Ecosystem Monitoring in the CHARS Experimental and Reference Area


Photo: Susan Kutz

Terrestrial Ecosystem Monitoring Plan

PILOT PHASE (2017-2019)

August 2017

To the Reader

Thank you for your interest in this document. This terrestrial component of the Pilot Phase of the CHARS ERA Monitoring Plan covers a wide range of areas of expertise and we are actively seeking input and comment on those areas where you feel your expertise will add value to the plan. We realize that we have not provided clear monitoring methodologies for all variables – think of this as the frame for the beginning of a process and we are looking for broad input as to the best way to go forward during the Pilot Phase. Of course monitoring plans need to be flexible and evolve with new developments, but we are hoping to get some consensus on some issues to initiate implementation. Please forward all feedback to Donald McLennan at the contact information provided below.

The terrestrial slug *Deroceras leave* plays intermediate host to the larval stages of protostrongylid lungworms that infect muskoxen in the Greiner watershed – parasites that have migrated to the Cambridge Bay area over the last 8 years in response to climate warming.

Cover Photo: Muskoxen (*Ovibos moschatus*) are resident to the Greiner watershed, are an important source of food for Cambridge Bay residents, and have recently experienced a dramatic decline in the area.

For Feedback Please Contact:

Dr. Donald McLennan
Head - Monitoring Science
Canadian High Arctic Research Station/Polar Knowledge Canada
613-295-6135   **donald.mclennan@polar.gc.ca**
170 Laurier Avenue West, Suite 200, Ottawa, ON K1P 5V5.

Table of Contents

1. Introduction

The amplification of climate warming at more than double the global average in northern latitudes (ACIA 2005, IPCC 2007, Larsen *et al*. 2014, Serreze *et al.* 2009, AMAP 2017) means that abiotic and biotic components of Canada's subarctic and arctic ecosystems are changing, and will continue to change in ways that are highly complex and difficult to predict with any certainty (Callaghan *et al.* 2011a, Derksen *et al.* 2011, Francis *et al.* 2009, Lawler *et al*. 2009). It is because of this accelerated rate of change and high uncertainty that many summary reports on climate-driven change at subarctic and arctic latitudes have recommended the immediate establishment of coordinated and integrated monitoring networks that can generate timely information on how climate change is driving ecological change at Arctic latitudes (ACIA 2005, SWIPA 2011, Forbes *et al.* 2009, Bidwell *et al.* 2013. AMAP 2017).

The Canadian High Arctic Research Station (CHARS) is in a unique position to make a valuable contribution to Arctic environmental monitoring because of POLAR's mandate for coordinating across governments, communities and industry, its focus on long term monitoring, the science capacity to be located at the Station, and the location of CHARS adjacent to the Hamlet of Cambridge Bay so that 12 month a year sampling is feasible and local knowledge can be incorporated into the design and delivery of the program. A central objective of the CHARS monitoring program is to the inclusion of the Indigenous Knowledge of local residents in plan design and implementation, and the location of CHARS within a northern community like Cambridge Bay will help make this possible.

As a Flagship Arctic site, and with a considerable in-house science staff, CHARS can act as a knowledge centre for Arctic monitoring by developing and demonstrating best monitoring practices, conducting research to inform the development of monitoring protocols, acting as a data management centre for monitoring data, and by reporting the results of monitoring in summary monitoring publications. As a long-term goal, we will work to make monitoring at CHARS part of a national and international network of coordinated monitoring sites that track change in a core set of mutually agreed on components of Arctic ecosystems. From a biodiversity perspective, much of this work has been completed through the marine, freshwater, terrestrial and soon coastal monitoring plans under the Circumpolar Biodiversity Monitoring Program (CBMP) – a product of the Committee on Arctic Flora and Fauna (CAFF) Working Group of the Arctic Council. The Arctic is vast and constituent ecosystems vary greatly across the range of Arctic regional climates, so a coordinated network is fundamental to understanding and communicating ecosystem change across the circumpolar area.

This document provides a framework for developing a comprehensive monitoring approach for monitoring, understanding and reporting change in the CHARS ERA – it does not yet contain for example, all of the detailed monitoring questions and protocols that a complete monitoring plan requires. We hope to refine and improve the plan based on consultations with knowledge users such as Kitikmeot communities, decision-makers and industries, and through cooperative research with the various communities of national and international Arctic scientists that will help develop the most cost-effective and informative approaches to developing the required knowledge. The approach is to actively and continuously seek and incorporate the input of both knowledge users and knowledge developers in a cycle of continuous learning and improvement. The financial and human investment in the CHARS monitoring program, and in Arctic monitoring in general, will be justified if the program can generate and communicate useful and timely information on how and why Arctic ecosystems are changing, change to be expected in the near future, and potential impacts these changes may have on Arctic communities, industries and ecosystems.

2. The CHARS Experimental and Reference Area (ERA) Monitoring Program

2.1 General Program Goals and Approach

The aspiration for the CHARS monitoring program is to utilize a holistic social-ecological system approach at a range of scales across the CHARS ERA. The monitoring plan will be used as a template to inform Arctic ecosystem modeling across Canada, and will link to similar monitoring initiatives internationally across the circumpolar Arctic. To establish this Flagship site we will develop a regionally and globally linked, and locally informative, sustainable program that can track, report, attribute, predict and communicate change in relevant, prioritized components of the CHARS ERA social-ecological system. Monitoring will scale up local observations to regional scales and work towards the integration of ecological realms (terrestrial, freshwater, coastal and marine) and human social systems. The monitoring program will incorporate both scientific and Indigenous Knowledge traditions, will rely strongly on support from community-based monitoring data, and will evolve as consultations with communities in the ERA and the national and international science communities provide input and feedback to this plan.

The intention is that the Flagship monitoring site at CHARS will provide the central hub of a coordinated network of monitoring sites across the Canadian North, e.g., with CNNRO sites and communities, and will link to circumpolar monitoring initiatives through international cooperation and engagement, e.g., CAFF CBMP and INTERACT. A vision document outlining a national-scale 'Northern Knowledge System' based on the approaches described here is in progress.

2.2 A Pilot Phase: 2017-2019

The Pilot Phase of the CHARS ERA monitoring program is envisioned as a period of consultation, with some testing and analysis as possible up to 2019, where the framework put forward in this document is populated with the most appropriate monitoring protocols, experimental designs are developed and implementation initiated, and the document in general is modified and improved through direct feedback from the national and international science community, from consultations with Kitikmeot communities in the CHARS ERA, and from others as consultations evolve.

This document presents a framework for a Pilot Phase for the development of terrestrial monitoring in the CHARS ERA. The first sections of the document outline a proposal for POLAR-led monitoring in the CHARS ERA including the geographic framework, a social-ecological resilience context, key monitoring elements and goals, and the roles for Indigenous Knowledge and community-based monitoring. Within this context, the second part of the document proposes a framework for long-term, experiment-based monitoring of terrestrial ecosystems in the CHARS ERA and identifies proposed monitoring questions and indicators, an experimental design for hypothesis-based monitoring, approaches for scaling up and modeling out to the whole CHARS ERA, and a general plan for implementation. Monitoring plans for freshwater, marine and social components of the CHARS ERA, and a social-ecological system conceptual model to frame the plan will follow.

2.3 Science Collaborations and Partnerships

The monitoring framework presented here is ambitious and aims to cover all components of ecosystems within the CHARS ERA – from bacteria to Arctic wolves, their interactions with each other and with humans, and including the suite of interacting environmental drivers that in large part determine their distribution and abundance. To implement the CHARS monitoring plan in the CHARS ERA, science collaborations will be required across a number of science communities. For example, in the CHARS Intensive Monitoring Area, science collaboration will be required to design, establish and maintain long-term experiments to develop process-based models of CO_2-CH_4 net flux for terrestrial ecosystems. Factors will include understanding and tracking the behaviour of the soil decomposer community, monitoring changes in climate-driven abiotic factors such as soil moisture and temperature, organic matter decomposition, and nitrification/denitrification processes, capturing the variability in these factors across different terrestrial ecosystems, and addressing the challenge of extrapolating results across regional scales. The proposal here is that we approach this problem through a science collaboration composed of researchers with different skill sets that can contribute to designing, implementing and publishing the research. The collaboration would be funded by a combination of the direct participation of CHARS technical and science staff, instrumentation provided by CHARS and collaborators, competitive CHARS-funded projects such as the recent POLAR Grants and Contribution funding, and the in-kind human and financial contributions of academic research collaborators. Ideally, such cooperation would be able implement the latest developments in the field, improve the approach as new developments occur and, through these activities, develop a national and international community of practice where the long-term experiments maintained in the CHARS ERA serve as an example of best practices in this area of interest. Similar collaborations could be formed to address the range of issues covered in the CHARS monitoring program including, among others, terrestrial to freshwater to marine connectivity, vegetation, small mammals, ungulates, arthropods and birds.

Outside the CHARS ERA, the CHARS monitoring program is envisioned as the activities of an Arctic Flagship Arctic monitoring site linked internationally to similar Flagship sites across the Arctic, and nationally to a coordinated, ecologically representative network of long term monitoring sites across the Canadian North. Realization of these objectives, from the CHARS ERA across Canada to the circumpolar North will require the engagement and coordination of much academic, government, community, industrial and not-for-profit collaborators and partners, and will take many years to achieve. Although ambitious, this kind of national and international coordination is the key to developing and implementing a useful and comprehensive knowledge system that can provide the information required by governments and decision-makers towards the development of proactive adaptation strategies in the most rapidly changing area of the Planet.

2.4 Long Term Hypothesis Based Ecosystem Monitoring Experiments

The term ‘hypothesis-based monitoring’ was proposed recently in a seminal monitoring paper prepared by Lindenmayer and Likens (2010). Although originally proposed to address long term monitoring in terrestrial ecosystems, hypothesis-based monitoring is equally suited to freshwater and coastal-marine systems. Hypothesis-based monitoring is grounded in an *a priori* conceptual understanding of how the systems being monitored work through the development of simple conceptual models and sub-models, and creates clear questions that are answered through implementation of long term monitoring experiments. This kind of monitoring blurs the line between monitoring and research, and intends to understand not only 'how' ecosystems are changing (surveillance or mandated monitoring), but also 'why' they are changing, i.e., what are the drivers and ecological processes that are responsible for the observed changes, how are they changing, and what does that mean in the near future for targeted ecosystem elements?

This approach has three important benefits:

1. results and analysis can identify the key abiotic drivers that lead to changes in targeted monitoring indicators;
2. these relationships can be used to develop process-based predictive models to test hypotheses about these relationships and can be linked to climate change effects using scenarios assuming a range of changes in the drivers, i.e., a range of climate change scenarios, and;
3. the local scale modeling creates the possibility for adaptive monitoring - an ongoing question and answer 'learning loop', where monitoring answers create deeper questions that improve our understanding of how the systems we are monitoring work.

Knowledge derived from these experiments provides the basis for much more informed mitigation and adaptation decision-making, includes the potential for continuous learning, and reduces the potential for negative ecological 'surprise'.

The long term goal for monitoring in northern Canada should be a geographically-representative network of similar hypothesis-based monitoring/research experiments that will represent the kind of active knowledge system required to guide informed management of northern ecosystems in Canada. A network of long term monitoring experiments also responds to the expressed need for sustained process-based studies designed to anticipate change:

> "*It is critical to anticipate changes in the Arctic rather than respond to them, but to do this requires sustained observations and improved understanding of local, regional, and global processes. These research challenges must be addressed in a coordinated and timely manner to ensure sustainable development and resilient Arctic communities and ecosystems.*"
>
> IASC Toyama Statement 2015

2.5 A Systems Approach

Factors that drive social-ecological change in the CHARS ERA act at local to regional spatial scales and across temporal scales that range from days to years to decades. For example, temperature increases caused by global-scale accumulation of greenhouse gas emissions drive regional to local scale ecological change, but considerations of the impacts of this change on Kitikmeot communities needs to also account for legacy change driven by social-economic factors that have been occurring over the last century of European contact, and that are rapidly evolving today (Coates 1985, Larsen and Fondahl 2014). As another example, the Slave Geological Province within the CHARS ERA is one of the richest mineral areas in Canada (SENES 2008) but future sustainable development of this important resource base remains a complex matter. A recent lengthening of the ice free season is increasing the potential for marine-based transportation of products from mining sites but, although impacts and benefits would have important local scale outcomes, project economic viability is driven by global commodity prices far removed from the area. These social-ecological factors are influenced increasingly by temperature-driven change including increases in ungulate disease, new northward-moving species, decreases in sea ice, lake ice, and snow season, increasing shrub coverage, warming permafrost and soils, and changes to stream discharge, and all of these factors interact in complex ways that are poorly understood. In the context of these examples, a long range goal of the CHARS ERA monitoring program is to frame monitoring and research within the context of a multi-scalar, multi-disciplinary social–ecological system model (e.g., Binder *et al*. 2013, Schluter *et al*. 2014, Bennett *et al*. 2011, Petrov *et al.* 2016). Actions taken to implement the CHARS Monitoring Plan will take the first steps towards the development of a holistic social-ecological approach.

Conceptual ecological models that link terrestrial, freshwater and marine/coastal ecosystems to human use and effects will contribute as sub-models to the overall social-ecological system model for the area (Figure 1). Such an ecosystematic

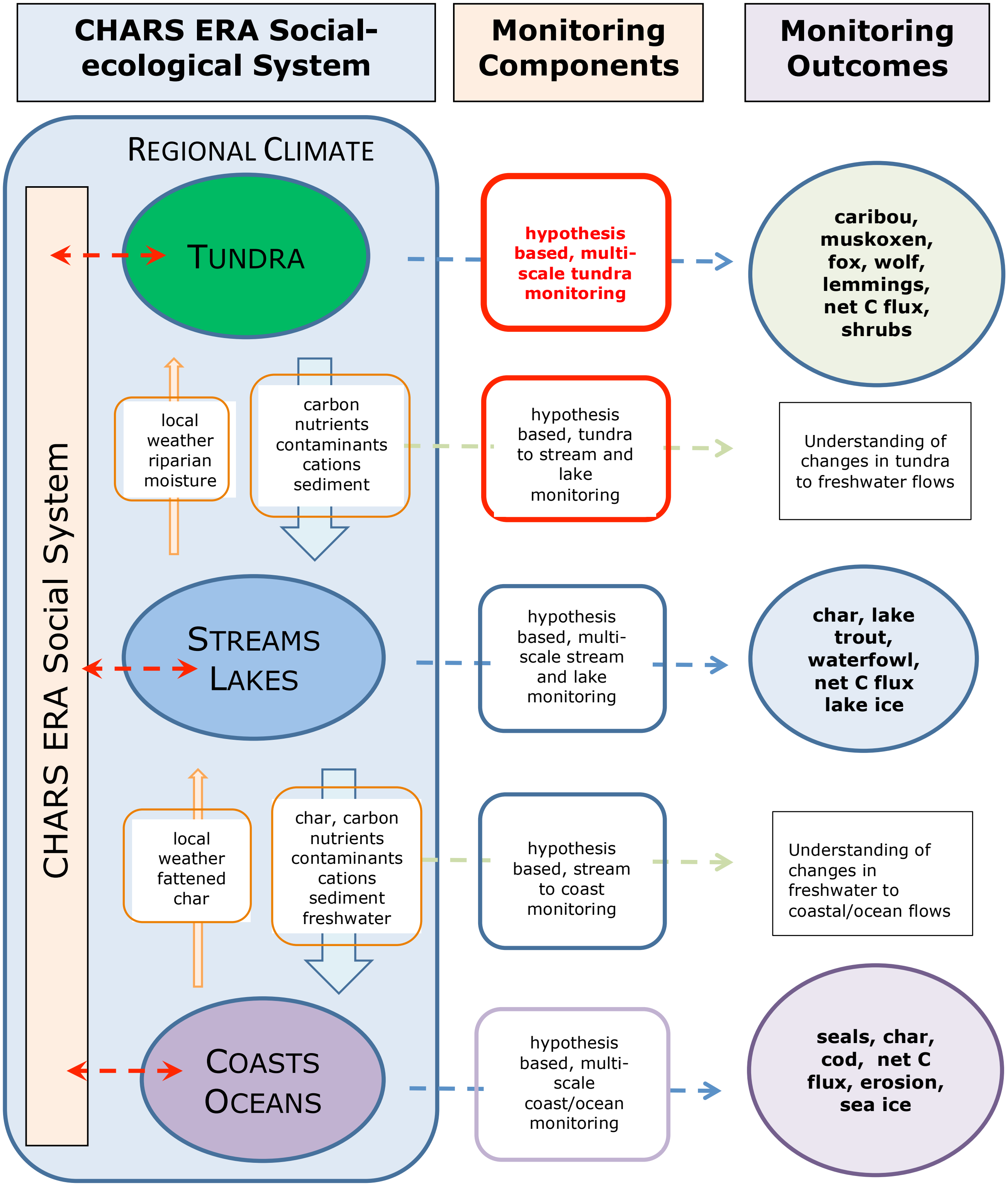


Figure 1: Integrated monitoring in the CHARS ERA links ecological realms to the human social systems and through the Monitoring Outcomes to important social issues (C flux, country food, safe travel) through the implementation of spatially coordinated, long term, hypothesis-based monitoring experiments.

approach will increase our understanding of linkages among abiotic drivers and monitoring or research outcomes, and will help to ensure the social relevance and impact of CHARS-led research and monitoring efforts.

2.6 Working Together for Social-ecological Resilience in the Kitikmeot Region

Establishing a comprehensive social-ecological approach to help foster resilience in Northern communities will involve the integration of efforts and resources from experts in northern environmental and social systems, economics, governance and many other fields. Through the CHARS Monitoring Plan we propose to initiate the approach in consultation with residents initially in the Kitikmeot region and, given a mandate and direction from communities, work cooperatively to develop a broad social-ecological systems model and begin to establish some of the environmental components of a larger social-ecological approach.

Some of the organizations who could be involved in the Pilot Phase CHARS ERA Monitoring Plan in the Kitikmeot region include:

- local community government bodies, e.g., Hunters and Trappers Organizations, Hamlet Councils;
- Inuit affiliations and associated organizations - Nunavut Tunngavik Incorporated (NTI), Inuit Tapiriit Kanatami (ITK), Nunavut Inuit Secretariat (NIS);
- relevant departments within the Nunavut (Department of the Environment) and federal (INAC, DFO, ECCC-CWS) governments;
- co-management boards created under the Nunavut Land Claims Act (Nunavut Wildlife Management Board [NWMB], Nunavut Planning Commission [NPC], the Nunavut Impact Review Board [NIRB], the Nunavut Water Board [NWB] and the Nunavut Surface Rights Tribunal [NSRT], and;
- industry, academics and NGOs operating in the region.

The long range goal is that Kitikmeot residents and governing organizations are active partners in the development of holistic approaches to sustaining social-ecological resilience, i.e., that community members identify priorities for monitoring and research, are trained and employed to conduct community-based monitoring (CBM) in and around their communities, conduct other aspects of the program such as data analysis and compilation, and cogenerate knowledge, bringing both IK and science to inform science-based decision making.

2.7 Indigenous Knowledge and Community-based Monitoring

Inuit residents of Cambridge Bay and the Kitikmeot Region are the modern representatives of a very long knowledge tradition based around securing food, shelter and spiritual enrichment in one of the harshest environments on the Planet. A key focus of the CHARS ERA monitoring program will be to honour Indigenous Knowledge of local ecosystems, and modern traditional/ecological uses of land and sea, by consulting with and engaging local Inuit on program design (what and where to monitor) and implementation (contributing to the monitoring). Regional and local scale environmental monitoring will build on successful projects already occurring in the area (e.g. DFO-led Canadian Rangers Ocean Watch (CROW), GN Fisheries and Sealing N-CAMP).

Kitikmeot Inuit are active fishers, hunters and trappers and there is a real opportunity to create an effective participatory CBM program associated with harvested species to track a range of important monitoring indicators that inform sustainability, as well as species and human health, e.g., levels of contaminants in country food and trapped species, DNA from blood and scat, and the occurrence of new pathogens and disease.

2.8 Linkage to CAFF and other Circumpolar Monitoring Plans

The CHARS monitoring program is coordinated with, and in large part directed by the Circumpolar Biodiversity Monitoring Plan for terrestrial (Christensen *et al*. 2013), freshwater (Culp *et al*. 2012), marine (Gill *et al*. 2011) and coastal (McLennan *et al*. in prep) ecosystems. This report deals with the terrestrial ecosystem component of the CHARS ERA and takes direction from the CBMP Terrestrial Plan, from the national work of the Canadian Terrestrial Expert Monitoring Group, and from objectives specific to the CHARS monitoring program. Subsequent versions of this document will include monitoring designs and sampling approaches for freshwater and coastal-marine ecosystems in the CHARS ERA. The plan is also informed by international monitoring programs, e.g., Greenland's ZERO (http://zackenberg.dk/) and NERO (http://nuuk-basic.dk/), the US LTER (https://lternet.edu/) and NEON programs (http://www.neonscience.org/), and work at Barrow by the NGEE team (http://ngee-arctic.ornl.gov/). It is also a key goal to be linked nationally and internationally to the myriad ongoing monitoring networks, e.g., ILTER (https://www.ilternet.edu/), GEO BON (http://geobon.org/), INTERACT (http://www.eu-interact.org/), GTN-P (http://gtnp.arcticportal.org/), around the circumpolar area, and these linkages are indicated in the descriptions of the different components of the CHARS monitoring program.

2.9 Data Management

The key output for any monitoring program is the data generated – a resource that increases in value over time so that long term trends in ecosystem variables can be analyzed, projected and made useful for informing decisions by governments, communities, and industry, and for contributing to a deepening science understanding of Arctic ecosystem change.

The management of monitoring data generated by the CHARS monitoring program will follow policies and processes outlined in '*Data Management Principles and Guidelines for Polar Research and Monitoring in Canada'* (draft available soon) – a policy document being developed collaboratively by the Northern Contaminants Program, the Nunavut General Monitoring Plan, and Polar Knowledge Canada. Policies developed are consistent with other Canadian data management initiatives and have been modeled after leading international data management practices and principles.

An important feature of data management for the program is that metadata generated will be available as soon as possible in the Polar Data Catalogue (https://www.polardata.ca/) to communicate what variables are being measured, and when and where they were collected. Full data records for all projects will be housed in a permanent, public access, online archive and publications will follow the lead of new journals such as Nordicana D (http://www.cen.ulaval.ca/nordicanad), where data collectors are acknowledged and doi referencing greatly facilitates data access.

Program data will be tabulated, synthesized and reported annually through the POLAR Technical Report Series, and associated research in science journals. A full synopsis that will include completed assessments and modeled predictions to be produced every 5 years in a 'State of the CHARS ERA' report.

2.10 A Northern Knowledge System

A key objective for the pilot phase of the CHARS monitoring program is to provide a proof-of-concept model for demonstrating the feasibility and structure of a pan-Northern knowledge system – envisioned here as a coordinated and ecologically-representative network of hypothesis-based experimental sites across northern ecological realms (terrestrial, freshwater and coastal-marine) designed to reach out regionally through remote-sensing based models using extensive monitoring networks adjacent to communities, and existing monitoring programs for calibration and validation.

The two key monitoring and research elements of such a system are:

- an ecologically-representative network of hypothesis-based monitoring sites implementing a coordinated monitoring program that provides timely and useful information for decision-making, supports regional modeling, and provides long term logistic support for northern science infrastructure, and;
- the empowerment of northern communities as ‘knowledge centres’ (Forbes *et al.* 2016) to act as a foundational component of a monitoring and research network aimed at ensuring the resilience and sustainability of northern communities at a time of rapid and accelerating change.

The overall goal for the northern knowledge system is to mobilize and integrate the potential of northern communities and northern scientists, and to provide long term support for northern science infrastructure to collect, analyze and communicate the information needed for proactive adaptation in Canada’s North - one of the most rapidly changing areas on the Planet.

3. The CHARS Experimental and Reference Area (CHARS ERA)

3.1 CHARS ERA

The CHARS ERA (Figure 2) includes marine areas from Dolphin and Union Strait to Bellot Strait and McClintock Channel, the watersheds that flow into them and directly impact their ecological processes and biota, and the four Kitikmeot coastal communities within the area – describing a large social-ecological system for CHARS-based research and monitoring.

Figure 2: The CHARS Extra-regional ERA. Letters are Circumpolar Arctic Vegetation Map Bioclimatic Subzones (CAVM 2005) with mean July temperature ranges. Red triangles show proposed locations for Intensive Monitoring Areas (IMAs) at Daring Lake (south) and CHARS (north); yellow triangles potential locations for regional Extensive Monitoring Grids (EMGs), and blue triangles potential additional IMAs. These terms are described in the report.

The CHARS ERA demonstrates a strong climatic gradient that includes 4 of the 5 CAVM Terrestrial Bioclimatic Subzones that occur in the circumpolar Arctic. Owing to the steep climatic gradient, the region has been identified through global modeling exercises (Lawler *et al*. 2009) as a 'hemispheric hot spot' where major climate-driven biodiversity shifts are predicted. Within this context of rapid ecological change the CHARS ERA terrestrial ecosystem includes important wildlife populations also undergoing recent change – areas on the mainland support critical calving and summering grounds of the plummeting Bathurst, Bluenose East and Beverly barren ground caribou herds (Adamczewski 2009, CARMA 2016); muskoxen are an important subsistence and commercial species, but are also showing recent dramatic declines on Victoria Island (Tomaselli *et al.* 2016, Species at Risk Committee 2013); the large Queen Maud Gulf Migratory Bird Sanctuary supports over 90% of the world's population of Ross's Goose and 8% of the Canadian population of Snow Goose (ECCC 2016). The area also includes a wide variety of other wildlife and is an active hunting area for local communities.

Coastal-marine ecosystems in the CHARS ERA are strongly influenced by seasonally pulsed freshwater discharges from summer sea ice melt and runoff from terrestrial watersheds, creating a uniquely low-saline upper layer in Queen Maud and Coronation Gulfs (Carmack *et al*. 2015, McLaughlin *et al*. 2006). Arctic char are commercially harvested near Cambridge Bay and are a vital subsistence species throughout the region. Seals are commonly harvested and Beluga are harvested at the far north (Taloyoak) and southeast (Kugluktuk) areas where the eastern and western populations (respectively) reach their summer seasonal migratory limits. Though Narwhal are rarely seen in the region, it is possible that low ice conditions and predators could drive eastern arctic populations more frequently to the region – as witnessed in Cambridge Bay in 2012 and 2013. The Dolphin and Union Caribou Herd relies on the fall formation of sea ice to cross from Victoria Island to wintering areas south of the Queen Maud and Coronation Gulfs and this are tightly linked to changing sea ice (Poole *et al.* 2010).

Ongoing and accelerating environmental changes will affect the food security and traditional lifestyles of Kitikmeot residents, impact existing infrastructure, complicate planned developments, and make difficult the separation of the effects of industrial project developments from those occurring as a result of regional climate drivers. For all of these reasons the CHARS ERA is an area requiring strategic research and long-term monitoring investments to begin to understand how, and how rapidly ecosystems and biota are changing, how these changes are and will interact with existing and planned industrial developments and activities, and the significance of these developments at local to global scales.

3.2 CHARS ERA – Sub-regional Scale

The sub-regional scale of the CHARS ERA is nested defined by the boundaries of the ~1,500 km^2 Greiner Lake watershed (Figure 3) and adjacent marine/coastal areas of Dease Strait. The Greiner watershed was selected for the sub-regional component of the CHARS ERA monitoring plan because of its representativity of terrestrial ecosystems across Victoria |Island, its proximity and relative ease of access to CHARS, the significant subsistence char fishery it supports, and the important Indigenous Knowledge held by local residents of Cambridge Bay. The Greiner watershed is dominated by a tundra landscape

Figure 3: The CHARS Sub-regional ERA around the community of Cambridge Bay and CHARS, including the watershed boundaries of Greiner Lake and proposed sub-regional coastal/marine ERA boundaries.

typical of base rich vegetation communities of Bioclimatic Zone D (CAVM Team 2003) with many lakes and ponds connected by streams and seepage areas (Figures 4a and 4b). The low relief watershed is characterized on mesic sites by Dwarf Shrub Tundra with scattered sedge fens and related wetland types in depressions.

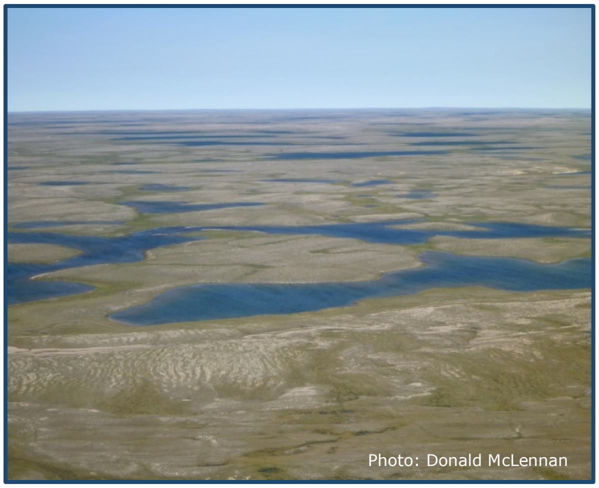


Figure 4a: The Greiner watershed landscape looking north from the top of Mt. Pelly.

Figure 4b: A view of the Greiner watershed showing the south end of Greiner Lake, the Freshwater Creek outlet and the access road to Mt. Pelly.

Coastal-marine components at the sub-regional scale include Dease Strait, an area where marine waters are funneled through a narrow channel with west to east flowing marine water, and a marine biodiversity ‘hotspot’ around the Finlayson Islands. The coastal-marine areas are linked directly to the terrestrial-freshwater component through Freshwater Creek and Cambridge Bay – especially by the seasonal migrations of char, a population very important to local residents of Cambridge Bay.

4. Terrestrial Monitoring in the CHARS ERA

4.1 Terrestrial Ecosystem Monitoring Questions

A well-designed monitoring program requires clear monitoring questions that are considered relevant to the needs of northern knowledge clients such as communities, government decision-makers and the national and international academic community. Monitoring questions are necessarily hierarchical and range from the broad overview questions that we list here, to specific and quantitative questions associated with particular monitoring protocols.

The CBMP Terrestrial Monitoring Plan (Christensen *et al*. 2013) provides broad overview direction with a goal to ‘…detect, understand and report on long-term change in Arctic terrestrial ecosystems and biodiversity’ and identifies four key groups of terrestrial biodiversity - vegetation (including fungi and bacteria), invertebrates (including some arthropods with life stages in aquatic environments), birds (resident and migratory), and mammals (resident and migratory). Monitoring of these four aspects of terrestrial Arctic biodiversity is framed within the following four general monitoring questions:

1. What are the status, distribution, and status of terrestrial focal species, populations, communities, and landscapes/ecosystems and key processes/functions occurring in the Arctic?
2. How and where are these terrestrial focal species, populations, communities, and landscapes/ecosystems and key processes/functions changing?
3. What and how are the primary environmental and anthropogenic drivers influencing changes in biodiversity and ecosystem processes?
4. Where are the areas of high ecological importance including, for example, resilient and vulnerable areas (related to the FECs) and where are drivers having the greatest impact?

Questions 1 and 2 are intentionally very broad and aim at assessing changes in the status and trend of Arctic 'focal species' (Focal Ecosystem Components or 'FECs' in CBMP terminology) that have been identified through broad consultations in the development of the CAFF CBMP Terrestrial Monitoring Plan- CBMP Terrestrial FECs are listed in Appendix A.

Through a similar process, Valued Ecosystem Components ('VECs') have been identified through broad public consultations in the Canadian North by the Nunavut and NWT government monitoring programs – the Nunavut General Monitoring Program (NGMP), and the NWT Cumulative Impacts Monitoring program (CIMP) – see Appendix A.

Based on broad public consultations across Nunavut, the development of land use policies that protect VECs is the central focus of the most recent draft of the Nunavut Land Use Plan (NPC 2016). The Plan also calls on CHARS and the NGMP to '…work cooperatively to ensure that research of the highest priority is occurring' as outlined in NPC (2016).

Finally, VECs are also identified through public consultations surrounding major industrial developments such as the Baffinland Iron Ore Project on Baffin Island and various projects in the Slave Geological Province in NWT and Kitikmeot. VECs not included in the above lists will be incorporated as possible as the plan evolves.

Overall FECs and VECs have a lot of overlap with VECs developed for a specific project or area essentially a subset of the broad spectrum of FECs identified under the CAFF CBMP terrestrial monitoring plan.

In this Pilot Phase of the CHARS Monitoring Program, design and implementation will also put forward a number of additional questions deemed relevant to northern decision-makers, northern communities, and scientists:

5. What are the key environmental drivers determining net ecosystem flux of CO_2/CH_4, how do these relationships vary in different terrestrial ecosystems, how is C flux changing, and how are identified changes related to changes in the environmental drivers?
6. How are atmospherically-deposited contaminants (principally Hg and POPs) processed and transmitted through the tundra ecosystem of the CHARS ERA, and how does this affect delivery to freshwater and marine systems? What are contaminant levels in tissues of important country foods and other targeted species, and how are these levels changing?
7. How are parasites, pathogens and disease impacting terrestrial biota and how are they changing?
8. What are the key atmosphere-land surface controls and feedbacks determining the surface energy balance in the CHARS ERA, how are these relationships changing, and what are the implications for the local to regional climate system?

Adressing these last 4 questions will require the cooperation and collaboration of national and international researchers and this points out the need for the establishment of a long term science partnership between CHARS and the researchers that visit the station.

Monitoring of a subset of the VECs and FECs listed in Appendix A will act as a starting target for the CHARS monitoring plan and will begin to meet the needs of knowledge clients by tracking change in important country food species and species of conservation concern, detect invasion by new species, and track changes in pathogens and contaminants. Through the implementation of long term, hypothesis based monitoring experiments the program will also link abiotic drivers to VECs/FECs to understand how changes in drivers result in changes in the VECs/FECs (to address CBMP Question 3 above) - also creating a knowledge frame for continuous learning and for predictive modeling of anticipated changes. Specific emphasis for the program will be refined as consultations with knowledge clients are carried out.

4.2 Monitoring Across Scales

The approach to implementing multi-scale terrestrial monitoring in the CHARS ERA is to establish a distributed set of local-scale Intensive Monitoring Areas (IMAs) where selected terrestrial indicators and selected abiotic drivers will be co-located and replicated in a series of long-term, hypothesis-based experiments to establish causative relationships among environmental drivers and monitoring indicators. Monitoring in the IMAs will be supported and extended to broader areas using a combination of Long Monitoring Transects (LMTs) and Extensive Monitoring Grids (EMGs) to support remote sensing based gradient models. Ground monitoring will thus support model calibration-validation so that models can be scaled-up using classified remotely-sensed data from aerial overflights and satellite data at a range of scales from extra-local to extra-regional (see Table 1).

Table 1: Proposed nomenclature for multi-scalar monitoring in the CHARS ERA.

Scale	Distances	CHARS ERA Monitoring Program
Local	1-200m	Intensive Monitoring Area (IMA)
Extra local	200m-5 km	sub-catchments containing the IMAs
Sub-regional	5km-40km	Greiner watershed
Regional	40km-200km	calcareous areas of CAVM Subzone Zone D
Extra-regional	200km-600km	CHARS Extra-Regional ERA

To demonstrate the multi-scale approach laid out in Table 1, the pilot IMA to be situated on the north shore of Greiner Lake overlaps two sub-drainages (Figure 5) several kilometers in length (extra-local scale). In the sub-catchments outside the IMA we will conduct more extensive monitoring (LMTs and the EMGs) that can be linked to remote sensing based modeling techniques to calibrate and validate scaled up predictions for the sub-catchments. Using this approach, local-scale monitoring observations will be linked to extra-local, sub-regional (Greiner watershed), and regional (base-rich areas of the CAVM Subzone D in the CHARS ERA – see Figure 2) scales.

It is important that the ecologically-unique results of the experiments conducted in the IMA are not scaled up and applied to areas that do not have the same ecological characteristics. For example, terrestrial dwarf-shrub ecosystems in the IMA and the Greiner watershed are characterized by calcareous, limestone-based soils with high pH and a plant species and faunal list that manifest these conditions. Local scale relationships between abiotic drivers and vegetation established through the pilot IMA experiments may not apply for example to the area south of Queen Maude Gulf that is in the same regional climatic subzone (CAVM Subzone D), but is dominated by granitic soils of low pH with different fauna, flora and soil-plant relationships. For these reasons it is assumed that local

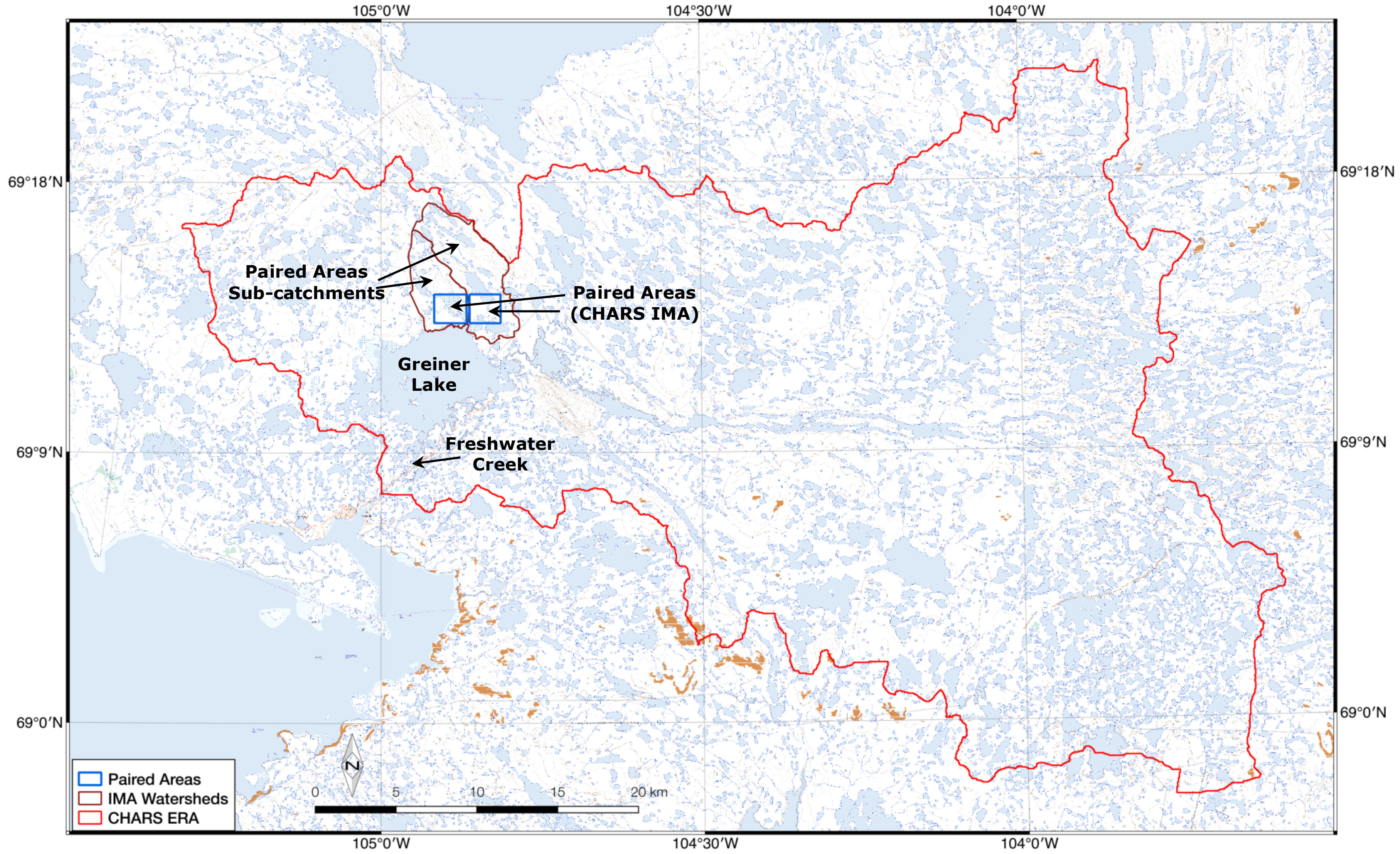


Figure 5: Greiner Lake watershed showing the locations of the 2 Paired Area catchments that include the 2 Paired Areas and encompass the CHARS Intensive Monitoring Area (IMA). Freshwater Creek is the main drainage creek for Greiner Lake although another drainage outlet operates seasonally.

relationships can be scaled to calcareous soils in CAVM Subzone D, a large area covering much of southern Victoria Island. These assumptions can be tested as the modeling evolves as part of the monitoring program as it ispossible some measures can be scales across ecologially-uniform areas.

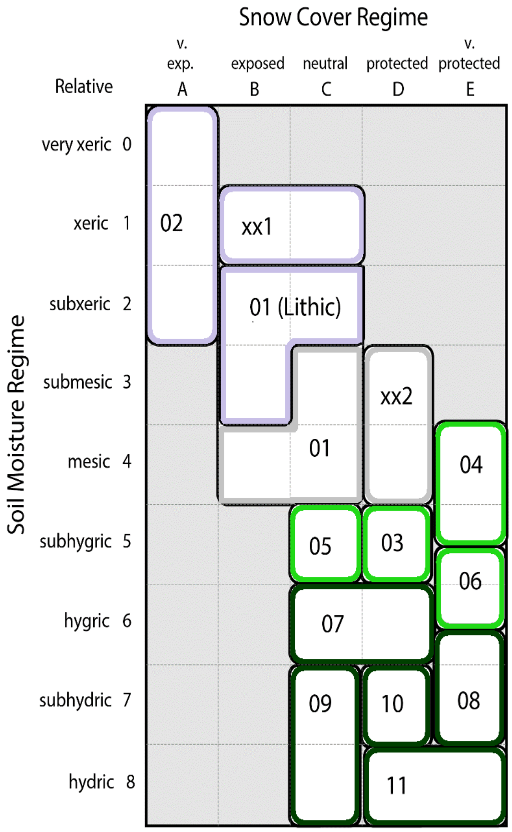
Similar local- to regionally-scaled monitoring schemes will be established across the CHARS ERA, e.g., for CAVM Subzones E (establish an IMA at Daring Lake) and C (establish an IMA on northern Victoria Island), and granitic areas of CAVM Subzone D (establish an IMA at a mining site or research cabin in Subzone D south of Queen Maude Gulf). This group of IMAs would make up an experimental transect that runs from Daring Lake in the south the south end of Hadley Bay in the north (see Figure 2), supported by less intensive monitoring at EMGs and LMTs between IMAs, and linked through remote sensing data along the transect and would provide an ideal natural setting for tracking ecological change across a very strong climatic and ecological gradient. By providing logistical support and baseline studies it is hoped that such a transect will be appealing to national and international scientists using CHARS and looking to test a variety of hypotheses across such a gradient.

IMA protocols in subzones outside of the initial IMA in the CHARS ERA will be much less intensive than in the CHARS pilot IMA, but are important as they will serve as a model for working with partners to establish an informative but sustainable core set of local monitoring experiments in a connected network across the North.

4.3 Terrestrial Ecosystem Classification

The plant communities that characterize and help identify distinct tundra ecosystems change across the landscape in response to the effects of abiotic drivers that largely control their species composition, structure and productivity (CAVM Team 2005, Edlund 1989, 1990, Gould *et al.* 2003, Flynn and Francis 2013, Walker 1995, Walker *et al.* 2008). A description of the classification and characteristics (plant species lists, soils, site and physiographic characteristics) of the terrestrial ecotypes identified for the Greiner watershed are detailed in Mackenzie *et al*. (2014), and a summary is shown in Figure 6.

Our preliminary classification (Figure 6) and ecosite description process qualitatively identified two key abiotic drivers that can help explain much of the spatial variability in tundra communities in the Greiner watershed – soil moisture regime and the degree of snow protection during severe winter weather. Other important abiotic factors include soil depth, texture and mineralogy, active layer depth, landscape position, wind, and year to year climatic variability. Biogeographic context for the study area, and species interactions, e.g., competition, symbiosis,



Site Series

01 (Arc041) Mountain-avens - Curly sedge

02 (Arc) Three-toothed Saxifrage - Blackish locoweed

xx1 (Arc) Arctic willow || xx2 Mountain-avens - Oxytropis

03 (Arc) Mountain-avens - Net-veined willow

04 (Arc027) Mountain-heather - Mountain-avens

05 (Arc) Mountain-avens - Water sedge - Arctic willow

06(Arc) xxMountain-avens - Horsetail - Bearberry||Polar willow - Moss

07 (Arc) Arctic willow - Water sedge - Scorpidium

08 (Arc) Richardson's willow - Water sedge

09 (Arc) Water sedge

10 (Arc) Dupontia - Water sedge

11 (Arc) Arctophila fulva

Figure 6: Classification of terrestrial ecosystems (ecotypes) in the Greiner Lake watershed arranged along the two principle axes of abiotic drivers (soil moisture and degree of winter snow protection) principle determinants of the tundra ecotype mosaic.

parasitism, commensalism, are also important. Parallel baseline studies over the pilot phase of the monitoring will work to quantify these relationships between abiotic drivers and the distribution of tundra communities.

The terrestrial ecosystem classification system employed in the CHARS ERA follows the approach of the mature Biogeoclimatic Ecosystem Classification (Pojar *et al.* 1987) widely used for land management applications and climate change modeling in British Columbia (Gayton 2008, Hamman and Wang 2006, Pojar 2011, Wang *et al.* 2012) and is presently being developed and applied in the Yukon Territory (Flynn and Francis 2015). Parks Canada Agency has recently applied the system to create ecosystem classifications and maps for all Arctic national parks (PCA 2014). Building on work already completed in the Greiner watershed, we will work with partners to apply this system to the CHARS Regional ERA and demonstrate its usefulness for coordinated research and monitoring.

The plant community classification that is at the heart of the ecosystem classification is linked to the Arctic Vegetation Archive (Walker *et al.* 2013) in Alaska, and the Canadian National Vegetation Classification (CNVC 2016) to standardize nomenclature for sub-arctic and tundra communities across North America and the circumpolar North. This standardized approach to plant community classification provides the opportunity to link research and monitoring results and climate change projections nationally, and around the circumpolar area.

To provide an ecological template for implementing the terrestrial monitoring, high resolution ecotype maps are being developed over the pilot Intensive Monitoring Area to facilitate an effective experimental design that stratifies the tundra landscape into ecotypes that have similar and recurring groups of plant species (plant communities), abiotic drivers and ecological processes. This will provide the ecological basis for extrapolating local scale monitoring results to broader scales. Ecosystem maps delineating ecotypes (or amalgamated ecotypes) will also be developed for the Greiner Lake watershed, and for the Regional ERA, using modeling approaches and remote sensing data (see for example Fraser *et al.* 2012). The ecosystem classifciation approach to be employed in the CHARS ERA is also linked through in its theoretical approach and through the Arctic Vegetation Archive (Walker *et al*. 2013) to the circumploar area permitting broad extrapolation of reserach and monitoring results.

4.4 Monitoring Methods

A number of monitoring methods will be utilized to track ecological change at a range of scales from local and extra-local through sub-regional (Greiner Lake watershed) to extra-regional. Figure 7 shows potential locations of two proposed

Intensive Monitoring Areas (IMAs), 3 weather stations, and a network of Long Monitoring Transects (LMTs) linked to Extensive Monitoring Grids (EMGs) to be established adjacent to a number of remote research/monitoring cabins. These ground monitoring approaches will be supported and extended by aerial surveys and satellite remote sensing data as described below.

Figure 7 also presents a map of terrestrial ecotypes that have been agglomerated into 3 functional ecotype groups - upland (mesic to xeric unprotected ecotypes), lowland (snow protected ecotypes) and wetland ecotype groups (see Figure 6 for color coding for ecotype groups) across the Greiner watershed. As discussed above ecosystem maps of this nature will be used to determine the locations of EMGs and LMTs and upscale local monitoring observations to sub-regional and regional scales.

4.4.1 Intensive Monitoring Areas (IMAs)

Intensive quantitative monitoring relying on an array of instrumentation with co-located abiotic and biotic variables will be piloted in an IMA situated on the north shore of Greiner Lake (Figure 5). This location is proposed because of its access to Cambridge Bay, its relative isolation from human disturbance, and the representativity of its terrestrial ecosystems. The IMA is bisected by streams and dotted with many shallow lakes and ponds of various sizes to permit co-located monitoring of freshwater ecosystems, and studying connections between terrestrial and freshwater ecosystems. It is also encompasses the stream mouths of two sub-catchments flowing into Greiner Lake (Figure 5), and thus provides an opportunity to compare terrestrial and freshwater monitoring results across two paired drainages, and for scaling up to an extra-local scale over the two independent sub-catachments. Finally, the location of related infrastructure in the IMA on Greiner Lake provides the opportunity for logistical support for limnology monitoring and research activities on Greiner Lake itself.

A tentative location for a future IMA is proposed in the south east corner of the watershed (Figure 7) because of its access by a short float plane flight or feasible snowmobile ride, the representativity of its terrestrial ecosystems, and its location on a lake supporting overwintering arctic char for freshwater research. A second IMA monitoring area will expand the representativity of the hypothesis-based monitoring and provide additional sites for calibration and validation of the predictive modeling.

Details of plot layout and design in the Pilot IMA are presented in the next section.

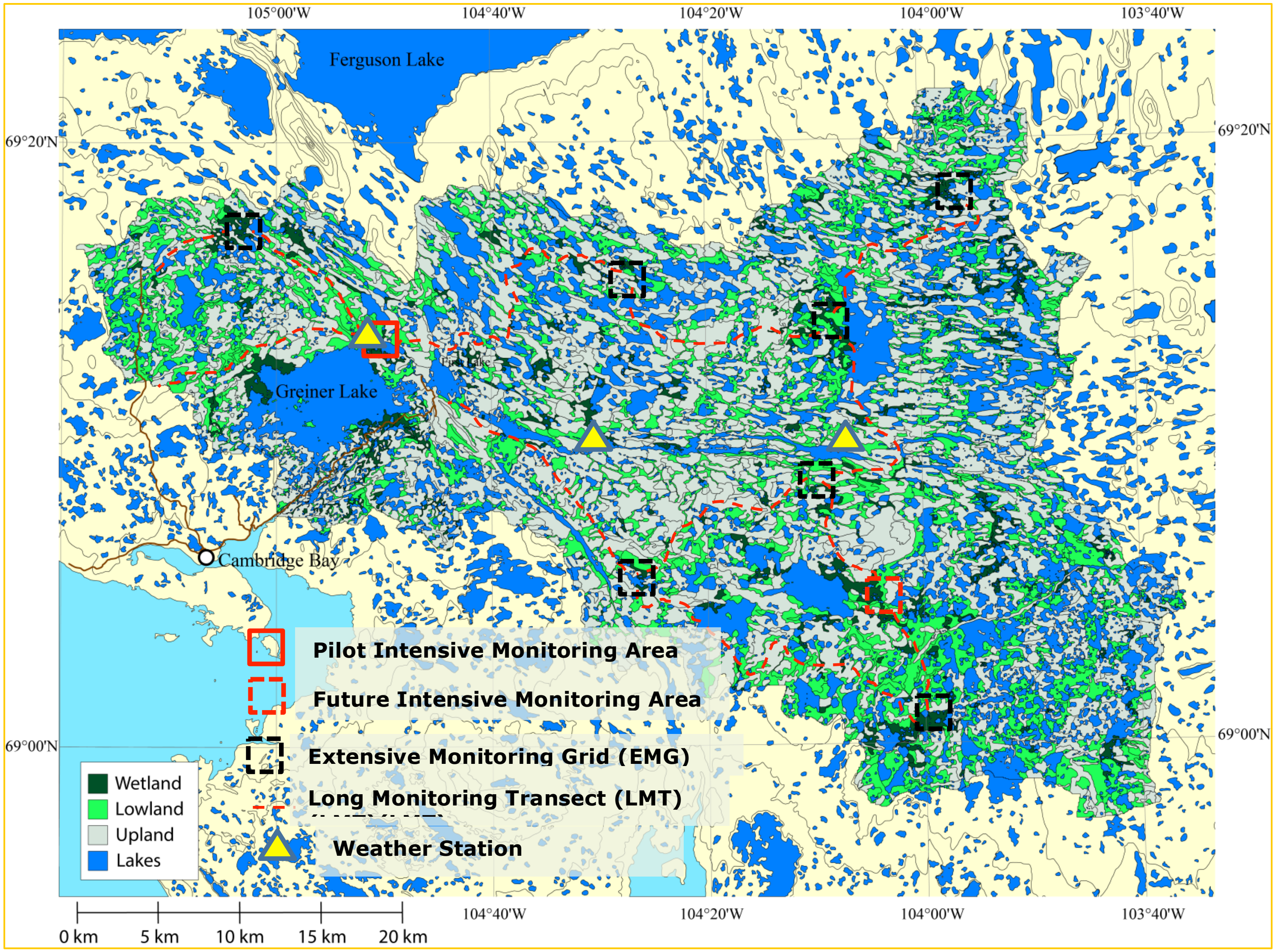


Figure 7: The ca 1,500 km^2 Greiner watershed (approximate boundaries) showing groups of ecotypes (see Table 2), locations of pilot and future Intensive Monitoring Areas (IMAs), Extensive Monitoring Grids (EMGs), and proposed Long Monitoring Transects (LMTs).

4.4.2 Long Monitoring Transects (LMTs)

Long Monitoring Transects (see Figure 7) are intended to provide a systematic and repeatable approach to tracking a number of monitoring components across a broad cross-section of the Greiner Lake watershed. Sampling along the LMTs will take place throughout the year and monitoring indicators assessed will also change seasonally – example parameters are listed in Table 2.

Table 2: Examples of typical seasonal sampling along the Long Monitoring Transects

Season	Approximate Dates	Proposed Monitoring Activities
Late Winter- Early Spring	Late May to mid-June	• staging and early nesting birds • lemming winter nest counts • scat, tracks, and direct observation of ptarmigan, muskoxen, caribou, Arctic hare, Arctic fox, wolf, and grizzly bear • snow depth, lake ice thickness
Late Spring - Early Summer	Early to mid-July	• nesting/resident birds • scat, tracks, and direct observation of ptarmigan, muskoxen, caribou, Arctic hare, Arctic fox, wolf, grizzly bear • snow depth, lake ice thickness • presence of sun crusts/rain crust • snow off date (photo)
Mid-Summer	End of July – early August	• nesting birds – broods • scat and direct observation of muskoxen, ptarmigan, caribou, Arctic hare, Arctic fox, wolf, and grizzly bear
Late Summer-Early Fall	Early to mid-September	• fall staging birds • scat and direct observation of muskoxen, ptarmigan, caribou, Arctic hare, Arctic fox, wolf, and grizzly bear • snow on date (photo) • snow depth, lake ice thickness
Monthly Winter	Over the snowmobiling season – mid October to May	• scat and direct observation of ptarmigan, muskoxen, Arctic hare, Arctic fox, wolf, and grizzly bear • snow depth, lake ice thickness

In addition to wildlife and snow observations, geo-referenced digital photography of ground vegetation classified to ecotype will provide calibration-validation data to support regional ecosystem modeling and mapping.LMTs have been initiated by POLAR staff in 2014 and 2015 in the Kent Peninsula in Regional ERA recording selected variables to assess potential environmental assets and impacts in areas of high potential for future mineral development.

4.4.3 Extensive Monitoring Grids (EMGs)

EMGs will be established to increase areal coverage of selected monitoring indicators, and to calibrate and validate scaling up models using remote sensing data and local scale models established in the IMAs. The locations of seven proposed locations for a series of Extensive Monitoring Grids (EMTs) distributed within the Greiner Watershed are also indicated in Figure 7, along with the approximate routes of the LMTs between EMG locations. EMG locations were determined by dividing the Greiner lake watershed into 7 equal area segments, selecting a random coordinate within the segment, and then moving the EMG location to the nearest deep lake (to also permit limnology research and monitoring) that would also support float plane landing.

It is proposed that a core set of monitoring measures be established at all EMG locations, and that new measures be added opportunistically on a project basis, i.e., for a specific modeling project. Examples of core monitoring indicators for the EMGs are listed in Table 3. At each EMG station, a random process will be used to establish the centre point of a monitoring grid that would cover a number of terrestrial ecostypes, and EMG measures will be then stratified by ecotype for scaling up and reporting. EMG stations could also be established adjacent to Kitikmeot communities across the CHARS Regional ERA to monitoring used to scale up models to regional and extra-regional scales (see Section). Community-based monitoring approaches copuld be used to maintain these extra-regional EMGs.

4.4.4 Aerial Surveys

Aerial survey transects from fixed wing planes, helicopters or UAVs will be important to provide information on wide ranging species such as muskoxen, caribou, polar bears, grizzly bears, and wolf. A census of these mammalian species across Nunavut is the responsibility of the Nunavut Department of Environment, Wildlife Management Division. However, annual aerial surveys for these species that cover all of Nunavut, or even the Kitikmeot region, are not feasible. The proposal here is to conduct annual surveys across the Greiner watershed and along the south shore of Victoria Island where the Dolphin-Union caribou herd assembles in the fall to wait to cross the sea ice at Dease Strait. Such an annual survey over a small area would not be overly expensive and would provide an annual indicator to inform the timing, accuracy and location of broader surveys by government agencies, and support ground monitoring of ungulates, e.g., IK observations, tracks along the LMTs and DNA from scat. Techniques and seasonal timing to conduct the aerial surveys will be developed in concert with the Nunavut Department of Environment, Wildlife Management Division, so that the data gathered can contribute to both the CHARS ERA monitoring program and the mandated needs of government agencies.

Table 3: Examples of proposed core monitoring measures for EMG sites.

Ecosystem Components	Monitoring Measures	Monitoring Frequency
soils and snow	• soil temperature depth transect • active layer depth/season • snow depth transect • photo-based snow season	• continuous • continuous • May annually • continuous
vegetation	• ITEX vegetation sample • photo-based plant phenology	• bi-annually • continuous
fauna	• all bird presence/absence • lemming nest counts • widlife scat plots • wildlife camera record	• June annually • June annually • June annually • continuous

Like the ungulate surveys, annual or semi-annual waterfowl surveys over the relatively small area of the Greiner watershed and south-eastern Victoria Island would help inform the timing, accuracy, and location of broader surveys, and support ground monitoring of waterfowl along the LMTs and in the IMAs. Techniques and survey design will be developed in concert with Ducks Unlimited (DU) and ECCC so that the data gathered can contribute to both the CHARS ERA monitoring and the mandated needs of government agencies and of not-for-profit groups like DU.

Depending on the availability of different kinds of instrumentation and evolving partnerships, aerial overflights of the Grenier watershed with platforms carrying advanced instrumentation also provide the opportunity to collect high resolution optical, laser and radar data from a range of sensors for variables such as micro-topography, vegetation characteristics (NDVI, biomass, functional types), CO_2/CH_4 low atmosphere concentrations, snow depth distribution and seasonality, surface water distribution and soil moisture. For example, in April 2017 POLAR partnered with the British Antarctic Survey to conduct surveys of top of snow LiDAR, Ka-band radar, and radiometric sensors to assess snow distribution and depth. In August 2017 a partnership with NASA will see a NASA aircraft fly AVIRIS-NG to complete hyper-spectral remote sensing (https://aviris-ng.jpl.nasa.gov/) over the entire 1,500 km^2 area of the Greiner lake watershed. These data and others will support research and monitoring, and assist with mapping and scaling up exercises, aimed at linking ground based observations and UAV-derived data, to wide regional areas using fixed-wing and satellite based platforms and modeling.

4.4.5 Satellite Remote Sensing

Data from satellites will provide critical broad landscape-level data for the Greiner watershed and the CHARS ERA, and will provide the basis for ground validation of satellite imagery and ecological classification of the region.

Standard methods for monitoring and modeling landscape level change using satellite data have been developed for the Arctic, e.g., in Arctic National Parks, other northern agencies (e.g., CCRS and ECCC) and by university researchers. These methods include change in terrestrial ecosystem area, functional groups (e.g., shrubs), vegetation biomass, date of green-up, active layer depth, and lake ice and snow phenology. These protocols will be adopted for use in the Greiner watershed and for the Regional ERA, and will be updated as methods evolve. Ground data to calibrate and validate the remotely-sensed data and models will be an important component of the CHARS monitoring program and will make use of the IMAs, LMTs and EMGs to provide a wide, ground-based sample of the area within the watershed.

Baseline studies using new and archived satellite data (Landsat) are being carried out to track historical (mid 1980s to present) changes in land cover properties including length of the growing season, NDVI, and biomass. A sub-pixel fractionation approach (Fraser *et al.* 2012a) will be used to track historical change in vegetation functional groups (relative coverage of shrubs, herbs, and moss), and will be linked to the ecosystem classification to overlay areas of change on mapped ecological units. This will provide the opportunity to link changes in vegetation functional types with the postulated ecological processes that define the different ecotypes, helping develop testable hypotheses to guide research into vegetation change. This will be completed with recent high-resolution visible imagery of the Greiner watershed using GeoEye, QuickBird2 and WorldView for current land cover conditions across the watershed.

Other planned backcasting studies include change in the length of the snow season, changes in active layer depths, in the thaw dates of watershed lakes and in the occurrence of rain-on-snow (ROS) events and presence of ice layers in snow. The ROS work requires passive (Langlois *et al.* 2016) and active (e.g. King *et al.* 2015) microwave radiometry. Specifically, for active layer monitoring (e.g. freeze-thaw), L-band passive microwave from the Soil Moisture Active Passive (SMAP) and the Soil Moisture Ocean Salinity (SMOS) can be used (Derksen *et al.* 2016; Roy *et al.* 2015). The historical record of passive microwave brightness temperatures at other frequencies are available back to 1979, and include the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus-7 satellite, the Special Sensor Microwave Imager (SSM/I and SSMIS), which was flown on the Defense Meteorological Satellite Program (DMSP) satellites, and the Advanced Microwave Scanning Radiometer(AMSR-E and AMSR2) (Royer and Poirier 2010).

5. Pilot Intensive Monitoring Area (IMA)

A hypothetical layout for the pilot IMA (Figure 8 – see Figures 5 and 7 for location) provides a visualization of how the experimental design and plot layout could look once established. The key to the design is to co-locate the measurement of VECs/ FECs with abiotic drivers in the IMAs (spatial co-location) and to coordinate the timing of all measurements so that changes in abiotic measures can be linked in time (temporal co-ordination) to changes in selected VECs/FECs (e.g., to changes in small mammals, shorebirds, songbirds, and the pitfall and Malaise arthropod traps) to permit process-based interpretation of changes in the indicators, and for local-scale process model development. Targeted monitoring will also be implemented as needed within and adjacent to the Paired Areas in the Intensive Monitoring Area, e.g., to locate streams for black fly stream stone monitoring or find suitable ponds for mosquito sampling.

5.1 Selecting Ecotypes for Intensive Monitoring

We have identified 11 major ecotypes in the Greiner watershed (Figure 6) and it is clearly not feasible to install instrumentation and intensive monitoring in all ecotypes. As a compromise, four ecotypes (Table 4, Figure 8) have been selected based on their having the predominant areal coverage in the watershed, and according to the following rationale:

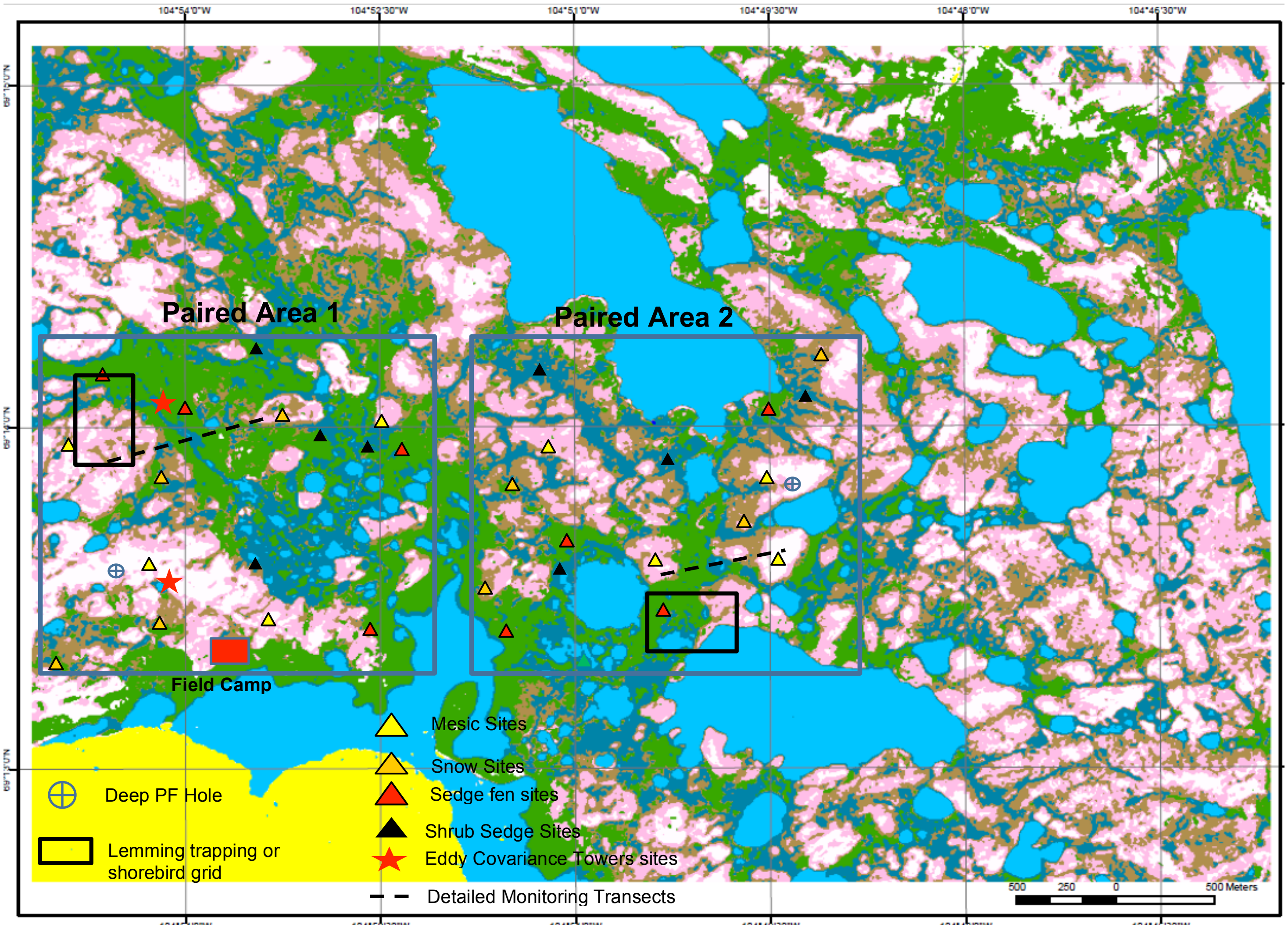


Figure 8: Possible layout of 2 Paired Areas within the Pilot IMA showing locations of 24 Experimental Monitoring Plots (colour coded triangles), Experimental Monitoring Transects, 2 eddy covariance towers, lemming trapping/shorebird grids, and 2 deep permafrost monitoring holes. Map colours show distributions of terrestrial ecotypes in the IMA.

Figure 9: Four ecotypes selected for intensive monitoring (all photos – Donald McLennan).

1. **Zonal Ecotype - 01** (*Dryas integrifolia-Carex rupestris*): The Zonal Ecotype is that ecosystem most reflective of regional bioclimate, i.e., it is the Zonal ecotype for the CAVM Zone D in which the Greiner watershed is located. Monitoring the Zonal Ecotype thus provides an ecological basis for comparing change across Arctic Bioclimatic Zones. The Zonal Ecotype is also important as habitat for Collared Lemmings, and as winter foraging areas for Arctic Hare and Muskoxen.

Table 4: Ecotypes identified and classified in the Greiner watershed, sites selected for intensive monitoring (yellow), for installing, eddy covariance towers (**) and Ecotype groupings for scaling up (see Figure 6).

Ecosite	Code	Scaling Groups
Dryas integrifolia – Carex rupestris ** (Mountain Avens-Curly Sedge) – 'Zonal Ecotype'	01	Upland Sites
Saxifraga tricuspidata- Oxytropis arctobia (Three-toothed Saxifrage Blackish Locoweed)	02	Upland Sites
Dryas integrifolia–Salix reticulata (Mountain Avens–Net Veined Willow)	03	Snow Protected Sites ("Lowland')
Cassiope tetragona-Dryas integrifolia (Mountain Heather – Mountain Avens) – 'Snow Ecotype'	04	Snow Protected Sites ("Lowland')
Dryas integrifolia–Carex aquatilis-Salix arctica (Mountain Avens-Water Sedge-Arctic Willow)	05	Snow Protected Sites ("Lowland')
Dryas integrifolia–Equisetum arvense-Arctostaphylos (Mountain Avens-Horsetail Bearberry)	06	Snow Protected Sites ("Lowland')
Salix arctica-Carex aquatilis-Scorpidium scirpoides (Arctic Willow-Water Sedge-Scorpidium)	07	Snow Protected Sites ("Lowland')
Salix richardsonii-Carex aquatilis (Richardson's Willow–Water Sedge) – 'Shrub Sedge Fen Ecotype'	08	Wetlands
Carex aquatilis ** (Water Sedge) – 'Sedge Fen Ecotype'	09	Wetlands
Dupontia fisheri-Carex aquatilis (Dupontia-Water Sedge)	10	Wetlands
Arctophila fulva *(Pendant Grass Marsh)*	11	Wetlands

2. **Snow Ecotype - 04** (*Cassiope tetragona-Dryas integrifolia*): The Snow Ecotype is afforded the highest winter snow protection and as a result features warmer winter soils, deeper active layers and supports unique flora that would otherwise not be able to survive under prevailing winter conditions in the study area. The reliable deep snow in this ecotype also provides critical wintering areas for Collared and Brown lemmings, a keystone species that drives abundance of many predator species.
3. **Shrub-sedge Fen Ecotype – 08** (*Salix richardsonii-Carex aquatilis*): The Shrub-Sedge Fen Ecotype supports the tallest shrub communities in the Greiner watershed and provides important summer forage for caribou, muskoxen, brown lemming and Arctic hare.
4. **Sedge Fen Ecotype - 09** (*Carex aquatilis*): The Sedge Fen Ecotype is the most common wetland type in the Greiner watershed and throughout the mid-Arctic area. The Sedge Fen Ecotype provides important summer forage for caribou, muskoxen, Brown Lemmings and Arctic Hare.

5.2 Design for Laying out the Hypothesis-based Monitoring

Monitoring within the two Paired Areas will be distributed across the 4 Ecotypes selected above, to be replicated 3 times each for a total of 12 Experimental Monitoring Plots in each Paired Area – so 24 Experimental Monitoring Plots overall (Figure 10). The Paired Area approach is proposed for the design to support non-destructive experimental manipulations, e.g., ITEX plot greenhouses, fertilization, watering, or exclosures, and to test the local scale predictive models, i.e., process models developed from driver-indicator experimental data relationships in one Paired Area can be compared to results in the adjacent Paired Area, and *vice versa*. Modeling predictions will also be calibrated and validated across a much wider area of the watershed through the establishment of calibration-validation monitoring sites along the LMTs and the EMGs at the remote monitoring cabins. Lastly, the Paired Areas are situated at the distal ends of two different sub-catchments (Figure 5) to provide an additional component of spatial variability, especially for hydrologically related variables such as flooding and soil solution chemistry.

Replication requirements (precision and power trade-offs) can also be tested (three replicates for each of four ecotypes) for the range of variables measured in the Monitoring Plots. It is anticipated that different variables, e.g., soil temperature, foliar nutrients, and active layer depths, will have different variabilities and Pilot Phase results will inform a determination of optimal replication for the Detailed Monitoring Plots. Based on the power analysis sampling effort can be adjusted up or down given measured variabilities of targeted monitoring components.

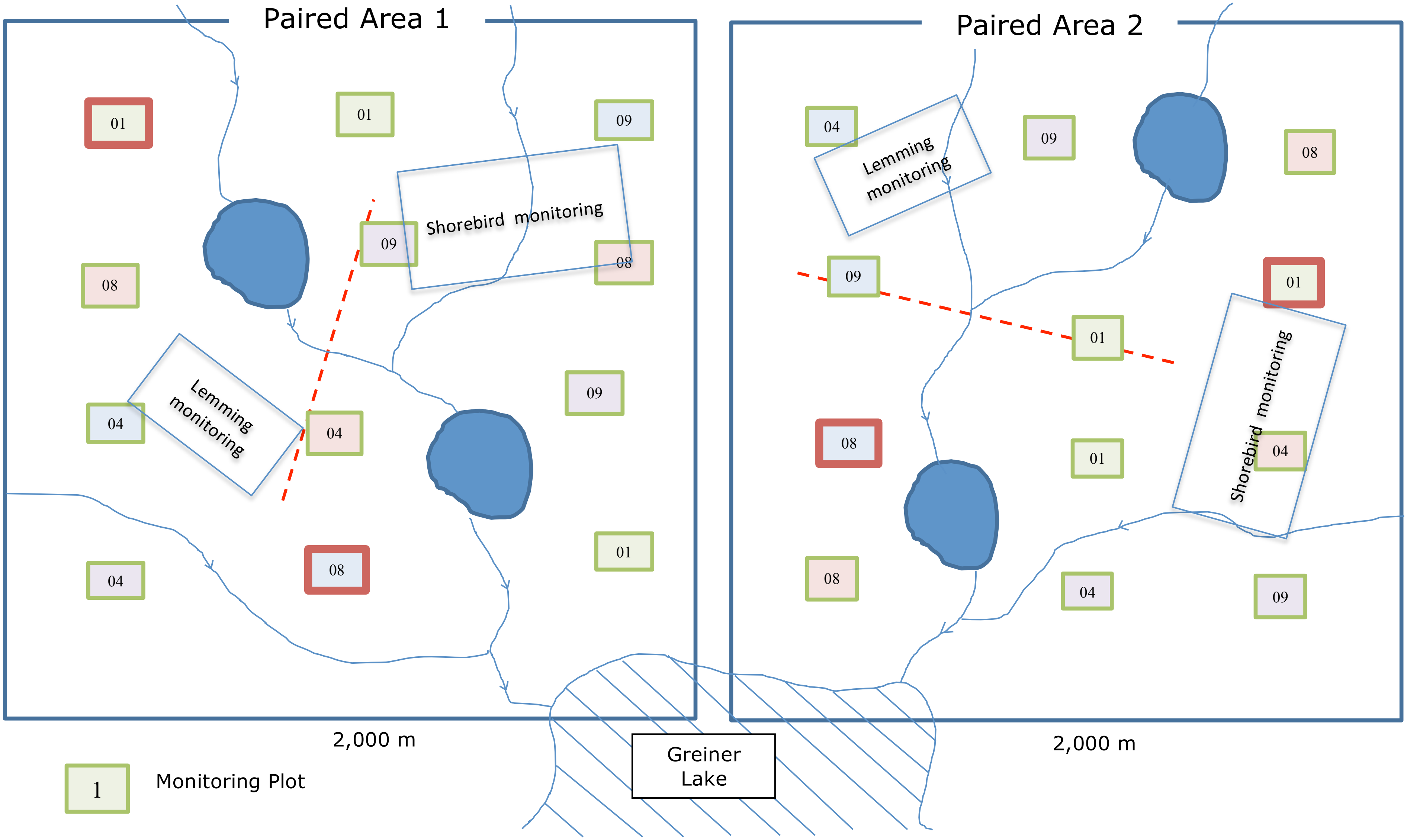


Figure 10: Schematic of the layout for 2 Paired Areas showing 12 Monitoring plots selected from 4 ecotypes, replicated 3 times, and randomly assigned within each Paired Area. Ecotype codes are the same as in Table 3.

The paired design also allows the comparison of spatial variability in indicator measures such as songbird/shorebird nesting, arthropod abundance and lemming populations. Finally, to assess year to year change in the VECs/FEC, control plot data from the two Paired Areas can be combined to provide a large monitoring sample to track change in the indicators.

5.2.1 Experimental Monitoring Plots

The Experimental Monitoring Plots are proposed to be 400m^2 (20x20m or 11.28m radius circular) in area and will be situated completely within mostly uniform ecosites, surrounded by a 10m buffer of the target ecotype. In the first stage we will establish the locations of 4 vegetation plots (ITEX-like protocols), 12 snow monitoring sticks, and a central soil monitoring station that will include a frost tube (NRCan design), soil temperature depth array including permafrost temperature, soil solution chemistry (gravimetric or suction lysimeters) and a continuous monitoring soil moisture probe (Figure 11).

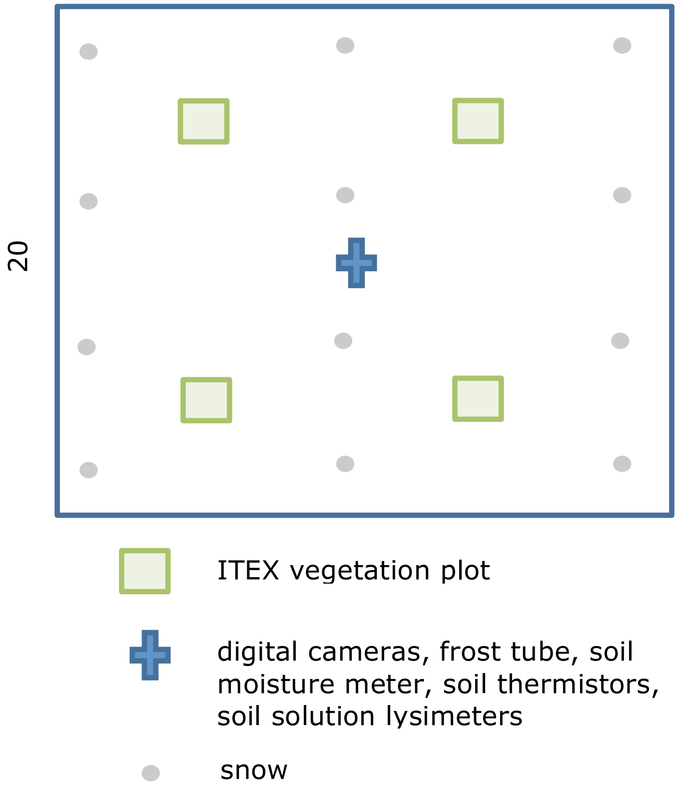


Figure 11: Proposed layout of Experimental Monitoring Plots, to be replicated 3 times across 4 Ecotypes in each of the Paired Areas (3x4x2=24 monitoring plots).

Other instrumentation may be applicable based on expert review of this design. For example, 6 snow thermocouples could be installed at depths of 0 (soil interface), +2cm, +5cm, +10cm, +15 cm and +30cm and 2 additional thermocouples placed in the soil at depth of -5cm and -10cm ten intervals over the active layer. Finally, iButtons can be placed below each snow stick for spatio-temporal monitoring of snow-soil interface temperatures within the study plot.

In 2 randomly selected Experimental Monitoring Plots (in Ecotypes 01 and 08) we will install eddy covariance towers and automated soil gas flux systems to monitor annual and year-to-year changes in net ecosystem CO_2/CH_4 flux – linked to soil abiotic factors as described above and to bacterial activity and soil respiration.

Pitfall traps for monitoring change in ground-based arthropods and slugs will be established in a subset of the Experimental Monitoring Plots across all 4 targeted ecotypes.

Aerially-deposited contaminants (Hg and POPs) will also be tracked in the Experimental Monitoring Plots in the soil, vegetation and in associated animals (lemmings, shorebirds and songbirds, arthropods)

5.2.2 Experimental Monitoring Transects

The Experimental Monitoring Plots are designed to capture and replicate states of and relationships among abiotic and biotic monitoring measures within the 4 targeted ecotypes, whereas the Experimental Monitoring Transects are designed to measure changes between ecotypes, at ecotonal transition zones, and from terrestrial to freshwater realms (Figure 12). The following monitoring actions are planned for the Experimental Monitoring Transects:

1. annually complete a vegetation line transect protocol along the length of the transect, including species intersections and mean maximum height measurements of functional types/species in 1 m subsections;
2. weekly during the thawed season, measure the depth of the active layer in frost tubes situated along the transect; frost tube measures of active layer depth will be used to validate continuous electrical resistivity tomography (ERT) data along the transects;
3. within ecotypes along the transect, establish soil process monitoring using the same measures and protocols as for the Experimental Monitoring Plots, i.e., frost tube, soil moisture probe, soil temperature depth array and lysimeters;

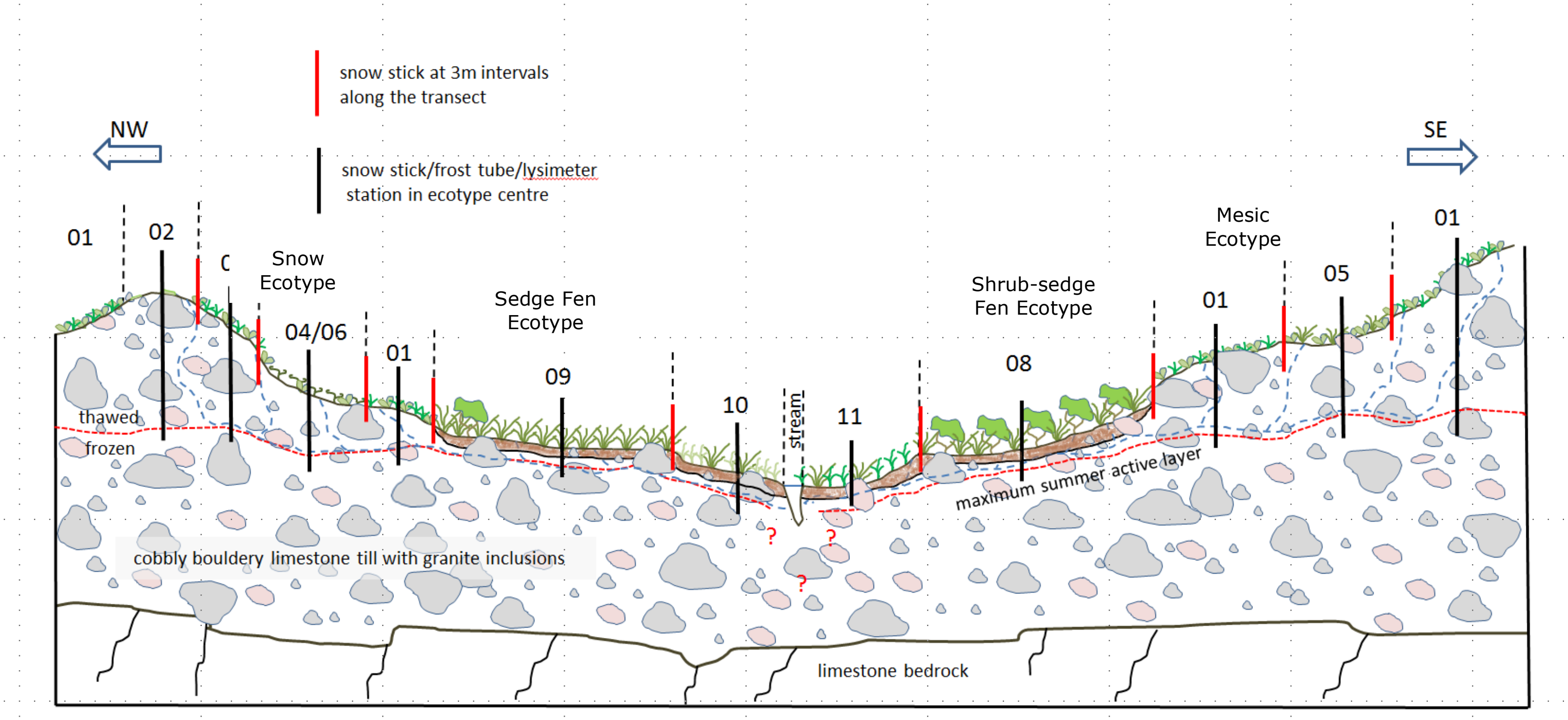


Figure 12: Schematic cross-section of landscape profile typical of the Greiner watershed, and Experimental Monitoring Transects to be established in each of the Paired Areas. For codes to Ecotypes see Table 4.

over the snow season measure snow depth and SWE weekly, and;

4. weekly (or semi-weekly) during the spring flood, use a labeled stake to mark the boundary of flooded areas along the transect; mark the date and time on the stake; these stakes will be surveyed to a relative elevation baseline at the end of the flood season and linked to hydrographic and detailed elevational data.

5.3 Protecting Sites from Long Term Degradation

The degradation of the areas adjacent to long term monitoring sites through soil compaction, vegetation trampling and resultant changes in local soil drainage in wetlands is an important consideration for site design and maintenance (Vincent 1996). This is especially important in fragile tundra ecosystems and especially in tundra wetlands with saturated soils over shallow permafrost. We will draw on the experience of other Arctic monitoring sites (Figure 13) to develop protection approaches that minimize the impact of foot traffic caused by repeated visits to monitoring sites and instruments. These will include permanent and temporary walkways to frequently visited sites, elevated sampling platforms (Figure 13), temporary mats for sites only visited periodically, designated routes for all traffic in and out of the IMA, and ATV and other vehicle restrictions and prohibitions.

Figure 13: Examples of protective walkways and sampling stractures from the Toolik LTER site in Alaska.

6. Key Monitoring Measures and Indicators

The long term goal of the CHARS terrestrial monitoring program is to develop an integrated, comprehensive and process-based understanding of how and why key

VECs/FECs are changing in the CHARS ERA, and how we might expect that they will change in the near and long range future. Achieving such a goal requires a multi-scalar approach where local observations and models developed in the IMAs can use data from the LMTs and EMGs, and the terrestrial ecosystem classification to calibrate and validate models that that can use aerial and satellite remote sensing data to reach out to sub-regional, regional scales and ultimatly circumpolar scales. Achieving this goal also requires an ecosystematic approach where linkages among and between abiotic and biotic ecosystem elements provide a frame for designing the monitoring, and for developing the process-based models. A key near term goal is to pilot a number of monitoring methods within the ecological context of the Greiner watershed to establish the monitoring frame to develop this understanding for the Greiner watershed, with a long term goal to develop these approaches further over the Regional CHARS ERA.

A high-level conceptual model (Figure 14) shows the main abiotic and biotic ecosystem elements within the Greiner Lake watershed, and some of the interconnections among them. The model emphasizes the dominant role played by climate in controlling and driving abiotic processes, and the direct and indirect effects of climate on watershed biota. Climate directly impacts soil processes which, with physiographic and other effects, control the distribution of tundra ecosystems, as discussed above. In turn, the composition, structure, and productivity of tundra ecosystems, acting with physical drivers such as snow distribution and phenology, determine habitat value for mammalian herbivores, water birds and arthropods that support watershed predator species. Humans form a final interface as resource users (hunters and trappers). Pests like Muskoxen lungworm and pathogens such as the bacterium presently impacting muskoxen (Kutz *et al*. 2012) may signifciantly affect all levels of the food chain in ways that are presently very poorly understood. Processes in the ecosystem also feed back to the atmosphere and effect regional climate through net flux of CO_2/CH_4 and through changes in land surface processes. Another output from the terrestrial ecosystems is through soil water and surface runoff discharge to adjacent stream and lake ecosystems, or directly to the ocean.

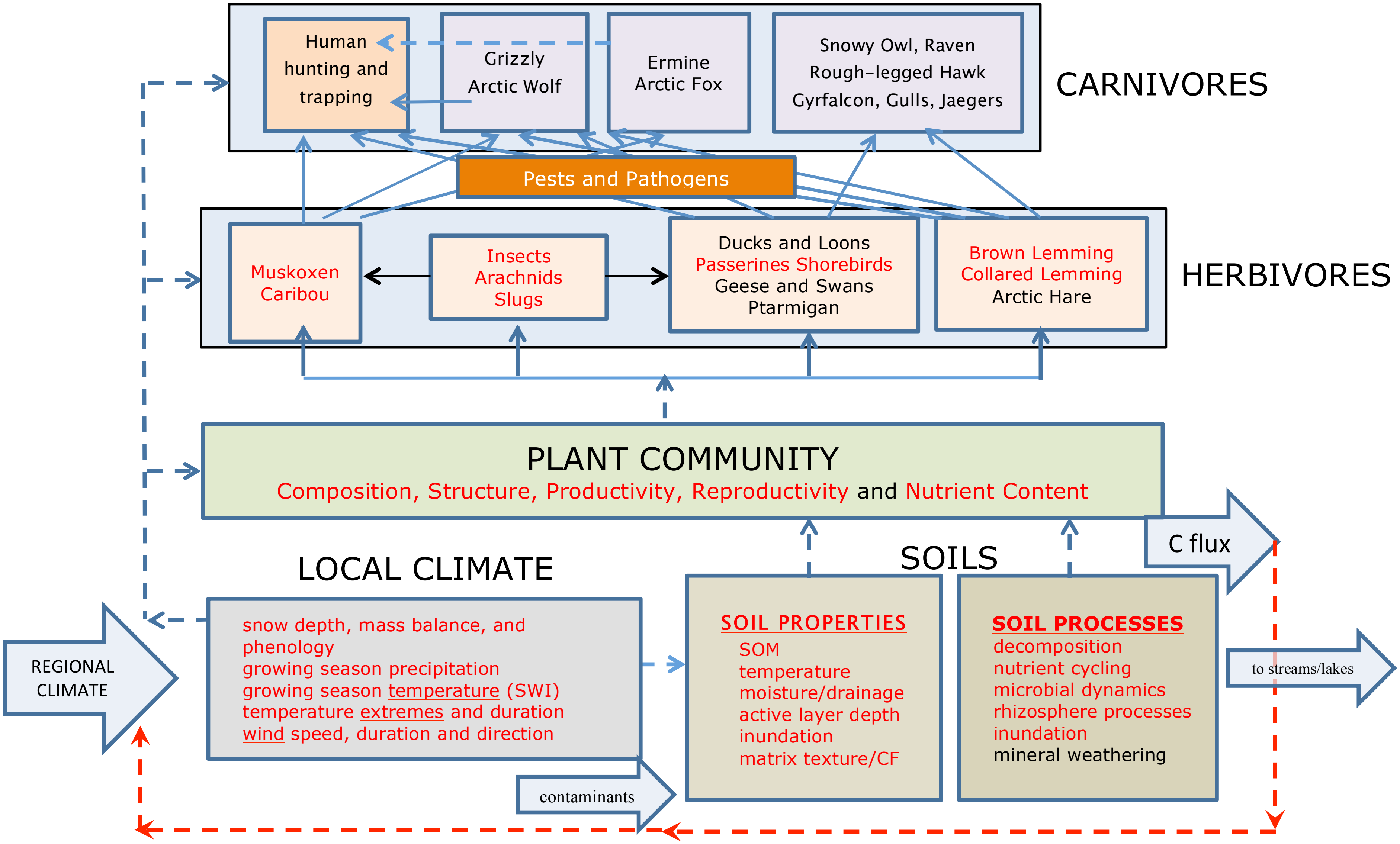


Figure 14: Conceptual model of the CHARS terrestrial ecosystem area showing abiotic drivers, vegetation, herbivores and carnivores and high level linkages among components. Arrows show process linkages between ecosystem components.

Contaminants such as Hg and POPs are brought to the watershed primarily through atmospheric deposition where they are carried through the food chain and can impact the health of those consuming harvested species such as caribou, muskoxen, waterfowl and fish. Red type in Figure 14 highlights those ecosystem elements we will target for monitoring in the 2017-2019 pilot phase of the CHARS monitoring program.

This section provides a brief discussion of research and monitoring context for each category of the main ecosystem elements to be monitored, outlines general monitoring considerations for each category, and proposes a monitoring approach using the monitoring methods discussed above. Tables in Appendix B provide a preliminary list of monitoring protocols, monitoring partners and monitoring methods to be used for each category. Many of the monitoring elements included in this section are not yet fully developed, and, through the review process, we are seeking input from subject area experts to unsure we develop the most up-to-date, reliable and cost-effective monitoring methodologies.

6.1 Monitoring Abiotic Components

6.1.1 Climate and Hydrology

Local climate (following IMO standards) and stream parameters will be monitored in both of the Paired Areas in the IMA (Appendix Table B1) – the climate stations will be maintained for 12 months of the year using Campbell Scientific weather stations (Figure 15). Paired weather stations will permit the comparison and calibration of local scale variability in instrumented data for the establishment of monitoring experiments– one of the weather stations will be moved to the future IMA following the calibration period. The locations of two additional weather stations are indicated in Figure 7 and are being established to provide more detailed coverage of watershed-scale climate variability.

The main streams in the IMA will also be monitored to link terrestrial to freshwater systems, with periodic sampling of stream water chemistry linked to soil water monitoring through the lysimeter network. Initial parameters for stream monitoring are also listed in Appendix Table B1 with the understanding that these will be improved as the more comprehensive stream monitoring program is established.

6.1.2 Soil

Key soil processes such as decomposition and mineralization of soil organic material, nitrogen fixation, and microbial diversity and activity are well understood to be climate-driven through direct and indirect effects on soil temperature and moisture (Chapin and Shaver 1996, Grogan and Chapin 1999, Schmidt *et al.* 2002, Borner *et al.* 2008, Deslippe *et al.* 2011), and monitoring these changes is an important component of the ecosystem-based monitoring approach for the Greiner watershed. A recent conceptual model (Figure 16) that shows soil components, processes and interactions with each other and with vegetation and gas efflux provides a schematic representation of the complexity of interactions between soil abiotic drivers, soil processes and the vegetation FECs/VECs of interest. In particular, we want to link vegetation productivity and composition, and net ecosystem CO_2/CH_4 flux to this complex of factors over the long term and across contrasting ecosystems in the replicated Experimental Monitoring Plots within the two Paired Areas. Similar monitoring along the Experimental Monitoring Transects will support this work and show linkages among ecotypes and with soil solution chemistry and terrestrial input of soil water and surface runoff to streams. We will consult experts in each of the relevant areas of expertise to assist with the design and installation of these experiments. A preliminary list of soil components we are intending to measure and replicate in the Experimental Monitoring Plots and in the Experimental Monitoring Transects is presented in Appendix Table B2.

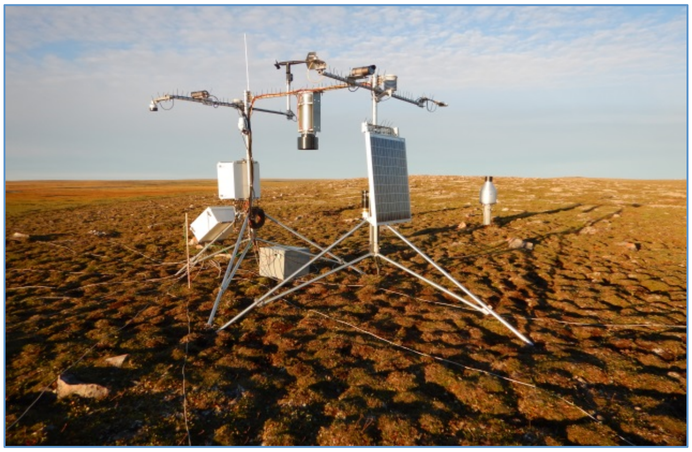


Figure 15: Climate monitoring instrumentation established in the IMA in summer 2016.

6.1.3 Snow and Permafrost

The role of snow in protecting and insulating tundra vegetation from the extreme influences of an Arctic winter, and for providing summer moisture are critical determinants of vegetation composition, structure and productivity (AMAP 2011, Bokhorst *et al.* 2016). Snow distribution, depth, structure and persistence are also critical factors for animal habitats (Gauthier *et al.* 2011, Gilg *et al.* 2009, Krebs *et al.* 2011, Miller and Barry 2009), drive watershed hydrology (AMAP 2011, Bokhorst *et al.* 2016, Vincent *et al.* 2011) and have important regional scale feedbacks to the climate system (Beringer *et al.* 2005, Eugster *et al.* 2000, Chapin *et al.* 2000, Pearson *et al.* 2013). For all of these reasons monitoring changes in the

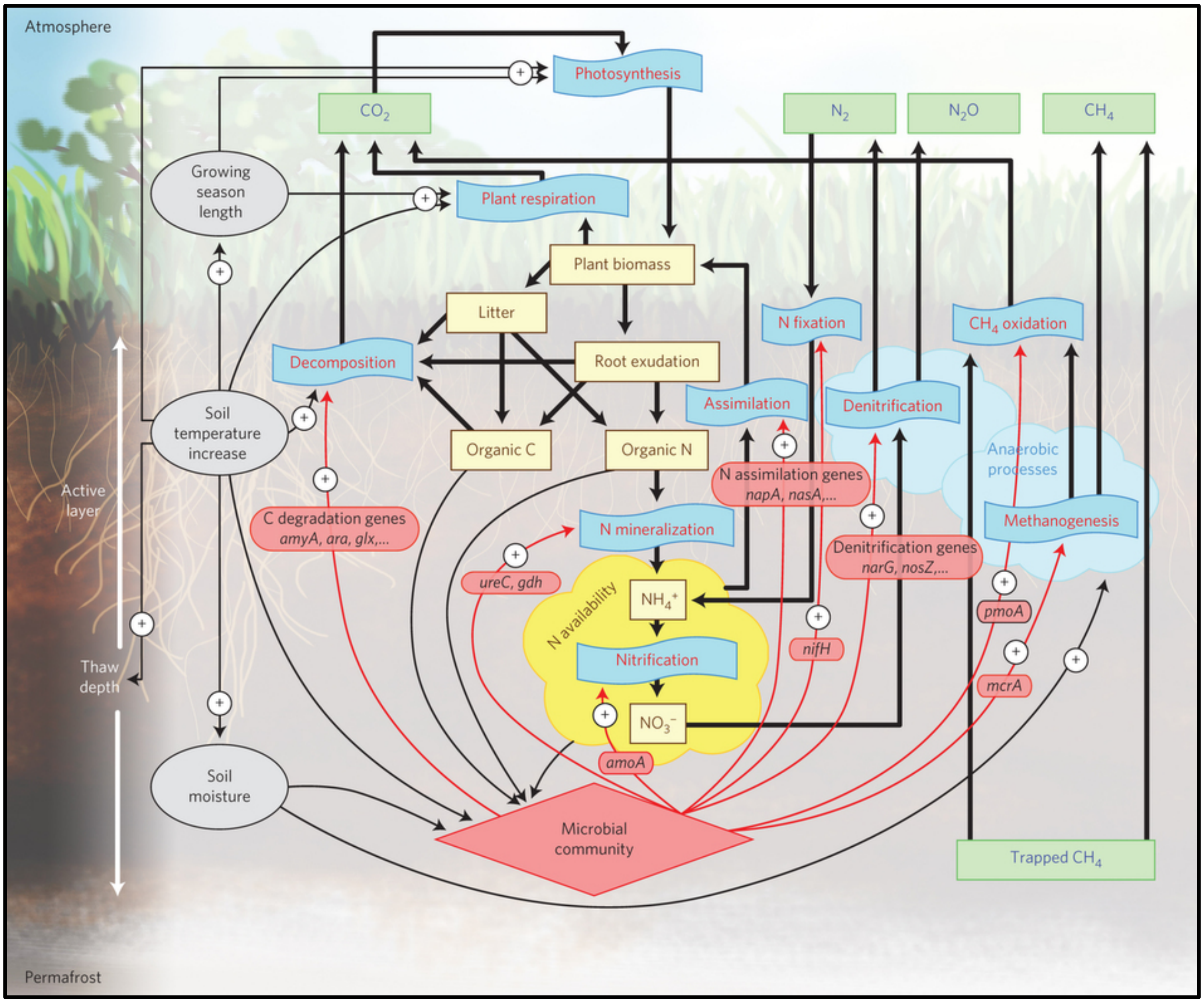


Figure 16: Conceptual model of soil components, processes and interactions with each other and with vegetation and gas efflux to be monitored in the Monitoring Plots. Greenhouse gas pools are represented by green square frames, material pools by yellow square frames, and biological processes by frames in the shape of blue punched tape. Material flows are indicated by thicker black arrows (conceptual model from Kai Xue *et al*. 2016 *Nature Climate Change* **6**, 595–600 (2016) doi:10.1038)

distribution, character and seasonality of snow is considered a priority and will be assessed at a range of scales with a range of tools (Appendix Table B3). Linkages to factors potentially impacted by a changing snow system will be made through the design and implementation of the CHARS monitoring program, as discussed previously. As for the establishment of the soil monitoring, we will work with experts in the area of snow measurement for the design and establishment of the snow monitoring at CHARS.

Increases in permafrost temperature have been recorded across North America and are one of a number of changes in the cryosphere with important implications for ecosystems and infrastructure (AMAP 2011, Callaghan *et al.* 2011, Smith *et al.* 2010). Permafrost temperature will be monitored following national (NRCan-Canadian Cryospheric Information Network) and international (Global Terrestrial Network for Permafrost) protocols by a series of surface boreholes (< 10m), frost tubes, and thermistor arrays at the Experimental Monitoring Plots and along the Experimental Monitoring Transects. Use will also be made of electrical resistivity tomography (ERT) to link with *in situ* vegetation and snow monitoring, track changes in active layer deepening and subsurface drainage patterns, and validate permafrost modeling. Two intermediate depth boreholes (25-125m) with thermistor arrays in each of the 2 Paired Areas to track temperature will be established to monitor change at greater permafrost depths. Monitoring permafrost temperature in the Greiner watershed will fill an important spatial gap in national coverage of permafrost change (Smith *et al.* 2010).

6.2 Monitoring Flora

The current local and regional geographic pattern of Arctic vegetation, as expressed through studies of the stability of the artic-subarctic interface (treeline), is the result of thousands of years of relative stability in regional climates (Lavoie and Payette 1996, MacDonald *et al.* 2000, Payette 2006), inferring that Arctic vegetation composition and structure has been in a vegetation-climate dynamic equilibrium for a very long time. This equilibrium is now changing towards unidirectional warming, and Arctic vegetation is beginning to respond both through '‘greening’ as measured by satellites through increases in Normalized Difference Vegetation Index (an indicator of biomass and leaf area index increases (Bhatt *et al.* 2012, Fraser *et al.* 2009, 2011, 2012, Jia *et al*. 2003, 2009)), and through measured site level changes (Bockhorst *et al.* 2009, Callaghan *et al.* 2011b, Chen *et al.* 2012). A well-reported *in situ* result of warming climates at northern latitudes is the increase in shrub dominance and local encroachment which has feedback influences on snow depth, soil temperature, active layer depth, surface to atmosphere feedbacks (albedo) and habitat impacts (Myers-Smith *et al.* 2011, Nalto *et al.* 2011, Sturm *et al.* 2001,2005a, 2005b, 2006).

As a result of its direct linkage to temperature and its key roles in terrestrial ecosystems, the habitat role it plays for herbivores, its role in C sequestration for estimation and monitoring of net ecosystem CO_2/CH_4 flux, and vegetation-earth surface feedbacks to the regional climate system - a considerable effort will be made to monitor and report change in vegetation in the CHARS ERA at a range of scales (Appendix Table B4). In the Experimental Monitoring Plots we will follow the general protocols and approaches of the International Tundra Experiment (http://ibis.geog.ubc.ca/itex/) and related approaches, to provide continuity with work carried out around the circumpolar north (Natali *et al.* 2011, Elmendorf *et al.* 2012, Hill and Henry 2011, Hudson and Henry 2010, Walker *et al.* 2012). Shrub chnage will be tracked across ecotypes following approaches outlined in Myers-Smith *et al.* (2011). These local scale measures will be linked at extra-local to extra-regional scales using a combination of calibration-validation data from the EMGs and remote sensing data. Monitoring will be designed to track change in shrub cover and height, and on the in-migration of new plant species, with special emphasis on potential alien invasive species and rare species in response to climate warming.

6.3 Monitoring Fauna

6.3.1 Shorebirds and Songbirds

It is estimated that of the 21 shorebird species that breed in the Canadian Arctic, 13 are experiencing declining population trends, and several of these shorebird species are listed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) or the *Species at Risk Act*, or are being assessed for listing. Following Arctic Program for Regional and International Shorebird Monitoring (PRISM) protocols, the CHARS site will become a part of the Arctic Shorebird Demographic Network, a network of field sites across Alaska and Canada focused on investigating the impacts of environmental change on the demography of migratory shorebirds in the Arctic. Additionally, Arctic PRISM was designed to support the goals of the Canadian Shorebird Conservation Plan and is identified in the Northern Shorebird Conservation Strategy as a high priority action item for monitoring shorebirds. For more information on shorebirds and PRISM see: https://www.ec.gc.ca/reom-mbs/default.asp?lang=En&n=D1870263-1)

Although the species diversity of Arctic songbirds is relatively low compared to Arctic shorebirds and waterfowl, they are a characteristic and highly visible component of avifauna in the Greiner Lake watershed (Obst 2015). As a result of their mobility they can rapidly take advantage of warming summer temperatures, are highly responsive to habitat change, and thus are excellent indicators of environmental change (Canterbury *et al.* 2000, Glennon and Porter 2005, Wilson and Bayley 2012). Indeed several studies are beginning to record the expansion of boreal songbirds intro sub-arctic, sub-alpine and arctic biomes (Boelman *et al*. 2015, Whitaker *in prep*), and other studies have pointed out the complexities of songbird responses and the role of habitat change, principally the development of shrub communities (Henden *et al.* 2013, Ims *et al.* 2012, Mizel *et al.* 2016, Sokolov *et al.* 2012). As for many of the other variables, songbird monitoring will be piloted to assess levels of effort required for desired levels of precision and accuracy in estimating population change. Songbirds will be assessed at the same time as shorebirds using similar techniques – with PRISM Tier 2 monitoring in the Paired Areas and Tier 1 along the LMTs (Appendix Table B5).

6.3.2 Waterfowl

Of the more than 100 species of migratory birds known to nest in the Canadian Arctic 30 species are entirely dependent on the Arctic for nesting and rearing habitat (CWS Waterfowl Committee 2015, ECCC 2016). To be successful in rearing young the birds need to make up for weight lost during the northern migration, support egg production and rearing of young in time for fall migration in a small 2-3 month window of time (ECCC 2016). With its abundant lakes and ponds abutting various wetland ecotypes, terrestrial ecosystems in the Greiner watershed provide staging, nesting and rearing habitat for a number of waterfowl species such as Canada goose, Greater white-fronted goose, Tundra swan, Yellow-billed loon, Pacific loon, Common eider, King eider, and Long-tailed duck (Obst 2015). Eggs and meat of waterfowl are also an important component of the country food diet of Cambridge Bay residents. As a result, these species are considered socially important and there is an important base of Indigenous Knowledge that can be incorporated into waterfowl research and monitoring. Ground-based waterfowl monitoring (Appendix Table B5) will be synchronized with shorebird and songbird monitoring and supported by aerial surveys following standard approaches to provide both local and regional assessments of changes in waterfowl diversity and abundance.

6.3.3 Lemmings

In their role as a major prey species, lemmings are widely recognized as keystone species in Arctic tundra ecosystems (Gauthier *et al.* 2011a, 2011b, Gilg *et al.* 2009, Krebs *et al.* 2002, 2003, 2011). Their characteristic cyclic population patterns have been linked directly and indirectly to population shifts in avian and mammalian predators (Gauthier 2011 b, Gilg *et al.* 2003), and in prey shifts for tundra predators (Gauthier *et al.* 2011a). Also well documented is the role of deep snow (> 60 cm) in providing sub-nivean temperatures suitable for lemming survival and reproduction over severe Arctic winters (Reid *et al.* 2012). For these reasons monitoring changes in Collared and Brown lemming populations in the IMA, and much more broadly in the Greiner Lake watershed, is a key objective for the CHARS monitoring program. A range of well-established monitoring protocols will be used as outlined in the Arctic Development and Adaptation to Transition (ADAPT) Protocols (Appendix Table B6).

6.3.4 Arthropods and Slugs

Arthropods are abundant in Arctic terrestrial ecosystems and perform many critical ecological functions acting as herbivores and pollinators, enabling organic decomposition, and as blood-suckers and vertebrate prey, and thus are considered as key elements of the functioning of tundra ecosystem in the Greiner watershed (Bolduc *et al.* 2013, Christensen *et al.* 2013, Schmidt *et al*. 2017). Arthropods are cold-blooded, many are highly mobile and are relatively easy to sample so they make excellent indicators of ecosystem change (Danks 1992).

Pilot arthropod monitoring has already been initiated in other areas of the Greiner watershed and will be implemented within the Paired Areas to link changes in arthropod population abundance and composition to abiotic drivers. Arthropods are also critical prey for shore birds, waterfowl and songbirds and are especially important to their young (McKinnon *et al*. 2012), so arthropod monitoring will be co-located spatially and temporally with the shorebird, songbird and waterfowl monitoring (Appendix Table B7).

Terrestrial slugs are important to watershed biota because of the role they play as intermediate host for the lungworm that infects muskoxen, and recent research has shown the gradual migration of slugs across Victoria Island since 2008 (Kutz *et al.* 2013). Slug monitoring will coincide with arthropod monitoring because the efficacy of pitfall traps for monitoring slugs has been demonstrated through our arthropod pilot projects in the Greiner watershed (Sullivan *et al.* 2016).

6.3.5 Ungulates

Resident Muskoxen and the migrant Dolphin Union Caribou Herd utilize foraging habitat in the Greiner Lke watershed (Gunn 1990, Gunn *et al*. 2000, Gunn and

Paterson 2012, Leclerc 2015, Tomaselli *et al.* 2016). In the context of the ecosystem classification outlined in Figure 6, Muskoxen spend the summers in small family groups grazing primarily in Sedge Fen and Shrub Sedge Fen Ecotypes, and in winter seek forage on wind-exposed mesic, sub-mesic and sub-xeric ecotypes. The Dolphin Union Caribou Herd travels through the Greiner watershed and congregates on the south shore of Victoria Island waiting for the sea ice to freeze before carrying on to wintering areas south of Queen Maud Gulf and Dease Strait (Miller *et al.* 2005, Nishi and Gunn 1998, Poole *et al.* 2010). They return on the sea ice in the spring and calve in early to mid-June throughout the eastern and northern areas of Victoria Island (Gunn and Fournier 2000). Ungulates will be monitored using a number of approaches as outlined in Appendix Table B8. Ungulates are a key country food for local residents and local knowledge will be sought to inform sampling and conduct monitoring.

6.3.6 Other Species

A number of other species are present in the Greiner watershed (refer to Figure 12) that will be monitored as possible along LMTs, in the aerial surveys (Appendix Table B9), and through partnerships with national and international researchers.

A small population of Grizzly Bears has appeared on Victoria Island since about 2008. Grizzlies are abundant on the mainland south of Victoria Island where berries and caribou are abundant – their long term status on Victoria Island is not clear at this time.

According to local knowledge Arctic Wolf is common, with population levels following those of their main prey species, Muskoxen and Caribou.

Arctic Fox is abundant, is a key predator and scavenger, and is an important source of revenue for local trappers who have important knowledge of Arctic Fox biology that will improve our understanding of changes in fox population and health.

Short-tailed Weasel (ermine/stoat) population trends follow those of their main prey – Collared and Brown Lemming. This is true as well for Arctic Fox, and to a lesser extent for Arctic Wolf.

A number of raptors are common in the area (Figure 14), and like mammalian predators, rely heavily on lemmings, although other prey is also sought. Snowy owls are very abundant in some years and largely absent in others, depending on lemming population trends. Jaegers are common in all years, as are Glaucous Gull and Rough-legged Hawk.

Willow and Rock Ptarmigan are also common in the Greiner lake watershed and are certainly preyed on to various extents by the predators listed above. They are also an important food source for local residents and local knowledge will be sought to assist with monitoring these species.

6.3.7 Faunal Contaminants

It is well documented that globally-sourced contaminants such as metals like Hg and Cd, as well as historic and emerging persistent organic pollutants (POPs) are deposited from the atmosphere onto terrestrial, freshwater and marine surfaces across the Arctic, and that these substances are taken up into the tissues of Arctic plants and animals (NCP 2013). Overall, there have been fewer studies of contaminants in terrestrial ecosystems compared to aquatic systems, primarily because of the comparatively low levels of contaminants measured in terrestrial organisms (Braune *et al.* 1999, Gamberg *et al.* 2005). Kelly and Gobas (2001) found low levels of POPs in lichen and willow in the Bathurst Inlet and Cambridge Bay areas and demonstrated significant bioaccumulation factors in caribou and wolves for some POPs. Kelly and Gobas (2003) used these POP levels in lichen, willow, caribou and wolf in the Bathurst Inlet – Cambridge Bay area to parameterize a model that successfully predicted POP bioaccumulation factors in caribou and wolf from POP concentrations from local atmospheric and snow pack melt water inputs. These studies demonstrate the potential for the long term contamination of country foods important to local residents, the ongoing development and dispersion of new POPs, and the delivery of POPs and metals from the terrestrial to freshwater and marine systems.

Working with the Northern Contaminants Program (NCP 2016), and guided by the concerns and input of local residents, contaminant monitoring will be included in the CHARS ERA monitoring program. Taking an ecosystematic approach, we will work with partners to monitor atmospheric deposition of contaminants, chemical transformations in soil and uptake by vegetation and soil invertebrates, the role of microbes, and the export of contaminants to streams from snow melt in the spring and from sub-surface flows during the thaw period (Appendix Table B10). Working with local hunters to provide tissue samples from harvested species, we will also monitor the concentrations of targeted contaminants in animal tissues and organs including lemmings and ungulates, shorebirds and waterfowl egg shells, and predators.

7. Scaling up from Local Observations

Many important monitoring and prediction questions will need to be answered using a range of modeling approaches at sub-regional and regional scales in the CHARS ERA. What significant changes are happening in the calving and summer ranges of Bathurst and Bluenose east caribou herds? Does this vary within the Zone of Influence of mining operations? How can habitat be expected to change in the near future? How rapidly are shrubs beginning to dominate Arctic tundra? What processes are driving this change? How will shrub tundra ecosystems change in the next 10 years? How do vegetation or changes in snow phenology and cover impact surface energy balance? How might this feed back to regional climate? Can local-scale measures of net ecosystem flux of CO_2 and CH_4 be correlated with terrestrial ecosystems or other measures (biomass, NDVI), and scaled up to sub-regional and regional levels? Are active layers getting deeper and how might this impact water quality and sediment and nutrient delivery to coastal marine ecosystems in the CHARS Regional ERA?

It is important that ground-based monitoring be designed appropriately so that data from the long term monitoring experiments in the IMAs, regional baseline inventories and the LMTs/EMGs can be linked to ecotypes, ecotype groups or other classifications to inform the development of empirical and mechanistic models aimed at answering some of these important questions.

For the Pilot Phase of the CHARS monitoring plan the immediate goals to enable scaling up observations are to:

1. complete ecotype mapping at appropriate scales for the Greiner Lake watershed and the Regional ERA;
2. characterize mapped ecotypes/ecotype groups in terms of key scalable indicators;
3. establish EMGs and /or LMTs in the IMA sub-catchments, in the Greiner Lake watershed, and near Kitikmeot communities and other available infrastructure to calibrate and validate regional maps and models, and;
4. select a number of empirically-derived models for initial test-validation in the CHARS ERA.

7.1 Terrestrial Ecosystem Mapping

Multi-scalar classification and mapping of terrestrial ecosystems in the CHARS Regional ERA is a fundamental baseline task that will provide an ecosystem template for many regional monitoring and research activities including developing habitat maps for calving and summer caribou, identifying ecosystems at risk to permafrost degradation, locating key areas of shrub encroachment, linking to snow modeling and mapping, and informing regional change modeling. Recent progress in developing an improved DEM for the area will greatly improve mapping accuracy and provide the basis for an ecological site classification that will be robust to vegetation change as climates warm.

Classification work to support the regional mapping will need to provide local scale detail to CAVM Subzone boundaries and account for elevational change within present CAVM units. Within subzones throughout the CHARS Regional ERA, ecological sites and ecotypes will need to be described and classified as has been completed for the Greiner watershed (Figure 5).

Mapping of terrestrial ecosystems in the CHARS Regional ERA will rely primarily on optical imagery (high resolution World View and medium resolution Landsat) and will be supported by predictive variables derived from the enhanced DEM. Data and processing tools to complete the work will link to the NASA ABoVE Science Cloud (http://above.nasa.gov/sciencecloud.html) for access to satellite data, and to provide super-computing capabilities. Pixel-based and object–based approaches will be applied using progressive Random Forest simulations (Fraser *et al.* 2012; Parks Canada Agency 2014). Targeted field work to develop the ecotype classifications and existing mapping in the area (e.g., mine related vegetation mapping in the MMG, TMAC, and Ekati mine areas and detailed mapping at Daring Lake) will be used to calibrate and validate the regional-scale mapping and modeling.

Another important element of the scaling up process is to develop regional-scale baseline information on selected scalable ecosystem elements such as soil C stores, LAI, vegetation biomass, and active layer depth. Data collection will be coordinated with ecosystem classification and mapping activities to optimize logistical costs and ensure strong linkages among the measured elements and the ecotypes and ecotype groups. These variables will be linked to the distributions of mapped ecosystem units (ecotypes and ecotype groups) to promote understanding of the environmental processes interacting with and/or driving spatial and temporal change. The particular ecosystem elements to be inventoried will depend on the regional models that are developed, and will support a range of remote sensing activities, e.g., CHARS funded projects, NASA ABoVE Airborne Campaign.

7.2 Engaging Kitikmeot Communities

An important objective of the CHARS monitoring program is to understand how ecosystems are changing to inform proactive climate adaptation approaches in Kitikmeot communities and begin to develop important components of social-ecological resilience. For the Pilot Phase of the program community engagement will work to:

- consult with communities to gain a clearer understanding of the most pressing terrestrial research and monitoring priorities; take direction from communities on the design and implementation of local monitoring; promote and support research and monitoring initiatives to help meet identified needs;
- develop approaches for accessing and utilizing IK as a component of the monitoring program;
- establish EMGs and/or LMTs adjacent to Kitikmeot communities and other suitable infrastructure (e.g., mining camps) to provide ground calibration and validation data to support remote-sensing based scaling up models; typical monitoring indictors could include snow depth transects, soil moisture monitoring, maintenance of soil thermistor stations, seasonal active layer depths/frost tubes, vegetation measurements (height growth, phenology, berries), lemming winter nests, arthropod pit fall traps, and wildlife observations, and;
- work with partners to train and employ community members to participate in the sampling that is established around Kitikmeot communities.

7.3 Modeling

It has been identified by many recent science reviews that a key Arctic science need is to not only monitor rapid change at Arctic latitudes, but also to understand the environmental components and processes that are driving the changes observed (ACIA 2005, AMAP 2011, Bokhorst *et al.* 2016, Forbes *et al.* 2010). Co-located monitoring experiments in the IMAs are designed to establish and model these relationships at local scales, and to scale-up these locally-derived, driver-indicator relationships to extra-local to extra-regional scales. The benefits of accurate and reliable scaled-up models include being able to develop regional assessments of environmental change and being able to make short and long term predictions of change in the variables modeled across a range of potential climate change or development scenarios.

Model domains are nested and will include:

1. a local domain at the IMA sites where fundamental driver-indicator relationships will be developed;
2. an extra-local domain – the 2 IMA sub-catchments
3. a sub-regional domain, e.g., the Greiner Lake watershed
4. a regional domain that will include base-rich areas of the CAVM Subzone D

Similar nested model domain hierarchies could be developed for base-poor areas of the CAVM Subzone D and for the CAVM Subzone E that covers much of the southern portion of the CHARS Regional ERA. A priority is to work with partners to help build on existing work to establish an IMA at the Daring Lake Research Station in CAVM Zone E to support scaling up and modeling in that bioclimatic subzone.

Given design linkages between the ecosystem mappin approach in the CHARS ERA and the CAVM Team (2005) circumpolar ecosystem map, CHARS could also work with international partners to link to other ground –based studies and develop scaled map products and analyses for the entire circumpolar area.

Both empirically-based and mechanistic, process-drive models will be developed, to be calibrated and validated by monitoring in the IMAs, from the regional baseline inventories and from the regional EMGs. Ground data collected will include a core set of regional monitoring variables, and will also be designed as required to support the particular sub-regional and regional models being developed.

The terrestrial ecosystem mapping will be a critical component of the scaling up modeling by capturing landscape scale heterogeneity in vegetation composition and structure, landform and soils, and characteristic combinations of modeled variables. For example, active layer depths are predictably much shallower under organic layers due to their impacts on soil thermal regime, and this is captured in the ecotype classification, and so can be used to classify change in active layers across the landscape (Cable *et al*. 2016, Zhang *et al.* 2013, 2014). Ecotypes also capture a unique combination of ecological processes such as rates of nutrient cycling, winter snow protection and seasonal soil moisture regimes, and these can be generalized through the ecotypes for the development of mechanistic, process-based models.

To develop the models we will rely and build upon the considerable work that is already occurring in this area in Canada and Alaska (Atkinson and Treitz 2013, Cable *et al.* 2016, Chen 2009a, Chen 2009b, Fraser *et al.* 2009, Fraser *et al.* 2011, Rastetter 2003, McGuire *et al.* 2012, NGEE 2016, Olthof *et al.* 2007, SNAP 2016, Stow *et al.* 1998). For example, work in NWT, Yukon and Alaska (Cable *et al*. 2016, Zhang *et al.* 2013, 2014) has shown deepening of soil active layers over the last 15 years and has predicted continuing deepening as climate change proceeds. In the CHARS ERA monitoring program, local scale experiments in the IMAs will define soil thermal relationships in the context of active layer depth and soil temperature by ecotype, and these relationships can be modeled to broad scales using calibration-validation data from the EMGs and the regional baseline inventories. Using these relationships, future changes in soil active layers can be predicted and in fact validated through the long term monitoring to directly measure the accuracy of the predictions, i.e., models and our understanding of the processes can me refined through comparison of model results with the results of the long term monitoring.

Finally, we can link the deepening of regional or sub-regional soil active layers to changes in stream water nutrients and carbon, and trace these effects to coastal marine ecosystems through a coordinated regional experimental design for the CHARS ERA monitoring program.

8. Program Implementation

Implementation of the Pilot Phase CHARS ERA monitoring plan is targeted for 2019 and will require considerable coordination from CHARS staff, technical input from a wide range of experts, and consultations with the residents of Cambridge Bay and other Kitikmeot communities. For some variables, we can use 2-year results to perform power analysis and logistic and financial considerations to assess the feasibility of sustaining long term monitoring. Factors such as the number of replicates and the linkages to scaling up models will also be assessed for going forward with plan implementation in 2019 and beyond. For many variables, it will take at least 10 years to establish trends and report change and it is important that the plan be viewed with an eye to the long-term benefits of repeated measures to assess meaningful ecological change. A draft implementation schedule (Appendix C) outlines the key steps to initiate and fully implement the plan.

8.1 Key Steps to Program Implementation

1. Consulting on the monitoring plan:
    a. consult with the national and international science community for input on technical aspects of the various monitoring indicators, experimental design and modeling approaches;
    b. consult with Kitikmeot residents to identify the most useful monitoring indicators and approaches from a community perspective; identify areas opportunities for community-based monitoring and capacity-building; establish EMGs and LMTs as possible;
2. develop a process for consensus on establishing monitoring protocols that may be employed nationally and internationally;
3. develop a process for long term management and dissemination of program data, including the POLAR Technical Report Series, the POLAR web page and refereed journal publications;
4. finalize a study design and install instruments and other monitoring equipment in the Pilot IMA, including in the Detailed Monitoring Plots and along the Detailed Monitoring Transects; install required logistic infrastructure;
5. establish Greiner Lake LMTs and EMGs,;

6. establish aerial transects and protocols;
7. develop a linked long term plan for satellite remote sensing;
8. initiate development of local-, sub-regional-, and regional-scale conceptual driver-indicator models;
9. analyze preliminary Pilot Phase data to develop estimates of variation in parameters to be measured and conduct power analysis of existing parameter data to determine optimal sampling effort required, and;
10. produce the first iteration of the CHARS Terrestrial Monitoring Plan based on all work completed by March 2019.

8.1.1 Consult on the Pilot Phase of the Monitoring Plan

Consultations will be sought by targeting national and international monitoring specialists and experts in various aspects of the Plan, and by a general request for input from the northern science community through posting on the POLAR website. The Plan will also be presented in Cambridge Bay to members of the EHTO and the community at large, and in other Kitikmeot communities as opportunities arise. The objective is to have a first draft for the Pilot Phase to initiate implementation in summer 2017.

8.1.2 Develop Consensus on Monitoring Protocols

A clear statement of the procedures used, the clear monitoring questions, experimental layout and design, and other logistical and technical aspects of conducting the monitoring for each indicator will need to be compiled and will form the heart of the CHARS ERA monitoring program. Much work has already been completed across the Arctic on protocol development for many variables (CBMP and many others), and existing protocols will be adopted or adapted wherever there is community consensus that monitoring methods are robust and clearly answer the monitoring question. POLAR is presently part of an international team led by INTERACT to develop standard monitoring approaches for terrestrial and freshwater ecosystems across the circumpolar Arctic. Where necessary, we will work with subject experts to develop new protocols that can be tested in the CHARS ERA and posted on the POLAR website for community review. The process to develop a consensus on monitoring protocols will be initiated through the plan consultations but it will take many years to complete and will continue to evolve over time.

8.1.3 Develop a Long Term Data Management Plan

As stated above, the key output for any monitoring program is the data generated and POLAR staff is presently working with staff at the Northern Contaminants Program and the Nunavut General Monitoring Plan to develop a coherent approach for policies and processes around effective data management. Key principles of all monitoring data generated by the CHARS monitoring program are that they are properly preserved in the long term, discoverable through standardized metadata records, publically accessible to ensure full, free and open access and are ethically managed to respect legal and ethical considerations.

8.1.4 Lay out IMA Experimental Monitoring Plots and Transects

Within each Paired Area, locations for 12 Experimental Monitoring Plots will be selected by locating, on the detailed ecosystem map for the area, all suitable polygons for each of the 4 targeted Ecotypes, and then randomly selecting the polygons in which the Experimental Monitoring Plots will be located. A map of the area showing how this might look is shown in Figure 8. Where selected polygons are not suitable, e.g., the wrong ecotype classification or too small to include the plot and the buffer, then additional polygons will be selected until 3 suitable replicates of the 4 Ecotypes are located within each Paired Area, for a total of 24 Experimental Monitoring Plots within the two Paired Areas. Locations for the Experimental Monitoring Transects will be subjectively located to ensure inclusion of targeted ecotypes along a hydrological gradient that crosses a perennial stream.

8.1.5 Establish the LMTs and the Greiner Lake EMGs

The LMTs will be established sequentially and monitoring methods along the LMTs will be tested as LMTs are laid out and monitoring methods piloted. We are proposing 6 LMTs be established by the end of the Pilot Phase in 2019. Based on monitoring results, additional LMTs will be established as needed after 2019. LMTs are designed to monitor transects across the Greiner watershed between remote cabins so the distances need to be traversable in the course of a day of hiking. This will not be an issue in the winter when the LMTs are sampled using snowmobiles.

The remote cabins are being established to provide shelter for monitoring and research teams working in more remote areas of the Greiner watershed. They will be situated on larger, connected lakes to permit float plane access and fish studies. Once cabins are constructed (3 in 2017, 3 in 2018) a systematic random process will be used to establish a grid of calibration-validation monitoring plots (EMGs) to help develop and validate watershed-scale modeled predictions of terrestrial ecosystem change, to support satellite and fixed wing remote sensing studies, and to provide better overall coverage of the variability of monitoring indicators, e.g., lemmings, shorebirds, vegetation change, within the watershed.

Depending on the results of community consultation we may also be able to establish EMGs and/or LMTs adjacent to communities based on community direction for best monitoring locations and other logistical factors, e.g., presence iof cabins, distance from the community.

8.1.6 Establish Aerial Transects and Protocols

Aerial transect monitoring methods for wildlife observations are well developed by territorial and federal land management agencies. The aerial transects will be initiated in 2017 over the Greiner watershed and southern Victoria Island in consultations with Nunavut wildlife and ECCC. Protocols for aerial surveys over the long term for the CHARS ERA monitoring program, e.g., flight paths, timing, number of observers, will be developed in cooperation with the relevant agencies.

POLAR is presently working very closely with the NASA ABoVE project and we hope to take advantage of new sensors (e.g., UAVSAR, AIRMOSS, AVIRIS, LVIS) being deployed under the ABoVE Aerial Campaign to be flown in 2017 and 2019. Ground observations in the IMA, along the LMTs and at EMGs the remote cabins will be designed to support instrumented observations from the aerial platforms. The data will greatly enhance the data base in the Greiner watershed, making it possible to construct very accurate DEMs, and, compared to satellite approaches, improve on understanding and mapping a number of watershed components such as wetland identification and mapping, active layer depths, vegetation classification and mapping, and snow studies.

8.1.7 Develop a long term, linked plan for satellite remote sensing

Satellite data provides the opportunity to scale up ground monitoring observations to the watershed and appropriate regional areas. Working with RS specialists we will conduct backcasting studies for NDVI, biomass, sub-pixel fractionation of vegetation life forms, snow phenology, active layer depth and lake ice thaw date by March 2019. Ground data from the LMTs and the EMGs at the remote cabins will be used to calibrate and validate the models as possible. Results will be overlain on the terrestrial ecosystem mapping to link changes to terrestrial ecosystems to generate hypotheses that will inform ongoing monitoring, e.g., shrubification, habitat change.

Over the long term the program will develop a set of routine imagery needs to feed ongoing RS based monitoring projects. For example, seasonal measures of lake ice season will require a specific set of RadarSAT 2 data (and RCM ongoing) so systems will need to be established to ensure long term acquisition and processing of these data. RS based monitoring projects will need to evolve to take advantage of new deployments of RS resources.

8.1.8 Develop Preliminary Models

Detailed driver-indicator predictive models can only be developed over the long term as relationships are established through local-scale measurements in the IMAs. Preliminary driver-indicator models can be developed from the remote sensing data and the backcasting studies by linking the changes since the early 1980s to gridded climate data, and then projecting forward under a range of scenarios through gridded data. Although not technically process-based models, models developed in this way can reveal important trends in the modeled variables, e.g., predicted changes in the active layer, shrub growth and lake ice thaw date. Where possible these kinds of models will be developed by 2019 to inform directions for monitoring and research.

8.1.9 Analyze Pilot Phase Data – Power Analyses

Where sufficient data have been collected we will assess the feasibility of including individual monitoring indicators in the CHARS monitoring program. Where appropriate, powner analyses will permit assessments of indicator variability and our ability to measure significant change in a cost effective manner. Sampling costs, time and human resource needs will also be considered in these assessments. Feasibility assessments for many variables will need to occur over longer time periods to provide sufficient data on year to year variability.

8.1.10 First Iteration – CHARS Terrestrial Monitoring Plan

Based on consultations and the results of activities described above, the first iteration of the CHARS Terrestrial Monitoring Plan will be produced by March 2019. This plan will evolve over the 5 years following 2019 based on data derived from the program, ongoing consultations and new developments. Plain language summaries and a range of communication approaches (e.g., videos, pamphlets, podcasts) will be developed to communicate the implementation and results of the monitoring up to 2019. These communication tools will be used to frame consultations with the science community and Kitikmeot residents.

9.0 Acronymn Glossary

Acronym	Full Name
CAFF	Committee on Arctic Flora and Fauna
CAVM	Circumpolar Arctic Vegetation Map
CBM	Community-based Monitoring
CBMP	Circumpolar Biodiversity Monitoring Program
CCRS	Canadian Centre for Remote Sensing
CHARS	Canadian High Arctic Research Station
CNNRO	Canadian Network of Northern Research Operators
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CROW	Canadian Rangers Ocean Watch
CWS	Canadian Wildlife Service
DFO	Department of Fisheries and Oceans
ECCC	Environment and Climate Change Canada
EMG	Extensive Monitoring Grids
EMP	Experimental Monitoring Plot
EMT	Experimental Monitoring Transect
ERA	Experimental and Reference Area
IASC	International Arctic Science Committee
IMA	Intensive Monitoring Area
IMA	Intensive Monitoring Area
IMO	International Meteorological Organization
INAC	Indian and Northern Affairs Canada
INTERACT	International Network for Terrestrial Research and Monitoring in the Arctic.
ITEX	International Tundra Experiment
ITK	Inuit Tapirit Kanatami
LMT	Long Monitoring Transect
NASA	National Aeronautical and Space Administration
NCP	Northern Contaminants Program
NDVI	Normalized Difference Vegetation Index
NGEE	Next Generation Ecological Experiments
NGO	Non-government Organization

Acronym	Full Name
NIS	Nunavut Inuit Secretariat
NSRT	Nunavut Surface Rights Tribunal
NTI	Nunavut Tunngavik Incorporated
NWMB	Nunavut Wildlife Management Board
PCA	Parks Canada Agency
POLAR	Polar Knowledge Canada
POP	Persistent Organic Pollutant
ROS	rain on snow

10.0 References Cited

ACIA (2005) *Arctic climate impact assessment*. Cambridge University Press, Cambridge.

AMAP. 2011. Snow, water, Ice and Permafrost in the Arctic (SWIPA): Climate change and the cryosphere, xii–538. Oslo: Arctic Monitoring and Assessment Programme (AMAP).

Adamczewski, J., J. Boulanger, B. Croft, D. Cluff, B. Elkin, J. Nishi, A. Kelly, A. D. Hont, and C. Nicolson. 2009. Decline in the Bathurst Caribou Herd 2006-2009: A technical evaluation of field data and modeling. GNWT DRAFT Technical Report, December 2009.

AMAP. 2017. http://www.amap.no/swipa2017

Atkinson, D.M., and P. Treitz. 2013. Modeling Biophysical Variables Across an Arctic Latitudinal Gradient using High Spatial Resolution Remote Sensing Data. Arctic, Antarctic, and Alpine Research 45(2):161-178. 2013

Bennett, E.M., Peterson, G.D. & Gordon, L.J. (2009) Understanding relationships among multiple ecosystem services. Ecology Letters, 12, 1394-404. DOI: 10.1111/j.1461-0248.2009.01387.x

Beringer, J., F.S. Chapin III, C.C. Thompson and A.D. McGuire. 2005. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. Agriculture and Forest Meteorology 131:143-161.

Berkes, F. and D. Jolly. 2001. Adapting to climate change: social-ecological resilience in a Canadian western Arctic community. Conservation Ecology **5**(2): 18. [online] URL: http://www.consecol.org/vol5/iss2/art18

Bhatt, U.S., D.A. Walker, M.K. Raynolds, J.C. Cosimo, H.E. Epstein, G. Jia, R. Gens, *et al*.. 2010. Circumpolar Arctic tundra vegetation change is linked to sea ice decline. Earth Interaction 14, no. 8: 1.

Bidwell, D., Dietz, T., and Scavia, D. 2013. *Fostering knowledge networks for climate adaptation*. Nature Climate Change 3, pp 610-611. doi:10.1038/nclimate1931

Binder, C. R., J. Hinkel, P. W. G. Bots, and C. Pahl-Wostl. 2013. Comparison of frameworks for analyzing social-ecological systems. Ecology and Society 18(4): 26. http://dx.doi.org/10.5751/ES-05551-180426

Boelman, N. T., L. Gough, J. Wingfield, S. Goetz, A. Asmus, H. E. Chmura, J. S. Krause, J. H. Perez, S. K. Sweet, and K. C. Guay. 2015. Greater shrub dominance alters breeding habitat and food resources for migratory songbirds in Alaskan arctic tundra. Global Change Biology 21: 1508-1520.

Bokhorst, S. *et al*.. 2009. Winter warming events damage sub-Arctic vegetation: consistent evidence from an experimental manipulation and a natural event. *J. Ecol*. 97, 1408-1415

Bokhorst , F., S. Pedersen, L. Brucker, O. Anisimov, J. W. Bjerke, R. D. Brown, D. Ehrich, R. L. H. Essery, A. Heilig, S. Ingvander, C. Johansson, M. Johansson, I. S. Jo´nsdo´ttir, N.Inga, K. Luojus, G. Macelloni, H. Mariash, D. McLennan, G.N. Rosqvist, A. Sato, H. Savela, M. Schneebeli, A. Sokolov, S. A. Sokratov, S. Terzago, D. Vikhamar-Schuler, S. Williamson, Y. Qiu, T.V. Callaghan. 2016. Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modleing, and impacts. Ambio. Published online. DOI 10.1007/s13280-016-0770-0.

Bolduc, E., N. Casajus, P. Legagneux, L. McKinnon, H.G. Gilchrist, M. Leung, R.I. Guy Morrison, D. Reid, P. A. Smith, C.M. Buddle, J. Bety. 2013. Terrestrial arthropod abundance and phenology in the Canadian Arctic: modeling resource availability for Arctic-nesting insectivorous birds. Can. Entomol. 145: 155–170

Borner, A.P., K.Kielland, and M.D. Walker. 2008. Effects of simulated climate change on plant phenology and nitrogen mineralization in Alaskan Arctic tundra. Arctic, Antarctic and Alpine Research 40:27-38.

Braune B, D. Muir, B. de March, M. Gamberg, K. Poole, R. Currie, M. Dodd, W. Duschenko, J. Eamer, B. Elkin, M. Evans, S. Grundy, C. Hebert, R. Johnstone, K. Kidd, B. Koenig, L. Lockhart, H. Marshall, K. Reimer, J. Sanderson and L. Shutt. 1999. Spatial and temporal trends of contaminants in Canadian Arctic freshwater and terrestrial ecosystems: a review. Sci Total Environ. 230: 145-207.

Cable, W. L., V.E. Romanovsky, and M.T. Jorgenson. 2016. Scaling-up permafrost thermal measurements in western Alaska using an ecotype approach, The Cryosphere 10: 2517-2532, doi:10.5194/tc-10-2517-2016, 2016.

Callaghan, T.V.*et al*.. 2011a. Feedbacks and Interactions: From the Arctic cryosphere to the climate system . *Ambio* 40: 75-86.

Callaghan, T.V*. et al.*. 2011b. Multi-decadal Changes in Tundra Environments and Ecosystems: synthesis of the International Polar Year Back to the Future Project. *Ambio* 40(6) 705-716.

Callaghan, T.V., M. Johansson, R.D. Brown, P. Ya, G. Groisman, N. Labba, and V. Radionov. 2011c. Changing snow cover and its impacts. In Snow, water, ice and permafrost in the Arctic (SWIPA), Chapter 4. Oslo: Arctic Monitoring and Assessment Programme (AMAP).

Canterbury, G.E., T.E. Martin, D.R. Petit, L.J. Petit, and D.F. Bradford. 2000. Bird communities and habitat as ecological indicators of forest condition in regional monitoring. Conserv. Biol. 14, 544–558.

CARMA. 2016. http://carma.caff.is/

Carmack, E.C., M. Yamamoto-Kawai, T. Haine, B. Bluhm, S. Bacon, C. Lique, H. Melling, I. Polyakov, F. Straneo, M.L. Timmerman, W. Williams. 2015. Fresh water and its role in the Arctic marine system: sources, delivery, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. Journal of Geophysical Research-Biogeosciences, 120, doi: 10.1002/2015JG003140. (see: http://agupubs.onlinelibrary.wiley.com/agu/issue/10.1002/(ISSN)2169-8961(CAT)SpecialIssues(VI)FRESHWATER1/)

CAVM Team. 2003. Circumpolar Arctic Vegetation Map. (1:7,500,000 scale), Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

Chen, W., P. Zorn, N. Foy, I. Olthof, Y. Zhang, J. Li, R. Fraser, *et al*.. 2012. Final IPY report. Final report on plant growth and seasonality changes in Canada's four northern national parks during 1985–2010, monitored using satellite remote sensing. Hull, QC: Parks Canada

Chapin, F.S., III, and G.R. Shaver. 1996. Physiological and growth responses of arctic plants to a field experiment simulating climate change. Ecology 77:822-840.

Chapin, F.S. III, W. Eugster, J.P. McFadden, A.H. Lynch, and D.A. Walker. 2000. Summer differences among Arctic ecosystems in regional climate forcing. J. Climate 13: 2002-2010.

Christensen, T., J. Payne, M. Doyle, G. Ibarguchi, J. Taylor, N.M. Schmidt, M. Gill, M. Svoboda, M. Aronsson, C. Behe, C. Buddle, C. Cuyler, A.M. Fosaa, A.D Fox, S. Heidmarsson, P. Henning Krogh, J. Madsen, D. S. McLennan, J. Nymand, C. Rosa, J.Salmela, R. Shuchman, M. Soloviev, and M. Wedege. 2013. The Arctic Terrestrial Biodiversity Monitoring Plan. CAFF Monitoring Series Report Nr. 7. CAFF International Secretariat. Akureyri, Iceland. ISBN 978-9935-431-26-4

Chen, W., Blain D., Li J., Keohler K., Fraser R., Zhang Y., Leblanc S., Olthof I., Wang J., McGovern M. 2009a. Biomass measurements and relationships with Landsat-7/ETM+ and JERS-1/SAR data over Canada's western sub-arctic and low arctic. *International Journal of Remote Sensing* 30(9): 2355 — 2376.

Chen, W., Li J., Zhang Y., Zhou F., Koehler K., Leblanc S., Fraser R., Olthof I., Zhang Y., Wang J. 2009b. Relating biomass and leaf area index to non-destructive measurements for monitoring changes in arctic vegetation. *Arctic*, 62(3): 281–294

CNVC. 2016. http://cnvc-cnvc.ca/

Coates, K. 1985. Canada's Colonies: A History of the Yukon and Northwest Territories. Lorimer, Toronto.

Culp, J.M., W. Goedkoop, J. Lento, K.S. Christoffersen, S. Frenzel, G. Gudbergsson, P. Liljaniemi, S. Sandoy, M. Svoboda, J. Brittain, J. Hammar, D. Jacobsen, B. Jones, C. Juillet, M. Kahlert, K. Kidd, E. Luiker, J. Olafsson, M. Power, M. Rautio, A. Ritcey, R. Striegl, M. Svenning, J. Sweetman, M. Whitman. 2012. The Arctic Freshwater Biodiversity Monitoring

Plan. CAFF International Secretariat, CAFF Monitoring Series Report Nr. 7. CAFF International Secretariat. Akureyri, Iceland. ISBN 978-9935-431-19-6

CWS Waterfowl Committee. 2015. Population Status of Migratory Game Birds in Canada: November 2015. CWS Migratory Birds Regulatory Report Number 45.

Danks, H.V. 1992. Arctic insects as indicators of climate change. Arctic 45(2):159-166.

Derksen, C., Smith, S.L., Sharp, M., Brown, L., Howell, S., Copland, L., Mueller, D.R., Gauthier, Y., Fletcher, C.G., Tivy, A., Bernier, M., Bourgeois, J., Brown, R., Burn, C.R., Duguay, C., Kushner, P., Langlois, A., Lewkowicz, A.G., Royer, A., and Walker, A. 2012. Variability and change in the Canadian cryosphere. Climatic Change (2012) 115: 36-59. DOI 10.1007/s10584-012-0587-1

Derksen, C.S, X. Xu, R. S. Dunbar, A. Colliander, Y. Kim, J. Kimball, A. Black, E. Euskirchen, A. Langlois, M. Loranty, P. Marsh, K. Rautiainen, A. Roy and A. Royer. 2016. Retrieving landscape freeze/thaw state from Soil Moisture Active Passive (SMAP) radar and radiometer measurements, IEEE Transactions on Geoscience and Remote Sensing,submitted, October 2016.

Deslippe, J.R., M. Hartmann, W.W. Mohn, and S.W. Simard. 2011. Long term experimental manipulation of climate alters the ectomycorrhizal community in *Betula nana* in Arctic tundra. Global Change Biology 17:1625-1636.

Duchesne, D., G. Gauthier, and D. Berteaux. 2011. Habitat selection, reproduction and predation of wintering lemmings in the Arctic. Oecologia 167: 967–80.

ECCC. 2016. Key Habitat Sites for Migratory Birds in the Nunavut Settlement Area. ECCC's input to the Nunavut Planning Commission. ECCC Ottawa Canada. http://www.nunavut.ca/files/2016-05-31%20ECCC%20Key%20habitat%20sites%20for%20migratory%20birds%20in%20the%20NSA.pdf

Edlund, S.A. 1990. Vegetation, Central Queen Elizabeth Islands, District of Franklin, Northwest Territories, Map 1755A. Ottawa: Geological Survey of Canada.

Edlund, S.A., and B.T. Alt, B.T. 1989. Regional congruence of vegetation and summer climate patterns in the Queen Elizabeth Islands, Northwest Territories, Canada. Arctic 42:3–23.

ECCC. 2016. https://www.ec.gc.ca/ap-pa/default.asp?lang=En&n=20CAE357-1.

EEA 2007. The DPSIR framework used by the European Environmental Agency. http://ia2dec.pbe.eea.europa.eu/knowledge_base/Frameworks/doc101182

Elmendorf, S.C. *et al.*. 2012: Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Climate Change*, 2, 453-457.

Eugster, W., W.R. Rouse, R. Pielkle, J.P. McFadden, D.D. Baldocchi, T.G.F. Kittel, F.S. Chapin III, G. Liston, P.L. Vidale, E. Vaganov, and S, Chambers. 2000. Land atmosphere energy exchange in Arctic tundra and boreal forest: available data and feedbacks to climate, Global Change Biol. 6 (Suppl. 1): 84-115.

Evans, L.S., C.C. Hicks, P. Fidelman, R.C. Tobin and A.L. Perry. 2013. Future Scenarios as a Research Tool: Investigating Climate Change Impacts, Adaptation Options and Outcomes for the Great Barrier Reef, Australia. Hum Ecol Interdiscip J. 2013; 41(6): 841–857

Flynn, N., and S. Francis. 2015. The Yukon Ecosystem and Land Classification: Overview and Concepts. Yukon ELC Working Group. Whitehorse, YK.

Forbes, D.L. (editor). 2011. State of the Arctic Coast 2010 – Scientific Review and Outlook. International Arctic Science Committee, Land-Ocean Interactions in the Coastal Zone, Arctic Monitoring and Assessment Programme, International Permafrost Association. Helmholtz-Zentrum, Geesthacht, Germany, 178 p. http://arcticcoasts.org

Forbes, D.L., T. Bell, M. LeTissier, A. Petrov, P. Pulsifer, D. E. Atkinson, L. Eerkes-Medrano, J. Nymand Larsen, N. Couture, G. Kraev, E. Marino, P. Overduin, R.O. Rasmussen, R. Riedlsperger, P. Schweitzer, T. Vlasova and K. Wilson. 2016. CACCON and Partner Knowledge Networks: Arctic Coastal Engagement Network of Future Earth Coasts. White Paper Arctic Observing Summit, Fairbanks, March 2016.

Francis, J., White, D., Cassano, J., Gutkowski, W., Hinzman, L., Holland, M., Steele, M., Vorosmarty, C. 2009. An arctic hydrologic system in transition: feedbacks and impacts on terrestrial, marine and human life. J Geophys Res. 114 (G04019). Doi:10.1029/2008JG000902.

Fraser, R.H., Olthof, I., and Pouliot, D. 2009. Monitoring land cover change and ecological integrity in Canada's national parks. *Remote Sensing of Environment,*113:1397–1409.

Fraser, R.H., Olthof, I., Carriere, M., Deschamps, A., and Pouliot, D. 2011. A Method for Trend-based Change Analysis in Arctic Tundra using the 25-year Landsat Archive. Accepted for *Polar Record*.

Fraser, R., D.S. McLennan, S. Ponomarenko, and I. Olthof. 2012. Image-based predictive ecosystem mapping in Canada's Arctic parks. International Journal of Applied Earth Observation and Geoinformation. 14 :129-138.

Fraser, R.H., I. Olthof, M. Carriere, and D. Pouliot. 2011. Detecting long-term changes to vegetation in northern Canada using the Landsat satellite image archive. Environmental Research Letters 6: 045504.

Fraser, R.H., I. Olthof, M. Carriere, A. Deschamps, and D. Pouliot. 2012. A method for trend-based change analysis in Arctic tundra using the 25-year Landsat archive. Polar Record 48: 83–93.

Gamberg, M., B. Braune, E. Davey, B. Elkin, P.F. Hoekstra, D. Kennedy, C. Macdonald, D. Muir, A. Nirwal, M. Wayland, B. Zeeb. 2005. Spatial and temporal trends of contaminants in terrestrial biota from the Canadian Arctic. Sci. Total Environ. 351-352: 148-164.

Gauthier, G., and D. Berteaux (eds). 2011a. ArcticWOLVES: Arctic wildlife observatories linking vulnerable ecosystems, Final synthesis report. Quebec City, Quebec, Canada: Centre d'etudes nordiques, Universite´ Laval.

Gauthier, G., D. Berteaux, J. Bety, A. Tarroux, J.-F. Therrien, L. McKinnon, P. Legagneux, and M.C. Cadieux. 2011b. The tundra food web of Bylot Island in a changing climate and the role of exchanges between ecosystems. Ecoscience 18: 223–35.

Gayton. D. 2008. Impacts of climate change on British Columbia's Diversity: A literature review. Forrex Forest Research Extension Partnership, Kamloops, BC. Forrex Series 23. url: http://www. forrex.org/publications/forrexseries/fs23.pdf

Gilg, O., I. Hanski, and B. Sittler. 2003. Cyclic dynamics in a simple vertebrate predator–prey community. Science 302: 866–8.

Gilg, O., B. Sittler, and I. Hanski. 2009. Climate change and cyclic predator–prey population dynamics in the high Arctic. Global Change Biology 15: 2634–52.

Gill, M.J., K. Crane, R. Hindrum, P. Arneberg, I. Bysveen, N.V. Denisenko, V. Gofman, A. Grant-Friedman, G. Gudmundsson, R.R. Hopcroft, K. Iken, A. Labansen, O.S. Liubina, I.A. Melnikov, S.E. Moore, J.D. Reist, B.I. Sirenko, J. Stow, F. Ugarte, D. Vongraven, and J. Watkins. Arctic Marine Biodiversity Monitoring Plan (CBMP-MARINE PLAN), CAFF Monitoring Series Report No.3, April 2011, CAFF International Secretariat, Akureyri, Iceland. ISBN 1. 978-9979-9778-7-2

Glennon, M.J. and W.F. Porter. 2005. Effects of land use management of biotic integrity: an investigation of bird communities. Biol. Conserv. 126, 499–511.

Gould, W.A., D.A. Walker and D. Biesboer. 2003. Combining Research and Education: Bioclimatic Zonation along a Canadian Arctic Transect. Arctic 56(1) 45– 54.

Grogan, P., and F.S. Chapin III. 1999. Arctic soil respiration: effects of climate and vegetation depend on season. Ecosystems 2:451-459.

Gunn A. 1990. The decline and recovery of caribou and muskoxen on Victoria Island. *In*: Canada missing dimension science and history in the Canadian Arctic. Ed C.R. Harington. Natural Museum of Nature, Ottawa, Ontario, Vol. 2, pp. 590-607.

Gunn, A. and B. Fournier. 2000. Seasonal movements and distribution of satellite collared caribou on Victoria Island, 1987-88. Department of Resources, Wildlife and Economic Development, Government of the Northwest Territories, File Report No. 124. 72 pp.

Gunn, A., B. Fournier, and J. Nishi. 2000. Abundance and distribution of the Queen Maud Gulf caribou herd, 1986-98. Department of Resources, Wildlife and Economic Development, Government of the Northwest Territories, File Report No. 126. 75 pp.

Gunn, A., and B.R Patterson. 2012. Distribution and abundance of Muskoxen on southeastern Victoria Island, Nunavut. Manuscript Report No. 222. Department of Sustainable Development, Government and Nunavut, Kugluktuk, NU.

Harmann, A., and T. Wang. 2006. Potential effects of climate change on ecosystem and tree species distributions in British Columbia. Ecology 87;2773-2786.

Henden J. A., N. G. Yoccoz, R. A. Ims, and K. Langeland. 2013. How spatial variation in areal extent and configuration of labile vegetation states affect the riparian bird community in Arctic tundra. PLoS ONE 8: e63312.

Hill, G.B., and G.H.R. Henry. 2011. Responses of high Arctic wet sedge tundra to climate warming since 1980. Global Change Biology 17: 276–87.

Hudson, J.M.G., and G.H.R. Henry. 2010. Increased plant biomass in a high Arctic heath community from 1981 to 2008. Ecology 90: 2657–63.

Hudson, J.M.G., G.H.R. Henry, and W.K. Cornwell. 2010. Taller and larger: shifts in Arctic tundra leaf traits after 16 years of experimental warming. Global Change Biology, doi: 10.1111./j.1365-2486.2010.02294.

Ims, R. A., and J. A. Henden. 2012. Collapse of an Arctic bird community resulting from ungulate-induced loss of erect shrubs. Biological Conservation 149: 2-5.

IPCC. 2007. Climate Change 2007. The Physical Science Basis. In: Solomon, S., Qin, M., Manning, Z., Marquis, M., Averyt, K., Tignor, M., and Miller, H. (eds.) Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jia, G.J., and H.E. Epstein. 2003. Greening of Arctic Alaska. Geophysical Research Letters 30: 2067.

Jia, G.J., H.E. Epstein, and D.A. Walker. 2009. Vegetation greening in the Canadian Arctic related to decadal warming. Journal of Environmental Monitoring 11: 2231–8.

Kelly B.C. and F.A.P.C Gobas. 2001. Bioaccumulation of persistent organic pollutants in lichen-caribou-wolf food chains of Canada’s Central and Western Arctic. Environ. Sci. Technol. 35: 325-334.

Kelly B.C. and F.A.P.C Gobas. 2003. An arctic terrestrial food chain bioaccumulation model for persistent organic pollutants. Environ. Sci. Technol 37: 2966-2974.

Kerbes, R.H., K.M. Meeres, J.E. Hines, and D.G. Kay. 2008. Lesser Snow Geese, Chen caerulescens caerulescens, and Ross’s Geese, Chen rossii, of Jenny Lind Island, Nunavut. Canadian Field-Naturalist 122(1): 34-39.

King, J., Kelly, R., Kasurak, A., Duguay, C., Gunn, G., Rutter, N., Derksen, C. (2015). Spatio-temporal influence of tundra snow properties on Ku-band (17.2 GHz) backscatter. Journal of Glaciology,61(226), 267–279.

Krebs, C. J., A. J. Kenney, S. Gilbert, K. Danell, A. Angerbjorn, S. Erlinge, R. G. Bromley, C. Shank and S. Carrière. 2002. Synchrony in lemming and vole populations in the Canadian arctic. Canadian Journal of Zoology 80:1323-1333.

Krebs, C. J., K. Danell, A. Angerbjorn, J. Agrell, D. Berteaux, K. A. Brathen, O. Danell, S. Erlinge, V. Fedorov, K. Fredga, J. Hjalten, G. Hogstedt, I. S. Jonsdottir, A. J. Kenney, N. Kjellen, T. Nordin, H. Roininen, M. Svensson, M. Tannerfeldt, and C. Wiklund. 2003. Terrestrial trophic dynamics in the Canadian Arctic. Canadian Journal of Zoology 81:827-843.

Krebs, C.J., D. Reid, A.J. Kenney, and S. Gilbert. 2011. Fluctuations in lemming populations in north Yukon, Canada, 2007–2010. Canadian Journal of Zoology 89: 297–306.

Kutz, S.J., S. Checkley, G.G. Verocai, M. Dumond, E. Hoberg, R. Peacock, J. Wu, K. Orsel, K. Seegers, A. Warren, and A. Abrams. 2013. Invasion, establishment, and range expansion of two protostrongylid nematodes in the Canadian Arctic. Global Change Biology 19(11): 3254-3262. Doi 10.1111/gcb12315.

Langlois, A., Johnson, C.-A., Montpetit, B., Royer, A., Blukacz-Richards, E.A., Neave, E., Dolant, C., Roy, A., Arhonditsis, G., Kim, D.-K.F, Kaluskar, S., and Brucker, L. 2016. Detection of rain-on-snow (ROS) events and ice layer formation using passive microwave radiometry: A context for the Peary caribou habitat in the Canadian arctic, Remote Sensing of Environment, Submitted, RSE-D-16-00412.

Lantz, T.C., C. Marchildon, J. Leathem and H. Gill. 2014. Monitoring vegetation in the Northwest Territories. Field manual for a community-based protocol prepared for the Cumulative Impact Monitoring Protocol. NWT Cumulative Impacts Monitoring Program (NWT CIMP). Yellowknife, NT. Available online: http://ale.uvic.ca/Projects/Veg%20Protocol_June_online.pdf

Larsen, J.N. *et al*.. 2014. Chapter 28 - Polar Regions. In: IPCC WGII AR5. Final draft available on: http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap28_FGDall.pdf

Larsen, J.N., and G.Fondahl (eds.). 2014. Arctic Human Development Report Regional Processes and Global Linkages. ISBN 978-92-893-3883-7 (PDF)

Lavoie, C., and Payette, S. 1996. The long-term stability of the boreal forest limit in subarctic Quebec. Ecology, 77, 4, 1226-1233.

Lawler, J.L, S.L. Shafer, D. White, P. Kareiva, E.P. Maurer, A.R. Blaustein, and P.J. Bartlein. 2009. Projected climate-induced faunal change in the Western Hemisphere. Ecology, 90(3), 2009, pp. 588–597

Leclerc, L-M. 2015. Muskox (*Ovibos moschatus*) distribution and abundance, muskox management unit MX-7, Victoria Island, September 2013-2014.

Lindenmayer, D. B., and Likens, G.E. 2010. *Effective ecological monitoring*. CSIRO Publishing and Earthscan, London, UK.

MacDonald, G.M., Velichko, A.A., Kremenetski, C.V., Borisova, O.K., Goleva, A.A., Andreev, A.A., L.C., Riding, R. T., Forman, S.L., Edwards, T.W.D., Aravena, R., Hammarlund, D. 2000. Holocene Treeline History and Climate Change Across Northern Eurasia. Quaternary Research **53,** 302–311 doi:10.1006/qres.1999.2123

McKinnon, L., M. Picotin, E. Bolduc, C. Juillet, and J. Bety. 2012. Timing of breeding, peak food availability, and effects of mismatch on chick growth in birds nesting in the High Arctic. Canadian Journal of Zoology 90: 961–71.

McLaughlin F.A., E.C. Carmack, R.G. Ingram, W. Williams and C. Michel. 2006. Oceanography of the Northwest Passage. In: The Sea, Volume 14B, Chapter 31, A. Robinson and K. Brink, eds., Harvard Press, 1213-1244.

McGuire, A.D., T. R. Christensen, D. Hayes, A. Heroult, E. Euskirchen, J. S. Kimball, C. Koven, P. Lafleur, P.A. Miller, W. Oechel, P. Peylin, M. Williams, and Y. Yi, 2102. An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. Biogeosciences, 9, 3185–3204, 2012

McLennan, D.S. 2013. A Potential Role for CHARS in Leading Development of the Canadian Arctic Monitoring and Prediction Network (CAMPNet). White paper submitted to the Arctic

Observing Summit, Vancouver B.C. (http://www.arcticobservingsummit.org/aos-2013-white-papers)

McLennan, D.S., and J. Wagner (eds). 2015.Towards the Development of the Canadian High Arctic Research Station (CHARS) as a Centre for Science and Technology in Canada and the Circumpolar North - Regional Social and Ecological Context, Baseline Studies, and Monitoring Pilots. Unpublished report. Canadian High Arctic Research Station, Cambridge Bay, NU. http://above.nasa.gov/Documents/CHARS_Science_Summary_June_2015_DRAFT.pdf

McLennan, D.S., D. Meidinger, and W. MacKenzie. 2016. The Arctic Vegetation Archive as the basis for a Canadian arctic terrestrial ecosystem classification: Application to establishing arctic terrestrial ecosystem monitoring. White paper submitted to the Arctic Observing Summit, Vancouver B.C. (http://www.arcticobservingsummit.org/aos-2016-white-papers-and-short-statements-public)

McLennan, D.S., T. Jones, S., C. Behe, S. Weggeberg, M. Pettersvik-Arnes, L. Sergienko, C. Price, J. Taylor, and T. Christensen. In prep. The Arctic Coastal Biodiversity Monitoring Plan. CAFF Monitoring Series Report. CAFF International Secretariat. Akureyri, Iceland.

Meidinger, D., W. Mackenzie, and J. Wagner, 2015. Vegetation and Ecosystems. *In*: McLennan, D.S., and J. Wagner (eds):Towards the Development of the Canadian High Arctic Research Station (CHARS) as a Centre for Science and Technology in Canada and the Circumpolar North - Regional Social and Ecological Context, Baseline Studies, and Monitoring Pilots. Unpublished report. Canadian High Arctic Research Station, Cambridge Bay, NU. http://above.nasa.gov/Documents/CHARS_Science_Summary_June_2015_DRAFT.pdf

Miller, F.L., Barry, S.J., and Calvert, W.A. 2005. Sea-ice crossings by caribou in the south-central Canadian Arctic Archipelago and their ecological importance. Rangifer, Special Issue 16:77–88.

Miller, F.L., and S.J. Barry. 2009. Long-term control of Peary caribou numbers by unpredictable, exceptionally severe snow or ice conditions in a non-equilibrium grazing system. Arctic 62: 175–89.

Mizel, J. D., J. H. Schmidt, C. L. McIntyre, and C. A. Roland. 2016. Rapidly shifting elevational distributions of passerine species parallel vegetation change in the subarctic. Ecosphere 7: e01264.

Myers-Smith, I.H., *et al*.. 2011. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environmental Research Letters*, 6(4), 045509, doi:10.1088/1748-9326/6/4/045509.

Natali, S. M., E.A. Schuur, and R.L. Rubin. 2012. Increased plant productivity in Alaskan tundra as a result of experimental warming of soil and permafrost. *J.Ecol.* **100**,488–498.

Nalto, A.T., and D.M. Cairns. 2011. Relationships between Arctic shrub dynamics and topographically derived hydrologic characteristics. Environmental Research Letters 6, doi: 10.1088/1748-9326/6/4/045506

National Park Service, 2013. Using Scenarios to Explore Climate Change: A Handbook for Practitioners. National Park Service Climate Change Response Program. Fort Collins, Colorado.

NCP 2013. Canadian Arctic Contaminants Assessment Report On Persistent Organic Pollutants – 2013. Muir D, Kurt-Karakus P, Stow J. (Eds). Northern Contaminants Program, Aboriginal Affairs and Northern Development Canada, Ottawa ON. xxiii + 487 pp + Annex

NCP. 2016. Northern Contaminants Program. http://www.science.gc.ca/default.asp?lang=En&n=7A463DBA-1

NGEE 2016. Next-Generation Ecosystem Experiments. Modeling and Scaling Strategy. http://ngee-arctic.ornl.gov/teams/modeling-and-scaling-strategy

Nishi, J.S. 2000. Calving and rutting distribution of the Dolphin and Union caribou herd based on radio telemetry, Victoria Island (1994–1997). Department of Resources, Wildlife and Economic Development, Government of the Northwest Territories,. No. 127. 65 pp.

Nishi, J.S. and A. Gunn. 1998. An estimate of herd size for the Dolphin and Union caribou herd during the rut, October 1997. Department of Resources, Wildlife and Economic Development, Government of the Northwest Territories, Manuscript Report.

Nunavut Planning Commission. 2016. Nunavut Land Use Plan. http://www.nunavut.ca/en/draft-plan

Obst, J. 2012. Bird Monitoring Pilot. *In*: McLennan, D.S., and J. Wagner (eds): Towards the Development of the Canadian High Arctic Research Station (CHARS) as a Centre for Science and Technology in Canada and the Circumpolar North - Regional Social and Ecological Context, Baseline Studies, and Monitoring Pilots. Unpublished report. Canadian High Arctic Research Station, Cambridge Bay, NU. http://above.nasa.gov/Documents/CHARS_Science_Summary_June_2015_DRAFT.pdf

OECD. 2003. OECD Environmental Indicators. Development, measures and use. https://www.oecd.org/env/indicators-modleing-outlooks/24993546.pdf

Ohlson, D.W., G.A. McKinnon and K. G. Hirsch. 2005. A structured decision-making approach to climate change adaptation in the forest sector. The Forestry Chronicle 81 (1).

Olthof, I., and R.H. Fraser. 2007. Mapping northern land cover fractions using Landsat ETM+. *Remote Sensing of Environment,* 107: 496-509.

Ouellet, F., Langlois, A., Johnson, C.-A., Richards, A. and Royer, A. 2015. Spatialization of the SNOWPACK Snow Model in the Canadian Arctic for Peary Caribou Winter Grazing conditions Assessment. Physical Geography, TPHY-2015-0077.

Payette, S. 2006. Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational lag. Ecology, 88, 3, 770-780.

Pearson, R.G., M.M. Phillips, P.A. Loranty, T. Beck , T. Damoulas , S.J. Knight and S.J. Goetz. 2013. Shifts in Arctic vegetation and associated feedbacks under climate change. Nature Climate Change Letters.
Published online DOI:10.1038/NCLIMATE1858

Petrov, A.N., S. BurnSilver, F.S. Chapin III, G. Fondahl, J. Graybill, K. Kell, A.E. Nilsson, R. Reildsperger, and P. Schweitzer. 2016. Arctic sustainability research: toward a new agenda. Polar Geography. http://dx.doi.org/10.1080/1088937X.2016.1217095.

Pojar, J., K. Klinka, and D. Meidinger. 1987. Biogeoclimatic ecosystem classification in British Columbia. Forest Ecology and Management 22: 119-154.

Pojar, J. 2011. A new climate for conservation - nature, carbon, and climate in British Columbia. Report to the Canadian Parks and Wilderness Association. http://cpawsbc.org/upload/NewClimate_report_CPAWS.pdf

Poole, K.G., A. Gunn, B.R. Patterson and M. Dumond. 2010. Sea ice and migration of the Dolphin and Union Caribou Herd in the Canadian Arctic: An uncertain future Arctic 63 (4):414-428.

Rastetter, E.B., J D. Aber, D.P.C. Peters, D.S. Ojima, and I. C. Burke. 2004. Using Mechanistic Models to Scale Ecological Processes across Space and Time. Bioscience 53)1):58-76.

Reid, D., F. Bilodeau, C.J. Krebs, G. Gauthier, A.J. Kenney, B.S. Gilbert, M.C.Y. Leung, D. Duchesne, and E. Hofer. 2012. Lemming winter habitat choice: a snow-fencing experiment. Oecologia 168: 935–46.

Robertson, C.G. D. E. Coleman, C. S. Bledsoe, and P. Sollins (eds). 1999. Standard Soil Methods for Long-Term Ecological Research. New York: Oxford University Press. xvii+462 pp. Tables, figures, notes, references, index. ISBN 0195 120833.

Roy, A. A. Royer, C. Derksen, L. Brucker, A. Langlois, A. Mialond, and Y. Kerr. 2015. Evaluation of Spaceborne L-band Radiometer Measurements for Terrestrial Freeze/Thaw Retrievals in Canada. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8(9), 4442-4459.

Royer, A. and S. Poirier. 2010. Surface temperature spatial and temporal variations in Northern America from homogenized satellite SSMR-SSM/I microwave measurements and reanalysis for 1979-2008. Journal of Geophysical Research, 115, D08110, DOI:10.1029/2009JD012760.

Schlüter, M., J. Hinkel, P. W. G. Bots, and R. Arlinghaus. 2014. Application of the SES framework for model-based analysis of the dynamics of social-ecological systems. *Ecology and Society* **19**(1): 36.
http://dx.doi.org/10.5751/ES-05782-190136

Schmidt, I.K., S. Jonasson, G.R. Shaver, A. Michelsen, and A. Nordin. 2002. Mineralization and allocation of nutrients by plants and microbes in 4 Arctic ecosystems: responses to warming. Plant and Soil 242:93-106.

Schmidt, N-M, B. Hardwick, O. Gilg, T. T. Høye, P.H. Krogh, H. Meltofte, A. Michelsen, J. B. Mosbacher, K. Raundrup, J. Reneerkens, L. Stewart, H. Wirta, and T. Roslin. 2017. Interaction webs in arctic ecosystems: Determinants of arctic change? Ambio 2017, 46(Suppl. 1):S12–S25 DOI 10.1007/s13280-016-0862-x

SENES. 2008. West Kitikmeot-Slave State of Knowledge Report - 2007 Update. Report Prepared by SENES Consultants Ltd. For the West Kitikmeot Slave Study Society. http://www.enr.gov.nt.ca/sites/default/files/reports/west_kitikmeot_slave_study_2007_update.pdf

Serreze, M.C., A.P Barrett, J.C. Stroeve, D.N. Kindig, and M.M. Holland, 2009. The emergence of surface-based Arctic amplification. The Cryosphere, 3, 11–19.

Smith, S.L., V.E. Romanovsky, A.G. Lewkowicz, C.R. Burn, M. Allard, G.D. Clow, K. Yoshikawa, and J. Throop. 2010. Thermal state of permafrost in North America: contribution to the International Polar Year. Permafrost and Periglacial Processes 21: 117–35.

SNAP. 2016. Scenarios Network for Alaska. https://www.snap.uaf.edu/projects

Sokolov V, Ehrich D, Yoccoz NG, Sokolov A, Lecomte N (2012) Bird Communities of the Arctic Shrub Tundra of Yamal: Habitat Specialists and Generalists. PLoS ONE 7(12): e50335. doi:10.1371/journal.pone.0050335

Species at Risk Committee. 2013. Species Status Report for Dolphin and Union Caribou (Rangifer tarandus groenlandicus x pearyi) in the Northwest Territories. Species at Risk Committee, Yellowknife, NT.

Stow, D. A., Hope, A. S., Boynton, W., Phinn, S., Walker, D., and Auerbach, N. A., 1998: Satellite-derived vegetation index and cover type maps for estimating carbon dioxide flux for Arctic tundra regions. *Geomorphology*, 21: 313–327.
Sturm, M., C. Racine, and K.Tape. 2001a. Climate change: Increasing shrub abundance in the Arctic. *Nature* 411, 546-547 doi:10.1038/35079180

Sturm, M, T. Douglas, C. Racine, and G. Liston. 2005a. Changing snow and shrub conditions affect albedo with global implications. Journal of Geophysical Research 110: G01004.

Sturm, M., J. Schimel, G. Michaelson, and J.M. Welker. 2005b. Winter biological processes could help convert Arctic tundra to shrubland. BioScience 55: 17–26.

Sullivan, J., D.S. McLennan, S. Checkley, F. Chan, A. Massolo, and S. Kutz. In press. A Comparison of Techniques for Sampling Terrestrial Gastropods in the Arctic. Can. Field Nat.

Tape, K.D., M. Sturm, and C.H. Racine. 2006. The evidence for shrub expansion in northern Alaska and the panArctic. Global Change Biology 12: 686–702

SWIPA. 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. SWIPA Scientific Assessment Report. Arctic Monitoring and Assessment Program, Oslo.

Tomaselli, M., S. Kutz, and S. Checkley. 2016. Local knowledge from Ikaluktutiak, Nunavut, on muskoxen and the Dolphin Union caribou herd. Interim Report, Faculty of Veterinary Medicine, University of Calgary.

Vincent, W.F. (ed.). 1996. Emnvironmrntal management of a Cold Desert ecosystem: the McMurdo Dry Valleys. Desert Research Institute, University of Nevada, USA, Special Publication, 57pp.

Vincent, W.F., T.V. Callaghan, D. Dahl-Jensen, M. Johansson, K.M. Novacs, C. Michel, T. Prowse, J.D. Reist, and M. Sharp. 2011. Ecological implications of changes in the Arctic cryosphere. Ambio 40: 87–99.

Walker, D.A., Alsos, I.G., Bay, C., Boulanger-Lapointe, N., Breen, A.L., Bültmann, H., Christensen, T., Damgaard, C., Daniëls, F.J.A., Hennekens, S., Raynolds, M.K., Le Roux, P.C., Luoto, M., Pellissier, L., Peet, R.K., Schmidt, N.M., Stewart, L.,Virtanen, R. Yoccoz, N.G., and M.S. Wisz, M.S. 2013. Rescuing Valuable Arctic Vegetation Data for Biodiversity Models, Ecosystem Models and a Panarctic Vegetation Classification. Arctic 66 (1): 133-138.

Walker, D.A., H. Epstein, and J.M. Welker. 2008. Introduction to a special session on the biocomplexity of tundra ecosystems. Journal of Biophysical Research 113:G03000. doi:10.1029/2008JG000740.

Walker, M.D. 1995. Patterns and causes of arctic plant community diversity. In: Chapin, F.S., III, and Körner, C., eds. Arctic and alpine biodiversity: Patterns, causes, and ecosystem consequences. Ecological Studies 113. Berlin: Springer-Verlag 3–20

Walker, M.D., C.H. Wahren, R.D. Hollister, G.H.R. Henry, L.E. Ahlquist, J.M. Alatalo, M.S. Bret-Harte, M.P. Calef, T.V. Callaghan, A.B. Carrolla, H.E. Epstein, I.S. Jónsdóttir, J.A. Kleinl, B.Magnússon, U. Molaug, S.F. Oberbauer, S.P. Rewa, C.H. Robinson, G.R. Shaver, K.N. Suding, C.C. Thompson, A. Tolvanen, Ø. Totland, P.L.Turner, C.E. Tweedie, P.J. Webber, and P.A. Wookey. 2006. Plant community responses to experimental warming across the tundra biome. *Proc. Natl Acad. Sci. USA* **103**, 1342–1346.

Wang, T., E.M. Campbell, G.A. O’Neill, and S.N. Aitken. 2012. Projecting future distributions of ecosystem climate niches: uncertainties and management implications. Forest Ecology and Management (279):128-140.

Whitaker, D. in prep. Expanded Range Limits of Boreal Birds in the Torngat Mountains of Northern Labrador. In revision at Can. Field Naturalist.

Wilson, M.J., and S.E. Bayley, 2012. Use of single versus multiple biotic communities as indicators of biological integrity in northern prairie wetlands. Ecological Indicators 20 (2012) 187–195.

Zhang, Y., X. Wang, R. Fraser, I. Olthof, W. Chen, D. McLennan, S. Ponomarenko, and W. Wu. 2013. Modeling and mapping climate change impacts on permafrost at high spatial resolution for an Arctic region with complex terrain. The Cryosphere, 7, 1121–1137. doi:10.5194/tc-7-1121-2013

Zhang, Y, I. Olthof, R. Fraser, and S. A. Wolfe. 2014. A new approach to mapping permafrost and change incorporating uncertainties in ground conditions and climate projections. The Cryosphere, 8, 2177-2194. doi:10.5194/tc-8-2177-2014.

Appendix A – VECs and FECs

This Appendix will be expanded to include VECs from development proposals in the ERA

CBMP Focal Ecosystem Components (FECs) – Terrestrial Ecosystems

VEGETATION		ARTHROPODS		BIRDS		MAMMALS	
FEC	**Attribute(s)**	**FEC**	**Attribute(s)**	**FEC**	**Attribute(s)**	**FEC**	**Attribute(s)**
All native vegetation communities	diversity, spatial structure, composition, and abundance	**Blood feeding Insects**	diversity	**Insectivores**	abundance, spatial structure, demography and phenology	**Large Herbivores**	abundance, demographics, spatial structure and health
	productivity	**Pollinators**	diversity and ecological function	**Carnivores**	abundance, spatial structure, and demography	**Medium-sized Herbivores**	abundance, demographics, health and phenology
	phenology	**Decomposers**	diversity, abundance and distribution	**Herbivores**	diversity, composition, spatial structure, and health	**Small Herbivores**	abundance, health and phenology
Rare Species	abundance, diversity, health and spatial structure	**Vertebrate Prey**	abundance, spatial structure, productivity and phenology	**Omnivores**	diversity, composition, spatial structure, health and prey cycling	**Large Predators**	spatial structure and diversity
Invasive Species	abundance and spatial structure	**Herbivores**	diversity and ecological function	**Piscivores**	abundance, spatial structure, and demographics	**Medium-sized Predators**	abundance, health and phenology
Food Species	productivity, quality, phenology and health					**Small Predators**	abundance, health and phenology

Valued Ecosystem Components (VECs) for Terrestrial Ecosystems – Nunavut General Monitoring Program (NGMP) and Cumulative Impact Monitoring program (CIMP)

	CBMP	**CIMP**
Mammals	Caribou, Muskoxen, Wolverine, Polar Bear, Grizzly Bear, Wolves, Foxes, Rabbit/Hare, Small mammals, (muskrat, Arctic ground squirrel)	caribou, moose, other mammals
Birds	**Breeding Birds:** Ptarmigan - Shorebirds - Passerines (Songbirds) Waterfowl and **Water Birds:** Loons, Swans, Geese, and Ducks - Sea Ducks Raptors, Seabirds	other wildlife (avian)
Other - Biotic	Insects /Invertebrates Vegetation Species at Risk	vegetation
Other - Abiotic	Greenhouse Gases Air Quality	climate, snow, ground ice and permafrost

Appendix B – Monitoring Indicators, Partners and Protocols

Appendix Table B1: Climate and streams.

Parameter	Protocols	Partners	Rationale and Ecological Linkages
air temperature relative humidity	HC2-S3-L Relative Humidity (0 to 100%) & Air Temperature Probe; 10 Cable Model : L27746 Range: 50C to +50C	Campbell Scientific Université de Sherbrooke ECCC	Monitoring the complex of climate factors that are directly and indirectly driving all aspects of the terrestrial ecosystems in the IMA is fundamental to understanding climate-ecosystem relationships, and for developing predictive models that link climate changes to ecosystem change.
barometric pressure	CS106 Vaisala PTB110 Barometric Pressure Sensor 500mb - 1100mb PR RM Young barometric pressure		
precipitation	T-200B-3 Geonor Precipitation Gauge 600mm, 3 Sensors, 3 Signal Interfaces CS125 visibility sensor		
solar radiation and long-wave radiation	CNR4-L Kipp & Zonen Net Radiometer Sensor; 4 Components (short- long-wave)		
snowfall, depth and water equivalent	CS705 Snowfall Conversion Adapter (for Texas Electronics TE525WS Tipping Bucket) CS725 Snow Water Equivalent Sensor SR50A Sonic ranger 50 KHz (-45 +50C)		
snow temperature	SI-111 infrared radiometer (-55 +80C) 109AM-L Soil/water temperature probe (-50 +70C)		
wind	05103AP-10 RM Young Wind Monitor Alpine Version - CSC Spec		
stream depth, turbidity, and temperature	PLS-L OTT Pressure Level Sensor with SDI Output; OBS-3A Turbidity & Temperature Monitoring System; ADC-2H OTT ADC Acoustic Digital Current Meter with 6M Cable and Adapter		Continuous measures of stream depth we can quantify export of nutrients and C for terrestrial ecosystems and link to soil lysimeters data

Appendix Table B2: Soils.

Parameter	Protocols	Partners	Protocol Link/Reference	Rationale and Ecological Link
soil nutrient content; pH	all macro- and micro-nutrients	TBD	LTER Standard Methods: Robertson *et al.* 1999	The availability of soil nutrients is an important determina and foliar nutrient content; link to soil decomposition and temperature and moisture.
soil decomposition index	tea bag index Cellulose strip	TBD		The rate at which soil organic matter is decomposed to pr is the result of a complex of abiotic and biotic factors but moisture are key drivers. It is expected that soil decompo warming temperatures which will in turn influence plant p and C flux.
soil solution chemistry	gravitational and/or suction lysimeters	TBD		The chemical composition of the soil solution (e.g., DOC, K, Mg, Na) largely determines the groundwater compositi through lateral flow from soils; with warming it is expecte thawed more deeply and thus alter the chemistry of strea deliver more C and nutrients into streams, lakes and the
microbial communities and activity	TBD	TBD		The present state and changes in the activity of soil micro in soil productivity and gas efflux and will initially be mon soil parameters with eddy covariance towers and gas exc
soil moisture	rooting zone neutron probe	Campbell Scientific	Campbell Scientific HydraProbe	Soil moisture is a key determinant of vegetation producti decomposition, mineral weathering, and nutrient uptake
soil temperature	thermistor arrays to bottom of AL	N/A	Tidbit waterproof temp loggers; optic USB base station	As for soil moisture, soil temperature is a key determinar microbial activity, organic matter decomposition and min
active layer depth (frost tubes)	AL Phenology and Depth	NRCan	FRESA Precision Machining Inc. Ottawa, Canada	Deepening of the active layer is anticipated with climate for C flux, soil solution chemistry and soil water discharge

Appendix Table B3: Snow and permafrost.

Component	Protocols	Partners	Protocol Link/Reference	Rationale and Ecological Linkages
snow depth, microstructure and duration	Paired Areas Detailed Monitoring Transects	Université de Sherbrooke ECCC NASA	TBD	A series of 12 snow sticks will be installed in each of the Mo (Figure 6) and snow depth measured weekly during the sno capture small scale spatial and temporal variability in snow seasonality for each Ecotype. Snow pits to assess snow stra ice crusts and rain-on-snow and other geophysical propertie will be conducted in a subset of the Monitoring Plots for eac transect of snow sticks will also be installed along the Detai Transects and monitored weekly during the snow season to scale spatial and temporal variability in snow depth and sea and between ecotypes along the transect (Figure 7).
	Extensive Monitoring Grid		TBD	A series of snow stick arrays will be established in sections adjacent to the Intensive Monitoring Area and adjacent to t monitoring cabins (Figure 2). Bi-weekly (weekly if possible approaches) sampling of these snow sticks will provide a br assessment of snow depth and water equivalent and durati watershed to support the remote sensing data and provide assessment of ecotype-snow relationships.
	Entire Greiner watershed and surrounds		TBD	Remote sensing tools at a range of scales (*in-situ*, airborne will be used to monitor snow properties across the Greiner farther afield depending on linkages to other monitoring, e. of ungulates, feedbacks to regionally-scaled climate modeli
permafrost temperature	Paired Areas	NRCan CEN	CCIN/GTN-PF Bore Holes	An intermediate (25-125m) depth bore hole fitted with ther will be drilled in each of the Paired Areas to monitor and co permafrost temperature

Appendix Table B4: Vegetation

Parameters	Protocols	Partners	Protocols	Rationale and Ecolog
relative frequency, height, phenology, fruit production, and herbivory	<u>Monitoring Plots/Transects</u> point frame, berries and phenology <u>Extensive Monitoring Grid</u>	ITEX network UBC	ITEX Manual Line Transect	ITEX protocols provide a basis for mea quantitative change in vegetation; the developed and widely used so results and international synopses A reduced version of the ITEX plot wil calibration-validation at the Extensive
CO2/CH4 net ecosystem flux	<u>Monitoring Plots</u>	TBD	Canadian Carbon Exchange Study FluxNet	The contribution of soil carbon stores sufficient to alter the global balance o impact climate change at a global sca
foliar nutrient content	<u>Monitoring Plots</u> Chemical analysis of macro and micronutrients	TBD	LTER Standard Methods: Robertson *et al.* 1999	Foliar nutrients are excellent indicator and a measure of nutritional value as
‘shrubification’	<u>Shrubification Plots</u> <u>Detailed Monitoring Transect</u>	TBD	CIMP Shrub Protocol Line transect	We will monitor changes in shrubs as using common protocols and at CHAR abiotic and other factors, and remote model development.
cover of functional groups, biomass, leaf area index, NDVI, community change	<u>Aerial Transects</u> <u>Satellite Remote Sensing</u>	NASA NRCan-CCRS	NASA NRCan-CCRS	In partnership with NASA ABoVE prog opportunity to utilize some of the late platform (UAVSAR, AIRMOSS, AVIRIS Through partnership with CCMEO-CC expertise using satellite remote sensi change in the CHARS ERA

Appendix Table B5: Shorebirds and waterfowl.

FEC/VEC	Monitoring Area	Partners	Protocol	Rationale and Ecological Linkages
shorebirds songbirds	Paired Areas Long Monitoring Transects Extensive Monitoring Grid	ECCC EHTO	PRISM Tier 2 PRISM Tier 1	The CHARS ERA is in PRISM Area 8 and in the IMA we are propo Tier 2 PRISM surveys to provide annual information on the bree shorebirds and songbirds. If feasible (i.e., if other monitoring is not too disruptive to shore propose to establish PRISM Tier 2 grids within both Paired Area close proximity. In this way we can directly link the arthropod m all of the associated abiotic monitoring, to the results of the sho monitoring to develop causative models for long term changes i other variables. We also propose to apply Tier 1 PRISM protocols annually along that have suitable shorebird nesting habitat. Suitable areas can terrestrial ecosystem classification mapping being developed fo watershed. Double sampling will be carried out to provide an ur population size in the areas sampled and, by locating across the provide a good landscape level estimate of shorebird numbers t detailed shorebird nesting work in the IMAs.
waterfowl	Long Monitoring Transects	Ducks Unlimited CWS	CWS-USFWS Waterfowl Breeding Program	Waterfowl monitoring will be designed with the assistance of EC Unlimited biologists to ensure strong linkages and contributions monitoring programs. IK of Cambridge Bay citizens will also con and implementation of the waterfowl monitoring. A combination supported by ground monitoring (laying date, hatch date, clutc density) will be implemented, following methods developed thro Waterfowl Breeding Population Surveys.

Appendix Table B6: Lemmings.

FEC/VEC	Monitoring Area	Partners	Protocol	Rationale and Ecological Linkage
collared lemming brown lemming	Paired Areas	CEN U Calgary NCP	ADAPT Fixed Area Count	A fixed area count of winter nests will be carried out annually the two Paired Areas to provide a density estimator to track y lemming populations linked to changes in the abiotic measure ground temperature and snow depth, extent and condition.
			ADAPT Live Trapping with Marking	Live trapping with marking will also be conducted periodically absolute density and other demographic parameters not possi Area Count.
	Intensive Monitoring Area		ADAPT Snap Trapping	Snap trapping will be carried out periodically in the Intensive outside the Paired Areas to measure contaminant levels in blo parasites and disease and other population parameters.
			Sub-nivean winter monitoring	Lemmings will be monitored under the snow to determine asp population biology and predation by Short-tailed weasel
	Long Monitoring Transects Extensive Monitoring Grid		ADAPT Winter Nest Counts	Lemming winter nests will also be enumerated along the Long Late Winter–Early Spring sampling period (see Table 1). Winte along the LMTs, i.e., all winter nests 5 m on either side of the Transects transect will be tallied according to Ecotype. Supporting fixed area counts may be installed near the remote Extensive Monitoring Grids

Appendix Table B7: Arthropods and slugs.

FEC/VEC	Monitoring Area	Partners	Protocol	Rationale and Ecological Linkage
arthropods	Paired Areas	McGill U U Calgary	TEMG Pitfall Traps TEMG Malaise Traps	A series of 10 yellow pitfall traps will be sampled weekly durin across the 4 experimental Ecotypes and co-located in or adjac Plots Arthropod sampling using Malaise traps will be implemented t growing season in the Sedge Fen Ecotype and the Mesic Ecoty
	Intensive Monitoring Area		TEMG Mosquito Monitoring TEMG Black Fly Monitoring	Mosquitos will be sampled in suitable ponds within the IMA on season. Black flies will be sampled on rocks in suitable streams within once during the growing season.
terrestrial slugs	Paired Areas		TEMG Pitfall Traps	Slug (*Deroceras leave)* monitoring will be carried out with the trapping weekly during the growing season - across the 4 exp co-located in or adjacent to the Monitoring Plots

Appendix Table B8: Ungulates.

FEC/VEC	Monitoring Area	Partners	Protocol	Rationale and Ecological Lin
caribou muskoxen	Long Monitoring Transects	GN Wildlife U Calgary Université de Sherbrooke	Late winter scat collection	a program to collect muskoxen and caribou scat will be scat on snow) for both DNA analysis and to monitor the pathogens
			Scat Plots	area-based counting of ungulate scat will be carried out preference and any future changes in preference
			Winter tracks	all ungulate winter tracks will be recorded and analyzed
	Intensive Monitoring Area		Forage quality	changes in ungulate forage quality (e.g., nitrogen, neu matter digestibility) will be monitored in the IMA and ir needed to track changes in nutritional value of watersh
	Aerial Surveys		GN Wildlife Survey Methods	an aerial census of both muskoxen and caribou will be c in the fall when caribou are gathering on the south shor
	Entire Greiner watershed and surrounds		Satellite remote sensing (Langlois *et al*.., 2016)	detection algorithms for rain-on-snow and ice layer pres conditions
	CHARS Regional ERA		snow modeling (Ouellet *et al*.., 2016)	modeling snow conditions at 1km and 32 km spatial sca thresholds for food access

Appendix Table B9: Other Species.

FEC/VEC	Monitoring Area	Partners	Protocol	Rationale and Ecological Linkage
grizzly bear Arctic wolf	Long Monitoring Transects Aerial Surveys	CEN GN Wildlife	Winter track and scat Hair snagging stations GN Wildlife Survey Methods	winter tracks will be monitored and analyzed, and a program and Grey Wolf scat will be conducted in late spring (fresh scat other scat collections) for both DNA analysis and to monitor th parasites and pathogens DNA can also be collected form predator species such as grizz will be established in concert with the remote cabins. Grizzly Bear and Grey Wolf will be counted along the ungulate
raptors rock and willow ptarmigan	Long Monitoring Transects		ECCC Bird Counts	Raptors and Rock and Willow ptarmigan will be monitored alor seasons; nests will be geo-located
Arctic fox	Long Monitoring Transects		Winter track and scat Arctic WOLVES Den Surveys	winter tracks will be monitored and analyzed, and a program will be conducted in late spring (fresh scat on snow – with the for both DNA analysis and to monitor the occurrence of parasi Dens of Arctic fox will be survey along the LMTs and possibly on resources
short-tailed weasel/ermine	IMA Paired Areas		TBD - CEN	Ermine will be monitored under the snow with winter sub-nive lemmings. + in lemming winter nests, I guess

Appendix Table B10: Faunal Contaminants.

FEC/VEC	Monitoring Area	Partners	Protocol	Rationale and Ecological Linkage
Soil and vegetation	IMA Paired Areas	NCP ECCC EHTO GN Wildlife	Foliar contaminants Soil invertebrates Other arthropods	Contaminants in vegetation, soil, soil invertebrates, and pitfall be measured and monitored in selected Experimental Monitori
Snow	Long Monitoring Transects		tbd	Levels of contaminants in snow will be monitored in the spring changes in over winter contaminant accumulations and source lakes and coastal ecosystems
Lemmings	IMA Paired Areas		ADAPT Snap Trapping	contaminants will be monitored in the blood and tissue of lem sampling; given their role as a keystone prey species, contam key vector for bioaccumulation in terrestrial ecosystems
Arctic Fox, Grey Wolf, ungulates, ptarmigan	Greiner watershed		Various tissue contaminant analysis methods	Working with local residents through the Elakhuktutuk Hunter Organization (EHTO) tissues will be collected annually as a pa trapping captures and frozen for analysis of contaminants

Appendix C – Detailed Implementation Tasks and Schedule (2016-2019)

Under separate cover