US National Vegetation Classification (USNVC) (Faber-Langendoen *et al* 2014) and the Canadian National Classification (CNVC) (MacKenzie and Klassen 2004). It will likely continue to gain favor in North and South America.

We do not advocate one approach over the other because each approach has its advantages and will likely be continued where it is now practiced. However, one major advantage of the Br.-Bl. method for Arctic vegetation classification is that it has been applied in most regions of the Arctic and new data and analyses can build on the existing data and typologies. There is currently a lack of such an Arctic tradition with the EcoVeg approach. We recommend that future Arctic vegetation surveys adopt sampling methods that are compatible with the Br.-Bl. approach. These survey methods are generally compatible with the USNVC methods, and the data should be useable in classifications using either approach. With the advent of massive vegetation databases in the Arctic, both systems could be used to develop independent classifications from the same database, and evaluated regarding the efficacy of each.

6. Conclusion

Satellite-based remote-sensing data provide the means to characterize and monitor changes to Arctic tundra vegetation at circumpolar, regional, and landscape scales, but we will continue to need information collected from vegetation plots at the ground level to make sense of the spatial and temporal patterns observed from space. Although vegetation plot data are expensive to obtain, particularly in remote areas, the data and resulting classifications provide a set of operational units that are useful for description, understanding and management of vegetation and vegetation change at all scales in a rapidly changing Arctic. Moving forward with future vegetation surveys and analyses in the Arctic should build on the information collected by previous vegetation scientists, but also learn from the these previous surveys to create datasets that can be used for a wide variety of applications. For now we recommend continued collection of plot data following the Br.-Bl. protocols, mainly because the method has been used in most areas of the Arctic. We also recommend a series of international workshops to standardize plot-based observations and to begin a more focused effort to develop a truly circumpolar characterization and classification of Arctic vegetation.

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