Title: **The Arctic Vegetation Archive as the basis for a Canadian arctic terrestrial ecosystem classification: Application to establishing arctic terrestrial ecosystem monitoring**

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Introduction

The Arctic Vegetation Archive (AVA) initiative has the critically important goal of locating, rescuing and consolidating existing arctic relevé data, and using these data to coordinate pan-Arctic vegetation classifications (Walker et al 1994, Walker and Raynolds 2011, Walker et al 2013, 2014). The AVA takes a 'network of networks' approach, and the Canadian contribution to the AVA is coordinated through the Canadian National Vegetation Classification (CNVC), which represents a partnership of provincial and territorial vegetation classification practitioners in Canada (http://cnvc-cnvc.ca/). Until recently, CNVC work focussed on forest ecosystem classification, but funding provided under the International Polar Year (IPY) created the opportunity to collect and develop draft classifications for both subarctic and arctic vegetation communities in the Canadian North (Levesque et al 2014, Mackenzie 2014).

This paper outlines how a coordinated arctic vegetation classification under the AVA and CNVC can be used to calibrate a Canadian terrestrial ecosystem classification (TEC) covering both Arctic and Sub-arctic landscapes, using approaches well developed in southern Canada (Ponomarenko and Alvo 2001). As a demonstration of system applications, we discuss how the TEC can provide an ecosystem-based template for designing and coordinating terrestrial monitoring objectives across the Canadian North, and across the circumpolar Arctic.

From Vegetation Classification to Ecosystem Classification

The key application of the AVA/CNVC explored in this paper is the use of a pan-arctic vegetation classification as the standardized, correlated basis for linking plant communities to ecological sites to calibrate a useful TEC for the Canadian Arctic and Sub-arctic. TEC has a long history of development, with its roots in Russia and northern Europe, and many variations in Canada and the United States. Over the last 25 years there has been a consistent effort by all Canadian provinces to develop provincial forest ecosystem classifications, many of which are similar in structure, and include similar concepts (although different terms) of ecological site, plant community, plant association, and ecological community. Following the early approaches of Hills and Pierpoint (1960) and Krajina (1959, 1965), more modern examples are Meades and Moores (1996) in Newfoundland, Neily et al. (2003) in Nova Scotia, Mason and Power (1996) and Zelazny et al. (1989) in New Brunswick, Bergeron et al. (1992) and Saucier et al. (1998) in

Quebec, Lee et al. (1998) and Sims et al. (1989) in Ontario, Zoladesky et al. (1995) in Manitoba, Beckingham et al. (1996a) and McLaughlan et al. (2010) in Saskatchewan, Beckingham et al. (1996b) and Corns and Annas (1986) in Alberta, Pojar et al. (1987) in British Columbia, and more recently Flynn and Francis (2011) for the Yukon Territory.

At the heart of a northern TEC is the marriage of the biotic (plant community) and abiotic (ecological site) components of arctic and sub-arctic landscapes. Krajina (1960) initiated these ideas for forest ecosystems in British Columbia based on the Russian concept of the biogeocoenose (Sukachev 1960, Sukachev and Dylis 1964), i.e., areas of a landscape that are relatively homogenous in terms of species composition and vegetation structure, in hydrologic, atmospheric and soil conditions, and in the type and matter of energy exchange and interactions among all components (also adapted from Teplyakov et al. 1998).

Biogeocoenose can be thought of as a synonym for the more modern term – (terrestrial) <u>ecological community</u> (Ponomarenko and Alvo 2001) which we will use here. A terrestrial ecological community includes all of the biota on a site, from soil microbes and invertebrates, through to the plants, pathogens, herbivores and predators. The concept also includes the environmental factors that in part control biotic composition, abundance and productivity, and the interactions between all abiotic and biotic components. It is impossible of course to account for the myriad of individual ecosystem components and interactions, even in relatively simple arctic ecological communities. For practical purposes, in the course of terrestrial ecosystem classification, we describe and classify ecological communities using the co-distributions of plant communities (using relevés), and the ecological sites [using standardized site and soil description methods such as MOELF (1998)] on which they occur. Similar ecological communities typically repeat themselves in a predictable pattern across the landscape, recurring in similar environmental settings. Boundaries between ecological communities may be abrupt, as at the margin of a wetland or floodplain, or they may change gradually, as along an even slope, where downslope seepage is the driving ecological factor.

The functional linkages between the biotic and abiotic components of ecological communities provide the basis for assessing and extrapolating the role of ecological processes in determining their nature and distribution across an Arctic landscape. Typically, these processes are inferred from an analysis of the ecosystem data collected in the field, e.g., soil depth, texture, coarse fragment content, depth to permafrost, and the presence of soil mottling or gleying for mineral soils, or the nature and depth of organic strata and water tables in organic soils. Site factors are also part of the overall description and include assessments and measurements of slope angle and slope position (e.g., upper, mid, lower, toe, depression), site aspect and exposure to sun and wind, elevation, landform, as well as observations and assessments of other relevant factors such as the presence, frequency and duration of riverine or estuarine flooding, sedimentation and erosion, snow bed persistence, or soil instability [see MOELP (1998) for standardized methods].

Field data are integrated and interpreted to develop a qualitative understanding of the key driving processes that control vegetation composition, structure and productivity in each ecological community. Taken together for all ecological communities in a given landscape, we develop a comprehensive and integrated understanding of regional terrestrial ecosystem pattern and process that provides ecological rationale for establishing more quantitative ecosystem monitoring and research, for developing interpretative classifications such as habitat suitability or risk of permafrost degradation, for developing effective, ecosystem-based land use strategies and impact assessments, and as the basis for process-based modelling of ecological change.

To develop the TEC for pan-arctic ecological communities we propose to implement the mature approaches developed under the Biogeoclimatic Ecosystem Classification (BEC) System in British Columbia (Pojar et al. 1987), and more recently by Flynn and Francis (2011) in the Yukon. The BEC approach uses established functional relationships between ecological communities and key environmental drivers to organize and classify terrestrial ecological communities in order to classify and map regional bioclimates, and within bioclimates, to organize and classify constituent ecological sites and communities along predominant ecological gradients (Meidinger and Pojar 1991, MacKenzie and Moran 2004).

To classify and identify the ranges of regional bioclimates, Pojar et al. (1987) use the zonal concept, also utilized in other areas of Canada and the Arctic, e.g., Saucier et al. (1998), Ecosystems Working Group (1998), Walker et al. (2005), Gould et al. (2003), Flynn and Francis (2011). The concept of zonal ecosystems flows from the early work in Russia attributed to Dokuchaev, that linked broad patterns in soil types to regional climatic gradients – a concept brought to North America by early soil scientists, e.g., Marbut (1935). Zonal ecological sites have a list of defining physical characteristics such as being positioned on moderate slopes, and having well-drained soils of at least medium depth with loamy texture and low coarse fragment content. As a result, zonal ecological sites and communities are assumed to best represent regional climates, in that climate at the site level is least modified by local-scale site factors (Pojar et al. 1987). Late seral plant communities situated on zonal ecological sites form the zonal ecological communities that typify and are used to locate the boundaries of regional bioclimates (for example see https://www.for.gov.bc.ca/hfd/library/documents/treebook/biogeo/biogeo.htm). A zonal plant community classification, e.g., Klinka et al. (1979, 1991), can be developed to identify, classify, and map biogeoclimatic subzones – the regional scale ecosystems of the biogeoclimatic classification in the TEC. Biogeoclimatic subzones are the basic unit of the TEC regional ecosystem, and can be agglomerated into biogeoclimatic zones defined by the same vegetation Order, or by the next hierarchical level in the vegetation classification system. In practice, the zonal concept may need to be adapted to account for distinct differences in late-seral zonal ecological communities within the same regional climate due to differences in predominant parent material, e.g., calcareous versus non-calcareous substrates (Walker 2000), or by dominating successional drivers such as high frequency fire (Payette and Delwaide 2003, Girard et al. 2008). A correlated pan-arctic vegetation classification such as the AVA initiative is fundamental to developing and implementing this regional scale, biogeoclimatic classification level of the TEC.

All ecological sites and communities within a biogeoclimatic zone or subzone that are not zonal are termed ‘azonal’, because they lack the defined characteristics of zonal sites. In azonal ecological communities and sites, environmental drivers such as excessive soil drainage or persistent downslope seepage, persistent soil waterlogging (wetlands), direct exposure to desiccating and abrasive winter winds, accumulations of deep, persistent and protective snow blankets, or seasonal flooding, sedimentation and erosion along rivers, lakeshores and estuaries, modify the effects of regional climates and result in distinctive azonal ecological communities comprised of a suite of species co-adapted to each set of recurrent ecological site conditions. Zonal and azonal ecological communities thus make up the repeating pattern of tundra and semi-forested ecosystems that we see when travelling across or flying over tundra or sub-arctic landscapes.

To classify ecological sites and communities within bioclimates, we propose to use the concept of ecological equivalence – a concept that comes from the original work of Cajander (1926) and Bakuzis (1959), and has been successfully applied in the BEC System in British Columbia (Pojar et al 1986, Meidinger and Pojar 1991, Klinka et al 1996), and in Quebec (Saucier et al. 1998). It states that all ecological sites that have the same late seral plant community will have similar ecological potential or productivity. The strong correlation between the site index of major commercial tree species and the ecological site classification in British Columbia presents strong evidence for the usefulness of this approach (http://www.for.gov.bc.ca/hre/sibec/). The concept of ecological equivalence is useful for ecosystem classification in that it permits the field identification of ecologically-equivalent, enduring ecological sites that are affected by similar driving ecological processes, have similar ecosystem productivities, and consequently provide a similar range of ecological services. As for the zonal classification of regional bioclimate, the classification of equivalent ecological sites and communities across the arctic also requires the kind of coordinated classification of vegetation communities proposed under the AVA initiative.

Concepts outlined above to develop a TEC link mature plant communities to ecological sites, and assume development under conditions of relative climatic stationarity, as witnessed by stability of North American and Eurasian treelines for the last 3,000 to 4,000 thousand years (Lavoie and Payette 1996, MacDonald et al 2000, Payette 2006). This has permitted the creation of distinctive terrestrial ecological communities under relatively constant environmental conditions, so that correlative relationships between ecological communities and regional climates and other driving site factors can be clearly established, e.g., BEC climate and site units in British Columbia (Pojar et al. 1986, Klinka et al 1996), forest management units in Quebec (Saucier et al 1998). Clearly, this overall consistency in climate and related drivers, e.g., mean summer temperature, snow regimes, ground ice processes, active layer depths, is changing, and it is to be expected that arctic and sub-arctic plant communities will change in response (ACIA 2005, SWIPA 2011). For example, the *in situ* relative dominance of species is already changing on many ecological sites across the Arctic (Henry et al 2012, Hudson et al. 2011), and we can expect that vegetation community composition will eventually change as well, with southern species slowly replacing arctic and sub-arctic obligate species from south to north. In that these changes are only beginning to happen, long-term monitoring of plant communities on similar ecological sites along a south to north gradient can provide a standardized approach to help document climate-driven ecosystem changes.

Applications of Terrestrial Ecosystem Classification and Mapping to Northern Terrestrial Monitoring Objectives

The amplification of climate warming at more than double the global average in northern latitudes (ACIA 2005, IPCC 2007, Serreze et al 2009) means that abiotic and biotic components of Canada's sub-arctic and arctic ecosystems are changing, and will continue to change in ways that are highly complex and difficult to predict with any certainty (Francis et al 2009, Derksen et al. 2011). It is because of this high uncertainty that many summary reports on climate-driven change at sub-arctic and arctic latitudes have recommended the immediate establishment of coordinated and integrated monitoring networks that can generate timely information on how ongoing climate change is driving ecological change in northern Canada (ACIA 2005; SWIPA 2011; Bidwell et al 2013). Recently the European Commission called for proposals that will contribute to an improved Arctic Observation System, stating that '… an integrated and multi-disciplinary Arctic observation system is becoming essential for studying, forecasting and assessing changes that support the region's sustainable development.' Here we discuss how a vegetation-based TEC that captures ecological variability at regional to local scales could provide a fundamental tool for producing an effective national and international monitoring sample design that would underlie coordinated sub-arctic and arctic monitoring.

Under the Arctic Council's Conservation of Arctic Flora and Fauna (CAFF) Working Group, monitoring programs have been developed for marine, freshwater and terrestrial ecosystems, as 3 components of the CAFF Circumpolar Biodiversity Monitoring Program. General monitoring questions identified in the development of the CAFF CBMP Terrestrial Biodiversity Monitoring Plan (http://www.caff.is/terrestrial/terrestrial-monitoring-plan) provide coordinated direction to inform local monitoring questions. Through the CBMP Terrestrial Expert Monitoring Group process, *Essential* and *Recommended* Focal Ecosystem Components (FECs) of terrestrial ecosystems were selected by a team of specialists in terrestrial ecosystems, creating an internationally agreed on set of monitoring indicators that can be used to summarize the condition of terrestrial biodiversity across the circumpolar North. An approach outlining design options for plot layout and transect locations is thoroughly described in the Arctic Regions Essential Components (*AREC*) Integrated Monitoring Design (Ibarguchi et al 2015). The arctic–subarctic TEC proposed in this paper would provide a standardized nomenclature for ecological communities across all sample sites, would summarize the key drivers controlling ecosystem composition, structure and productivity, will provide a standardized approach for scaling up regionally using remote sensing tools, and will provide the basis for comparing monitoring results across different biomes.

At a regional scale a biogeoclimatic classification based on the distribution of zonal, late seral ecological communities will provide a first level of national and international ecological stratification. In Canada the Walker et al (2005) CAVM Team map can be used identify climatically uniform areas in the arctic component, and the Ecoclimatic Zones (Ecosystems Working Group 1989) can be used to stratify sub-arctic areas – providing an ecosystem basis ensuring that monitoring will be representative of the complete range of arctic and sub-arctic climates. Using this approach, a first criterion for establishing a network of monitoring sites will be to ensure, as much as possible, that stations are selected to represent sub-arctic and arctic biogeoclimatic zones. This representation is critical for ensuring that the monitoring network can report on ecological change across the range of arctic and sub-arctic biogeoclimatic variability, and can capture this variability in scaling up exercises to apply local, place-based monitoring results to representative eco-regional areas.

At each site where monitoring is established, a recommended approach would be to use the TEC to design the locations of question-based monitoring experiments (Lindenmeyer and Likens 2010). Question-based (or hypothesis-based) monitoring is essentially a series of replicated long term experiments that measure changes in important ecosystem indicators, and the abiotic drivers that control them, against hypothesized outcomes. For example, key environmental drivers such as air and soil temperature, precipitation and soil moisture, active layer depth, and snow depth and duration are co-located with measures of vegetation response, and changes in nutrient cycling, arthropods, small mammals, and shorebirds to provide an assessment of how and why terrestrial ecosystems are changing, and to permit modeled projections of how the indicators may change in the future under different climate scenarios. This approach was also recommended in Ibarguchi et al (2015) where capacity exists to implement the experiments. Work ongoing under the International Tundra Experiment (ITEX) meets many of the criteria for question-based monitoring (http://www.geog.ubc.ca/itex/about.php). Over time, model predictions can be compared against monitored outcomes to improve the models and can be extrapolated across representative eco-regional areas.

A conceptual ecosystem model is developed for each monitoring experiment to link vegetation (and other terrestrial biotic) indicators to the environmental drivers that determine change, and the monitoring questions that frame the experiments. Monitoring questions are central to the development of the experiments and should be developed through a consultative process involving the range of local and regional stakeholders involved in establishing the monitoring program.

In an ideal world we would want to establish question–based monitoring at all ecological communities at each monitoring site, but in practice this will be prohibitively expensive given the number of ecological communities and the considerable costs of establishing and replicating monitoring experiments that integrate a suite of monitoring measures and ecological drivers. So it will be necessary to select certain ecological communities for monitoring, or to combine communities, e.g., all wetland communities, all snow protected communities, and sample across them. To prioritize local ecological communities for monitoring one approach that utilizes the TEC would be to select:

- <u>zonal ecological communities</u> at all monitoring sites to provide a co-ordinated basis for assessing and comparing changes across regional, national and international scales, and:
- <u>azonal ecological communities</u> based on international to local priorities, e.g., ecological communities that are important habitat for focal species such as caribou or muskoxen, climate refugial or snow bed communities important for conservation objectives, communities potentially impacted by resource development, communities expected to change quickly such as moist, rich sites with a vigorous shrub component, or estuarine communities that act as important migration staging areas. Other priorities may flow from ongoing research, so it may be a local priority to monitor ecological communities where net ecosystem carbon flux or cryosphere change is being measured.

The selection of ecological communities to establish this question-based monitoring at each research station will be constrained by logistical issues such as site access, spatial orientation of ecological communities, and replication requirements. The site selection process can be facilitated using a large scale map of ecological communities generated from high resolution satellite imagery or aerial photography. The map will delineate distributions of ecological communities within the sample area, and will provide the information required to optimize the location of potential monitoring sites, given monitoring priorities and logistical constraints. Such detailed maps of local scale ecological communities would support the monitoring transect approaches proposed in Ibarguchi et al (2015), with the additional benefit of providing information on identified ecotonal areas between ecological communities.

A high resolution map of ecological communities can also be used to monitor areal change at the landscape scale, e.g., expansion or shrinkage of ecological communities, changes in vegetation biomass or shrub cover, or changes in important wildlife habitat, and to link the results of the question-based monitoring to broad areas through remote sensing approaches (Zhang et al 2013, Fraser et al (2011). By agglomerating site units or ecological communities, local scale monitoring and derived models can be scaled-up from detailed ecological community maps using high resolution imagery (e.g., 1 m WorldView of QuickBird) to maps based on regional scale imagery such as SPOT 4/5 or Landsat 8 to cover ecologically-representative regional areas, i.e., TEC subzones.

Whatever ecological communities are selected for monitoring, the point here has been to demonstrate how the TEC acts as an ecological template providing a clear rationale for selecting sites to monitor, and for linking monitoring results across northern monitoring sites in different areas of the Canadian and circumpolar Arctic and Sub-arctic. By contributing the baseline information that informs the TEC, the AVA is fundamental for the development of long-term monitoring and other ecosystem based management systems for the Arctic.

Summary

This paper has presented the important role that a correlated AVA could play in providing a strong biological basis for developing an TEC for Arctic and Sub-arctic terrestrial ecosystems and has proposed how such a TEC would provide a strategic ecosystem-based foundation for implementing monitoring across the vast areas of Canada's North. The international nature of the AVA also means that monitoring and research in the Canadian North can be linked across the circumpolar area to help coordinate the implementation of the CBMP Terrestrial Ecosystem Monitoring Program (Christensen et al 2013).

Although applications to pan-Arctic monitoring are explored here, a similar argument can be made for the role of a correlated arctic TEC in developing a strategic approach for implementing coordinated research across the Arctic and Sub-arctic. For example, a key five year research priority for POLAR is to develop an understanding of terrestrial cryosphere change as it affects northern ecosystems, communities, and industrial activities. A strategic approach to implementing cryosphere research could utilize an arctic-subarctic TEC in the same way presented here for monitoring. Similarly, impact assessments and other land use management, e.g., road locations, pipeline issues, priority conservation areas, and terrain trafficability, can be informed by ecosystem maps linked to the arctic-subarctic TEC.

For all of these applications, a Canadian Arctic-Subarctic TEC, grounded by a correlated AVA initiative, can provide an ecosystem-based template for framing issues across this vast area, for developing strategic experimental designs, for extrapolating point based observations through remote sensing approaches to broad geographic areas, and for communicating monitoring and research results nationally and internationally.

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