The Arctic-Boreal Vulnerability Experiment – *Understanding Northern Ecosystems in Transition*

ABoVE Science Definition Team

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Forword

Climate change in the Northern High Latitudes is unfolding faster than anywhere else on Earth, resulting in widespread transformations in landscape structure and ecosystem function in the circumpolar arctic and boreal region. In addition to producing significant feedbacks to climate through changes in ecosystem processes and energy, water and carbon cycles, environmental change in this region is increasingly impacting society in many ways. Recognizing its sensitivity, vulnerability and global importance, national- and international-level scientific efforts are now advancing our ability to observe, understand and model the complex, multi-scale and non-linear processes that drive the regions natural and social systems. Long at the edge of our mental map of the world, environmental change in Northern High Latitude ecosystems is increasingly becoming the focus of numerous policy discussions at the highest levels of decision-making.

Because of the rapid changes that are presently occurring, a significant amount of research is being carried out on Northern High Latitude terrestrial and aquatic ecosystems. A key component of these studies is the collection and analysis of a wide range of remotely sensed data (both airborne and spaceborne) that help quantify and understand ongoing changes to the Earth surface and adjacent boundary layer of the atmosphere. Recognizing the importance of remotely sensed data, NASA's Terrestrial Ecology Program funded the development of a Scoping Study Report that provided the proof-of-concept demonstration of feasibility for a field campaign to study the vulnerability of arctic and boreal social-ecological systems to environmental change. This report was reviewed by an expert panel, which made several recommendations. These recommendations were the focus of a subsequent workshop that resulted in a revised Executive Summary for the Arctic-Boreal Vulnerability Experiment (ABoVE)[1]. The document presented here, which is based on the outcomes from these previous activities, represents the ABoVE Concise Experiment Plan that will guide NASA's Terrestrial Ecology Program in funding the research for this field campaign.

ABoVE is a large-scale study of environmental change in the Arctic and Boreal Region of western North America and its implications for social-ecological systems. The experiment plan outlines the conceptual basis for the field campaign and expresses the compelling rationale explaining the scientific and societal importance of the study. The experiment plan presents both the science questions driving ABoVE research as well as the study design that will address them. It defines ABoVE's science objectives, broadly focused on 1) developing a fuller understanding of ecosystem vulnerability to environmental change in the western North America Arctic and Boreal Region, and 2) providing the scientific basis for informed decision-making to guide societal responses at local-to-international levels. The ABoVE campaign will involve linking field-based, process-level studies with geospatial data products derived from airborne and spaceborne sensors, providing a foundation for improving the modeling capabilities needed to understand and predict ecosystem responses and societal implications.

[1] All materials related to the development of ABoVE can be found at the following URL: above.nasa.gov.

ABoVE Vision

Over the past 100 years, the Northern High Latitudes have experienced more rapid climate warming than anywhere else on Earth, and this trend is expected to continue over the next century. Terrestrial and aquatic ecosystems in arctic and boreal regions are already undergoing changes in response to this warming, often proximally caused by rapid thawing of frozen ground (permafrost) and changes to disturbance regimes and surface hydrology. In turn, changes to the land surface can exert strong feedbacks to regional and global climate as well as impact the goods and services ecosystems provide, with far-ranging consequences for society. Although there is a considerable legacy from previous and ongoing research focused on the drivers and impacts of environmental change in arctic and boreal regions (including that sponsored by land management agencies), significant gaps in integrated knowledge compel additional research. ABoVE will provide the opportunity to expand and coordinate a set of focused, interdisciplinary research activities designed to further understand the causes and consequences change in the social-ecological systems of the arctic and boreal regions of western North America. The unique perspective gained from multi-temporal and spatially explicit data collected by remote sensing systems provides a practical means to monitor changes to ecosystems, extend field-based measurements and inform next generation modeling efforts. Given the size and remoteness of the Northern High Latitude regions, remote sensing observations improve scientific capabilities for investigating complex interactions across multiple spatial and temporal scales. When interpreted synergistically with the results from field-based observations and monitoring, research and modeling carried out by ABoVE will provide new scientific knowledge needed for society to develop policies and implement management strategies to address the impacts of environmental change across the circumpolar arctic and boreal region.

1. Introduction

The western North American Arctic and Boreal Region (WNAABR) contains vast expanses of tundra, boreal forest, and peatland – globally significant biomes whose unique properties make them particularly sensitive to environmental change. The sub-biome or ecoregion heterogeneity is considerable, ranging from densely forested lowlands to high arctic deserts to flat, poorly drained terrain covered by ponds, small lakes, and wetlands. With an average annual temperature less than 0°C, a significant portion of the WNAABR is underlain by permanently frozen ground (permafrost). Throughout this region, the cold, poorly drained ground conditions have resulted in the formation of large reservoirs of carbon in thick surface organic layers and frozen mineral soils. The streams and rivers in this region deliver significant inputs of freshwater, sediment, and dissolved organic matter to coastal oceans, which in turn, contribute to the regulation of oceanic ecosystems and processes. The terrestrial and aquatic ecosystems of the WNAABR provide habitat to a large number of fish, mammal, and bird species, with many migratory species using this region as their primary breeding ground. Although they are lightly populated and largely unmanaged by humans, the terrestrial and aquatic ecosystems of the WNAABR are critical to society in a number of ways. This region is a homeland to a complex array of Aboriginal groups, and contains vast natural resources of economic, cultural, and aesthetic value, which provide a wide range of ecosystem services at local, regional, national, and international scales. There is recognition from decision-makers and land managers at all levels that improved scientific knowledge on the impacts of climate and environmental change, along with an understanding of how society is responding to these changes, is imperative to inform development of sound policies and management strategies.

While local and regional human activities (e.g., road development, natural resource exploration, and hunting) impact ecosystems in some places within the WNAABR, for the most part distinct changes to ecosystems are being driven by larger-scale processes related to changes in climate and disturbance regimes. Since 1960, the WNAABR (above 50° N) has experienced temperature increases of 0.3 to 0.4° C per decade. This rapid climate warming has been caused in part by physical feedbacks within the arctic/boreal system, where decreases in sea ice and snow cover have lowered surface albedo, enhanced absorption of shortwave solar radiation, and amplified regional warming. Significant changes to WNAABR ecosystems are being caused by both press and pulse disturbances. In this region, ***press disturbances*** associated with long-term climate change have impacts at decadal and longer time scales over large areas, including rapid permafrost thawing, changes to the hydrologic regimes (stream and river flow, lake and river ice phenology, surface water extent, and the frequency of droughts), seasonal plant phenology, and lengthening of snow-free periods. In contrast, ***pulse disturbances*** are one-time or shorter-term episodic events that occur at landscape to regional scales, including fires, biotic disturbance agents like insects and plant pathogens, and rapid permafrost thaw processes. Many areas of the WNAABR have experienced significant increases in the frequency and severity of pulse disturbances over the past half-century. In response to these disturbances, terrestrial ecosystems in many regions are undergoing significant changes, including shifts in vegetation cover, loss of permafrost, and changes to wildlife populations.

At local to landscape scales, some WNAABR ecosystems are resistant to the impacts of changes in press or pulse-disturbance regimes, while others are undergoing significant changes in response to these impacts. ***Resilience*** is the capacity of an ecosystem to maintain its function, structure and feedbacks in the face of a significant disturbance or perturbation. Resilient ecosystems recover to a similar pre-disturbance state because the internal ecological feedbacks that regulate system stability are robust. In other cases, internal, stabilizing feedbacks weaken or are disrupted, rendering ecosystems vulnerable to directional changes in structure and function. ***Vulnerability*** is the degree to which a system is likely to change in structure and function following a specific perturbation. Disturbances in vulnerable ecosystems may tip them into new states, where novel dynamics emerge.

Identification of these vulnerabilities is needed for predicting how changes in climate and disturbances will alter arctic and boreal ecosystems and landscapes, their role in the earth system, and the services they provide to society. In terms of quantifying these vulnerabilities, research is needed to improve our scientific understanding of: (1) what changes are occurring across the WNAABR landscape at multiple spatial and temporal scales; (2) the underlying processes driving these changes; (3) the impacts these changes are having on ecosystem services; and (4) how society is responding to the changes, which may influence future vulnerability. Addressing these four areas of investigation will provide the basis for developing the policies and management strategies needed to help mitigate and adapt to the changes that occurring to WNAABR ecosystems.

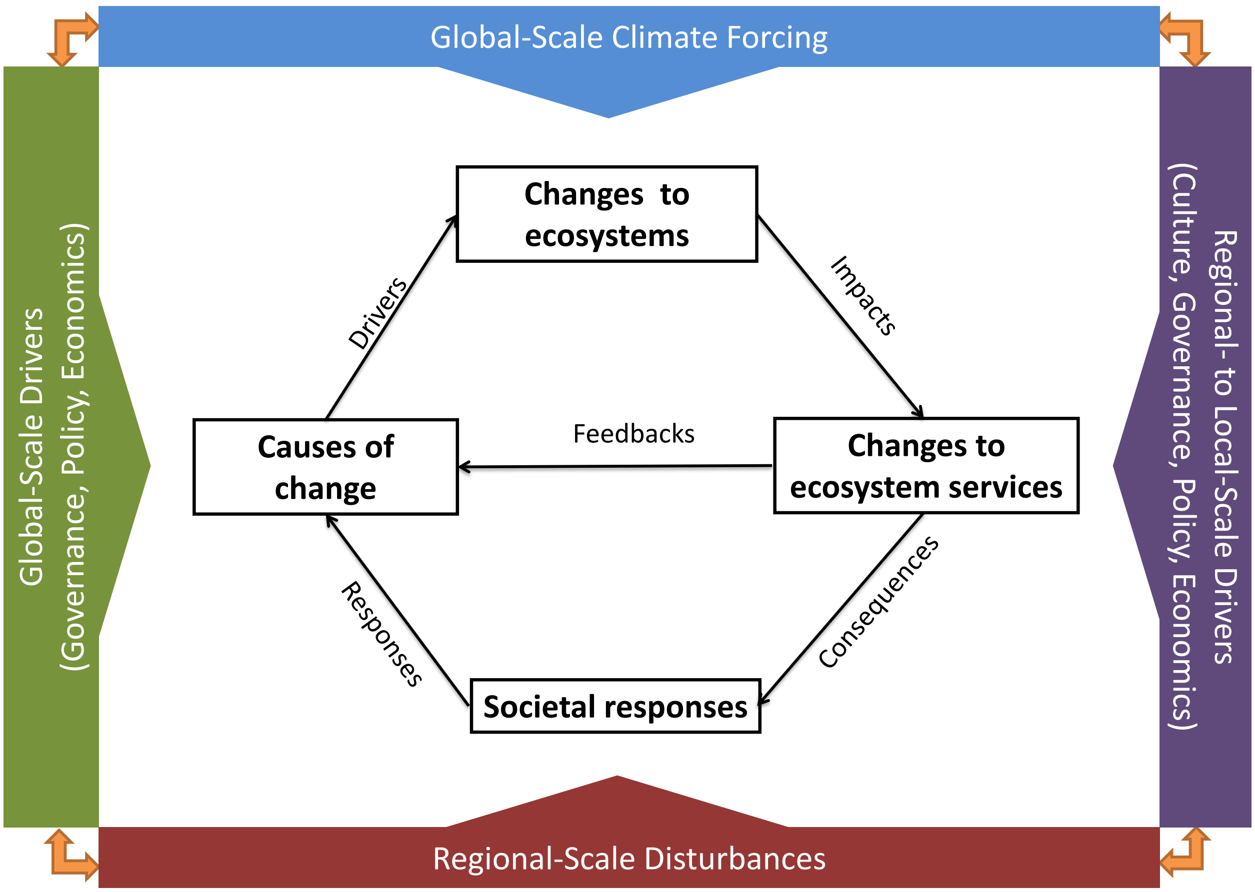
2. Research Framework and Overarching Science Question

Research carried out during ABoVE will address key scientific questions and cross-cutting research objectives most critical for understanding the vulnerability of social-ecological systems to environmental change in the WNAABR. The amplified climate warming across this region, combined with the particularly sensitive structure and functions of Northern High Latitude ecosystems, have resulted in significant changes recorded on the landscape in recent decades. While studies observing these changes continue to be important, a more comprehensive consideration of the drivers, impacts, consequences and feedbacks, as well as the areal extent and specific locations of these changes are necessary for assessing the vulnerability of this region's ecosystems and their societal dependencies. ***It is not enough to simply document the observable changes to the landscape (diagnosis); rather the grand challenge is to better understand why these changes are happening (attribution) and what are the actual and potential consequences of these changes for society within and beyond the region (prediction).***

The Vulnerability Research Framework

The science questions and objectives to be addressed during ABoVE are organized within a Vulnerability Research Framework (**Figure 2.1**). This framework provides the necessary holistic vision for a large-scale field campaign that places individual studies within a broader context, as well as providing a structure for developing synthetic, interdisciplinary and integrated assessments of vulnerability of social-ecological systems, change and response. Beyond observing and monitoring changes to ecosystem structure and function in the WNAABR, ABoVE research will further address questions of attribution through understanding the drivers of change, which is critical for projecting ecosystem change in the future. Accurate and reliable scenarios of future change are the key contribution needed by resource managers, policy-makers, and stakeholders at all levels. These projections must be provided at scales and information content that are appropriate for decision-making. The Vulnerability Research Framework views the observed and projected changes in ecosystem structure and function through the lens of their impacts on the services to society that these ecosystems provide. Determining the degree to which the WNAABR's ecosystem services are impacted will form the basis for considering the consequences of these changes for society – both within and beyond the region. Furthermore, how ecosystems change and society responds will in turn determine the future trajectory of WNAABR ecosystems. Thus, the various cascading effects and feedback pathways need to be addressed using an integrated framework that addresses the full interconnectedness and complexity of the system.

Figure 2.1. *Conceptual diagram of the research framework for organizing the science questions and objectives to be addressed by ABoVE. Overall changes to the social-ecological system (center boxes) within the ABoVE study domain (the western North American Arctic-Boreal Region – WNAABR) are being driven by a combination of global scale climate forcing that drive press disturbances (top arrows), regional-scale pulse disturbances (bottom arrows), and local to global-scale socio-economic processes (side arrows).*



Changes to Northern High Latitude social-ecological systems are ultimately being driven by a combination of global-scale climate forcings, regional-scale disturbances, and changes to socio-economic conditions at local to global scales (Figure 2.1). Ecosystem structural and functional dynamics across the region are responding to global changes in radiative forcing, atmospheric temperature, humidity and precipitation; relative to the rest of the Earth, an amplified climate warming signal at northern high latitudes was predicted and has been well-documented. Superimposed on this, regional- and local- scale landscape change is being driven by new and intensified disturbance events and regimes such as wildfire, rapid permafrost thaw, and biotic disturbances, along with human infrastructure development and resource extraction activities. At a local to regional scales, societal responses are not only driven by changes to ecosystem services, but by culture, global and regional economic forces, political systems, and changing demographics. In turn, decisions made by society in response to environmental change will impact both climate and disturbance regimes.

Substantial changes to the physical landscape and ecological functioning have been documented across the WNAABR in recent decades. Physical impacts on the terrestrial cryosphere are manifest in increasing permafrost temperatures, altered freeze / thaw cycles, and mass wasting and other landform changes resulting from permafrost degradation. Hydrological cycles have been altered through changing patterns in precipitation, vapor pressure deficit, surface water extent, river discharge rates, sediment loads, and snow extent and depth. Large-scale biological impacts have been observed in the form of changes in the abundance and composition of plant and animal communities, and in the timing of life history events (phenology). Also driven by climate change, both tundra and boreal forest ecosystems of the WNAABR have experienced increased frequency and severity of wildfire and other biotic disturbances such as insect outbreaks.

The rapid changes observed in the structure and function of WNAABR ecosystems have realized and potential impacts on key ecosystem services. The region's terrestrial and aquatic ecosystems supply important ***provisional services*** to society, including freshwater, food, fuel, wood and fiber. The vast areas of wilderness found throughout the WNAABR along with bird, fish, and wildlife species represent important ***cultural services***, supporting a wide range of educational, spiritual, and recreational activities and are central to subsistence lifestyles. The frozen ground, lakes, and rivers in this region provide critical ***supporting services***, allowing for stable building infrastructure and winter-time transportation networks for local communities as well as in support of mineral, oil, and gas resource development. WNAABR terrestrial ecosystems provide critical ***regulating services*** such as flood control and climate change mitigation, through their role in water, carbon, and energy cycling between the land and atmosphere. Within the WNAABR, flora and fauna represent important provisioning and cultural resources; both global-scale climate forcing and regional-scale disturbances are changing their habitat, abundance, health, phenology and migration patterns. Human infrastructure and transportation relies heavily on the supporting service of stable ground, which is threatened by warming-driven permafrost degradation and coastal erosion caused by sea ice loss and increasing storm surges. Carbon sequestration and storage in the vegetation and soils of WNAABR ecosystems benefits global society through climate change mitigation.

Carbon sequestration in WNAABR vegetation may be enhanced under future climate change by warmer temperatures, longer growing seasons, and increased levels of CO_2 in the atmosphere. On the other hand, carbon release from WNAABR soils may be expected to increase as permafrost thaws and other disturbances occur with greater frequency and severity. How climate change and disturbance will influence future amounts and movement of contaminants and pollutants in these environments also has consequences for human health and the quality of ecosystem services.

Altered provisioning of services directly impacts the vulnerability of human communities in the region and beyond, and how society responds to these changes will determine the future trajectories of change. WNAABR communities have a reputation of being highly resilient based on a long history of successful adaptation to environmental and technological change. However, recent decades have brought historically unprecedented rates of social, climate and environmental change to the WNAABR, as well as rapid economic development and increased connectivity with outside regions. In developing responses to these changes, people face great uncertainty about future conditions and the reliability of ecosystem services. Different people and communities may respond in different ways to a common environmental change, both because they place different values on particular ecosystem services and because they have differing options for adaptation. Responses are often mediated through formal and informal institutions (e.g., governments, kinship ties, social networks, shared cultural norms, etc.). Responses are also mediated by economic factors (cost of living, cost of moving, availability of jobs for cash) and by public policy.

Overarching Science Question and Objective

Within the context of the Vulnerability Research Framework, the studies conducted as part of ABoVE will focus on developing an improved understanding of the drivers, impacts, consequences and responses of environmental change in the WNAABR. The complex interdependencies and feedbacks across the components of this framework are reflected in the ***overarching science question*** that will guide ABoVE research:

How vulnerable and resilient are ecosystems and society to environmental change in the Arctic and Boreal region of western North America?

Within this framework, ABoVE will address specific science questions focused on the complex interactions of social-ecological systems in the WNAABR. Addressing these questions requires an integrated research approach based upon the following ***overarching research objective*:**

To understand how complex interactions control vulnerability and resilience in arctic and boreal ecosystems of western North America, and how changes in these interactions impact human societies within and beyond this region.

Recognizing that such a study needs to consider the complex interactions and feedbacks within and between research focus areas, integration and synthesis across the study is a key research objective for ABoVE. Studying the impacts of environmental change on ecosystem services within this Vulnerability Research Framework represents the critical bridge between environmental change and how people within and beyond the WNAABR are affected by and respond to this change. Ecosystem services are closely linked to the major components determining the structure and function of WNAABR ecosystems. These components are captured by the six ***focus areas*** for ABoVE research: society, disturbance, permafrost, hydrology, biogeochemical cycling of soil carbon, and flora and fauna. These focus areas, while not exclusive, represent the organizing elements for the set of second tier science questions and their associated research objectives that will be address during through ABoVE, as discussed in Chapter 3 below.

3. Research Focus Areas

Research carried out during ABoVE will address six specific science questions that focus on addressing key uncertainties in the response of WNAABR social-ecological systems to climate and environmental change. The scientific goals for ABoVE are presented as research objectives in addressing each of these questions (Table 3.1), most of which involve the study of complex interactions that control social-ecological systems, and provide the basis for an integrated research strategy required to assess the impacts of climate and environmental change in the arctic and boreal region of western North America

How are environmental changes affecting natural and cultural resources, human health, infrastructure, and climate regulation, and how are human societies responding?

***Rationale* –** Landscapes and ecosystems in the WNAABR are experiencing accelerated rates of anthropogenic impacts, both indirectly from climate change and directly from human activities. People have lived in and influenced the WNAABR ecosystem since the end of the Pleistocene, creating a vast cultural landscape and a complex social-ecological system. Today, this system encompasses a range of human activities common to WNAABR aquatic and terrestrial ecosystems, including commercial fisheries, subsistence, tourism, recreation, mining, energy development, and development and maintenance of community and industrial infrastructure. The circumpolar arctic and boreal region is home to millions of indigenous and non-indigenous people who directly derive numerous benefits from ecosystems (food, clean water, clean air, disease management, sense of place, erosion control, etc.). However, this region also contains significant forest, oil, gas, and mineral resources that provide the opportunities for economic development. In many cases, the extraction of these resources depends upon development of winter roads that cross frozen ground, lakes and rivers, a unique supporting ecosystem service. Finally, variations in a large number of Northern High Latitude ecosystem processes result in significant feedbacks to the regional and global climate, thus representing an important global-scale regulating ecosystem service.

The demand for ecosystem services and natural resources is increasing throughout the WNAABR, and current and future environmental change will significantly affect ecosystems, people, and their interdependencies. In many cases, there are significant tradeoffs between different land uses that are directly reflected in the ecosystem services WNAABR landscapes are providing. For example, how do exploration activities that are dependent on winter roads impact wildlife populations? How will these impacts change if all-weather roads are constructed to provide access to exploration areas? Understanding the consequences of different land uses within the context of a landscape that is rapidly changing in response to environmental change presents a key challenge to decision makers in the WNAABR.

WNAABR landscapes and their ecosystem services are foundational for cultural identity and continuity – they are not just aesthetic amenities. For example, 60% of Alaska lands are under the management of a number of federal government agencies which are mandated by law to identify and protect cultural resources, many of which have deep-rooted ties to nearby communities. These agencies are also required to consult with Alaska Native entities regarding the protection of these non-renewable resources. In a similar fashion, Aboriginal Peoples share responsibilities for co-governance with federal and territorial governments in northern Canada, and have considerable input in all land-use decisions occurring with their settlement areas. Understanding impacts on and responses of human societies requires an understanding of past, present, and future landscape and societal changes.

Additionally, environmental changes in the WNAABR will have significant impacts at scales beyond the local and regional levels. The abundance of natural resources in the ABR creates opportunities for the use and distribution of additional ecosystem services both locally and beyond, but the potential substantial losses of carbon sinks in vegetation and soil will result in a loss of the globally realized ecosystem service of climate regulation. Local changes are the result of both large-scale exogenous processes (e.g., global climate change, global market forces) and local to regional-scale processes (e.g., land use decisions, community-level ecological dynamics). Feedbacks among both social and ecological subsystems can be positive (self-reinforcing) or negative (self-attenuating). Responses in one sub-ecosystem can have effects on adjacent sub-ecosystems and the larger-scale ecosystem. Consideration of the historical drivers of landscape change (i.e. interpreting patterns of change that led to current conditions) can add time-depth to such spatially focused research. Therefore, it is important to consider interactions both between systems and across scales. The effects are often nonlinear, and hence they may be abrupt and/or not easily anticipated. Given these complexities and the rate of current environmental change in the ABR, there is high potential for large impacts on livelihoods and regional economic activity throughout the WNAABR and beyond.

While environmental change in the ABR is having significant impacts on a wide range of ecosystems services, research on social-ecological systems during ABoVE will focus on the following realms where WNAABR social-ecological systems are particularly vulnerable to the impacts of environmental change:

1. Distribution, abundance, access to and use of natural resources for provisioning and subsistence ecosystem services;

2. Direct and indirect effects on human health (e.g., disease vectors, food availability, mental health from fate control and intact culture, etc.); and

3. Rapid direct and indirect effects on hydrology, permafrost, and ice which impact infrastructure and landscapes (buildings, roads, airports, frozen rivers) and cultural heritage (practices, traditions, language, historically important places).

These three areas were selected because the societal impacts and responses in each are directly related to significant ongoing environmental change in the ABR, including changes to disturbance regimes, permafrost, hydrologic systems, and the flora and fauna endemic to northern high latitude ecosystems. These relationships provide a strong linkage to the research being conducted to address the other ABoVE science questions discussed in this chapter.

Key Research – In addition to research on the ecosystem services identified in this focus area, significant research carried out for the other ABoVE focus areas discussed in the following sections of this chapter will directly address the role that WNAABR regions serve as a regulating service to the Earth's climate system. Research on feedbacks to climate discussed in the other focus areas includes changes to water and energy exchanges between the land and atmosphere as part of the hydrologic cycle, changes to surface albedo from changes in vegetation and snow cover, and increased releases of carbon dioxide and methane presently stored as soil carbon.

Improving the understanding of the impacts of environment change on provisioning, subsistence, natural resources, human health, infrastructure and culturally important places will require interdisciplinary research approaches integrating socio-economic data with data on relevant landscape patterns and processes. This research will involve developing approaches for effectively engaging a range of stakeholders (from both the private and governmental sectors), ranging from individuals, to local communities, to regional to national). Environmental and climactic change in many parts of this region where people live is complex, requiring research on integrated biological, physical, and cultural processes. Coupled with socio-economic data, this research will require observations of landscape and ecological processes at multiple scales to investigate how these changes are affecting human societies. Research on the impacts of climate change on landscapes and ecosystems will carried out through addressing the questions and objectives for the other focus areas discussed in this chapter.

Baseline socio-economic data will be needed. Ideally, panel surveys such as the Survey of Living Conditions in the Arctic (SLiCA) would be repeated for specific regions within the WNAABR in order to follow people in the sample over time as they respond to environmental change. Since this approach is beyond the scope and capacity of the ABoVE field campaign, these data need to be obtained through some combination of existing or concurrent "conventional" social science research and additional contributions of capabilities that are special to NASA.

The information derived from satellite- and airborne-based remote sensing systems to address the questions and objectives for the other ABoVE focus areas will provide the means necessary to assess changes to key landscape characteristics that directly impact ecosystem services (Figure 3.1). Research is needed, however, to develop geospatial information products derived from remotely sensed data that can be used to directly assess the vulnerability of specific ecosystem services. In many cases, creating unique products will require the integration of remotely sensed products with other information needed to assess the vulnerability of a specific ecosystem service (for example, the integration of maps of vegetation cover with information on the seasonal ranges of specific wildlife species such as caribou). Research is also needed to develop the best practices in transforming the results of scientific research on the impacts of climate change into information products suitable for engaging and informing a broad range of stakeholders in the WNAABR. Finally, research is needed to determine how improved information resulting from ABoVE is used by stakeholders to address the actual and potential impacts of environmental change in the WNAABR. To succeed in carrying out research in these areas will require developing collaborations with a range of stakeholder groups that are either directly being impacted by environmental change or who have management and policy making responsibilities that are based on actual and projected impacts of climate change.

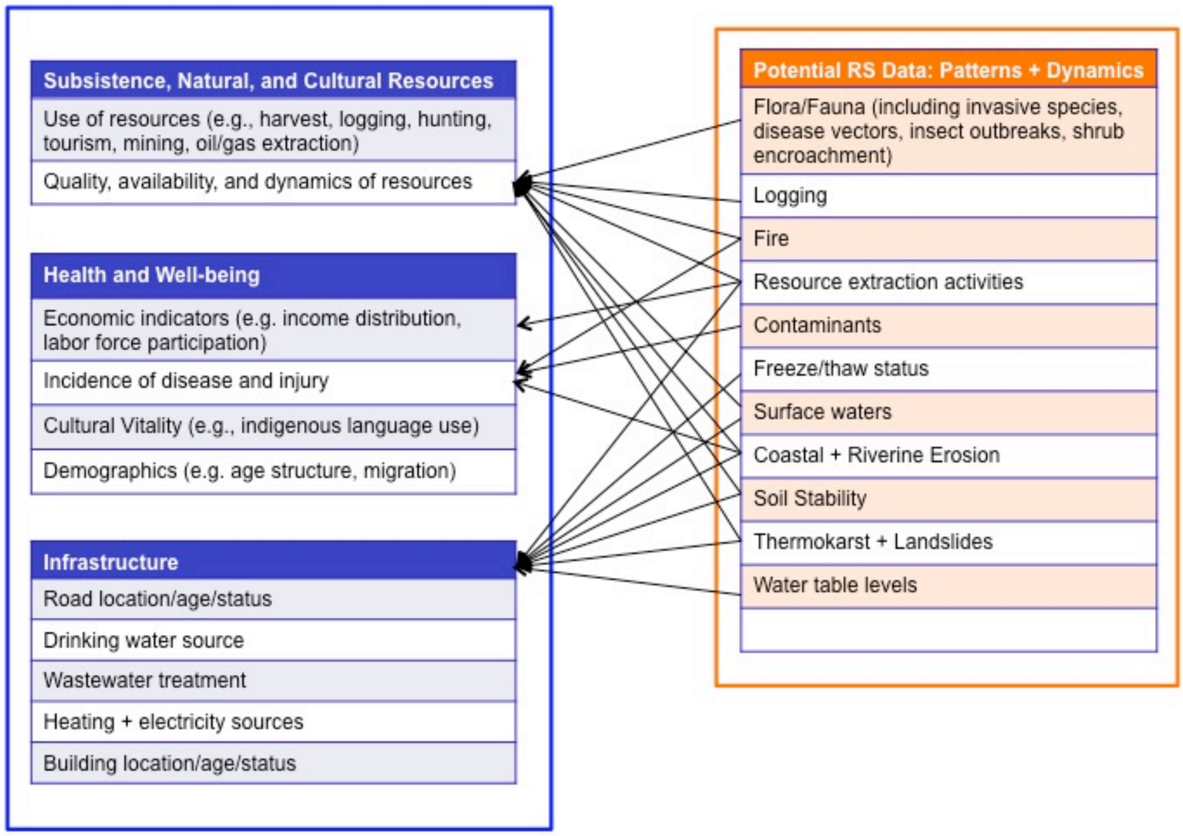


Figure 3.1. *The linkage of information provided through the analyses of remotely-sensed data to key ecosystem services in the WNAABR that will be studied during ABoVE.*

What processes are contributing to changes in disturbance regimes and what are the impacts of these changes?

Rationale – Although disturbances such as fire, biotic disturbance agents (including insects and plant pathogens), and permafrost-thaw events (here termed thermokarst) have been part of the historic disturbance regimes of arctic and boreal ecosystems, there is mounting evidence that their frequency, severity, and area affected are increasing in response to recent climate warming. At local to sub-regional scales, anthropogenic activities, especially those associated with exploration, resource extraction, and infrastructure construction are also impacting terrestrial ecosystems and the services they provide. Since these disturbances trigger a variety of responses in ecosystems and landscapes, the degree to which changes in disturbance regimes influence the vulnerability and resilience of social-ecological systems is central to determining how Northern High Latitude biomes are responding to climate change. Because of the large cumulative area impacted by disturbances and the rapidity of their effects, they are in many cases the most proximal agent for initiating changes to arctic and boreal ecosystems and landscapes. Land management agencies across the WNAABR not only require information on historical and current patterns of disturbance, but need to understand how key disturbance regimes are likely to change in the future.

Across the North American boreal forest, average annual area burned has increased over the past half-century. Late-season burning in Alaska has risen over the past decade, which in turn, has resulted in more severe fires. In particular, there has been an increase in deeper burning of surface organic soils, which in turn, reduces soil carbon stocks, causes more rapid warming of permafrost, and alters post-fire succession. The occurrence of large fires may also be increasing in tundra. While further climate warming is likely to increase potential for burning, changes in vegetation type, at least in boreal forests, will have a negative feedback on fire activity. Based on current understanding, it is challenging to predict future changes to the WNAABR fire regime and their subsequent impacts on ecosystems, society, and climate.

Biotic disturbance agents like insects and plant pathogens are likely to respond rapidly to climate change in the WNAABR. Unlike in some regions to the south, current evidence suggests that the impacts of these agents will become more severe in the WNAABR. For example, because pathogens can adapt to new climate conditions faster than the hosts, the vulnerability of shrubs and trees to disease is likely to increase with amplified climate warming. Many insect species also respond rapidly to environmental change due to their genetic variability, short life cycle, mobility, and high reproductive potential. Because of their physiological sensitivity to temperature, changing climate can be expected to strongly influence the survival, development, reproduction, dispersal, and geographic distribution of plant pests and their hosts. Plant susceptibility to biotic disturbance agents also interacts with a variety of climatically-induced inciting factors, including stress caused by changes in hydrologic regimes (particularly increased drought stress) and other complex host interactions that are difficult to forecast. Understanding factors controlling insects and pathogens and other disturbances is particularly important in the southern boreal forest where harvesting of wood products represents an important economic driver for local communities.

In many regions of Alaska and northwest Canada rapid permafrost thaw is on the rise as shown by observations of increased observance of thaw slumps, formation of new thermokarst lakes and ice wedge ponds, collapse of peat plateaus, and rapid lake drainage due to permafrost loss or near-surface degradation. These changes are occurring across the arctic at different rates controlled by variations in ground ice content, geomorphology, and vegetation, and are consistent with borehole-measured permafrost temperatures that have sharply increased in northern arctic areas by several degrees Celsius over the last three decades. Impacts of rapid permafrost thaw are also ongoing in boreal ecosystems with ice-rich permafrost. Changes to permafrost are already affecting important WNAABR ecosystem services, including damage to infrastructure and shortening the length of time available for winter transportation to remote areas.

Variations in disturbance severity controlled by vegetation cover, topography, soils and ground ice content and distribution control the manner in which WNAABR ecosystems are changing as well as creating ecological heterogeneity at scales that vary from tens to thousands of meters. Even within individual stands of similar vegetation and soil characteristics, disturbance severity often varies at scales of 1 to 10 m, imparting fine-scale heterogeneity. Ultimately disturbances have a major influence on land-atmosphere exchange of energy, water, and carbon (CO_2 and CH_4) as well as lateral fluxes of water, nutrients, contaminants, and carbon. The dominance, form, and function of these features are also likely to change as climate does, influencing ecosystem processes. Studies are needed at all these scales to understand the impacts of these various types of natural disturbance.

Key Research – Research is needed to refine and validate a wide range of models to account for factors that control the occurrence of disturbances at landscape to regional scales and represent the impacts of disturbances on ecosystem processes. This research will include landscape to regional scale observations of disturbance area and severity derived from remotely sensed data, as well as from land-management records and paleo proxies. While information on the areas disturbed by fire and some biotic disturbance agents are available from records maintained by land management agencies, the use of remote sensing data provides improved information on actual area disturbed, the timing of disturbances events, and the severity of the disturbances. Additional research is needed to develop and validate remotely sensed disturbance products across the WNAABR, in particular for insects, disease, and changes in landforms associated with rapid permafrost thaw.

Assessing factors controlling disturbance regimes will also require geospatial data on critical land characteristics (vegetation cover and condition, permafrost characteristics including temperature and ice content, active layer depth, soil moisture, surficial geology, topography, weather and climate). Ground-based observations at plot scales stratified across disturbance severity and the biotic and abiotic conditions at the time of disturbance are needed to quantify disturbance severity, the controls on severity, as well as understand the immediate impacts on ecosystems. Observations across sites and landscapes that differ in time after disturbance, as well as abiotic conditions (including remotely-sensed data), are needed to understand the consequences of past disturbances for ecosystem and landscape processes as well as to assess whether and how current disturbance regimes and their impacts differ from that occurred during past periods of rapid change. Ground-based observations are also needed to further develop and validate disturbance products from remotely sensed data. Long-term change in disturbance regimes can only be identified by comparing recent (i.e., the last 30 to 50 years) trends to historical records of disturbance, including regional stand age structure and paleo-ecological reconstructions from tree rings and sediment records. Analysis of paleo data can also provide critical information on the ambient conditions at the time of disturbance, but also on longer-term changes to community composition.

What are the changes in the distribution and properties of permafrost and what is controlling those changes?

Rationale – Arctic tundra and boreal forests are distinct biomes because of the dominating influence of snow, ice and frozen ground. The role of the cryosphere in the WNAABR makes this region especially sensitive to climate warming. Changes to these key components of the cryosphere are expected to have major and potentially irreversible consequences for social-ecological systems at multiple scales. All arctic tundra in the WNAABR land area is underlain by continuous permafrost, with substantial permafrost in the boreal forests of this region lying in the discontinuous and sporadic permafrost zones. Many landscapes in the WNAABR have already experienced a marked degradation of permafrost, which is expected to increase in the near future. Studying the forces driving changes in the state of permafrost and their consequences for ecosystems and society are therefore key research priorities.

Permafrost dynamics exert strong control on energy, water, and biogeochemical cycling, along with vegetation and disturbance processes, and are themselves driven by feedbacks with these ecosystem processes. Above permafrost, the seasonal active layer influences surface hydrology, vegetation cover and rooting zone depth, the severity of fire disturbances, and biogeochemical cycling. Permafrost and active layer characteristics are variable across spatial scales – while dominated by long-term climatic conditions, they are also regulated by a host of interacting local factors. Important consequences of rapid permafrost thaw and active layer change include potential soil carbon release, surface subsidence and hydrological change, and changes in vegetation cover.

The vulnerability and resiliency of permafrost to rapid thaw has significant consequences for society – both within and beyond the WNAABR – through impacts on ecosystem services. Permafrost strongly regulates surface water distribution and wildlife habitat, both of which are connected to key provisioning and subsistence services for the people of the WNAABR. Frozen ground supports infrastructure, transportation and other services that local communities rely on. Pan-arctic permafrost stores an enormous quantity of frozen soil organic carbon that is protected from release to the atmosphere – thus providing a critical climate regulation service for global society. The fate of the thawing permafrost landscape, along with associated changes in ecosystem structure and function, represents a critical uncertainty in projecting greenhouse gas feedbacks to future climate.

Key Research – Research to address this question will leverage existing process studies and monitoring networks designed to observe and quantify changes in the key indicators of permafrost condition. Previous field studies and existing, ground-based permafrost and active layer monitoring networks have advanced our understanding of the basic processes regulating the local formation and degradation of permafrost. However, observations also show that the rates of permafrost warming have not been uniform in time and space, indicating that permafrost is more vulnerable in some regions than others. ABoVE will develop a framework that integrates remote sensing and model development to scale local-to-landscape information on key system drivers and indicators to a broader understanding of regional-to-global consequences.

While characteristics of permafrost cannot be directly detected by remote sensing systems (with the exception of airborne electromagnetic resistivity measurements), information on a number of land surface characteristics that regulate near-surface permafrost dynamics can. During ABoVE, observations from satellite, airborne and ground-based remote sensing systems will be integrated to monitor and quantify these key land surface characteristics as well as key indicators of permafrost thaw and associated landscape-scale impacts. The temporal and spatial variation in the major driving factors of permafrost thaw and thickening of the active layer – such as freeze / thaw cycles, albedo, snow cover, patterns of vegetation cover and vegetation change, disturbance occurrence and severity, surface water coverage, and soil moisture – will be characterized over the WNAABR using a number of satellite and airborne remote sensing data and products. Studies of the indicators and impacts of permafrost thaw across the landscape – including ground subsidence, mass wasting, and lake formation or drainage – will also be carried out using high-resolution satellite and airborne remote sensing systems.

Remotely sensed observations will be used in conjunction with field-based measurements to understand driving processes and aid in the development of inputs for physical models projecting spatial and temporal patterns and future conditions of permafrost and active layer dynamics. Improving the representation of fundamental processes in these models will require integration, synthesis and scaling of field-based studies strategically sampled from different landforms and vegetation cover located across the major permafrost zones and encompassing variation in ice content and disturbances. The field-based studies will include static and dynamic measurement of depths and bulk densities of organic and mineral soils (in both the active layer and frozen ground), permafrost temperature and other physical properties, ground ice and liquid water content, seasonal active layer depths, vertical and lateral ground temperature and moisture profiles, seasonal and long-term thaw subsidence and frost heave, as well as vegetation cover, seasonal snow depths and snow water equivalent. While short-term observations are sufficient for some of these variables, others will require repeated or continuous observations. Permafrost models will be validated using existing longer-term records of permafrost temperature and active layer depth, as well as new observations of active-layer temperature and moisture and frozen ground ice content.

What are the causes and consequences of changes in the amount, temporal distribution, and discharge of surface and subsurface water in the ABR?

Rationale – The hydrologic cycle in High Northern Latitudes regions is dominated by winter water storage as snow, followed by high rates of runoff and stream and river flows in spring, and generally lower flows in summer and fall. Lakes, ponds and wetlands (that provide extensive habitat for fish, birds and other wildlife) are abundant on the landscape. Across the WNAABR, annual precipitation

(P) is nearly equally partitioned between rain and snow, with excess water above evapotranspiration (ET) being either stored as snow, surface water, and soil and groundwater or exported as stream and river flow to the Bering Sea and Arctic Ocean, where these inputs are particularly important in regulating coastal ocean processes. The hydrology of the WNAABR also influences land-atmosphere and water-atmosphere interactions and feedbacks that involve water, carbon dioxide, methane, and energy exchange, and a range of ecosystem processes. With respect to vegetation, the impacts of drought on productivity and mortality are particularly important. Intensification in fluxes of P, ET, and runoff are expected manifestations of a warming climate. Warming is also projected to lead to a shift from a surface-water dominated to a more groundwater dominated system, a transition that may alter the timing and decrease the amount of runoff.

Changes to hydrology in the WNAABR will impact ecosystem services by influencing water quantity and quality, transportation via rivers, fish and wildlife that provide the foundation for subsistence, as well as cultural, educational, and recreational experiences. Understanding factors controlling spring breakup of rivers and formation of ice jams is particularly important to the numerous NWAAB communities located immediately adjacent to rivers that are vulnerable to spring flooding.

A key and unique element of the WNAABR hydrologic system is the widespread presence of permafrost, and the fact the permafrost is undergoing rapid warming will to a large degree control the vulnerability of hydrologic systems. Permafrost influences infiltration, lateral runoff, groundwater flow, and associated soil groundwater storage. It is hypothesized that thawing permafrost will lengthen hydrologic flow paths and residence times, thus affecting water quality and the rate of biogeochemical processing of carbon, nutrients, and contaminants. Decreased permafrost extent has been linked to increased infiltration and subsurface flow, increased organic carbon mineralization (carbon dioxide or methane production), decreased organic carbon export, and increased inorganic carbon export across boreal and arctic regions. In most hydrologic systems, residence times are considered to be the travel times along surface and sub-surface flow paths; however, the WNAABR is unusual in having a long winter season during which water is temporarily stored as river and lake ice, snow, and frozen soil moisture. The period when water is frozen increases water residence times by months and impacts the timing of surface water export, if not the total export. The aquatic biogeochemical processing of carbon and nutrients is also slowed dramatically during the winter. These cryospheric delays introduce a timing mechanism into the material export system that is poorly understood, and is potentially critical to controlling ecosystem structure and function.

The unusual temporal-spatial distribution of water in the WNAABR has thermal as well as hydrologic impacts, and provides strong feedbacks to and regulation of climate. The snow that covers the ground from October through May not only represents half of the annual surface runoff, but also is an efficient thermal insulator and reflector of shortwave radiation that controls the surface energy balance. Snow insulating properties have a major impact on winter soil freezing and permafrost temperature and distribution. In addition, local distribution and depth of snow, is influenced by the type and structure of vegetation. When the snow falls, how it falls, and how long it stays has profound implications for WNAABR hydrology and ecosystem structure and function has to be considered as an integral part of the system.

Characterizing the spatial distribution of water and the amount and timing of water discharge across the WNAABR poses major challenges. While precipitation inputs and permafrost state are key controls on the spatial distribution and timing of water movement, other more local controls and how they may be modified are less clear. For example, the amount and concentration of materials (nutrients, inorganic and organic carbon, mineral and organic particulates, and contaminants) exported from a given watershed are controlled by the timing and magnitude of surface runoff and river flows, which in turn are controlled by local precipitation and soil surface conditions. In addition, erosion of thaw slumps from rapidly warming permafrost adjacent to streams and rivers also control patterns of material export. Surface waters also influence the carbon cycle through the exchange of gases between the land and atmosphere. Unlike terrestrial ecosystems that are spatially and temporally variable sources or sinks of carbon dioxide and methane, lakes, streams, and rivers are all net sources of these greenhouse gases (GHG) to the atmosphere, and commonly exhibit gas flux densities that far exceed terrestrial GHG fluxes.

Key Research – Regional surface water extent and soil moisture can be quantified using a number of different sensors and approaches, but estimates at finer spatial and temporal resolutions are needed. Understanding changes to the hydrologic system across the WNAABR and the primary controls on these changes will require observations and modeling targeted at the major storages and fluxes. Critical measurements for this research will include soil moisture, precipitation, snow depth and snow water equivalent, stream flow, and the extent and temporal variability of surface water distribution. A need is to observe the state and distribution of the hydrologic system (and water in its various phases) on a year-round basis, with particular attention to the shoulder seasons when water is changing phase. Research is required at a number of sites to provide the needed gradients to understand how different processes control surface and groundwater hydrology, including climate, permafrost, land-cover type, ecosystem dynamics and disturbance, with many of these observations being provided through analysis of remotely sensed data. Water chemistry and stable isotope measurements are needed across targeted catchments and should include observations from precipitation, snowpack, surface water, and ground water. Hydrologic observations at research sites should include baseline residence time estimates for soil and ground water pools. High-resolution satellite imagery and airborne LIDAR are needed to investigate effects of thermokarst and thermal erosion on surface and subsurface flows. Other measurements including concentrations and exports of organic matter, major ions, and sediment load are needed to quantify bulk materials exports. Measurements from aircraft and satellite-based instruments at a range of spatial scales are needed to quantify areas of saturated surfaces and inundation, particularly along riparian zones near rivers and streams. Water isotope measurements can help to quantify water sources, rates of transfer and storage residence times. Fine-scale topography, land cover, and soils data are among other key observations. Surface water characteristics derived from satellite remote sensing data include longer-term patterns of the number of small ponds and lakes and their area (using Landsat TM and spaceborne SAR), mapping of surface water extent and inundation (using data from spaceborne SARs, MODIS, AMSR-E), detection and mapping of floods (using MODIS and SAR data), and mapping of soil moisture (using data from airborne and spaceborne SARs, microwave radiometers, including SMAP). At research sites with flux towers, measurement of ET will help close the water budget for select watersheds. Measurements of snow depth, density, and water equivalent will be made by direct measurement and remote sensing where feasible.

How are flora and fauna responding to changes in biotic and abiotic conditions, and what are the impacts on ecosystem structure and function?

***Rationale* –** Long-term satellite remote sensing data records indicate that vegetation characteristics in undisturbed areas of the WNAABR are undergoing directional change at regional and in some cases, pan-Arctic scales. In response to climate warming, some regions have been increasing in productivity (greening), while other regions have experienced reduced productivity and increased mortality (browning). The same satellite sensors are revealing that at the pan-Arctic scale, growing seasons are lengthening primarily because warmer springs alter freeze-thaw dynamics and advance spring snowmelt and onset of plant growth. Climate-sensitive disturbance regimes in the WNAABR are intensifying, including those associated with wildfire, biotic disturbance agents, and thermokarst activity. These, too, are altering vegetation characteristics by initiating successional processes, altering the age structure of ecosystems on the landscape, and changing the composition of dominant species and growth forms. Overlain on these major trends in vegetation are more subtle changes revealed by repeat aerial photography and long-term, ground-based ecological and paleo-ecological records. These include shifts in the geographic ranges and / or dominance of species and growth forms that alter ecosystem structure and function, interactions with disturbance agents, and feedbacks to climate. Finally, human activities related to resource extraction are having increasing local and regional impacts on vegetation characteristics as cold regions become more accessible and the economic imperative for both global and local energy sources increases. The main drivers of all of these changing vegetation characteristics include the abiotic conditions associated with climate change (including arctic sea ice dynamics) and altered disturbance regimes. However, there are many aspects of these concurrent changes in WNAABR vegetation that are not yet well understood, including the degree of interaction between the underlying processes driving them, and how they feedback on climate, disturbance regimes, and anthropogenic activities.

Even less well understood is the degree to and mechanisms by which organisms at higher trophic levels exhibit top-down control over the WNAABR’s changing vegetation characteristics – and vice-versa – how changing vegetation impacts WNAABR fauna. Faunal influences on WNAABR ecosystem form and function include, but are not limited to, rodents altering cycles of tundra productivity that are detectable from satellite greening records, insect infestations defoliating large areas of boreal forest, and large mammal grazing that inhibits woody shrub productivity, alters secondary succession following wildfire or inhibits northward treeline advancement. A wide range of resident and migratory fauna depend on the unique habitat provided by the WNAABR for food and shelter. As a result of the aforementioned changes in WNAABR vegetation, the biophysical, compositional and temporal characteristics of wildlife habitats are being altered, and this is proving to have a variety of consequences for dependent fauna. For example, increasing woody shrub dominance in arctic tundra has been associated with greater overall abundance of songbirds with simultaneous shifts in community species composition. In addition, trophic mismatches are developing between WNAABR flora and fauna, such as caribou, as the advancement of vegetation phenology outpaces the rate at which these animals are able to adjust the timing of their nutritional requirements, which has led to major decline in their reproductive success.

Satellite remote sensing records have also revealed significant and contrasting trends in surface water extent within the WNAABR, with widespread and consistent increases in surface water inundation (wetting) occurring in zones of continuous permafrost, but drying trends in regions of sporadic/isolated permafrost. Similar to observed trends in vegetation growing season lengths, ice-cover duration on lakes and streams is shortening as a result of changes to freeze-thaw dynamics. In addition, there is recent evidence that tundra stream reaches are drying up in late summer. These changed patterns of ice cover, wetting and drying are likely to alter habitat availability and quality for the WNAABRs aquatic and semi-aquatic fauna, including birds, fish, mammals, and invertebrates. Every spring, millions of shorebirds, ducks, geese, loons and swans migrate to the WNAABR to breed, raise their young and feed in wetlands. Fresh water fish inhabit lakes and streams, and move between spawning and overwintering areas via stream networks. Beavers are a semi-aquatic and critical keystone species of the boreal forest, and thus changes in their habitat quality will likely have cascading impacts on ecosystem form and function

Humans, in addition to being drivers of change, are also responding to changes in the flora and fauna with respect to the ecosystem services they provide. People both within and beyond the WNAABR rely on the natural resources of this region for a range of cultural, spiritual, recreational, and subsistence activities. As a result, changes to the flora and fauna of WNAABR terrestrial and aquatic ecosystems will have a variety of cascading effects on the ecosystem services that society depends upon.

It is largely unknown which faunal species will be able to adapt and be resilient to the many biotic and abiotic changes occurring in the WNAABR, yet the resulting changes in both plant-animal and fresh water-animal interactions will strongly influence the response of ecosystem form and function. Further, because the WNAABR is relatively low in floral and faunal species diversity compared to temperate and tropical ecosystems, they likely have low functional redundancy – i.e. only one or very few species perform a given ecological role - leaving WNAABR ecosystem functions particularly vulnerable to the loss of individual and groups of species. Studies are needed that incorporate interactions among organisms at all trophic levels and examine their communal and interacting responses so that their collective impacts of ecosystem form and function can be quantified.

Key Research – Research to address this question will include ecosystem-, landscape- and regional-scale observations of vegetation characteristics and surface water extent derived from remotely sensed data, as well as observations to assess changes in terrestrial and aquatic growing season length (e.g. visible, infrared, and microwave data). While satellite data are needed to assess long-term trends at scales of 30 to 5000 m, airborne data may be required to collect data not available from satellite systems (in particular LiDAR and hyperspectral data) to provide observations of vegetation and surface characteristics at finer spatial scales (1 to 10 m). Assessing factors controlling vegetation characteristics, surface water extent, and growing season length will also require geospatial data on climate (air temperature, relative humidity, precipitation, climate indices), ice cover, burned area metrics, spatial distribution of biotic disturbance agents, resource extraction sites, active layer thickness, ground temperature, soil moisture, topography and soils, with many of these observations being provided using remotely sensed data. Regional-scale observations of spatial and temporal dynamics in wildlife habitat could include satellite (e.g. using ARGOS) and / or airborne and telemetry tracking of tagged or observed animals. Ground-based, plot level observations stratified across different tundra and boreal ecoregions/subzones, vegetation community types, burn scar properties, and wildlife habitats and migratory corridors will be required. Ground observations will also be necessary to gain a mechanistic understanding of the interactions and feedbacks among abiotic and biotic changes that together result in net changes in ecosystem form and function. Refinement of dynamic vegetation models will be needed to more realistically depict the interactions between the abiotic and biotic controls on terrestrial ecosystems, including both flora and fauna.

CH_4 and their isotopic signatures using aircraft and tall towers; and (d) the remotely sensed data at the landscape to regional scales needed to quantify spatial and temporal variations in factors regulating changes to soil organic carbon. Isotopic signatures of relevant gases are particularly important, because they help constrain flux source. For example, radiocarbon measurements permit estimation of CO_2 age, and hence the age of its source, and ^{13}C, deuterium, and ^{18}O measurements help identify biotic vs. abiotic CO_2 and CH_4 production and consumption processes and transport pathways, and hydrologic influences on SOC destabilization.

Modeling activities should consider on-going developments from other research, with particular attention paid to scaling with remotely sensed data. For example, a robust spatial representation of vegetation cover of the WNAABR is critical. This is a particularly valuable approach given apparent, recent boreal forest encroachment northward, and shrub encroachment into tussock tundra. Coupling soil C to vegetation cover can help understand the consequences of land cover changes induced directly or indirectly by future climatic regimes. Remotely sensed data can also be employed to characterize disturbances, seasonal patterns of soil moisture and freeze / thaw dynamics, permitting investigators to develop linkages among abiotic conditions, land cover, microbial resource availability, and SOC transformations. Remotely sensed soil moisture and vegetation data, when used in conjunction with soil nutrient status, can also be used to establish linkages between nutrient availability, microbial activity, and primary production.

How is the magnitude and fate of soil organic carbon pools changing, and what are the processes controlling the rates of those changes?

Rationale - The WNAABR contains a significant fraction of Earth's soil organic carbon (SOC) reservoir. The processes resulting in the formation of and changes to this reservoir represent an important ecosystem service in terms of long-term regulation of the earth's climate through removal and storage of a significant amount of atmospheric carbon. Presently, changes in the climate are destabilizing deeper pools of SOC in the WNAABR that have resided in soil profiles for hundreds to thousands of years, as well as accelerating the turnover of more labile SOC pools. This is particularly important in regions experiencing rapid permafrost warming and degradation, where SOC has previously remained stable due to low temperatures. However, destabilization of slow-turnover SOC is also an important feature of non-permafrost profiles, especially peatlands, where stabilization mechanisms of SOC may be more strongly linked to processes of formation of deep organic soil horizons. Finally, disturbance from fires plays an important role in SOC cycling either directly reducing organic soils through combustion or by changing ambient conditions. Understanding the complex interactions that contribute to the vulnerability of Northern High Latitude soil carbon stocks represents a major research challenge.

As the size of the WNAABR soil carbon pool is estimated to be more than twice that contained in the atmosphere, there is significant concern about its potential to feedback to climate through production of two key greenhouse gases: CO_2 and CH_4. Ongoing data collections for NASA's CARVE mission are showing that variations in boundary layer concentrations of CO_2 and CH_4 exhibit complex, emergent patterns at large spatial scales that cannot be readily predicted from ground-based measurements of these trace gasses. Simultaneous with enhanced SOC destabilization, climate changes are driving changes in disturbance regimes along with shifts in vegetation, soil temperature, and the hydrological cycle that can alter rates of heterotrophic respiration and SOC production. Which of these factors dominates the biogeochemical processes regulating C cycling in the WNAABR, what are the processes that drive their importance, and over what timescales they are most relevant remain unclear. Because these dynamics and their interactions ultimately drive important WNAABR feedbacks to climate, research is needed to provide a greater understanding of the production, transformations, and fate of SOC.

Research addressing SOC stabilization and destabilization must involve studies at multiple temporal and spatial scales. The ultimate drivers of releases of soil organic matter carbon through heterotrophic respiration – enzymes secreted by microorganisms – function in accordance with the biochemical properties of substrates and enzymes, as well as the physical characteristics of the environment. The microbes that demand the resources liberated upon substrate decay produce these secreted enzymes in response to competitive dynamics among microbial populations. A fraction of the C they take up can is allocated to CO_2 or, for methanogens, CH_4. Investigators typically measure the fluxes resulting from the complex interplay of biochemistry and ecology at various spatial scales using chambers, flux towers, flask measurements, and airborne systems.

In High Northern Latitude ecosystems, CO_2 and CH_4 fluxes are regulated by disturbances and hydrologic and permafrost processes that can readily be monitored using remotely sensed data, in particular, patterns of disturbance and disturbance severity, freeze/thaw cycles, and variations in vegetation cover, soil temperature and moisture, active layer depth, area of small lakes and ponds, and levels of inundation in wetlands. However, a key challenge currently hindering progress in more accurate predictions of soil microbial gas fluxes using information derived from airborne and satellite remote sensing systems is the lack of mechanistic models validated against large-scale remote measurements of state variables in the WNAABR. In addition to gaseous efflux of C to the atmosphere, carbon also can be liberated from these ecosystems into water and transported as particulate organic carbon (POC), dissolved inorganic carbon (DIC), and dissolved organic C (DOC) to streams, ponds, lakes and eventually to the coastal regions, where it can be buried or become available for decomposition to a different microbial community and potentially emitted to the atmosphere.

Only recently have researchers begun to incorporate critical drivers of microbial activity such as nutrient availability and substrate stoichiometry into models. Any research strategy must promote the development of empirical and theoretical modeling studies that link disciplines as diverse as biochemistry, microbial ecology, and biogeochemistry to broader-scale observations made from remotely-sensed data. In addition, these modeling studies need to capture the complex interactions that drive variations in the abiotic environment that control soil C, especially those focused on interactions between biota, hydrology, permafrost, and disturbances.

Key Research – Research to improve understanding of the factors controlling the vulnerability of soil organic carbon will employ landscape- and regional-scale observations of land cover classes, hydrological and C cycles, and other observations of state variables such as changes to permafrost. Where time series of state variables and ecological data are not obtainable, it will be necessary to include research based on space-for-time substitutions as a means of predicting future SOC stabilization and destabilization trends. Biogeochemical and ecological data needed from spatially disparate scales. These include: (a) observations of critical microbial processes and edaphic and abiotic features at the plot scale (i.e. nutrients, quantity and stoichiometry of soil inputs, moisture, pH, stable isotopes of SOC, dissolved species and trace gases, hydrologic connectivity or transport); (b) flux tower data quantifying meso-scale energy and fluxes of CO_2 and CH_4 and the isotopic signatures of these gases' fluxes; (c) large-scale flux observations of CO_2 and CH_4 and their isotopic signatures using aircraft and tall towers; and (d) remotely sensed data at the landscape to regional scales to understand patterns of biogeochemical fluxes across land cover classes as a function of time since disturbance where needed. Isotopic signatures of relevant gases are particularly important, because they help constrain flux source. For example, radiocarbon measurements permit estimation of CO_2 age, and hence the age of its source, and ^{13}C, deuterium, and ^{18}O measurements help identify biotic vs. abiotic CO_2 and CH_4 production and consumption processes and transport pathways, and hydrologic influences on SOC destabilization.

Modeling activities should consider on-going developments from other research, with particular attention paid to scaling with remotely sensed data. For example, a robust spatial representation of spatial and temporal variations in vegetation cover of the WNAABR is critical. This is a particularly valuable approach given recent boreal forest encroachment northward, and shrub encroachment into tussock tundra. Coupling soil C to vegetation cover can help understand the consequences of land cover changes induced directly or indirectly by future climatic regimes. Remotely sensed data should also be employed to characterize seasonal patterns of snow cover, soil moisture and inundation, changes in lake area, and freeze / thaw dynamics, permitting investigators to develop linkages among abiotic conditions, land cover, microbial resource availability, and SOC transformations. Remotely sensed soil moisture and vegetation data, when used in conjunction with soil nutrient status, can also be used to establish linkages between nutrient availability, microbial activity, and primary production.

Synthesis and Integration

Rationale – The previous sections of this chapter present the rationale and key research to be carried out during ABoVE. This research will address critical uncertainties in the response of WNAABR social-ecological systems to climate and environmental change. Table 3.1 presents the research objectives associated with each of the six thematic questions. While some of these objectives will require research specific to a single-thematic area (i.e., mapping severity of insect damage using remotely sensed data), many of the objectives in Table 3.1 are cross-cutting in nature (representing refinements of the overarching research objective for ABoVE), requiring a research strategy that targets complex interactions, including a well-orchestrated plan for synthesis and integration of the studies of the various processes that influence social-ecological systems in the WNAABR. In addition, research across the disciplinary themes will be required to provide the knowledge needed to understand the consequences of climate and environmental change on society, the ways that society is changing, and how it can respond in the future to these changes.

As is emphasized throughout this experiment plan, changes in ecosystem structure and function in the WNAABR have varied consequences for services provided by these ecosystems to human societies depending on the rate, variability, and magnitude of these changes in space and time. Because the response of ecosystems depend on complex interactions among the dynamics of people, permafrost, hydrology, disturbance regimes, and ecosystem processes, ABoVE must develop a framework for integration and synthesis that will facilitate the ability to (1) project trajectories of change in ecosystem structure and function in the WNAABR over decadal time scales, (2) estimate the potential impacts of trajectories on the services provided to society, (3) assess the consequences of changes in services for human societies, and (4) understand how societal responses to these consequences feedback to the social-ecological system.

Key Research – At the heart of addressing the ABoVE research objectives is the need to develop models of ecosystem structure and function that integrate and synthesize understanding on the dynamics of people, permafrost, hydrology, disturbance regimes, and ecosystem processes. In addition, some issues may also require the development of impact models and human consequence models. Research carried out as part of ABoVE needs to promote the development of a diversity of conceptual frameworks that are collectively capable of addressing a broad range of assessment issues relevant to the WNAABR. The design of these conceptual frameworks must clearly identify their scope and intended use. Key issues that need to be addressed in the design of conceptual frameworks for integration and synthesis include: (1)

connectivity among processes in the framework; (2) description of processes in the framework; (3) model parameterization; (4) model initiation; (5) model verification (reproducing data used in model development; (6) model validation (evaluation of model quality for independent data not used in model development); (7) model analysis (sensitivity/uncertainty analyses); and (8) collection and/or compiling the data needed to drive model application. The design of conceptual frameworks will need to elucidate how information that will be forthcoming from ABoVE research, as well as information available from other research efforts in the WNAABR, will be used address each of these issues. There are challenges cutting across these issues that need to be addressed, including scaling and model-data fusion. Finally, a major challenge is to bring together a collaborative team with the expertise and focus to successfully bring an integration and synthesis conceptual framework to fruition through the design, implementation, and application phases within a defined time window.

Table 3.1 Research Objectives for ABoVE in the Six Thematic Areas

Question	Objectives	
	Thematic	**Complex Interactions**
How are environmental changes affecting natural and cultural resources, human health, infrastructure, and climate regulation, and how are human societies responding?	Identify and map vulnerable and resilient social-ecological systems over time, with a focus on human responses and adaptation to changes in ecosystem services.	Assess how future climate warming is likely to affect infrastructure and transportation networks in the ABR. Determine how increases in the frequency and severity of press and pulse disturbances influence water quality and release and transport of contaminants in the ABR. Evaluate how changes to ABR ecosystems will influence subsistence opportunities. Analyze how changes to natural and cultural resources will impact local communities as well influence land management policies and practices. Determine the sources of variations in climate feedbacks from WNAABR ecosystems and assess the potential for future changes to climate regulating services. Determine the degree to which the changing environment in the ABR coupled with altered human activities results in tradeoffs and/or synergies between different ecosystem services.
What processes are contributing to changes in WNAABR disturbance regimes and what are the impacts of these changes?	Determine the controls on the spatial and temporal patterns of the primary natural disturbance regimes in the WNAABR (fire, biotic disturbances, rapid permafrost thaw).	Understand the consequences of variations in disturbance regimes for ecosystems and landscapes.
What are the changes in the distribution and properties of permafrost in the WNAABR and what is controlling those changes?	Identify the primary factors driving permafrost vulnerability / resiliency to thaw.	Improve understanding of how landscape-scale variations in air temperature, snow cover, disturbance, surface hydrology, soil properties, and vegetation cover interact to control the distribution of

		permafrost and permafrost degradation across the WNAABR.
What are the causes and consequences of changes in the amount, temporal distribution, and discharge of surface and subsurface water in the ABR?		Improve understanding of how rapid (fire) and longer-term (permafrost thaw; earlier spring melt) disturbances affect the ABR hydrologic system. Assess the impact of projected and observed changes in water discharge, storage, and hydraulic connectivity on materials exports in the ABR. Improve understanding of how changes to the hydrologic system affect ecosystem structure and function.
How are WNAABR flora and fauna responding to changes in biotic and abiotic conditions, and what are the impacts on ecosystem structure and function?	Identify and understand the combination of factors driving longer-term temporal and spatial changes in vegetation characteristics, including habitat quality, productivity and extent, as observed in the satellite data record.	Determine to what degree variations in WNAABR disturbance regimes are driving direct and indirect changes at both the ecosystem and landscape-scale, including successional rates and pathways within ecosystems, age and compositional structure, and plant-animal interactions. Document how changes in vegetation characteristics, surface water extent, and/or changes in faunal communities influence ecosystem processes and services.
How is the magnitude and fate of soil organic carbon pools in the WNAABR changing, and what are the processes controlling the rates of those changes?	Reduce uncertainties in destabilization rates of slow- to fast-turnover SOC pools through collection of data at multiple-scales across a range of permafrost and non-permafrost profiles in the WNAABR.	Understand how SOC stabilization may change in a future climate by assessing contributions of changes in above ground biomass, microbial activity, permafrost, hydrology, and disturbance to changes in SOC in a diversity of soil profiles in the WNAABR.