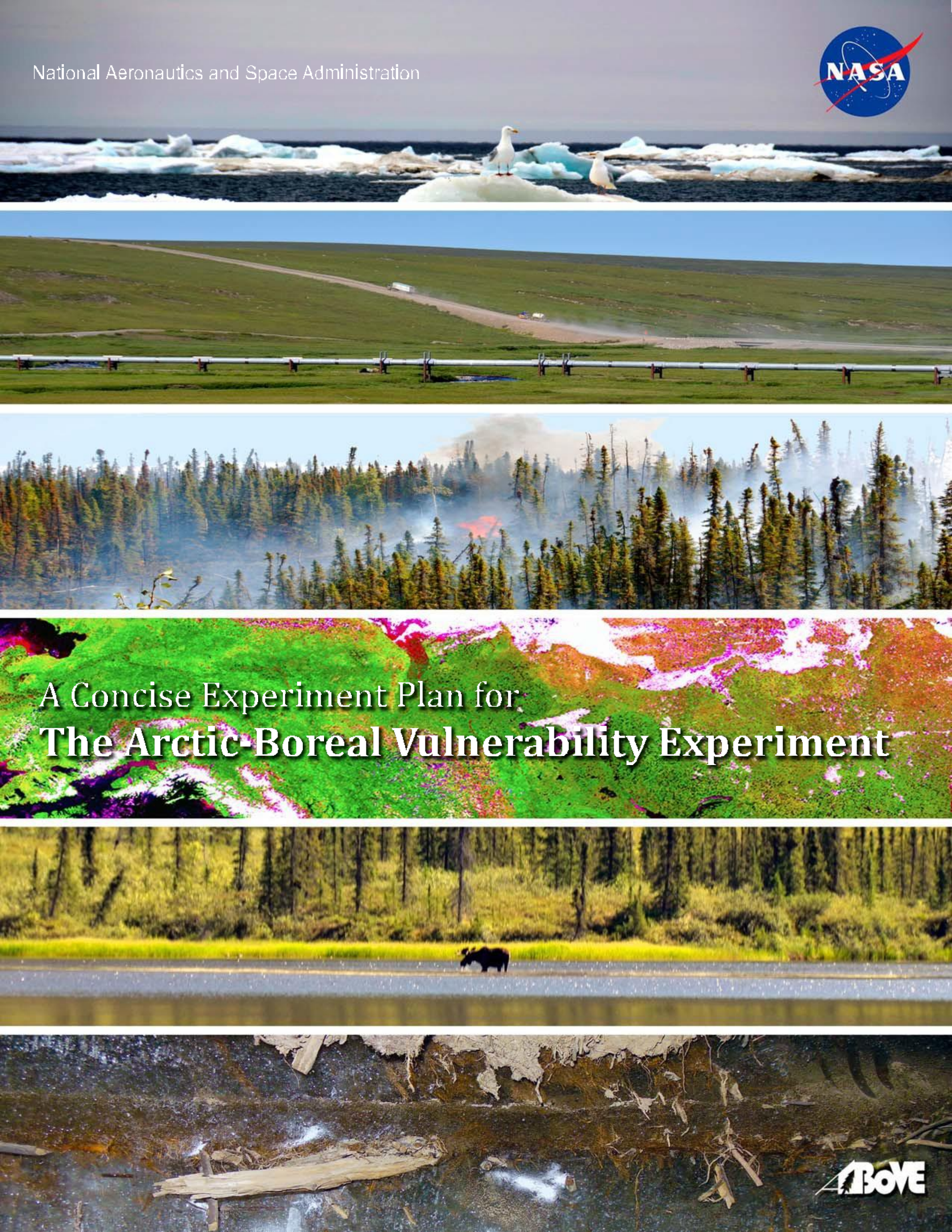
National Aeronautics and Space Administration

A Concise Experiment Plan for
The Arctic-Boreal Vulnerability Experiment



A Concise Experiment Plan for the Arctic-Boreal Vulnerability Experiment

ABoVE Science Definition Team

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Foreword

Climate change in the northern high latitudes is occurring 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 related to 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 region's 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 all levels of decision-making.

Rapid changes that are presently occurring in northern high latitude terrestrial and freshwater ecosystems (including wetlands in deltas and coastal estuaries) and the societal impacts of these changes have provided the impetus for significantly expanding research sponsored by a number of organizations. A key component of these studies is the collection and analysis of the wide range of remotely sensed data (both airborne and satellite) needed to 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 to provide the proof-of-concept demonstration of feasibility for a field campaign to study the vulnerability and resilience of Arctic and boreal social-ecological systems to environmental change. An expert panel reviewed this report and made several recommendations, which became the focus of a subsequent workshop that resulted in a revised Executive Summary for the Arctic-Boreal Vulnerability Experiment (ABoVE). The document presented here, which is based on the outcomes from these previous activities[1], represents the ABoVE Concise Experiment Plan that will serve as a guide to NASA's Terrestrial Ecology Program as it identifies the research to be conducted under 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 ABoVE Field Campaign and expresses the compelling rationale explaining the scientific and societal importance of the study. It 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 the vulnerability and resilience of Arctic and boreal ecosystems to environmental change in western North America, and (2) providing the scientific basis for informed decision-making to guide societal responses at local to international levels. Research for ABoVE will link field-based, process-level studies with geospatial data products derived from airborne and satellite sensors, providing a foundation for improving the analysis and modeling capabilities needed to understand and predict ecosystem responses and societal implications.

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

Acknowledgements

The Science Definition Team would like to acknowledge the contributions of the participants and members of previous workshops and review teams who contributed to the reports and recommendations that provided the foundation for this Concise Experiment Plan. We would also like to thank the individuals and organizations who met with the Science Definition Team and its members, in particular those who took time from their schedules to organize and lead visits to potential research sites or to organize meetings with those interested in collaborating with NASA during ABoVE. Finally, we thank the staff of NASA's Carbon Cycle and Ecosystems Office who ably supported the Science Definition Team during meetings and in the generation of this report.

Cover Images

From top to bottom:

View from the beach in downtown Barrow, Alaska (P. Griffith)

Pipeline and trucks on the Dalton Highway north of Toolik Lake (P. Griffith)

Fire amid spruce trees off the Dalton Highway north of Yukon Crossing (P. Griffith)

MODIS False Color Image (M. Carroll): MOD09A1 (8-day surface reflectance), June 18 – 25, 2013, Bands 1,2,3 assigned to RGB (Red --> Red; NIR --> Green; Blue --> Blue)

Moose in Grayling Lake, Alaska (P. Griffith)

Old soil carbon pools in permafrost deposits, US Army Corps of Engineers Permafrost Tunnel, Fairbanks (L. Kendig)

Cover design (E. Nelson)

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Executive Summary

In order to inform decision-making in the face of an uncertain future, numerous large-scale scientific efforts are now pushing to advance our ability to observe and understand the complex and interconnected processes that drive social-ecological responses to global environmental change. In recognition of their perceived but uncertain vulnerability to change, Arctic and boreal ecosystems of the northern high latitude region have become the focus of significantly expanding research sponsored by a number of organizations, institutions and agencies at local, national and international levels. Recognizing the important role that remote sensing can serve in these efforts – and based on a formal scoping study, expert review, and recommendation from the scientific community at large – NASA's Terrestrial Ecology Program is moving forward to lead a large-scale study of the vulnerability and resilience of Arctic and boreal social-ecological systems to environmental change.

This document presents the Concise Experiment Plan for the Arctic-Boreal Vulnerability Experiment (ABoVE) to serve as a guide to the Program as it identifies the research to be conducted under this study. Research for ABoVE will link field-based, process-level studies with geospatial data products derived from airborne and satellite remote sensing, providing a foundation for improving the analysis and modeling capabilities needed to understand and predict ecosystem responses and societal implications. The ABoVE Concise Experiment Plan (ACEP) outlines the conceptual basis for the Field Campaign and expresses the compelling rationale explaining the scientific and societal importance of the study. It presents both the science questions driving ABoVE research as well as the top-level requirements for a study design to address them.

Chapter 1 of the ACEP defines the Study Domain for ABoVE and provides the scientific and societal rationale for the study. The Core and Extended research areas of the Study Domain together cover most of the land area in Alaska in addition to all or parts of seven western Canadian provinces and territories. This large area contains vast expanses of Arctic tundra and boreal forest – globally unique and important biomes because of the ecosystem services that they provide to society, both within and beyond the region. The vulnerability of the region's ecosystems to various changes is a function of both their exposure and sensitivity to those changes. The social-ecological systems across the region are recently and currently exposed to substantial change through a combination of global-scale climate forcings, regional-scale disturbances, and changes to socio-economic conditions at local to global scales. Both the region's ecosystems and the people that depend on them face great uncertainty about future environmental conditions and the sustainability of ecosystem services. The challenge for scientific research is to better understand why these changes are happening, what the consequences are for ecosystems and society, and how societal actions to mitigate or adapt will affect future social- ecological systems.

Research on resilience and vulnerability in Arctic and boreal ecosystems is needed for predicting how they will be altered as a consequence of changes in climate and disturbances, the impacts on services they provide to society, and the potential societal responses to these changes. Chapter 2 of the ACEP introduces the Vulnerability/Resilience Framework that provides a structure for developing synthetic, interdisciplinary and integrated studies of the social-ecological systems across the Study Domain. Studying the impacts of environmental change on ecosystem services within this Vulnerability/Resilience Framework represents the critical bridge between environmental change and how people within and beyond the Study Domain are affected by and respond to this change. The complex interdependencies and feedbacks across the components of this framework are reflected in an overarching science question that will guide research during ABoVE:

> ***"How vulnerable or resilient are ecosystems and society to environmental change inthe Arctic and boreal region of western North America?"***

To address this overarching question, research during ABoVE will be organized around six Science Themes that represent critical aspects of Arctic and boreal social-ecological systems: society, disturbance, permafrost, hydrology, flora and fauna, and carbon biogeochemistry. These Science Themes present the opportunity to answer a key set of second tier science questions that will require research on the fundamental processes and their interactions that are driving changes to social-ecological systems. Chapter 3 of the ACEP presents for each theme: the associated Tier 2 science question, the rationale for study during ABoVE – including how ecological processes contribute to ecosystem services in the Study Domain, and the key research needs for scientific assessment. The scientific goals for ABoVE are presented as a set of cross-cutting, Tier 2 science objectives required to address these themes, most of which involve the study of the underlying processes and their interactions that control social-ecological systems, and provide the basis for an integrated research strategy. The Tier 2 science objectives follow the Vulnerability/Resilience Framework, with a set of Ecosystem Dynamics Objectives focused on the drivers and impacts of change on ecosystems and a set of Ecosystem Services Objectives focused on the consequences of and responses to environmental change.

The research needed for these two sets of Tier 2 objectives is closely connected, and the ACEP offers an integrated study design to address them. Chapter 4 of the ACEP puts forward the overall research strategy and approach based on an integrated study design in which targeted field based, remote sensing and modeling studies are integrated according to the scale and information content needed to support decision making. While the overall strategy for ABoVE follows an experimental design similar to those used for previous NASA Terrestrial Ecology field campaigns, it also requires novel approaches to address the full scope of research, particularly with respect to incorporating approaches to assess the societal responses to environmental change based on changes to key ecosystem services. The research for ABoVE will be carried out over a 9 to 10 year Field Campaign through individual Investigator Studies supported by NASA and its partners. The timeline for the Field Campaign follows three phases, where the research focus in phases I and II address the Ecosystem Dynamics and Ecosystem Services objectives, respectively, with the third and final phase dedicated to the analysis and synthesis of ABoVE research. The experiment design includes a spatial hierarchy within which research is to be carried out at Investigator Sites located in selected Research Areas across the Study Domain. The major portion of the field-based studies and airborne remote sensing campaigns will occur during a 5 to 7 year Intensive Study Period spanning phases I and II. Integration and scaling research will occur throughout the Field Campaign, as will an emphasis on stakeholder engagement and the development of decision support products derived from ABoVE research.

A data and information system will play a key role in the experiment through archiving and sharing of data, communicating the results from scientific research, and supporting the development and delivery of data products tailored for use by decision makers.

Chapter 5 of the ACEP outlines the top-level implementation requirements for conducting the ABoVE Field Campaign. These requirements include a schedule of activities related to data collection needs from both field-based research and airborne remote sensing campaigns. The setup and operation of the Science Team and support office are described with respect to their key roles in science coordination, planning and logistical support. ABoVE should also include activities to expand both training and education across a broad community that includes students and early career scientists, as well as a strong commitment to public engagement throughout the Field Campaign. ABoVE will not only provide many opportunities for interactions with complementary research programs within the Study Domain, but successful implementation will also require strong partnerships to be built and fostered with other national and international organizations, institutions and agencies.

Finally, Chapter 6 of the ACEP provides a brief summary of the rationale, research activities, and expected significance of ABoVE as a large-scale study conducted to understand the complex and interconnected processes and interactions controlling the vulnerability and resilience of the social-ecological systems in the Arctic and boreal region of northwestern North America. ABoVE research will improve our understanding of the consequences of, along with our confidence in making projections of the responses to, the critical environmental changes occurring across the Study Domain. Overall, ABoVE will build a lasting legacy of research through an expanded knowledge base, the provision of key datasets, the development of decision support products and the fostering of new partnerships.

1. Introduction

The Arctic and boreal region of western North America (hereafter referred to as the **Study Domain**[2] for ABoVE; Figure 1.1) contains vast expanses of tundra and boreal forest – globally important biomes whose unique properties make them particularly sensitive to environmental change. Controlled by variations in climate and physiography, 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, wetlands, and peatlands. With an average annual temperature less than 0°C, a significant portion of the Study Domain is underlain by permanently frozen ground (permafrost). Throughout this region, the cold and often poorly drained ground conditions have resulted in the formation of large reservoirs of soil carbon in thick surface organic layers and frozen mineral soils. Re-activating portions of this carbon reservoir through thaw and decomposition would affect atmospheric greenhouse gas composition with potentially global implications. The streams and rivers in this region provide fresh water, serve as a key transportation network, and deliver significant inputs of freshwater, sediment, and dissolved organic matter to coastal oceans. These, in turn, contribute to the regulation of oceanic ecosystems and processes. The terrestrial and freshwater ecosystems of the Study Domain provide habitat for a large number of fish, mammal, and bird species. Many migratory species use this region as their primary breeding ground. Although lightly populated by humans, the terrestrial and freshwater ecosystems of the Study Domain are critical to society in a number of ways. This area is home to a number of ethnically and culturally distinct indigenous and non-indigenous people that have unique and significant political relationships with state, territorial and federal governments. The Study Domain contains important natural resources of economic, cultural, and aesthetic value, which provide a wide range of ecosystem services at local, regional, national, and international scales. Decision-makers and land managers at all levels recognize that improved scientific knowledge on the impacts of climate and environmental change, and an understanding of how society is responding to these changes, is imperative to inform the development of sound policies and management strategies.

While local and regional human activities (e.g. hunting and subsistence activities, road and infrastructure development, natural resource exploration and extraction, and mineral, oil, and gas development) impact ecosystems in some places within the Study Domain, most ecosystem impacts are related to changes in climate, long-range transport of pollutants, and disturbances. Since 1960, the Study Domain has experienced temperature increases of 0.3 to 0.4° C per decade, 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. A range of disturbances is causing significant changes to ecosystems in the Study Domain. *Press disturbances* associated with long-term climate change cause gradual impacts at decadal and longer time scales over large areas. These include changes to hydrologic regimes (stream and river flow, surface water extent, snow

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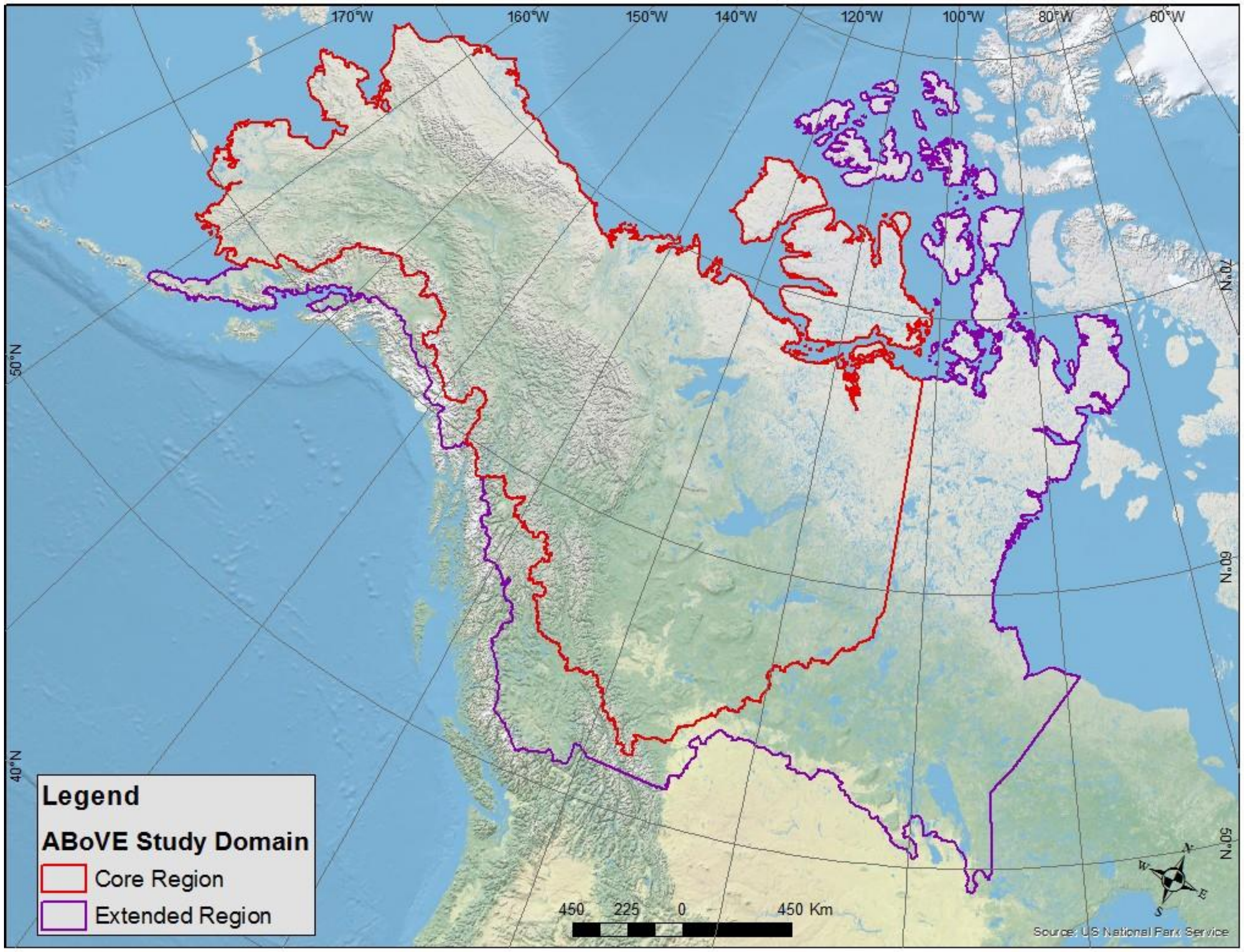
[2] Terms used to describe the hierarchy and organization for ABoVE that are capitalized are summarized in a Glossary at the end of this experiment plan.

Figure 1.1. *Boundary of the Study Domain for the Field Campaign during ABoVE. Appendix A presents a set of figures that illustrate spatial variations in important environmental conditions for the Study Domain.*



depths, and extent and the frequency of droughts), changes in vegetation phenology, lengthening of snow-free periods, thickening of the seasonally thawed soil active layer, and impacts on wildlife. *Pulse disturbances* are one-time or shorter-term events that occur at landscape to regional scales, including fires, disturbances from biotic agents like insects and plant pathogens, land conversion, and rapid permafrost thaw processes. The frequency and severity of pulse disturbances has increased in the Study Domain over the past half-century, and terrestrial and freshwater ecosystems in many regions are responding to these disturbances through shifts in vegetation cover, loss of permafrost, terrain instability, changes in lake/pond area, and changes to fish and wildlife populations. Some of the changes from these disturbances that required millennia to accumulate (such as loss of old soil carbon or ice-rich permafrost) are irreversible on human or societal time-scales.

At local to landscape scales, some social-ecological systems in the Study Domain are resistant to the impacts from changes in disturbance regimes, while others are not. *Resilience* is the capacity of a social-ecological system to maintain or recover its function, structure and feedbacks after a significant disturbance or perturbation. Resilient systems return to a similar pre-disturbance state because the internal feedbacks regulating system stability are robust. Where these stabilizing feedbacks weaken or are disrupted, social-ecological systems are rendered 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 systems may tip or direct them into new states as a result of transformations, where novel dynamics emerge.

Identification of resilience and vulnerability in Arctic and boreal ecosystems is needed for predicting how they will be altered as a consequence of changes in climate and disturbances, including their role in the Earth system, the services they provide to society, and societal responses to these changes. To quantify resilience and vulnerability, research is needed to improve our scientific understanding of: (1) what changes are occurring across the Study Domain at multiple spatial and temporal scales; (2) the underlying processes and their interactions driving these changes; (3) the consequences of these changes for ecosystem services; and (4) how society is responding to the changes, which may influence future resilience and 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 are occurring in the social-ecological systems of the Study Domain.

2. Research Framework and Overarching Science Question

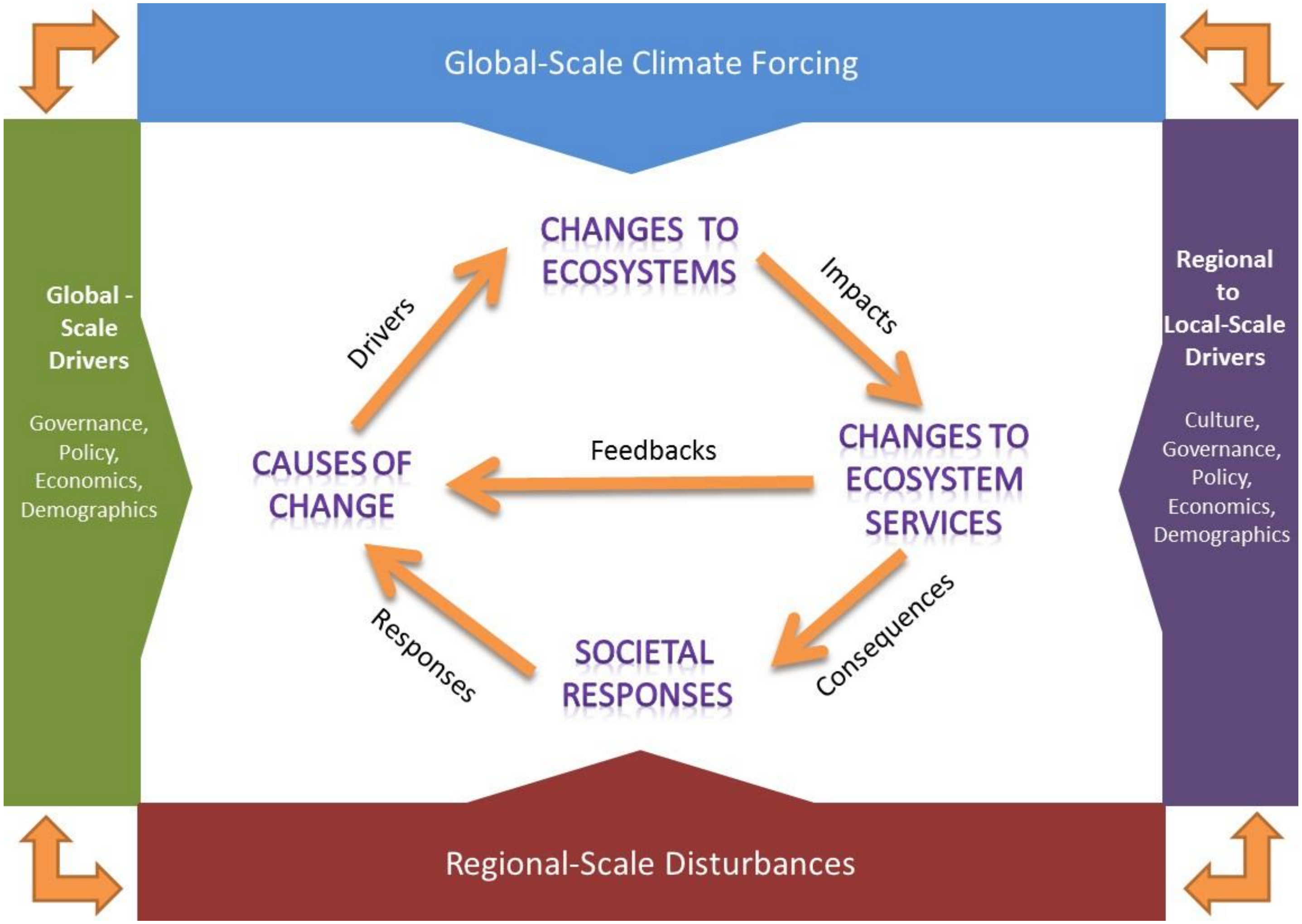
Research carried out during ABoVE will address key science questions and cross-cutting objectives most critical for understanding the vulnerability and resilience of social-ecological systems to environmental change in the Study Domain. While observing and quantifying these changes (i.e., diagnosis) continues to be important, a more comprehensive consideration of the drivers, impacts, consequences and feedbacks is necessary for assessing the resilience and vulnerability of this region's ecosystems and their societal dependencies. *The challenge is to better understand why these changes are happening (i.e., attribution), what are the actual and potential consequences for ecosystems and society within and beyond the region (i.e., prediction), and how societal actions to mitigate or adapt will affect future social-ecological systems.*

2.1 Vulnerability/Resilience Framework

The science questions and objectives to be addressed during ABoVE are organized in a framework that will allow understanding the vulnerability and resilience of social-ecological systems in the Study Domain. The ***Vulnerability/Resilience Framework*** in Figure 2.1 presents a holistic vision for a large-scale field campaign that places individual studies within a broader context. It provides a structure for developing synthetic, interdisciplinary and integrated assessments of vulnerability and resilience of the social-ecological systems in the Study Domain. Beyond the diagnosis of changes to ecosystem structure and function, research will address questions of attribution through understanding the drivers of and responses to change, which is critical for the prediction of future ecosystem change. The identification of plausible and probable future changes (i.e., scenarios) is a key need of resource managers, policy-makers, and stakeholders at all levels. Scenario projections must be provided as appropriate with the information content that is needed for decision-making, and thus the Vulnerability/Resilience Framework views the observed and projected changes in ecosystem structure and function through the lens of potential impacts on the services that these ecosystems provide. Determining the degree to which ecosystem services in the Study Domain are impacted will form the basis for considering the societal consequences of these changes within and beyond the region. Furthermore, the ways in which ecosystems change and society responds will in turn determine the future trajectory of northern high latitude ecosystems. Understanding the various cascading effects and feedback pathways requires an integrated framework that addresses the full interconnectedness and complexity of the system.

Changes to northern high latitude social-ecological systems are driven by a combination of global-scale climate forcings, regional-scale disturbances, and changes to demographic and socio-economic conditions at local to global scales (Figure 2.1). Ecosystems across the region are responding to global changes in radiative forcing, atmospheric temperature, humidity and precipitation. An amplified climate warming signal at northern high latitudes, relative to the rest of the Earth, 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

Figure 2.1. *Conceptual diagram of the Vulnerability/Resilience Framework used for organizing the science questions and objectives to be addressed during ABoVE. Changes to social-ecological systems (center) within the Study Domain are being driven by a combination of global-scale climate forcing that drive press disturbances, regional-scale pulse disturbances, and local- to global-scale socio-economic processes.*



accelerating human infrastructure development and resource extraction. At local to regional scales, societal responses are not only driven by changes to ecosystem services, but by cultural, global and regional economic forces, political systems, and changing demographics. In turn, societal responses to environmental change will impact both climate and disturbance regimes in the future.

Substantial changes to the physical landscape and ecological functioning have been documented across the Study Domain 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 and subsurface 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 productivity and composition of plant and animal communities, and in the timing of life history events (phenology). Both tundra and boreal forest ecosystems in the Study Domain have experienced increased frequency and severity of wildfire and other biotic disturbances such as insect outbreaks, which are also driven by climate change.

The rapid changes observed in the structure and function of ecosystems in the Study Domain have both realized and potential impacts on key ecosystem services. The region’s terrestrial and freshwater ecosystems supply important *provisioning services* to society, including fresh water, food, fuel, wood and fiber. The vast areas of wilderness found throughout the Study Domain along with bird, fish, and wildlife species provide important *cultural services*, supporting a wide range of educational, spiritual, and recreational activities that are central to tourism, subsistence and northern 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 to support mineral, oil, and gas resource development. Some supporting services are threatened by permafrost degradation and coastal erosion caused by sea ice loss and increasing storm surges. Northern high latitude 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. The capture and storage of carbon in the vegetation, soils, and inland waters of ecosystems in the Study Domain benefit global society through the prevention of additional greenhouse gas release to the atmosphere. Carbon uptake by 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 soils and lake sediments may be expected to increase from enhanced decomposition and burning of organic soils 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 ecosystem services directly impact the resilience and vulnerability of human communities in the region and beyond, and how society acts to adapt to or mitigate these changes will determine the future trajectories of change. Human communities in the Study

Domain have a history of being highly resilient based on a long record of successful adaptation to environmental and technological change. However, recent decades have brought historically unprecedented rates of social, climate and environmental change to this region, as well as rapid economic development and increased connectivity with outside regions. In developing responses to these changes, people face greater uncertainty about future conditions and the reliability of ecosystem services upon which their livelihoods depend. 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 mediated through formal and informal institutions (e.g., governments, kinship ties, social networks, shared cultural norms, etc.), by economic factors (cost of living, cost of moving, availability of jobs) and by public policy. In some cases communities are already undergoing important transformational change, such as an increased importance of a wage-based economy, in response to social and economic drivers.

2.2 Overarching Science Question and Objective

Within the context of the Vulnerability/Resilience Framework presented in Figure 2.1, the research conducted as part of ABoVE will focus on developing an improved understanding of the drivers, impacts, consequences and human responses to environmental change in the Study Domain. The complex interdependencies and feedbacks across the components of this framework are reflected in the *overarching science question* that will guide research during ABoVE:

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

To address this overarching question, research during ABoVE will be organized around six ***Science Themes*** that represent critical aspects of Arctic and boreal social-ecological systems: society, disturbance, permafrost, hydrology, flora and fauna, and carbon biogeochemistry. These Science Themes present the opportunity to answer important Tier 2[3] science questions that will require research on the key processes and their interactions that are driving changes to social-ecological systems. Addressing these questions requires an integrated approach based upon the following *overarching science objective*:

To investigate the underlying processes and their interactions that control vulnerability and resilience in Arctic and Boreal ecosystems of western North America to environmental change, and to assess how people within and beyond this region may respond to changes in these processes and interactions.

Studying the impacts of environmental change on ecosystem services within this Vulnerability/Resilience Framework represents the critical bridge between environmental change and how people within and beyond the Study Domain are affected by and respond to this change. The availability and use of ecosystem services depend on the major components

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[3] The Tier 1 or overarching Science Question and Objective are presented in this Chapter, while the Tier 2 Science Questions and Objectives are presented and discussed in Chapter 3.

determining the structure and function of ecosystems in the Study Domain. These components are captured by the six Science Themes for ABoVE. The themes, while not exclusive, represent the organizing elements for the set of Tier 2 science questions and objectives that will be addressed in Chapter 3.

3. Science Themes

Research carried out during ABoVE will address six Tier 2 science questions focused on addressing key uncertainties in how social-ecological systems in the Study Domain are affected by climate and environmental change. The scientific goals for ABoVE are presented as a set of cross-cutting, Tier 2 science objectives required to answer these questions (Table 3.1), most of which involve the study of the underlying processes and their 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.

3.1 Society

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

Rationale – Landscapes and ecosystems in the Study Domain are experiencing accelerated rates of direct and indirect human impacts. People have lived in and influenced ecosystems in the Study Domain since the end of the Pleistocene, creating a vast cultural landscape and a complex social-ecological system. Today, society in this region is involved in a range of activities that depend on or impact freshwater and terrestrial ecosystems, including commercial fisheries, subsistence, tourism, recreation, mining, and energy development, along with the 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, erosion control, tourism, unique lifestyles, etc.). However, this region also contains significant forest, oil, gas, and mineral resources that provide opportunities for economic development. In many cases, the extraction of these resources depends upon the development of winter roads that cross frozen ground, lakes and rivers, which represents a unique supporting ecosystem service. Finally, variations in a large number of ecosystem processes in this region result in significant feedbacks to 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 Study Domain, 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 that landscapes in the Study Domain are providing. For example, it is important to understand how exploration activities dependent on winter roads impact wildlife populations, and how these impacts will change if all-weather roads are constructed to provide greater 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 Study Domain.

Table 3.1. *Tier 2 science questions and objectives for ABoVE.*

<table>
<tr><th colspan="6"><i>Tier 2 Science Questions</i></th></tr>
<tr>
<td>Section 3.1: How are environmental changes affecting critical ecosystem services - natural and cultural resources, human health, infrastructure, and climate regulation - and how are human societies responding?</td>
<td>Section 3.2: What processes are contributing to changes in disturbance regimes and what are the impacts of these changes?</td>
<td>Section 3.3: What processes are controlling changes in the distribution and properties of permafrost and what are the impacts of these changes?</td>
<td>Section 3.4: What are the causes and consequences of changes in the hydrologic system, specifically the amount, temporal distribution, and discharge of surface and subsurface water?</td>
<td>Section 3.5: How are flora and fauna responding to changes in biotic and abiotic conditions, and what are the impacts on ecosystem structure and function?</td>
<td>Section 3.6: How are the magnitudes, fates, and land-atmosphere exchanges of carbon pools responding to environmental change, and what are the biogeochemical mechanisms driving these changes?</td>
</tr>
<tr><th colspan="6"><i>Tier 2 Science Objectives: Ecosystem Dynamics</i></th></tr>
<tr>
<td colspan="2">1. Determine how interactions among vegetation, soil characteristics, hydrology, and disturbances influence surface energy exchange and mediate permafrost vulnerability and resilience to climate change.</td>
<td>2. Determine how and where interactions among microbes, plants, and animals exert control over ecosystem responses to climate change and disturbances.</td>
<td>3. Understand how vegetation attributes and hydrologic conditions interact, and respond and feedback to disturbance.</td>
<td colspan="2">4. Quantify how changes in the spatial and temporal distribution of snow impacts ecosystem structure and function.</td>
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<tr>
<td colspan="2">5. Determine the causes of greening and browning trends and their impacts on ecosystem form and function.</td>
<td colspan="2">6. Elucidate how climate change and disturbances interact with above- and belowground communities and processes to alter carbon biogeochemistry, including release to surface waters and the atmosphere.</td>
<td colspan="2">7. Determine how the spatial and temporal dynamics in both faunal abundance and characteristics of fish and wildlife habitat co-vary across gradients of climate and disturbance.</td>
</tr>
<tr><th colspan="6"><i>Tier 2 Science Objectives: Ecosystem Services</i></th></tr>
<tr>
<td>1. Assess how future climate warming is likely to affect infrastructure and transportation networks.</td>
<td>2. Determine how changes to disturbance regimes, flora and fauna, permafrost conditions, and/or hydrology influence human health outcomes in the ABR.</td>
<td>3. Evaluate how changes to ecosystems will influence subsistence opportunities.</td>
<td>4. Analyze how changes to natural and cultural resources will impact local communities as well as influence land management policies and practices.</td>
<td>5. Determine the sources of variations in climate feedbacks from Arctic and boreal ecosystems and assess the potential for future changes to climate regulating services at regional to global scales.</td>
<td>6. Determine the degree to which changing environment and altered human activities result in synergistic or antagonistic changes in ecosystem services.</td>
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The landscapes and associated ecosystem services in the Study Domain 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 that 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 culturally unique, non-renewable resources, which once lost cannot be replaced. 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 Study Domain will have significant impacts at scales beyond the local and regional levels. The abundance of natural resources in northern high latitude regions creates opportunities for the use and distribution of additional ecosystem services both locally and beyond, but the potential substantial net changes to carbon sinks in vegetation and soil may 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 may be abrupt or not easily anticipated. Given these complexities and the rate of current environmental change in the Study Domain, there is high potential for large impacts on livelihoods and regional economic activity throughout this region and beyond.

While environmental change in the Study Domain 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 it is believed they are particularly vulnerable:

1. Distribution, abundance, access to and use of natural resources for provisioning and subsistence ecosystem services;
2. Direct and indirect effects on human health and safety (e.g., disease vectors, food availability, air and water quality, mental health from intact culture and perceived ability for self-determination);
3. Rapid direct and indirect effects of disturbances (such as fire) and changes to hydrology, permafrost and ice which impact infrastructure and landscapes (buildings, roads, airports, frozen rivers) and cultural heritage (practices, traditions, language, historically important places); and

4. Changes to ecosystems that directly feedback to climate and represent a critical regulating service.

These four areas were selected because the societal impacts and responses in each are directly related to significant ongoing environmental change in the Study Domain, including changes to disturbance regimes, the cryosphere, hydrologic systems, and the flora and fauna endemic to Arctic and boreal ecosystems. These relationships provide a strong linkage to the research being conducted to address the other Tier 2 science questions discussed in this chapter. It is expected that the specific research questions and methodological approaches about the vulnerability, resilience, and/or adaptive capacity of communities with respect to these four general research areas will be generated by investigators via their research plans for ABoVE participation.

Key Research – Improving the understanding of the impacts of environmental change on provisioning, subsistence, natural resources, human health, infrastructure and culturally important places requires interdisciplinary research integrating socio-economic data with information on relevant landscape patterns and processes. This research will need to effectively engage a range of stakeholders (from both the private and governmental sectors), ranging from individuals, to local communities, to regional, national and international entities. Environmental and climatic change in many parts of this region where people live is complex, requiring research on integrated biological, physical, and cultural processes. This research will require that observations of landscape and ecological processes be coupled with socio-economic data at multiple scales to investigate how these societies may be vulnerable and/or are adapting to these changes. Research on the impacts of climate and environmental change on landscapes and ecosystems should be carried out through studies that address the Tier 2 questions and objectives for the other science themes discussed in this chapter.

Studies on the range of underlying processes and interactions that provide feedbacks to climate in Arctic and boreal ecosystems across the Study Domain will be needed to determine changes to climate regulation. Research addressing climate feedbacks should include studies of changes in land cover that affect albedo and a range of processes influencing exchanges of water and carbon between the atmosphere and land surface. The details of this research are presented in the other science themes in this chapter.

Baseline socio-economic data will be needed. Ideally, panel surveys such as the Survey of Living Conditions in the Arctic (SLiCA) should be repeated for specific regions within the Study Domain in order to follow people in the sample over time as they respond to environmental change. These data should be obtained through some combination of existing or concurrent conventional social science research and information provided by research through ABoVE.

Information derived from satellite and airborne remote sensing systems to address the questions and objectives for the other ABoVE science themes will provide the means necessary to assess changes to key landscape characteristics that directly impact ecosystem services. Research is needed, however, to develop appropriate geospatial information products derived from remotely sensed data that can be used to directly assess the vulnerability and resilience of specific ecosystem services. In many cases, creating unique products will require the integration of remotely sensed datasets with other information needed to assess the vulnerability and resilience 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 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 Study Domain and elsewhere. Finally, research is needed to determine how improved information resulting from ABoVE is used by stakeholders in making decisions based on the actual and potential impacts of environmental change in the Study Domain. Success 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.

Modeling research is needed across three general areas. First, community- and regional-scale models of social systems and human well-being should be further developed and tested using available data, although major data gaps may prevent widespread application across the Study Domain. These models should emphasize human use of ecosystem services and should include human development outcomes – such as health measures – that are broader than the cash economy variables emphasized in most conventional economic models. Second, social variables and human-driven processes (e.g., oil development) should be incorporated into existing ecological modeling frameworks. Third, integrated models of social-ecological systems should be developed and applied to decision support challenges. These models can help inform the acquisition of integrated datasets mentioned above (i.e., which data are needed most? How should the data be organized?), and they can be vehicles for stakeholder input and discussion, especially if built around stakeholder-generated scenarios of future conditions.

3.2 Disturbance

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

Rationale – Although disturbance from fire, biotic disturbance agents (including insects and plant pathogens), and permafrost-thaw have always been part of historic disturbance regimes affecting Arctic and boreal ecosystems, there is mounting evidence that their frequency, severity, and area impacted 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 changing terrestrial and freshwater ecosystems and the services they provide (Figure A11). 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 ecosystems are responding to climate change. Because of the large cumulative area impacted and the immediacy of effects, disturbances are in many cases the most proximal agent for initiating changes to Arctic and boreal ecosystems and landscapes. Land management agencies across the Study Domain not only require information on historical and current patterns of disturbance, but also 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 the potential for burning, changes in forests dominated by conifers to deciduous vegetation will have a negative feedback on fire activity. Expanding human activities will increase ignitions. Based on the current understanding, it is challenging to predict future changes to fire regimes in the Study Domain 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 Study Domain. Compared to some regions to the south, current evidence suggests that the impacts of these agents will become more severe in the Arctic and boreal regions. For example, because pathogens can adapt to new climate conditions faster than their 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 stress to vegetation from increases in evapotranspiration without concurrent increases in precipitation) and other complex host interactions that are difficult to forecast (e.g., the impacts of differential temperature effects on the phenology of leaf maturation versus insect feeding). Understanding factors controlling insects and pathogens, and other forest dieback, is particularly important in the southern boreal forest where harvesting of wood products is economically important to local communities.

In many regions of Alaska and northwest Canada rapid permafrost thaw is on the rise as shown by observations of increased occurrence 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 as controlled by variations in geomorphology, ground ice content, and vegetation, and are consistent with borehole-measured permafrost temperatures that have steadily increased over the last three decades in northern Arctic areas. Impacts of rapid permafrost thaw are also ongoing in boreal ecosystems with ice-rich permafrost. Changes to permafrost are already causing 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 ecosystems in the Study Domain 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 should include landscape- to regional-scale observations of disturbance area and severity derived from remotely sensed data, as well as from land-management records and paleological 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 can provide improved information on actual area disturbed, the timing of disturbance events, and the severity of the disturbances. Additional research is needed to develop and validate remotely sensed disturbance products across the Study Domain, 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 important 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 to understand the immediate impacts on ecosystems. Observations across sites and landscapes that differ in time since 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 which 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-ecological data can help understand current and projected disturbance regimes in a historical context of landscape dynamics, provide critical information on the ambient conditions at the time of disturbance, and assess longer-term changes to community composition.

3.3 Permafrost

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

Rationale – Arctic tundra and boreal forests are unique biomes in large part because of the dominating influence of snow, ice, and frozen ground. The role of the cryosphere in the Study Domain makes this region especially sensitive to climate warming (Figures A8 and A9). Changes to key components of the cryosphere are expected to have major and potentially irreversible consequences for social-ecological systems at multiple spatial and temporal scales. All Arctic tundra in the Study Domain is underlain by continuous permafrost, with substantial permafrost in the boreal forests of this region being present in the discontinuous and sporadic permafrost zones. Many landscapes across the Study Domain with ice-rich permafrost have already experienced a marked degradation of permafrost, including the collapse of permafrost peat plateaus in southern regions of the domain, thermokarst lake growth and increasingly rapid coastal erosion in northern regions, and ice wedge melt and collapse even in the cold high Arctic regions. Because these thaw dynamics are 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 key research priorities.

Permafrost dynamics exert strong control on energy, water, and biogeochemical cycling, along with vegetation and disturbance processes in all major terrestrial (tundra, forest, and peatland) and freshwater ecosystems in the study domain, 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 instability, 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 Study Domain – 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 in the Study Domain. Frozen ground supports infrastructure, transportation and other services that local communities and industries rely on. The northern high latitude permafrost region stores an enormous quantity of soil organic carbon that while frozen 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 and active layer conditions. 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 to thaw in some regions and more resilient in others. Research is needed to develop a framework that integrates field and remote sensing observations 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), it is possible to detect changes to a number of land surface characteristics that are associated with near-surface permafrost dynamics. 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 the main 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, land surface temperatures, albedo, snow cover and density, patterns of vegetation cover and vegetation change, disturbance occurrence and severity, surface water coverage, and soil moisture – should be characterized over the Study Domain 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 – should also be carried out using higher-resolution satellite and airborne remote sensing systems.

Remotely sensed observations should be used in conjunction with field-based measurements to improve our understanding of the driving processes and aid in the development of inputs for physical models capable of 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 should 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 thaw depths, vertical and lateral ground temperature and moisture profiles, thermal conductivity of soil substrates, and seasonal to 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 should 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 ground ice content.

Currently, projections of permafrost extent, depth and change over time are primarily based on ecological modeling frameworks that simulate temperature profiles over a one-dimensional soil column. These models, along with a more detailed, three-dimensional representation of permafrost and ice structure, will be needed to better predict the spatial and temporal patterns of thaw and their impact on landscapes and ecosystems. High priority research in support of these models includes the development of high-resolution datasets of landscape parameters, including spatial variation in vegetation cover, soil type, topography and ground ice. The full expression of these models will require these and other similar initial conditions and meteorological forcings (particularly snow cover extent, timing and properties) to accurately describe contemporary states and project future changes. Soil thermal and permafrost models will be a critical link to the hydrology, soil carbon and vegetation models given their dynamic depiction of soil temperature variations with depth, the seasonal development of the active layer, and the impacts on landscape structure from thawing ground and melting ice.

3.4 Hydrology

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

Rationale – The hydrologic cycle in northern high latitude regions is dominated by winter water storage as snow and ice, followed by high rates of surface 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 (Figure A7). Across the Study Domain, annual precipitation is nearly equally partitioned between rain and snow, with excess water above evapotranspiration being either stored (as snow, surface water, and soil/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 (Figure A6). The hydrology of the Study Domain also influences land-atmosphere and water-atmosphere interactions and feedbacks that involve water, carbon dioxide, methane, and energy exchange, along with controlling a range of ecosystem processes. Understanding the impact on plant productivity and tree mortality from increased evapotranspiration due to warmer temperatures without concurrent increases in precipitation is particularly important. Intensification in fluxes of precipitation, evapotranspiration, and runoff are expected manifestations of a warming climate. Warming is also projected to lead to a shift between surface water and groundwater-dominated systems– transitions that may alter the timing and change the amount of stream and river flow.

Changes to hydrology in the Study Domain 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 the factors controlling spring breakup of rivers and formation of ice jams is particularly important to the numerous communities located immediately adjacent to rivers that are vulnerable to spring flooding.

A key and unique regulator of the hydrologic system in the Study Domain is the widespread presence of permafrost. The fact that 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 Arctic and boreal regions. In most hydrologic systems, residence times are considered to be the travel times along surface and sub-surface flow paths; however, Arctic and boreal regions are 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, yet is potentially critical to controlling ecosystem structure and function. Changes in the timing, thickness, and extent of lake and river ice cover will affect the timing and magnitude of runoff dynamics, connectivity of surface waters, habitat availability, surface energy balance, water-atmosphere exchanges, and thermokarst activity.

The unique spatiotemporal distribution of water in the Study Domain has thermal as well as hydrologic impacts, providing strong feedbacks to and regulation of climate. The snow that covers the ground from October through May not only represents approximately half of the annual surface runoff, but it is also 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, the local distribution and depth of snow are influenced by the type and structure of vegetation. When the snow falls, how it falls, and how long it stays all have strong implications for hydrology and ecosystem structure and function in Arctic and boreal regions; therefore, patterns of snowfall have to be considered as an integral part of the hydrologic system. Finally, snow depth, density, and duration, as well as the patterns of mid-winter thawing and refreezing of snow are all critically important habitat conditions that influence a number of important wildlife species.

Characterizing the spatial distribution of water and the amount and timing of water discharge across the Study Domain 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. A major portion of annual runoff happens during an intense spring runoff period, during which channelized runoff may increase by orders of magnitudes and non-channelized runoff occurs along poorly developed flow paths across the land surface that are difficult to measure in the field. 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 to the atmosphere, and commonly exhibit gas flux densities that far exceed terrestrial 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 Study Domain and the primary controls on these changes will require observations and modeling targeted at the major storages and fluxes. Critical measurements for this research should include seasonal and inter-annual variations in: soil moisture; evapotranspiration; precipitation; snow extent, depth and water equivalent; mid-winter thaw/freeze events; stream flow; water table depth; and the extent and temporal variability of surface water distribution and lake ice cover. The amount and distribution of water in its various phases needs to be observed 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 quantify hydrologic gradients and to understand how different processes control surface and groundwater hydrology, including climate, permafrost, land-cover type, ecosystem dynamics and disturbance. This research should be supported by *in situ* observations and through analysis of remotely sensed data. Water chemistry and stable isotope measurements are needed across targeted catchments and should include observations of precipitation, snowpack, surface water, ground water, and ground ice. Hydrologic observations should include baseline residence time estimates for soil and ground water pools. High-resolution satellite imagery and airborne LiDAR elevation data are needed to understand seasonally changing lowland water extent, investigate the effects of thermokarst and thermal erosion on surface and subsurface flows, and map the seasonal patterns of various snow characteristics. 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 the other observations needed during ABoVE. Surface water characteristics derived from satellite remote sensing data should include seasonal and longer-term changes in the number and surface extent of small ponds and lakes, as well as connectivity between these water bodies. Further, multi-temporal maps of floods, soil moisture, seasonal and snow extent, lake/pond surface temperature and ice cover, and maps of frozen/thawed conditions for land surfaces are needed. At research sites with eddy covariance flux towers, measurement of evapotranspiration will help close the water budget for select watersheds. Comparative measurements of snow depth, density, and water equivalent should be made directly by remote sensing where feasible.

Modeling research is needed across a range of approaches from simple water balance representations to large-scale, distributed three-dimensional landscape models. Hydrologic modeling studies are needed to improve the representation of: a) spatial and temporal variability in surface water extent and volume and the connections with surface meteorology; b) linkages between surface and subsurface flows; and c) the amount and timing of lateral transports of water-borne materials across the region. Field measurements of organic matter, major ions, and sediment load are needed for the parameterization and validation of models that simulate biogeochemical fluxes. As with other modeling activities, landscape initialization data are key needs for hydrological modeling in ABoVE research. Prognostic modeling of surface hydrography will best be advanced in scaling studies that leverage coincident observations from airborne and satellite data products using both active and passive microwave instruments.

3.5 Flora and Fauna

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 Study Domain are undergoing directional change at regional and, in some cases, circumpolar scales. In response to climate warming, some regions have been increasing in productivity (greening), while other regions (particularly those containing boreal forests) have experienced reduced productivity and increased mortality (browning) (Figure A5). The same satellite sensors are revealing that at the circumpolar scale, growing seasons are lengthening primarily because warmer springs alter freeze-thaw dynamics and advance spring snowmelt and the onset of plant growth. Climate-sensitive disturbance regimes in the Study Domain are intensifying, including those associated with wildfire, biotic disturbance agents, and thermokarst activity. These too are altering vegetation characteristics by initiating successional processes (especially in forests), 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 exploration and extraction are having increasing local and regional impacts on vegetation characteristics as Arctic and boreal 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 vegetation across the Study Domain that are not yet well understood, including the degree of interaction between the underlying processes driving them and how they feedback on climate (via changes in albedo and fluxes of greenhouse gases and water), 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 Study Domain’s changing vegetation characteristics and, vice-versa, how this changing vegetation impacts faunal dynamics. Faunal influences on 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 tree-line advancement. A wide range of resident and migratory fauna depend on the unique habitat provided by terrestrial and freshwater ecosystems in the Study Domain for food and shelter. As a result of changes in 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 flora and fauna in the Study Domain. For example, the advancement of vegetation phenology in some areas outpaces the rate at which caribou are able to adjust the timing of their nutritional requirements, and this may be contributing to the recent major decline in the reproductive success of some herds.

Satellite remote sensing records have revealed significant and contrasting trends in surface water extent within the Study Domain, 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 some tundra stream reaches are drying up in late summer. Thermokarst and other rapid permafrost thaw events are increasing sediment and dissolved organic matter inputs into aquatic systems, which in turn impact water quality and carbon and nutrient cycling. The changing patterns of ice cover, wetting and drying, and water composition are likely to alter habitat availability and quality for the freshwater and semi-aquatic fauna in the Study Domain, including birds, fish, mammals, and invertebrates. Every spring, millions of shorebirds, ducks, geese, loons and swans migrate to the Study Domain to breed, raise their young and feed in wetlands. Freshwater 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 Study Domain 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 terrestrial and freshwater ecosystems in the Study Domain will have a variety of cascading effects on the ecosystem services that society depends upon. Of particular importance is the role that Arctic and boreal terrestrial ecosystems have in climate regulation through critical feedbacks to the atmosphere. Variations in fluxes of CO_2 and CH_4 between the land and atmosphere are regulated by a number of factors that control photosynthesis, respiration, and combustion during fires (Figure A3). Changes in forest and vegetation cover and phenology have strong impacts on albedo, as well as the exchange of water between the land surface and atmosphere.

It is largely unknown which faunal species are resilient and will be able to adapt to the many biotic and abiotic changes occurring across the Study Domain, yet the resulting changes in both plant-animal and freshwater animal interactions will strongly influence the response of ecosystem form and function. Further, because Arctic and boreal ecosystems are 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 ecosystem functions in the Study Domain 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 effects on ecosystem form and function can be quantified.

Key Research – Research to address this question requires landscape to regional to domain wide observations of vegetation characteristics and surface water extent derived from remotely sensed data, as well as observations to assess changes in terrestrial and freshwater growing season length from across the electromagnetic spectrum (e.g. visible, infrared, and microwave data). Satellite remote sensing data are needed to assess seasonal, inter-annual and longer-term variations in vegetation characteristics at spatial scales of 5 to 5000 m. Remote sensing data products are also needed to assess changes in dissolved organic matter, suspended sediments, and chlorophyll in terrestrial water bodies. Airborne remote sensing is 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) and spectral resolutions. Assessing the factors controlling vegetation characteristics, surface water extent, and growing season length will also require geospatial data on climate (air temperature, relative humidity, precipitation, and other climate variables), ice cover, burned area metrics, the 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 should include satellite (e.g. 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 impacts on ecosystem form and function, including greenhouse gas fluxes and the exchange of energy and water. The 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.

For ABoVE, the priority should be given to the use of geospatial models of current and projected vegetation change and associated wildlife population dynamics at landscape-to-regional scales. Modeling activities should consider ongoing 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 Study Domain is critical. This is a particularly valuable approach given apparent, recent boreal forest encroachment northward, and shrub encroachment into tussock tundra. Predicting future changes in populations of key fauna species largely depends on projecting habitat change, which requires linkage between models of vegetation dynamics, hydrology, permafrost, and disturbance.

3.6 Carbon Biogeochemistry

How are the magnitudes, fates, and land-atmosphere exchanges of carbon pools responding to environmental change, and what are the biogeochemical mechanisms driving these changes?

Rationale – The size of the northern high latitude soil carbon pool is estimated to be more than twice that contained in the atmosphere (Figure A10). As a result, there is significant concern about potential climate feedbacks through exchanges of CO_2 and CH_4 between the land surface and the atmosphere. Simultaneous with enhanced decomposition of soil organic carbon, changes in climate are driving changes to disturbance regimes along with shifts in vegetation, soil temperature, and the hydrological cycle that alter the rates of aboveground net primary production, heterotrophic respiration, and soil organic carbon (SOC) production. Carbon also can be liberated from Arctic/boreal ecosystems into water and transported as particulate organic carbon (POC), dissolved inorganic carbon (DIC), and dissolved organic carbon (DOC) to streams, ponds, lakes, and eventually to the coastal regions, where it can either be buried or become available for decomposition and potentially emitted to the atmosphere. Which of these factors dominates the biogeochemical processes regulating carbon cycling in the Study Domain, what are the processes that drive their relative importance, and over what timescales are they most relevant remain unclear. Because these dynamics and their interactions ultimately drive important feedbacks to climate, research is needed to provide a greater understanding of the ecosystem processes and their interactions that control production, transformations, and fate of carbon resident in various pools across the Study Domain. Prompted by this uncertainty, the research needs previously presented for the different Science Themes identified for ABoVE specifically address many of the processes controlling carbon biogeochemistry and cycling. However, additional, more focused research on processes regulating land-atmosphere exchange of soil carbon biogeochemistry is required and presented here.

To understand how variations in abiotic and biotic conditions regulate the exchange of CO_2 and CH_4 between the land surface and the atmosphere over different spatial and temporal scales, investigations typically measure the fluxes of these greenhouse gases using chambers, flask measurements, flux towers, and airborne systems. In northern high latitude ecosystems (including forests, tundra, and peatlands), spatial and temporal variations in CO_2 and CH_4 fluxes from soils are regulated by vegetation, microbial, fungal, and invertebrate communities, disturbances and hydrologic and permafrost processes that can readily be monitored using remotely sensed data. In particular, methods have been developed to model or scale measures of CO_2 and CH_4 fluxes using information products derived from remote sensing data that provide information on spatial and temporal variations in disturbance area and severity, freeze/thaw cycles, and vegetation cover and condition, along with soil temperature and moisture, active layer depth, the area of small lakes and ponds, and the levels of inundation in wetlands. While studies of flask data have revealed considerable intra- and inter-annual and decadal variability in land-atmosphere exchanges of CO_2 and CH_4, ongoing data collections for NASA's CARVE mission demonstrate that variations in boundary layer concentrations of CO_2 and CH_4 in Alaska exhibit complex, emergent patterns at large spatial scales that cannot be readily predicted from ground-based measurements of these trace gasses at fixed locations.

Additional studies demonstrate that changing climatic conditions are accelerating the turnover rate of relatively labile portions of the SOC pool. Of even greater potential importance for understanding SOC feedbacks to climate is the apparent mobilization of deep SOC pools that have been sequestered from the atmosphere for hundreds to thousands of years. The processes controlling this mobilization are particularly important in regions experiencing rapid permafrost warming and degradation, where SOC has previously remained stable due to frozen ground conditions. However, the destabilization of slow-turnover SOC is also an important feature of non-permafrost profiles, especially in peatlands where stabilization mechanisms of SOC may be more strongly linked to processes controlling the formation of deep organic soil horizons. The destabilization of SOC, in both labile and slow-turnover pools, is further influenced by disturbance from fire, which plays an important role in SOC cycling either by directly reducing organic soils through combustion or by changing ambient conditions, patterns of vegetation recovery that provide inputs to organic soils, and the composition of microbial, fungal, and invertebrate communities that control decomposition. Understanding the interactions that contribute to the vulnerability of soil carbon stocks across the Study Domain represents a major research challenge.

A key challenge currently hindering progress towards more accurate predictions of SOC dynamics in the Study Domain, particularly 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. Research addressing SOC stabilization and destabilization should include studies of the factors that control soil biogeochemistry and soil physical processes (such as cryoturbation and permafrost degradation) at multiple temporal and spatial scales. The penultimate 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 then demand the resources liberated upon substrate decay produce these secreted enzymes in response to competitive dynamics among microbial populations and environmental conditions like temperature and resource availability. Because a fraction of the carbon microbes take up is allocated to CO_2 or, for methanogens, CH_4, soil microbes are considered a key agent of CO_2 and CH_4 production; predicting their behavior and how it is modified with a changing climate is an important research priority.

Continuing research to improve the representation of critical drivers of microbial activity such as nutrient availability and substrate stoichiometry into models is important. 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 carbon, especially those focused on interactions between biota, hydrology, permafrost, and disturbances.

Key Research – In addition to research discussed in the previous sections of this chapter focused on improving understanding of exchanges of carbon between the land surface and atmosphere, additional research to improve our understanding of the factors controlling the vulnerability of organic carbon is needed. This research should employ landscape- to regional-scale observations of land cover, hydrological and C cycles, soil dynamics and other observations of state variables such as changes to permafrost, soil moisture, and inundation. 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 soil organic stabilization and destabilization trends. The space-for-time approach may be especially important given the slow turnover time of many SOC pools of key interest. Biogeochemical and ecological data needed from spatially representative research sites include: a) observations of critical microbial processes and associated edaphic and abiotic features at the plot scale (i.e. nutrients, quantity and stoichiometry of soil inputs, moisture, pH, stable isotopes of soil organic carbon, dissolved species and trace gases, hydrologic connectivity or transport); b) flux tower data quantifying mesoscale energy and fluxes of CO_2 and CH_4 and the isotopic signatures of the fluxes of these gases; 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 landscape- to regional-scales to understand patterns of biogeochemical fluxes across land cover classes as a function of time since disturbance. Isotopic signatures of relevant gases are particularly important, because they help constrain the flux source. For example, radiocarbon measurements permit estimation of CO_2 and CH_4 age, and hence the age of its source, and ^{13}C, deuterium, and ^{18}O measurements help identify biotic versus abiotic CO_2 and CH_4 production and consumption processes and transport pathways, and hydrologic influences on soil organic carbon destabilization.

There are many existing modeling frameworks that drive global carbon biogeochemistry with ecosystem dynamics, but these have been shown to be highly uncertain or misrepresentative of processes unique to the northern high latitudes. Coupling soil carbon to vegetation cover can help investigators understand the consequences of land cover changes induced directly or indirectly by future climatic regimes. Remotely sensed data products 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 soil organic carbon transformations. Remotely sensed data products for soil moisture and vegetation cover, when used in conjunction with soil nutrient status, can also be used to establish linkages between nutrient availability, microbial activity, and primary production. It is also critical that these models include accurate representation of the freeze/thaw boundary, heterotrophic respiration, soil type, organic carbon content, and soil moisture and temperature sensitivities.

3.7 Tier 2 Science Objectives

Research during ABoVE will focus on addressing the Tier 2 science objectives presented in Table 3.1. These objectives are crosscutting in nature, where the studies for each would address a combination of the research priorities identified for the six Science Themes. The Tier 2 science objectives follow the Vulnerability/Resilience Framework in Figure 2.1, with the Ecosystem Dynamics Objectives focused on the drivers and impacts of change on ecosystems and the Ecosystem Services Objectives focused on the consequences of and responses to environmental change. The research needed for these two groups of Tier 2 objectives is closely connected. The studies addressing the Ecosystem Dynamics Objectives provide a foundation for assessing the impacts on key ecosystem services. In turn, understanding the impacts on ecosystem services will provide the basis for research on the consequences of environmental changes for society during studies focused on the Ecosystem Services Objectives. As illustrated in Table 3.2, addressing the Ecosystem Services Objectives will require integration and synthesis of the results from research addressing a number of Ecosystem Dynamics Objectives.

Table 3.2. *Research to address the ABoVE objectives needs to be carefully integrated, where the research on the objectives focused on the societal impacts of environmental change (Ecosystem Service Objectives) will be based on the research carried out to address objectives on the drivers and impacts of changes (Ecosystem Dynamics Objectives). The X's in represent instances where research conducted to address the Ecosystem Dynamics objectives would also support research on the Ecosystem Services Objectives.*

	Ecosystem Services Objectives					
	1 - Transportation & infrastructure	**2 - Human health**	**3 - Subsistence**	**4 - Land management**	**5 - Climate regulation**	**6 - Ecosystem services interactions**
Ecosystem Dynamics Objectives						
1 – Permafrost vulnerability/resilience	**X**	**X**	**X**	**X**	**X**	**X**
2 – Microbe, plant, animal interactions		**X**	**X**	**X**	**X**	**X**
3 – Vegetation, hydrology, disturbance interactions	**X**	**X**	**X**	**X**	**X**	**X**
4 – Snow impacts	**X**		**X**	**X**	**X**	**X**
5 – Greening and browning of vegetation			**X**	**X**	**X**	**X**
6 – Controls on carbon biogeochemistry		**X**		**X**	**X**	**X**
7 – Changes to fish and wildlife habitat		**X**	**X**	**X**		**X**

4. Research Strategy and Approach

While the overall strategy for ABoVE follows an experimental design similar to those used for previous NASA field campaigns such as BOREAS and LBA-ECO, it also requires novel approaches to address the full scope of research as outlined by the Vulnerability/Resilience Framework (Figure 2.1). The experiment design for ABoVE (Section 4.1) is similar to those from previous field campaigns in two ways. First, it is based on using Research Areas located across the Study Domain to study how ***environmental gradients*** are controlling important ecological processes and their interactions. And second, specific research activities will be carried out over the range of ***spatial and temporal scales*** needed to address the Tier 2 science questions and objectives (Table 3.1). The experiment design calls for studies of changes to important terrestrial and freshwater ecosystem processes and their interactions. These studies will be based on using a number of key datasets derived from field observations and airborne remote sensing data collected during an Intensive Study Period, as well as satellite remote sensing data and other datasets available from across the Study Domain. It also includes the application and refinement of both ecological and social system models to address the research questions and objectives. The experiment design for ABoVE goes beyond previous field campaigns by incorporating approaches to assess the ***societal responses to environmental change*** based on ***changes to key ecosystem services*** driven by changes to terrestrial and freshwater ecosystems. It also offers the opportunity to engage in decision support though the use of models both informed and improved by ABoVE research for diagnosis and prediction, as well as developing specific information products needed by stakeholders and decision makers.

Like previous NASA field campaigns, NASA intends to build strong, mutually-beneficial collaborations with partner organizations that are also invested in understanding the causes and consequences of environmental change on ecological and social systems in Arctic and boreal regions. Such collaborative activities during ABoVE may differ in nature and level of commitment depending on the goals and capabilities of each **Partner**, but could involve, for example, exchanging data, sharing access to research infrastructure, providing logistical support, supporting additional research activities, or participating in developing information products needed for decision support. The Study Domain and associated spatial hierarchy fundamental to the ABoVE experiment design (Section 4.1.1) was defined in part to be compatible with existing infrastructure and ongoing research by potential Partner organizations working in western North America.

The exact nature and extent of the activities of NASA and its Partners in implementing the recommendations in this experiment plan are expected to be defined and evolve over the next several years as specific agreements are reached, responsibilities defined, and levels of funding available to support research activities determined. In addition, research conducted during ABoVE should be coordinated with ongoing and future research activities sponsored by NASA in the Study Domain, including any relevant Earth Venture Suborbital (EVS) projects, activities in support of future satellite missions (SMAP, OCO-2, ICESat-2, NI-SAR), research for other campaigns funded by other NASA Programs, and new research projects that are part of specific activities funded through NASA ROSES.

The research for ABoVE would be carried out over a 9 to 10 year Field Campaign through individual ***Investigator Studies*** funded by NASA and, perhaps, some of its partners. The Field Campaign is organized according to a conceptual timeline that includes three phases (Section 4.1.2), where the research foci address the Ecosystem Dynamics and Ecosystem Services objectives successively in each of the first two phases, followed by a third phase dedicated to the analysis and synthesis of ABoVE research. To address the Tier 2 science questions and objectives, ABoVE will require research carried out at ***Investigator Sites*** located in different ***Research Areas*** across the Study Domain. Collectively, these Investigator Studies should include research activities (Section 4.2) based on field-based studies, social science research, the analysis of remotely sensing data, the use of models, and analyses based on integration and scaling. Collectively, this research will lead to the development and application of a range of decision support products guided by the needs of stakeholders (Section 4.3). A key element of the ABoVE experimental design is the development of ***Data and Information System*** (Section 4.4) and services to: a) allow for assembling, compiling and arranging for archive the new datasets that will be used for ABoVE; b) arrange for access to existing datasets needed for ABoVE that are stored elsewhere; c) facilitate the ability of investigators to integrate, synthesize, and analyze data collected from multiple sources; and d) compile and distribute a range of decision support products to stakeholders.

Research for ABoVE will require support for Investigator Studies that includes long-term planning, coordinating the collection of airborne remote sensing data, coordinating research logistical support, arranging for the collection of measurements for Core Variables at some sites, data compilation, the provision of data management infrastructure, and support for scientific meetings[4]. Regular ***Science Team Meetings***, at least annually, should be convened to aid in the ongoing planning and coordination that will be required for ABoVE, present and discuss results from ongoing research, and plan specific integration and synthesis activities across projects.

4.1 Experiment Design

4.1.1 Spatial Hierarchy

The spatial hierarchy of the ABoVE experimental design is comprised of the Study Domain, Core and Extended Regions, Research Areas, and Investigator Sites (Figure 4.1). The ***Study Domain*** includes most of northwestern North America north and east of the coastal mountain ranges and west of Hudson Bay. The Study Domain encompasses the variability in the key land surface features that are both unique to Arctic and boreal ecosystems in North America as well as being representative of the larger Northern High Latitude region (Appendix A). The ***Core Region*** of the Study Domain captures the regional-scale variations in surface and atmospheric conditions necessary to address the Tier 2 science questions and objectives (Table 3.1). It includes landscapes and ecoregions that are rapidly changing in complex ways as well as others that are not – a combination that allows for studies on both vulnerability and resilience. The Study

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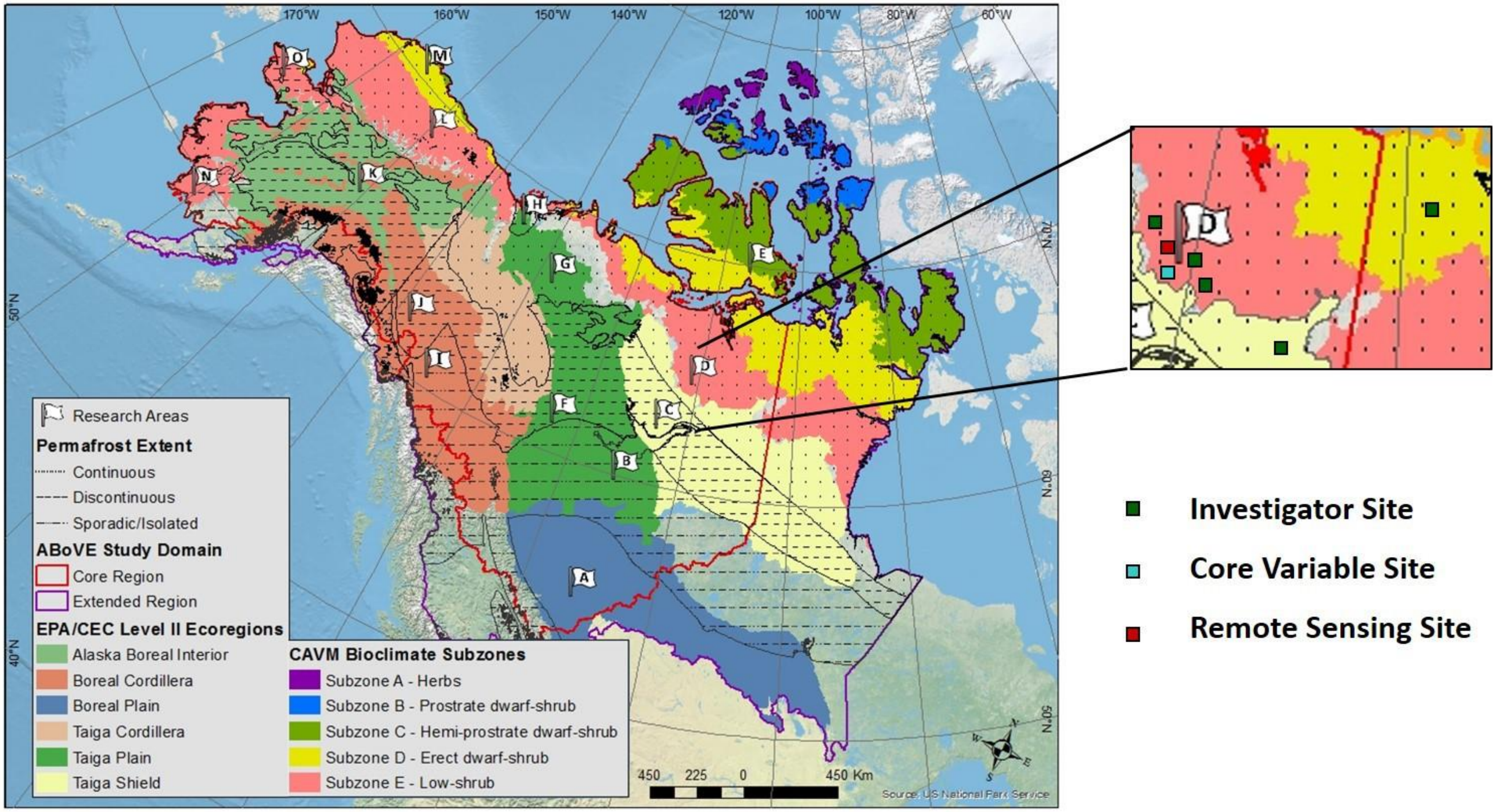
[4] It is anticipated that NASA's Carbon Cycle and Ecosystems Office (CCE Office) will be providing this overall support for ABoVE.

Figure 4.1. *Spatial hierarchy for ABoVE. Research Areas (marked with flags) for ABoVE are based on the intersection of key ecoregions/tundra vegetation subzones and permafrost zones as well as the presences of different disturbance regimes. The displayed locations of Investigator, Core Variable, and Remote Sensing Sites are for illustration purposes only, where the actual locations will be based on the Investigator Studies selected for ABoVE.*



Domain includes an ***Extended Region*** outside of the Core Region, which allows for studies focused on a subset of important changes that are not occurring in the Core Region (for example, insect outbreaks and forest dieback in the southern boreal forest). The Extended Region includes areas where research can focus on environmental conditions that are considered to be antecedent to those in the Core Region. Studies conducted in the Extended Region could also provide opportunities for collaboration with existing or planned research sponsored by Partners. To build partnerships that take advantage of existing infrastructure and logistical support and to provide the variations and gradients in important surface characteristic required to address the Tier 2 science questions and objectives, most investigations for ABoVE should take place in the ***Research Areas***. The fifteen Research Areas distributed across the Core Region contain ecosystems exposed to different disturbances (Figure A11) along climate gradients that control variations in permafrost (Figures A8 and A9), vegetation cover (Figures A3 and A4) and other important characteristics, such as variations in above and below ground carbon (Figures A3 and A10), surface water (Figure A7), and habitat for fish and wildlife species (Figure A12). The Study Domain can be used for research on how changes to Arctic and boreal ecosystems affect inputs to the western Arctic Ocean through major river systems (Figure A6).

The flags in Figure 4.1 represent the locations within the Research Areas where access and logistical support are available (Figure A1 in Appendix A). In some Research Areas, physical access to Investigator Sites will be available via road networks, while in others access is restricted to air or river transportation only. A summary of the key characteristics and features of each Research Area is presented in Table A1. The size of each Research Area will vary based on the locations of the Investigator Sites selected for ABoVE. While many of the Research Areas have a number of previous, ongoing, and planned studies that will provide a foundation for the ABoVE research, several do not and will require more investment in terms of logistical support and research infrastructure.

The locations of the ***Investigator Sites*** will be determined by the individual Investigator Studies selected to address the Tier 2 science questions and objectives. Only one or a small subset of Research Areas may be required for some investigations, while others may require less intensive work at a number of sites located in different Research Areas. The activities carried out at the Investigator Sites will likely include the collection and analysis of new field data. While the majority of the Investigator Sites should be located within the Research Areas, some sites may need to be located in other areas within the Core and Extended Regions that feature environmental conditions or phenomena necessary to address specific objectives (Figure 4.1). Many investigators will likely use locations that have been established specifically for conducting long-term research on Arctic and boreal ecosystems within the Study Domain when their research activities are compatible with the conditions for work at long-term sites (e.g., research stations in Figure A1), research sites that have been previously established by individual investigators, or sites that are part of a monitoring network (see, e.g., Table B1). However, research at new sites established in understudied regions may become important for addressing specific Tier 2 science questions and objectives. Since the selection of Investigator Sites will be based on addressing specific Tier 2 science objectives, the number of these sites is not likely to be the same in each Research Area.

Core Variables are measures of fundamentally important environmental characteristics that are presently under sampled by monitoring networks in Arctic/boreal regions. The data from ***Core Variable Sites*** located in the Research Areas along with those available from monitoring networks are needed to address the Tier 2 science questions and objectives on how the drivers of environmental change (e.g., weather station data) are controlling important ecosystem processes and their interactions (fluxes of land/atmosphere fluxes, stream flow, and permafrost dynamics) across the Study Domain (for a further discussion of Core Variables, see Section 4.2.1 below). The measurement of Core Variables would continue for the duration of the Intensive Study Period. Finally, field data will be collected at some Investigator Sites for the refinement and validation of products derived from remote sensing data (***Remote Sensing Site***) (Section 4.2.3).

4.1.2 Research Phases and Timeline

The conceptual timeline for ABoVE Research Activities presented in Table 4.1 generally follows three objective-driven phases over the 9 to 10 year period of the Field Campaign. During the different phases, individual Investigator Studies (assumed to be 3 years in duration, following the typical funding cycle) would carry out a combination of Research Activities (Section 4.2) to address each set of objectives. The research focus will evolve across each phase guided by the progression of scientific investigation represented in the Vulnerability/Resilience Framework (Figure 2.1), where studies of ecosystem dynamics in response to the major drivers of change provide the foundation for further research on the consequences and responses of society to changes in ecosystem services (Table 3.2). As the foundational science needed to address the research objectives for ABoVE, the Tier 2 science questions (Table 3.1) will provide the impetus for research throughout all phases of the Field Campaign. The first two phases will predominately focus on the Ecosystem Dynamics Objectives and the Ecosystem Services Objectives, respectively, and will include the bulk of the Intensive Study Period. A final phase focused on the analysis and synthesis of ABoVE research is needed following the completion of the main portion of field and airborne data collection activities.

Research conducted during ABoVE Phases I and II will require data collected at different spatial and temporal scales from the Investigator Sites over a 5 to 7 year **Intensive Study Period**. The major portion of the field-based studies, Core Variables collection, and airborne remote sensing campaigns will occur during this Intensive Study Period. The duration of the Intensive Study Period provides the opportunity to collect data records representing a sufficient length of time to capture the high level of inter-annual climate variability that exists in Arctic and boreal regions. The temporal extent of the field-based data at some Investigator Sites could be extended by taking advantage of data collected during previous research or through data collected at sites that are part of long-term monitoring networks or inventories (see, e.g. Figures A3 and A8; Tables B1). Other important environmental and socio-economic datasets covering different time scales are available from records maintained or surveys conducted by government and non-government organizations (Tables B2 to B4). Satellite remote sensing data

Table 4.1. *Schedule for Research Activities required for ABoVE that would be carried out over the timeline of the Field Campaign to address the objective-driven focus of each of three Phases of research. The darker shade of gray indicates when more intensive activities are expected to occur.*

	Phase I **Focus on Ecosystem Dynamics Objectives**			**Phase II** **Focus on Ecosystem Services Objectives**			**Phase III** **Focus on Analysis and Synthesis**		
	Yr1	Yr2	Yr3	Yr4	Yr5	Yr6	Yr7	Yr8	Yr9
Intensive Study Period	░	▓	▓	▓	▓	▓	░		
Research Activity Focus (4.2)									
Field-based research (4.2.1)									
Collection of field observations	░	▓	▓	▓	▓	▓	▓	░	
Synthesis, integration and scaling of field-based research			░	▓	▓	▓	▓	▓	▓
Societal Drivers, Consequences & Responses Research (4.2.2)									
Societal drivers, consequences and responses to change		░	▓	▓	▓	▓	░		
Decision support information product development						░	▓	▓	▓
Remote Sensing Research (4.2.3)									
Airborne data collection		▓	░	▓	░	▓			
Data product development - Ecosystem Dynamics	▓	▓	▓	▓	░	░			
Data product development - Ecosystem Services			░	▓	▓	▓	▓	▓	░
Modeling Research (4.2.4)									
Initial benchmarking with existing data	▓	▓	▓						
Refinement & assessment with ABoVE data			░	▓	▓	▓	░		
Integrated modeling - diagnosis and prediction						░	▓	▓	▓
Integration & Scaling Research (4.2.5)									
Integration of existing data and identification of gaps	▓	▓	▓	░					
Spatial-temporal integration across individual studies			░	▓	▓	▓	░		
Cross-activity, cross-disciplinary synthesis						░	▓	▓	▓

and products (Section 4.2.3) will also be important for temporally extending and spatially extrapolating ABoVE data collected during the Intensive Study Period.

Investigator Studies contributing to the **Ecosystem Dynamics Objectives** would form the emphasis for research during Phase I. These investigations should focus on the key areas of research identified for the different Science Themes on the responses to change in the social-ecological systems across the Study Domain. Phase I should involve field-based research that integrates and builds upon previous and ongoing studies to address the key uncertainties identified for the different science themes in Chapter 3. It should also include the development, refinement, and validation of both satellite remote sensing data products and the portfolio of models needed to integrate across the Tier 2 science questions and address multiple, interdisciplinary research objectives. These research activities should consider the major ecosystem responses to changes in drivers along with the complex interactions among the drivers and the responses. Research addressing the Ecosystem Dynamics Objectives will need to include basic ecological and social science studies driven by the Tier 2 science questions. To establish a basis for research on the Ecosystem Services Objectives that will be the focus of Phase II, some studies on the societal drivers and responses to change will need to begin during Phase I. Phase I research will make significant contributions to the observational data collections, model refinements and geospatial synthesis products that will provide the foundation for the Phase II and III research activities addressing the interdisciplinary research objectives.

Research addressing the **Ecosystem Services Objectives** will benefit from the new data and findings related to the Tier 2 science questions and the Ecosystem Dynamics Objectives, which will be provided by both previous studies and those conducted during the first phase of ABoVE. By the beginning of Phase II, the Science Team should be able to use the field and remote sensing data collected in Phase I to develop conceptual frameworks for the integration, scaling, and modeling activities necessary for addressing the Ecosystem Services Objectives. The field observations and airborne campaigns of the Intensive Study Period would continue to collect data through Phase II. The synthesis, integration and scaling of ABoVE data collections and analyses can begin by the beginning of Phase II, and this information will contribute to the refinement and assessment of integrated modeling frameworks. To address the Ecosystem Services Objectives, research on the societal drivers, consequences, and responses to change will need to continue as a focus in Phase II through the use of existing socio-economic datasets (Tables B2 to B4), collection of new data in the field, and incorporation of data and analyses from the Ecosystems Dynamics Activities. Research focused on the Ecosystem Services Objectives can begin in Phase II and continue through Phase III through development of data products, integrated modeling frameworks, and information needed for decision support.

Following the completion of the Intensive Study Period, studies conducted during Phase III should focus on cross-activity, cross-disciplinary research involving the **Analysis and Synthesis** of data and findings from the field based and airborne remote sensing activities conducted during ABoVE. Phase III provides the opportunity for investigators to make use of ABoVE research holistically to gain new insight by synthesizing the findings across Investigator Studies, to develop novel and unique data products, and to demonstrate the improvement in model process representation and prediction using ABoVE data. One of the major lessons learned through past field campaigns is that a dedicated period of funding for integrative data analysis and synthesis studies to follow the field phases is essential to achieving the full scientific return and societal impact of the field campaign. This phase should include the synthesis, integration and scaling of basic social and ecological research, the employment of integrated modeling frameworks for diagnosis and prediction, and the development of decision support information products.

The timeline presented in Table 4.1 offers a general guideline for the objective-driven focus of each research phase and includes the activities necessary to design and build information products for decision support. In reality, the timeline requires flexibility to provide overlap in the research activities needed to address the Tier 2 science questions and research objectives over the course of ABoVE (Figure 4.2, Section 4.2). In effect, while each phase has a focus area of research, this should not preclude studies designed to address the other questions and objectives as warranted. The science questions and research objectives were defined for ABoVE because of their importance in the region, connection to other Tier 2 science questions and objectives and potential for investigation using remotely sensed data. They offer a broad range of potential activities for individual investigators, who may design studies to address one or more of these questions and objectives. Furthermore, each research phase would include a group of Investigator Studies that collectively cover a range of Research Activities, including field based studies, remote sensing, modeling, and synthesis, integration and scaling. In addition, there are several activities that will help ensure that the research projects provide information that meet the decision support needs of relevant stakeholders (see Section 4.3).

Finally, the research activities carried out in individual Investigator Studies during the three Phases need to be integrated in order to address the Tier 2 science questions and objectives (Figure 4.2). Implementation of this integration requires that once investigators are selected and Partners identified, a ***Science Team***[5] be formed. In order for the researchers to be efficient in their activities and be represented in day-to-day ABoVE activities, a ***Lead Scientist*** should be identified for ABoVE. The Lead Scientist's responsibilities would include development of a detailed science plan that describes the ABoVE research to be conducted through NASA-funded Investigator Studies and Partner activities of all types, suggesting some forms of support that may be provided by the Carbon Cycle and Ecosystems Office, and coordinating with ongoing research and monitoring activities in the Study Domain.

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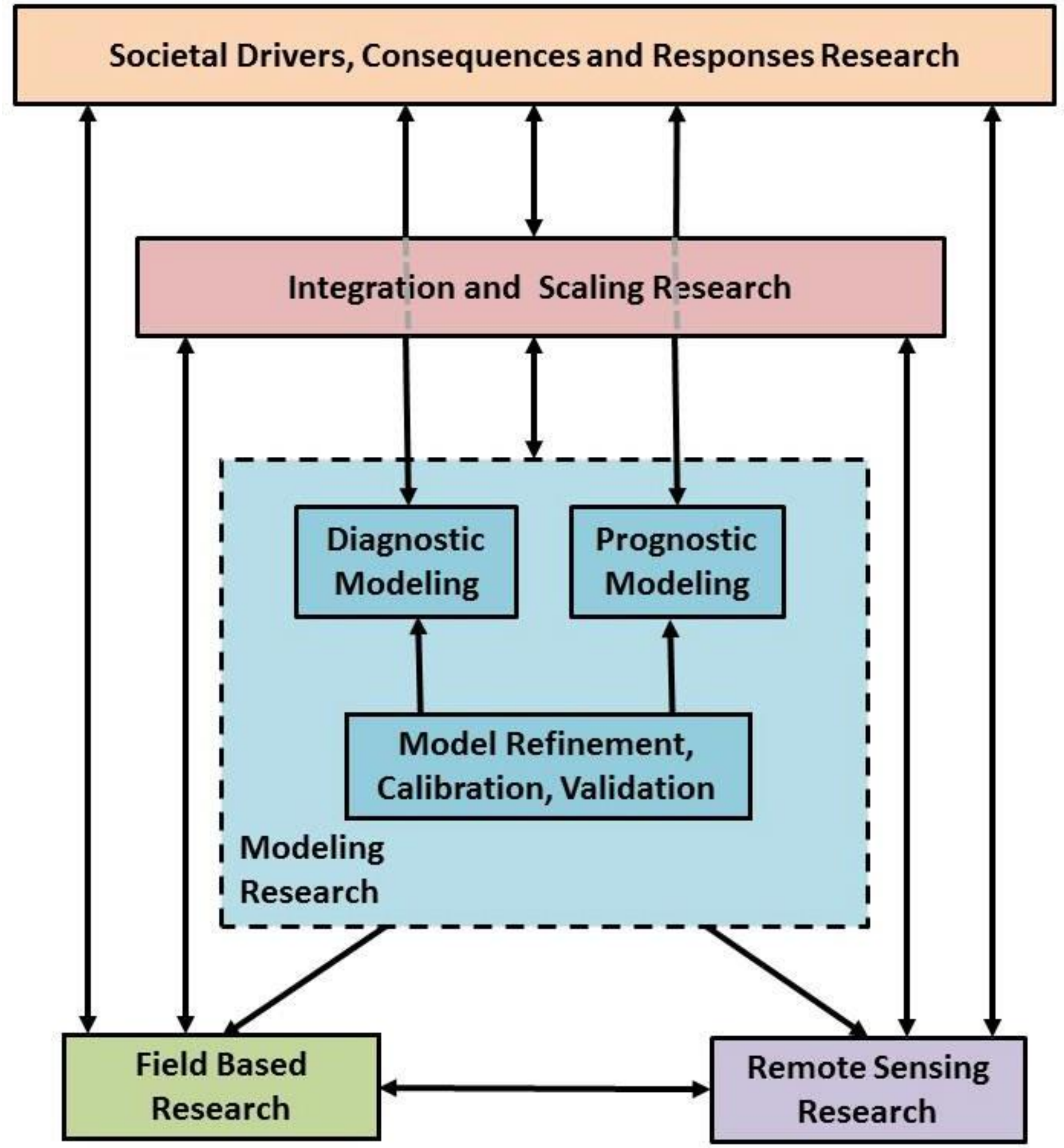
[5] The Science Team would include all researchers involved in Investigator Studies supported by NASA and its Partners, or researchers carrying out activities within Partner organizations that are contributing to ABoVE research.

Figure 4.2. *The experiment design for ABoVE is based on Investigator Studies that will carry out research activities in the different areas identified in this figure.*



4.2 Research Activities

4.2.1 Field-based Research

Previous field studies have demonstrated that dynamics of Arctic and boreal ecosystems are driven by highly-coupled processes that together determine the region's resilience and vulnerability to climate change and other external forcing. To address the Tier 2 science objectives, the knowledge gaps and key research areas identified for each Science Theme in Chapter 3 require studies, data collections, and interdisciplinary approaches to field-based research to support an integrated understanding of ecosystem change. To this end, field studies during ABoVE should contribute towards an improved mechanistic understanding of the most critical processes and their interactions needed to address the Tier 2 objectives, and towards determining the ecological impacts of these changes. Finally, field-based research should focus on mechanisms underlying relationships that can be generalized across the applicable areas of the Study Domain.

Both field-based research from ABoVE and data from a variety of other sources are needed to provide quantitative information to identify baselines, rates and directions of change, regions of stability, and causes and consequences of ecological change, from landscape and regional to domain-wide scales over seasonal to annual to inter-annual to decadal time scales. Data and results from field-based research are required for both modeling (Section 4.2.4) and for assessing the impacts of environmental change on ecosystem services (Section 4.2.2) (Figure 4.2). Field-based research for ABoVE should not only use data collected during the Intensive Study Period during Investigator Studies, but also data collected during previous and ongoing field-based studies that are not directly supported through ABoVE, from monitoring networks, and from field-based inventories. In selecting locations for Investigator Sites, researchers should be encouraged to use sites with previous and ongoing research, including sites associated with research stations, when their activities are compatible with the other work being conducted at these sites (see Appendix A). Using datasets from multiple sources requires that Investigator Studies devote attention to harmonization and incorporate integration and synthesis activities into their plans for using field research at specific Investigator Sites (Section 4.2.5).

Investigator Studies for ABoVE should be encouraged to develop collaborative research approaches that incorporate ongoing field research and monitoring funded by partner organizations or projects[6]. This will allow NASA and partner organizations to support Investigator Studies that are focused on addressing critical research gaps. This will allow for a range of field-based approaches in individual Investigator Studies, including (but not limited to): a) direct monitoring and measuring of processes and their interactions; b) space-for-time

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[6] Examples of large-scale or long-term monitoring and research projects that provide opportunities for collaborative field-based research during ABoVE include the National Ecosystem Observation Network (NEON) and the Long Term Ecological Research projects in Alaska and the Climate Impacts on Productivity and Health of Aspen (CIPHA) and Changing Cold Regions Network (CCRN) projects in Canada.

substitutions to understand long-term influences of climate change and disturbance; c) experimental manipulations to test causality on relatively short timescales; and d) retrospective studies employing tools such as dendrochronologies and sediment cores to quantify historic rates of ecosystem change and compare these to current dynamics.

Addressing many of the Tier 2 science objectives will eventually require results from research from multiple Investigator Studies be integrated and synthesized (Section 4.2.5). The data and results obtained through field-based research at individual Investigator Sites will be important for studies focused on integration and scaling across multiple spatial and temporal scales in several ways (Section 4.2.5). To address the Tier 2 research objectives, data products from airborne and satellite remote sensing will not only be used to study changes to important environmental characteristics (Section 4.2.3), but also for the spatial and temporal scaling of observations obtained during field-based research over a variety of scales (Section 4.2.5). This coupling requires that some of the Investigator Projects selected for the Intensive Study Period include both remote sensing and field research. In addition, some Investigator Studies will be based on the collection of specific Core Variables (Appendix B) in Research Areas not presently represented in monitoring networks, providing the basis for Investigator Studies to study key processes and their interactions at the different spatial and temporal scales; thus, the number of Core Variable sites will not be the same for each Research Area, and different Core Variables may be collected at different locations within a Research Area. Finally, integration, synthesis and scaling research also requires that the Implementation Plan developed by the Science Team includes identification of common protocols for the collection of similar field based data at multiple Investigator Sites.

4.2.2 Societal Drivers, Consequences and Responses Research

Research across all of the Science Themes is needed in order to address all components of the overarching science question for ABoVE: ***How vulnerable or resilient are ecosystems and society to environmental change in the Arctic and boreal region of western North America?*** While investigations addressing the Ecosystem Dynamics objectives will certainly result in significant enhancements to our basic understanding of ecosystem, landscape, and land- atmosphere dynamics and interactions, one of the primary motivations for ABoVE is the pressing need for actionable science for stakeholders and policy makers about how human activities are driving, interacting with, and responding to changes in ecosystems. The specific Tier 2 Ecosystem Services objectives were selected because they represent important areas for research where society is vulnerable to the impacts of environmental change over a range of spatial scales. Research investigating the Ecosystem Services objectives may utilize a combination of field data (both quantitative and qualitative), remote sensing data, and modeling approaches. When appropriate, researchers should work with communities to understand how to enhance their research through use of local and traditional knowledge. Some studies will likely rely on data collected by ABoVE researchers working on the Ecosystem Dynamics objectives, but may include data from other sources as well, such as: a) important social-economic and environmental data bases (including those based on local and traditional knowledge) compiled by government and nongovernment organizations (Tables B2 to B4); b) data products generated through integration of remotely sensed data products with other geospatial data; c) data products developed through the integration and synthesis of field-based research conducted during ABoVE and elsewhere; and d) outputs based on using the ecosystem models improved during ABoVE for diagnosis and prediction. The ABoVE research into societal drivers and responses also requires direct engagement of policy makers and stakeholders (Section 4.3) to gain insight into their local ecological knowledge and understand their information needs. This research should explore opportunities for collaboration with ongoing research focused on the responses of society to environmental change that is being sponsored by other agencies.

4.2.3 Remote Sensing Research

Addressing the Tier 2 science questions and objectives requires using existing and new data products derived from satellite and airborne remote sensing systems. Research using these data products should emphasize the unique capabilities provided by remote sensing data products for studying the seasonal and inter-annual variations in the important surface and atmosphere characteristics identified in Chapter 3. Research during ABoVE also needs to take advantage of airborne remote sensors that provide measurement sensitivity, or measurements not currently feasible from satellite systems, including finer spatial and spectral resolution and shorter revisit times. Studies on the synergistic use of different remote sensing data products is also required for analyzing factors that contribute to variations in a specific land surface or atmospheric characteristic. For example, growing season timing (and variance), snow melt, run-off, ground-water recharge rates, and atmospheric CH_4/CO_2 concentrations are all likely to show close temporal correlation at multiple time scales, but the details of these linkages have not been fully explored. Ensuring that the remote sensing data are compiled and co-registered is a key priority for developing a clearer understanding of linkages that are known to exist; thus, one of the most important opportunities for ABoVE is to develop a set of readily accessible, validated data products derived from multiple sensors that can be integrated to form the basis for investigations of ecosystem and societal responses over the entire Study Domain.

At landscape to regional scales, satellite and airborne remote sensing data products will be critical to the spatial and temporal scaling of observations made from field studies (Sections 4.2.1 and 4.2.5). In addition, these data products will be used for initializing, driving, calibrating, and validating models (Section 4.2.4), with the information from airborne data being particularly important for understanding processes that occur at finer spatial and temporal scales than can be measured using satellite observations. Some airborne data products will be needed for refinement and validation of satellite data products (e.g., snow depth, soil moisture, atmospheric CO_2). Finally, the information from some remote sensing data products will be integrated with other geospatial data to provide the basis for developing information products for decision makers and other stakeholders (Section 4.2.2).

A number of different satellite and airborne remote sensing data products are either available or their potential has been demonstrated for use during ABoVE (Tables C1 and C2). These include data products from satellite remote sensing systems that are expected to be deployed over the next several years (SMAP, OCO-2, ICESat-2, Sentinel-1, ALOS-2, and Radarsat

Constellation). Generation of some remote sensing products will require: a) collection of airborne remote sensing data during the Intensive Study Period; b) refinement and validation of existing satellite products for the unique conditions present in Arctic and boreal ecosystems; c) generation of additional products from existing satellite data archives; or d) the development and validation of new products. An evaluation of these remote sensing data products was carried out to identify those with the highest importance for addressing the Tier 2 science questions and objectives[7]. While other products could be used during ABoVE, highest priority should be given to those products presented in Table 4.2[8,9].

Several of the satellite remote sensing data products required for ABoVE will be based on using data collected by Landsat over multiple years (annual surface water extent, land disturbance products, and recovery of vegetation following fire). Production and analyses using these products, as well as integration and analyses using products from multiple sources, would all benefit from the availability of enhanced computational capabilities (Section 4.4). For some types of small-scale investigations, higher spatial resolution satellite data products will be highly desirable.

The specific requirements for the airborne remote sensing data collected during ABoVE should be based on individual Investigator Studies focused on addressing Tier 2 science questions and objectives. In order to study important ecosystem processes it will be necessary to conduct coordinated airborne remote sensing and field campaigns during all seasons, to include sampling throughout the growing season, the shoulder seasons (e.g., late spring and fall), and the winter. The frequency of sampling and sensors to be used will depend on the particular Tier 2 question to be addressed and may be constrained by the feasibility of making airborne and *in situ* observations under certain conditions. An iterative approach could be used for developing the airborne remote sensing campaign for ABoVE based on first determining the level of support available for data collections and identifying specific systems that would be used and their availability. This information could then be used to solicit Investigator Studies for a 3 to 4 year airborne remote sensing campaign that spans Phases I and II (Table 4.1). The selected projects would then provide the locations of Investigator Sites where airborne remote sensing data would be collected, as well as the requirements for the required frequency of data collection.

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[7] For further discussion on ranking the importance of remote sensing data products, see Appendix C.

[8] Table 4.2 and this section do not identify specific airborne sensors, but focus on the types of remote sensing systems (e.g., hyperspectral, LiDAR, SAR, etc.) that are needed to generate specific information products for ABoVE.

[9] Resolution for satellite systems in Table 4.2 are defined as follows: Fine resolution – pixel sizes < 2 m common to commercial satellite systems such as Quickbird, IKONOS, etc.; Medium resolution – pixel sizes between 10 and 100 m common to Landsat and similar satellites; Moderate resolution 200 to 5000 m common to MODIS, AVHRR and similar systems; Coarse resolution – pixel sizes greater than 10 km common to microwave radiometers, scatterometers, and atmospheric sensors.

Table 4.2. *High importance remote sensing data products (Importance Factor = 1 in Table C3) required for addressing ABoVE Tier 2 science questions and objectives. Maturity levels are based on NASA definitions discussed in Appendix C. (Maturity of satellite data products: A – research grade products where algorithms require further development and validation; B – Products based on existing algorithms that require further refinement and validation for the conditions present in Arctic and boreal regions; and C – Existing algorithms whose accuracies have been well quantified can be used to generate data products for ABoVE. Multiple sources are available for some of the satellite remote sensing data products, and are identified in Table C1).*

	Satellite Remote Sensing Data Products			**Airborne Remote Sensing Data Products**
		Domain Wide	**Landscape to Regional**	
Required Information	**Resolution**	**Maturity**	**Maturity**	**Airborne Sensors**
Seasonal Snow Depth	Coarse	A		Small footprint LiDAR, SAR, Microwave Radiometer
Atmospheric mole fractions of CO_2	Coarse	B		CARVE Payload, AFT
Snow extent time series (single product)	Moderate	B		
Soil Moisture	Coarse to Moderate	B		Microwave Radiometer, SAR
Wetland maps	Medium	B		
Winter thaw events	Coarse	B		
Annual maps of surface water extent (lake/pond)	Medium	C		
Forest cover change	Medium	C		
Area extent and severity of biotic disturbances	Medium		A	
Burn Severity (organic layer consumption, mortality, etc.)	Medium		A	Small footprint LiDAR, InSAR
Active layer (depth of thaw) dynamics	Medium		A	
Distribution and extent of thermokarst features	Fine to Medium		A	
Post-disturbance soil moisture	Medium		A	Microwave Radiometer, SAR
Post-disturbance vegetation recovery	Medium		A	
Anthropogenic disturbance	Fine to Medium		A	
Biomass/canopy Structure	Fine			Small footprint LiDAR, InSAR
Deep substrate properties	Fine			Electromagnetic Resonance Imager, SAR
Vegetation Composition	Fine			Hyperspectral Imager
Atmospheric CO_2, CH_4, CO	Fine			CARVE Payload, Airborne Fourier Transform
Season Surface Deformation	Fine			Small footprint LiDAR, InSAR

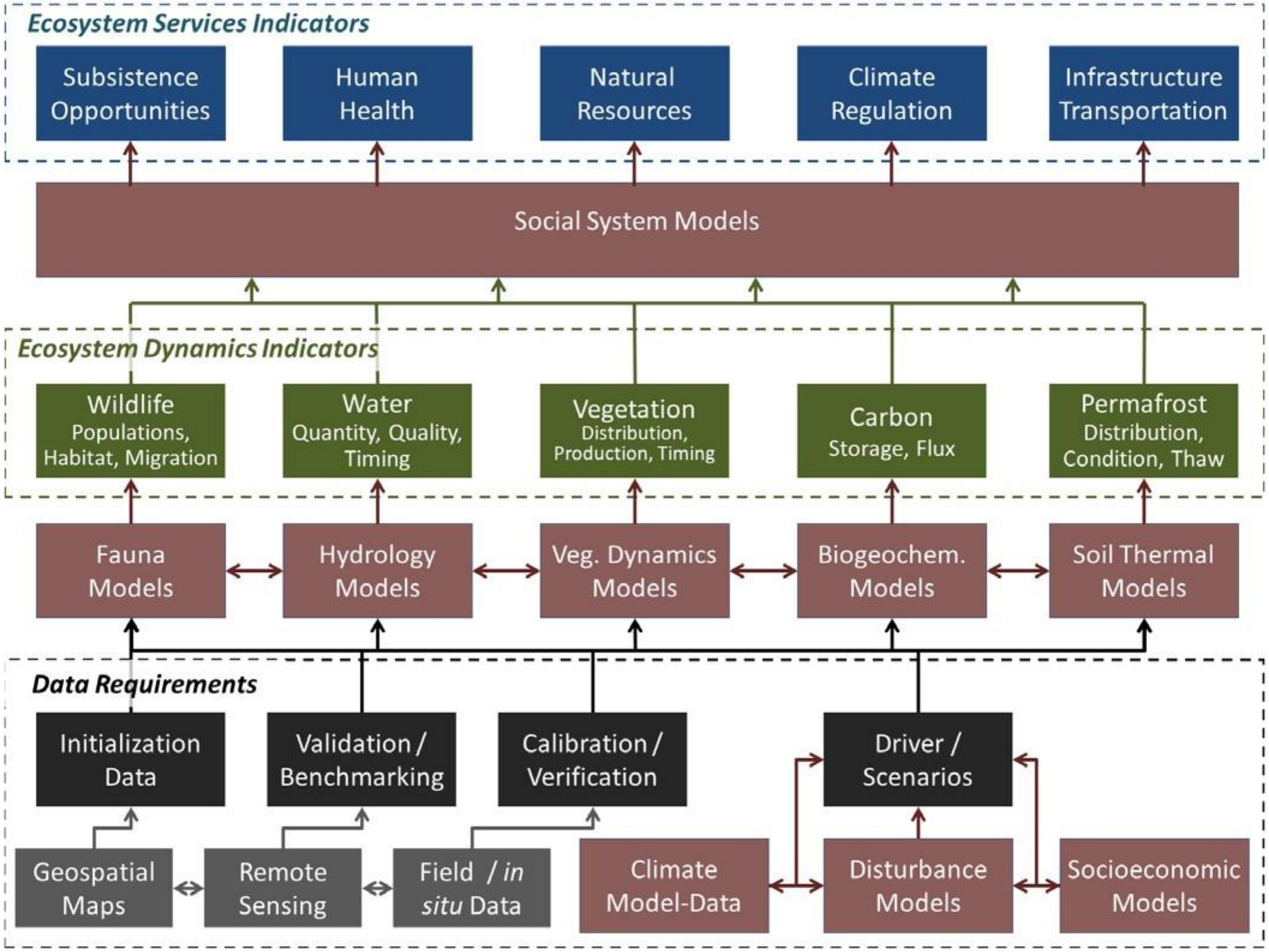
Field measurements will be required to provide the data needed to develop, refine, and validate remotely sensed data products, including field-based remote sensing observations. For some studies, these field observations will be a component of the data collected for field-based research or data collected from measurement networks; however, some investigations will likely require additional field based observations. The Implementation Plan developed by the Science Team should identify common protocols for the collection of similar field data needed for development, refinement, and validation of remote sensing data products at multiple Investigator Sites.

4.2.4 Modeling Research

Modeling provides an integrating framework for translating data from the field and remote sensing studies into diagnostic and predictive information products for scientific analysis and decision support (Figure 4.2). The data collected and knowledge gained from field and remote sensing studies should be incorporated in models explicitly for reducing the high-priority uncertainties that have been identified in Chapter 3. Diagnostic modeling is required to assess the rates, extent and severity of changes and their impacts on the key indicators of ecosystem dynamics across the Study Domain. Models should be run in simulation experiments to parse out the relative effects of various controls and sensitivities, and such experiments will be used in ABoVE for attribution of and sensitivity to the drivers of change. Models run in prognostic mode should provide information on possible outcomes for ecosystem services under different scenarios that will be used as a basis for decision support. The format, resolution and information content of model output will need to be carefully considered with an aim to facilitate model-data integration and interoperability for assessing various decision support outcomes.

Addressing the Tier 2 science questions and objectives will require a portfolio of physical, ecological and socio-economic models that simulate the processes that impact the key ecosystem services identified in the ABoVE science objectives (Figure 4.3). There are general categories of model types needed to address each ABoVE science question, across which there are common data requirements. Modeling research is needed across each of these categories, where disciplinary-focused models designed to address a particular theme-based, Tier 2 science question are aligned with a particular theme-based, Tier 2 science question. Because a suite of models already exists across these categories, modeling research should focus on the Ecosystem Dynamics objectives, which in turn, will provide the basis for also addressing the Ecosystem Service Objectives (Table 3.2). Because of the interdisciplinary nature of the objectives, this research will require integration of several of the model types. Terrestrial biosphere models (TBMs) already encompass some combination of model types linking various ecological and land surface processes, and these frameworks provide the foundation for simulating many of the key indicators of ecosystem dynamics. In many cases, TBMs or other frameworks will need additional integration with ecological and/or socio-economic models or features as required to address a particular science objective. Integrated social-ecological system models (e.g., agent-based simulations with empirically derived parameters) are an important part of this framework. They will be needed to link responses in socio-economic and

Figure 4.3 *Modeling research during ABoVE will involve a portfolio of model types (red boxes) needed to simulate the key ecological indicators (green) that impact ecosystem services (blue), across which there are generic needs for data (black) that can be satisfied by research products generated during ABoVE (gray).*



ecological indicators to consequences for ecosystem services and the social systems that depend on them.

Depending on the type, there are various datasets needed for initializing, driving, calibrating and validating models used in ABoVE research, in particular data collected as part of the field-based research described in Section 4.2.1. Initialization and driver data will be provided through local site characterizations and meteorological data from the Core Variable Sites and other field-based research conducted during ABoVE. For Domain-wide modeling research, initialization data will be primarily in the form of geospatial maps of key variables, and driver data may include gridded climate reanalysis products and remotely-sensed disturbance detection, for example. In many cases, initialization and driver data are already available from other sources or are being developed in pre-ABoVE projects. Field-based and remote sensing research conducted during ABoVE will improve the availability and quality of known critical initialization and driver data gaps, such as increasing the density of meteorological observations across the Study Domain, broadening the characterization of soil and permafrost conditions, and developing model-ready lake cover, vegetation and fire datasets. Important to the success of ABoVE modeling research, is organizing these critical driver datasets from previous/historical observations, as well as developing driver datasets for future scenarios. In general, calibration data are needed to guide model formulation and parameterization at site-level or local scales. For some of the most common requirements across multiple model types, calibration/verification datasets will be collected as part of the Core Variables (Appendix B). Model validation should be an ongoing activity throughout ABoVE as a means for assessing model performance with respect to confidence in diagnosing and predicting changes in the key ecological and social indicator variables. Whereas model calibration/verification will rely more on site-level *in situ* data, model validation should be performed across a broader spectrum of spatial and temporal scales. This requires a larger effort within ABoVE to organize the necessary set of benchmark datasets on the key indicators within a data management system that can be readily used for model validation. This effort will need to rely more on remotely sensed data and other geospatial map products that provide broader coverage of the Study Domain. Initial model benchmarking should make use of satellite-derived remote sensing products representing key variables (Tables C1, C2, and 4.2). Assessment benchmarking should continue with updated model validation activities that incorporate new spatial data products developed during ABoVE, particularly with observations of the key variables based on airborne remote sensing (Table 4.2).

4.2.5 Integration and Scaling Research

Addressing the cross-cutting research objectives for ABoVE requires an integrated, systems-level understanding of historic, current and future resiliency and vulnerability of Arctic and boreal social-ecological systems to change. As such, **Integration and Scaling Research** will necessarily play a key role in the overall study design as a means for connecting and translating results from field, remote sensing and modeling research toward a broader knowledge-base, with direct application to the information products needed for decision support and research on societal responses to changes to ecosystem services (Figure 4.2). While some of the science objectives require studies focused on a single thematic area, many are cross-cutting in nature and thus require a research strategy that targets important processes and their interactions across multiple scales in time and space. This requires a well-orchestrated plan for integration and scaling of the results from the individual Investigator Studies conducted as part of ABoVE, as well as with previous and ongoing research across the Study Domain. ABoVE should emphasize the development of frameworks that will facilitate the ability to a) project trajectories of change in ecosystem structure and function in the Study Domain over decadal time scales; b) evaluate the potential impacts of these trajectories on the key ecosystem services provided to society; c) assess the consequences of changes in services for human societies; and d) understand how societal responses to these consequences feedback to the social-ecological system.

ABoVE should promote the use of a diversity of conceptual frameworks that are collectively capable of addressing a broad range of assessment issues relevant to the Tier 2 science objectives. While integrated modeling will play an important role (Section 4.2.4), Integration and Scaling Research during ABoVE may take various forms depending on the science objective, data availability, and the phase of the activity. This research could include, for example: a) the temporal extension of key datasets and new understanding of system response through data synthesis and novel analyses across studies; b) the spatial scaling of individual studies across larger domains through remote sensing, geospatial mapping and analysis of environmental and social correlates; and c) the development of decision support products related to the vulnerability/resiliency of ecosystem services to change through integrated social and ecological studies. Whatever the form, the design of a conceptual framework must clearly identify its scope and intended use for addressing ABoVE objectives, including a description of the key processes and a mechanism for connectivity between them. Because of the importance of Integration and Scaling Research in addressing ABoVE objectives, there needs to be a coordinated and well-designed planning effort among the Science Team from the beginning of ABoVE to ensure that data are interoperable and research synthesizable across studies. This planning effort should also include key stakeholder groups so that careful consideration is given to developing data products at the scale and information content that maximizes their value for decision support.

Integration and Scaling Research is not envisioned to be only a concluding activity for ABoVE, but rather should take place throughout the duration of the Field Campaign. Initial activities in this area are required for providing the connection between ABoVE research and previous studies while determining the most important gaps in knowledge needed to address the Ecosystem Dynamics objectives. This research should also focus on identifying the spatial and temporal gaps in key datasets associated with these uncertainties in system-level understanding. The assessment of critical data gaps will form the basis for the prioritization of a) the field, remote sensing and modeling studies to be conducted in the latter phases of the Intensive Study Period and b) the key partnerships and collaborations with other relevant on-going research that need to be fostered. Data collection and research activities throughout the latter phases of ABoVE will be guided by the frameworks developed during this initial phase of Integration and Scaling research. After the initial phase, research should then focus on using these frameworks to build connections across the first set of results from the individual

Investigator Studies as they become available. Such integrated studies provide the opportunity to spatially expand datasets and results from individual studies across the different Research Areas to the larger Study Domain, as well as temporally extend previous research with data collected during ABoVE. Following the completion of the Intensive Study Period, new insights and understanding will be gained by employing frameworks for synthetic research that links the individual studies conducted during ABoVE across the various types of research activities (i.e., field, remote sensing and modeling) and different scientific disciplines (as represented by the Tier 2 science questions). This final phase of Integration and Scaling research should emphasize the integration of ecological and social science studies to address the Ecosystem Services objectives.

4.3 Decision Support Activities

Table 4.4 presents the societal objectives from Chapter 3 and gives examples of potential decision-support outcomes that may result from the individual investigations that are part of ABoVE. It is important to note that the research needed to address each Ecosystem Services objective will have its own respective spatial/temporal scales and set of decision makers. For example, the research required to evaluate the impact of environmental change on subsistence opportunities will need to engage with local communities to identify the questions, observations, and needs. Scientists studying human health and wellbeing may partner with public health officials or public works managers, as appropriate. Projects investigating changing conditions for natural resource use and extractions would presumably work with managers and policy makers in the government, private (NGO) and commercial sectors.

To address the Tier 2 Ecosystem Services objectives requires creating opportunities for meetings between ABoVE researchers and a variety of stakeholders for the purpose of: a) more clearly defining the research needs of stakeholders with respect to the Tier 2 Ecosystem Services objectives; b) informing stakeholders of planned research activities; c) discussing research results with stakeholders; and d) evaluating the utility of the decision support products based on the results from ABoVE activities. Addressing this set of needs requires that decision support activities continue throughout the ABoVE time period. These activities could include workshops or meetings focused on the decision support needs for specific Ecosystem Services objectives that includes stakeholders from different groups (e.g., local communities, state/provincial/territorial government, tribal government, federal government, industry, non-government organizations) as well as meetings with groups (e.g., local communities, state/provincial/territorial government, tribal government) that are interested in impacts on a range of ecosystem services. Developing a plan for meeting with different stakeholder groups for these decision support activities should include ABoVE Partners who are already conducting outreach/engagement activities. This plan should also be coordinated with other public engagement activities that are part of ABoVE (Section 5.5.2).

Table 4.4 *Examples of important decision support outcomes for the Tier 2 Ecosystem Services objectives*

Tier 2 Ecosystem Services Objectives	Example Decision-Support Outcomes
1. Evaluate how changes to ecosystems will influence subsistence opportunities.	Community planning for access to traditional hunting/recreation areas, subsistence harvest regulations, seasonal location of subsistence species (e.g., migratory caribou).
2. Evaluate how changes to ecosystems will influence natural resource use and extraction.	Land management planning and permitting for recreational, extractive, and renewable resource use.
3. Determine how changes to disturbance regimes, flora and fauna, permafrost conditions, and/or hydrology influence human health outcomes in the ABR.	Public health strategies for protecting and improving food security, reducing disease exposure, etc. Best practices for drinking and wastewater management.
4. Assess how future climate warming is likely to affect infrastructure and transportation networks.	Civil and environmental engineering, urban planning and design for future infrastructure, retrofit/replacement of existing infrastructure Planning and support for winter transportation networks
5. Determine the sources of variations in climate feedbacks from Arctic and boreal ecosystems and assess the potential for future changes to climate regulating services at regional to global scales.	Land management planning for climate change mitigation Informing national and international organizations formulating climate mitigation policies.
6. Determine the degree to which the changing environment and altered human activities results in self-reinforcing/synergistic and/or self-attenuating/antagonistic changes in ecosystem services.	Holistic, cross-sectoral planning and adaptive management activities.

4.4 Data and Information System Requirements

Experiences with past NASA field campaigns (BOREAS, LBA-ECO) and large-scale, interagency programs (NACP) have clearly demonstrated the importance of developing data and information management approaches that allow for archiving and sharing of data, and sharing and communicating the results from scientific research. In addition, based on the needs to support research in the field of macrosystems ecology as well as the demanding requirements for the processing, integration, and analysis of field observations in combination with data from remote sensing systems, the approaches for development of data and information systems are continuously evolving, driven by research funded by a number of organizations, including NASA. The data and information system for ABoVE should provide: a) support for a wide range of planning activities for the duration of ABoVE; b) the means to ingest, compile, store, and distribute the data, products, and results from the individual Investigator Studies; c) access to and the capabilities needed for the integration of the wide range of data required for the individual investigations; d) the ability to use new approaches for processing and analyzing complex datasets that incorporate field observations, remote sensing, and modeling; and e) the means for delivering information and data products required by decision makers and other stakeholders.

Development and implementation of the final plan for ABoVE will involve a wide range of planning activities that will require the sharing of data and information among different investigators as well as project managers at NASA and its Partners. These activities should commence as soon as possible and prior to the start of the Intensive Study Period. Information on data availability, logistics, and Partner activities will also be required to aid individual investigators as they prepare proposals. During ABoVE, information will be needed for planning many aspects of the research, especially that carried out during the Intensive Study Period, including selection of Core Variable Sites and planning for airborne remote sensing data collections and coordination of a variety of activities that are carried out as part of ABoVE. Finally, the planning activities should include developing a data sharing policy for the data and products that are created during ABoVE. In order to ensure the broad scientific and societal benefits anticipated from ABoVE, the data policy should be as free and as open as possible.

The data and information system for ABoVE should provide for other key components of the data life cycle for individual research investigations. To provide a framework for specific activities, NASA and its Partners should develop guidelines for data management plans that will be required for each investigation, including guidelines for metadata, quality assurance/quality control, and the format for different datasets that are shared among the Science Team and Partners during ABoVE. Planning activities should also consider: a) the responsibilities, procedures and computational infrastructure needed to collect, analyze and share the observations, measurements, results, and outputs from the research from investigators affiliated with ABoVE; and b) the documentation required for submitting the data and data products from ABoVE to long term archives. The timely availability of data across individual Investigator Studies conducted during ABoVE can greatly aid synthesis and integration in latter stages of the Field Campaign.

Investigations during ABoVE will require access to a significant number of data that have been or are being collected, compiled or generated by other organizations (see, e.g., Tables B2, B3, B4, B5, C1 and C2). Many of these datasets reside in existing data and information systems, and many datasets are curated and shared in cooperative or formal networks. The plan for designing and implementing the data and information system for ABoVE, should include activities devoted to accessing the specific datasets required for ABoVE, including the activities for integration of key datasets.

There are currently ongoing efforts in NASA and other organizations focused on developing systems that allow individual researchers to bring their models and algorithms and data into cloud-based storage and compute environments, which provide researchers with large amounts of data storage, high performance computing capabilities, and very high speed interconnects. Several pre-ABoVE projects selected by NASA are using a NASA cloud-based system for generation of data products that require the processing of large volumes of satellite remote sensing. If such cloud-based systems technology proves feasible and affordable, NASA should consider adopting it for use in ABoVE.

Finally, an important role for the data and information system will be the services it provides to support the development and delivery of data products tailored for use by decision makers. The decision support workshops recommended in Section 4.3 will identify products that are needed for decision support and the approaches required for the generation of these products. Since the data and information system for ABoVE has a finite lifespan, NASA and its Partners will need to work with these stakeholders to develop a plan for the transfer of capabilities to them.

5. Implementation Requirements

5.1 Schedule of Activities

The timeline presented in Table 4.1 and discussed in Section 4.1.2 assumes that an initial set of Investigator Studies could be initiated within 9-12 months following the delivery of this report, with the first major field activities then starting as soon as 2016, provided infrastructure and logistics support are available and necessary permits and permissions have been obtained. Because of the advanced preparation required to plan and schedule an airborne remote sensing campaign and align it with planned field activities, it is anticipated that the first airborne remote sensing data collection would not begin until a year or two after the field activities begin (Table 4.1). It is expected that NASA's Carbon Cycle and Ecosystem (CCE) Office will coordinate meetings between ABoVE researchers and relevant stakeholders in advance of beginning any field investigations. Throughout the ABoVE time period, meetings and workshops for stakeholder engagement and decision support activities should be organized and conducted in order to establish an ongoing dialogue regarding their information needs and to identify which of those needs ABoVE might be able to meet (Section 4.3). The results from these meetings would provide guidelines for ABoVE researchers to follow as they collect and analyze their data and prepare to make it available for decision makers. As the Intensive Study Period ends, ABoVE will move into an analysis and synthesis phase where there will be opportunities for new investigations focused on synthesis, integration, and scaling of the results from the earlier phases of ABoVE (Section 4.2.5). These studies could utilize data that have been archived within the Data and Information System, including Core Variable data, results from field-based studies, airborne and satellite remote sensing data, derived data products, and model products.

5.2 Science Team Activities

The ABoVE Science Team should include all researchers involved in the Investigator Studies funded by NASA and ABoVE researchers or ABoVE-affiliated researchers involved through agreements with Partners. Membership on the Science Team should be open to any researcher carrying out studies that are relevant to ABoVE, including those funded as part of a range of NASA post-doctoral programs. In order to ensure effective coordination of research activities and timely exchange of findings, the ABoVE Science Team should meet regularly – at least once per year – for the duration of ABoVE. When possible, ABoVE should schedule joint meetings with the science teams from other relevant large-scale research activities that are being carried out by Partners.

While this Concise Experiment Plan provides the overall framework for the research to be conducted during ABoVE, an Implementation Plan detailing the specific activities to be carried out (what, when, where, for how long, etc.) will be prepared based upon the Investigator Studies that are funded by NASA and its Partners, as well as other activities that are conducted through formal and informal collaborations with NASA. NASA should identify a Lead Scientist for ABoVE, whose responsibilities would include heading the Science Team, scheduling and developing the agendas for Science Team meetings, leading the development of the Implementation Plan, and coordinating synthesis activities initiated by the Science Team.

The Science Team should develop a plan for field measurement protocols and data organization (Section 4.2.1), as well as for the development, refinement, and validation of the remote sensing data products (Section 4.2.3). Because addressing the ABoVE Tier 2 science questions and objectives is expected to require significant ongoing modeling research and application activities, the Science Team should aid in the development of a plan for coordination of the modeling research for ABoVE with that being carried out by other organizations, particularly modeling activities being carried out by NASA Partners (Section 4.2.4). This plan should also address the various elements of the modeling research that need to be coordinated across investigations, including identifying benchmark data products and variables that are needed to initialize, drive, validate, and calibrate different models. In addition, investigators carrying out modeling research should participate in workshops with stakeholders to identify the needs of models for diagnosis and prognosis to address objectives related to the consequences of and responses to the impacts of environmental change (Section 4.3). While integration, synthesis, and scaling activities will occur within individual Investigator Studies (Section 4.2.5), it is anticipated that the Science Team will need to initiate some broader analysis and synthesis activities.

5.3 Planning and Logistics Support

In addition to organizing and supporting the annual Science Team Meeting (Section 5.2), NASA's CCE Office will be responsible for a number of activities to support planning for ABoVE and the Investigator Studies. First, support will be provided for a range of planning activities, including: a) planning by NASA and its Partners for organization of the various components of ABoVE; b) planning activities that are carried out by the Science Team; and c) planning for airborne remote sensing campaigns. Second, the CCE Office will arrange for the logistical support that is needed across studies (Section 5.3.1), in particular where Investigator Studies collecting Core Variables do not continue throughout the entire Intensive Study Period. Third, the CCE Office should provide support for the continuous collection of Core Variables throughout the Intensive Study Period. Fourth the CCE Office will assist the Science Team in planning and providing support for the decision support meetings and workshops (Section 4.3). Fifth, the CCE Office will coordinate outreach and engagement activities during ABoVE (Section 5.5.2). Sixth, the CCE Office will provide a Data and Information System capability to support ABoVE needs for data and information system services (Sections 5.4 and 5.5). In addition, support for the collection of Core Variables will be needed, specifically for those Core Variable Sites that require the installation and maintenance of equipment (Section 5.3.2), and it is recommended that the CCE Office assume this responsibility. It is also recommended that the CCE Office provide support in the compilation and integration of critical external datasets at the beginning of the Intensive Study Period (Tables B2 to B4), and assist in the compilation of datasets and products generated from Investigator Studies that are needed for research on synthesis and scaling, modeling, and decision support.

A number of logistical issues will have to be addressed in the planning for and implementation of ABoVE. These include securing required permits and permissions for field and airborne research, the support of the field-based research of Investigator Studies, the installation and maintenance of observational infrastructure and the collection of data at Core Variable and Remote Sensing Sites, and the support of collection of airborne remote sensing data. Some of the critical elements for these activities are discussed in the following sections.

5.3.1 Support of Field Activities

Individual Investigator Studies conducted during the Intensive Study Period will require support for the planning and coordination of research at the Investigator Sites. All research carried out as part of ABoVE will require permission from the owners/administrators of the land where the studies are being carried out, and in some cases, research permits will have to be acquired. Because access to field sites requires multiple layers of state, territorial, federal, tribal, and indigenous peoples' approvals, the CCE Office should be responsible for coordinating with ABoVE partners the applications for permissions and permits for all Investigator Studies. In many Research Areas, facilities exist to provide logistical support for researchers, including Research Stations within existing research areas. Since the capacity of these facilities and stations is limited, especially during the summer field season, the CCE Office will coordinate the activities of individual Investigator Studies as needed. Some Research Areas are in remote regions where logistical support does not currently exist. The CCE Office will need to develop a coordinated plan, including travel to and from the Investigator Sites when necessary, for research in these areas. Finally, there are many areas for risk management that need to be addressed for research carried out at Investigator Sites. These risks include unpredictable and harsh weather, the operation of motor vehicles, boats and aircraft in remote regions, threats from wildlife that are common in many areas, and the limited access to emergency medical care. Following established practices for NASA field campaigns, the CCE Office will develop and implement a risk management plan for ABoVE, including safety training for researchers participating in field-based activities.

5.3.2 Core Variables

The number of Core Variable Sites will be constrained by the cost of installation and maintenance of the infrastructure and instrumentation required to collect the data, and the degree to which organizations collaborating with NASA are willing to share existing data or the costs of data collection. In addition, the selection of Core Variable Sites that involve high costs for installation and maintenance of instrumentation will take into consideration the locations and distribution of sites where Core Variables are currently being collected (e.g., existing weather stations, eddy covariance carbon and energy flux towers, continuous soil temperature and moisture loggers) (Section 4.2.1).

5.3.3 Airborne Remote Sensing

Airborne remote sensing campaigns will require coordination for data collections across the Study Domain. Coordination is needed with respect to the field data being collected for refinement and validation of data products at different sites, collection of data from multiple airborne systems over the same site, and collections on the same days when data from medium-resolution satellite remote sensors are being collected. Planning for the collection of airborne remote sensing data also needs to account for obtaining permission for the use of airspace over and between the Investigator Sites being measured as well as consultation with the local communities, tribal authorities, and other stakeholders in the regions to be overflown. The CCE Office should work with the individual Investigator Studies using airborne remote sensing data and the managers for the different airborne platforms being used in developing and implementing a plan for the airborne remote sensing campaigns.

5.4 Data Management

A key activity for the CCE Office is the development of a Data and Information System for ABoVE, including providing the range of data management services identified in Section 4.4. Important considerations in the implementation of the Data and Information System should include coordination with the data management activities across NASA, its Partners, and other data management and cyber-infrastructure efforts that are being carried out by other organizations in the Study Domain. The CCE Office should participate in interagency and international efforts to promote, coordinate, and share Arctic cyberinfrastructure, and should implement for ABoVE and promote among ABoVE Partners a “Data-as-a-service” approach to cyberinfrastructure design. The CCE Office should also be responsible for exploring opportunities for efficient, cost-effective computational capabilities to support ABoVE’s data storage, processing, modeling, and data management needs.

5.5 Training, Education, and Public Outreach

ABoVE should include activities to expand both training and education across a broad community that includes students, early career scientists and the public. The Investigator Studies for ABoVE should include a training, education, and public outreach plan that provides formal educational opportunities through the proposers' institutions and other institutions within the Study Domain, and anticipates informal education and public outreach opportunities.

In addition, there are a number of ongoing activities within the Study Domain focused on K-12 education and public outreach, many of which are sponsored by Partners. In collaboration with the Science Team and Partners, the CCE Office should develop an education and outreach plan to coordinate the activities discussed below.

5.5.1 Education Activities

Education activities during ABoVE should include activities directly incorporated into the Investigator Studies and undertaken by the CCE Office, as well as participation by researchers affiliated with ABoVE in a wide range of programs specifically targeted at education and training. Through these activities, ABoVE should strive to develop a broad portfolio that includes education at all levels, from K-12 to vocational training, undergraduate, graduate, and post-doctoral students at colleges and universities, and the public. Researchers leading Investigator Studies should be encouraged to include technicians, undergraduate and graduate students and post-doctoral fellows on their projects. In addition to being directly involved in research, these students and post-docs should be encouraged to attend and participate in the annual Science Team Meetings, which in turn should be organized to highlight the contributions of this important group of researchers. NASA should consider the possibility of supporting post-doctoral researchers through the CCE Office to help organize, support, and/or conduct the data integration and synthesis activities of the Science Team.

5.5.2 Public Outreach

Opportunities for capacity building and public outreach abound across the Study Domain, including communications activities that are necessary to engage important stakeholders at all stages. The CCE Office should coordinate ABoVE public outreach during initial consultations, permitting, throughout the research phases, and at the end of the field campaign. Researchers involved in Investigator Studies should be expected to take advantage of time in the field to work with community colleges, museums, community centers, tribal councils, and other local organizations in outreach activities. In addition to participating in meetings or public presentations, researchers should also meet with members of the local print and broadcast media. These interactions can occur in a variety of ways with specific goals: social media (Facebook, Twitter, etc.), meeting with print and broadcast media, community science presentations, and tours of research sites. ABoVE researchers should be encouraged to participate in these activities. To facilitate outreach activities, the CCE Office should identify the important organizations and contacts for outreach in the different Research Areas. In identifying these contacts, the CCE Office should work with Partners and individual members of the Science Team who are already actively engaged in outreach activities. When appropriate, the CCE Office should provide assistance in coordinating outreach activities for researchers at the times they are working at their Investigation Sites.

5.6 Interactions and Partnerships

5.6.1 Engagement with Local and Regional Stakeholders

ABoVE will need to interact with and/or develop partnerships with indigenous peoples on whose land the research will take place as well as others with land ownership/usage rights. Such interactions with local communities, local, regional and national government organizations, and other stakeholders with interests in the ABoVE study domain will also be essential. These interactions will require early engagement, sustained attention, and appropriate acknowledgement – and must occur early in the preparation for ABoVE field activity and prior to site selection and the initiation of any field research. In some cases, these interactions may need to be coordinated with those of groups with existing activities in the same area.

The sustained engagement of local communities and aboriginal leaders and organizations will be of paramount importance within the Study Domain. Direct consultation and following established procedures in obtaining permissions, which will vary across jurisdictions, will be required. In some cases, such interactions are anticipated to lead to involvement of local people in ABoVE research and implementation activities and/or collaborations involving citizen science.

Also, ABoVE will need to support sustained interactions with organizations participating in ABoVE education and outreach activities as well as decision makers whose information needs may be met by ABoVE data and research products. These interactions are addressed in Sections 4.3, 5.5.1 and 5.5.2 of this report.

The CCE Office will need to organize and coordinate many of these interactions in order to ensure 1) they are timely and responsive to each partner's desires/requirements and 2) partners can engage efficiently with ABoVE as a whole as well as with multiple investigator teams working in their area(s) of interest. The specifics regarding which partners to engage and how the partnerships should be nurtured will follow as the ABoVE study design is finalized. Some partners are already engaged, some have been contacted, and others are yet to be identified or contacted. At this time, the key point is that partnerships with local and regional stakeholders will be essential and must receive early and appropriate attention by ABoVE management and researchers.

5.6.2 Engagement with Researchers and Resource Managers Working within the Study Domain

ABoVE research will be complementary to research and management activities being conducted contemporaneously by other programs and projects within the Study Domain, both in the U.S. and in Canada – and in many cases, with certain shared goals and objectives. In order to take full advantage of opportunities for synergistic interactions and to maximize the return on resource investments that ABoVE sponsors will make, strong, mutually beneficial partnerships with these programs and projects should be developed. The remote sensing-oriented, landscape-regional scale and integrative social-ecological science emphases of ABoVE should offer potential partners unique data, perspective, and context for their own work. For ABoVE, such partnerships should enable deeper understanding of processes and access to a richer and more diverse set of field-based observations, analysis, and modeling approaches. Together, ABoVE partners should be able to create new opportunities for synthesis and multi-disciplinary interactions that would help address the scientific and/or decision-support aspirations of all parties. ABoVE also may be able to help address certain data access and interoperability challenges faced by all.

It will be important to build upon and leverage international collaborations in the implementation of ABoVE. In addition to Canada, where the prospects for substantive partnerships are especially strong, ABoVE should pursue collaborations with other potential international partners who have maintained long-term measurement sites and who have acquired long time series of remote sensing images and derived products for Alaska and Canada (e.g., Japan, Europe, the European Space Agency). Interactions and collaborations with international groups working in Arctic and boreal ecosystems in eastern Canada and Eurasia are also of interest for sharing knowledge of these systems and in developing a pan-Arctic, circumboreal perspective on vulnerability and resilience. When ABoVE moves into its synthesis and integration phase, direct collaborations to yield a northern high latitude synthesis should be pursued.

The ABoVE study design described in Chapter 4 has been crafted to take into account existing field programs and infrastructure and therefore enable ABoVE managers to incorporate into their plans partnerships with scientists, managers, and funding sponsors of these programs and projects. The nature of these partnerships could vary from informal "best-effort" agreements to collaborate on specific tasks or share datasets, to exchanges of letters that document more substantive collaborations (perhaps with some interdependencies), to highly-structured and formal government-to-government agreements documenting specific, major contributions.

5.6.3 Key Considerations for Successful Scientific Partnerships

One essential requirement for all collaborations must be to have a clear data sharing policy to which all partners agree to adhere. NASA's Earth science data policy of free and open sharing of data, research products, and research results, with no period of exclusive use of data by investigators, should be the standard, but accommodations will need to be considered in certain instances. Exceptions will need to be made for data obtained from sources that bind users to more restrictive data policies or that are inherently sensitive in nature (e.g., commercial satellite data; confidential human-subjects data). ABoVE may also wish to consider short periods of exclusive use for students using the data they collect for Masters theses or PhD dissertations.

Building successful partnerships will likely require flexibility in the mechanisms used to cement the partnership as well as in what is expected on each side in a partnership. However, the minimum criteria for success are that each partner benefits from the interaction, that all commit to making the effort necessary to ensure that partners receive what has been promised, and that the scientific, resource management, and policy communities gain access to their data, products, and results. Regular interactions among Partners will be important as well. ABoVE should plan for substantive scientific exchanges with Partners though joint Science Team Meetings and/or each Partner attending the other's meetings, and for periodic meetings at the program/project management level to assess progress and address any issues.

There are many challenges in building effective partnerships, but some of the more difficult ones are often associated with aligning program/project schedules, resource availability (personnel, infrastructure, logistics, and funds), and required permissions to proceed (including international agreements and field research permits). ABoVE management should make every effort to explore and negotiate desired partnerships as early as possible in the implementation phase and to align its field activities with established plans/schedules of partners. It is also desirable, when possible and compatible with ABoVE science questions, to be somewhat flexible as to when and where work is done and to develop contingency plans to address unexpected changes in partner's plans.

Another challenge can arise in maintaining a strong, mutually beneficial partnership if it becomes difficult for all partners to be appropriately recognized for their contributions. This can be especially difficult if the relative contributions are unequal or if one partner's contribution is more visible than another's. As partnerships are established, ABoVE should create a clear public identity as a multi-partner, international collaboration (led by a single agency, perhaps, if no major partnership alters this situation). In this regard, ABoVE should develop a standard acknowledgement statement that can be used in all presentations and publications related to ABoVE that takes care to cite ABoVE as a multi-agency, international partnership and then names each and every sponsor of the particular activity presented (to include all resources made available – not just funds). It also must be made crystal clear which agency(ies) funded the results presented. ABoVE-related public engagement and interactions with the press should have similar standard messages and acknowledgement of sponsors/partners. The CCE Office can help to develop these materials, clear them with all partners, and then make them easily and widely available for use by all participants in ABoVE. Everyone must take care to give credit where credit is due.

6. Conclusion

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. Many terrestrial and freshwater ecosystems in Arctic and boreal regions are already changing in response to this warming, often proximally caused by the rapid thawing of frozen ground and changes to disturbance regimes and surface hydrology. These changes to the land surface can exert strong feedbacks to regional and global climate as well as impact the goods and services these ecosystems provide, with far-ranging consequences for society. How society responds to these changes through economics, governance and policy will in large part shape the region's future. These global-scale forcings and responses form the setting within which local-to-regional scale disturbances and socio-economic drivers are causing the rapid changes being observed across the intricately linked ecological and societal systems of northwestern North America. In selecting this region as the Study Domain for its next major field campaign, NASA aims to understand the processes and interactions controlling the vulnerability and resilience of its social-ecological systems, and to assess how people within and beyond this region can respond and adapt to current and future environmental and social change.

This Concise Experiment Plan for ABoVE puts forward the framework for studying the vulnerability and resilience of Arctic and boreal ecosystems through a series of interconnected, theme-based science questions that together address a key set of cross-cutting science objectives. Research carried out during ABoVE will address key uncertainties in the regional-scale responses of social-ecological systems to changes in disturbance regimes, permafrost, hydrology, flora and fauna, and carbon biogeochemistry. ABoVE research will improve our understanding of the consequences of, along with our confidence in making projections of the responses to, these critical environmental changes occurring across the Study Domain. Studies conducted during ABoVE will investigate the changes to Arctic and boreal ecosystems as viewed through the lens of the services that they provide to society, including infrastructure and transportation, human health, subsistence opportunities, natural and cultural resources, and climate regulation. Addressing the science objectives defined for ABoVE requires an integrated study design in which targeted field based, remote sensing and modeling studies are synthesized according to the scale and information content needed to support decision-making. In addressing these objectives, ABoVE will build a lasting legacy of research through an expanded knowledge base, the provision of key datasets, the development of decision support products and the fostering of new partnerships.

Glossary[10]

ABoVE: All the **Investigator Studies** that are carried out as part of the Arctic Boreal Vulnerability Experiment (ABoVE) over the entire length of research activities funded by NASA and its **Partners,** as well as all activities that support this research.

Core Region: That portion of the **Study Domain** where all **Research Areas** and the majority of **Investigator Sites** are located.

Core Variable Site: An **Investigator Site** where core variables will be collected.

Data and Information System: Includes all data processing, management, distribution, archiving, and information delivery activities that are part of the **Field Campaign**.

Data Products: Products that are generated through the processing and analysis of airborne and satellite remote sensing data.

CCE Office: NASA's Carbon Cycle and Ecosystem Office will be responsible for supporting a range of activities during the **Field Campaign.**

Extended Region: Areas of the **Study Domain** in addition to the **Core Region** that contain important opportunities for **Investigator Sites** needed to address a subset of Tier 2 objectives.

Field Campaign: Includes all planning and research activities that are carried out as part of **ABoVE**.

Investigator Site: A specific location that will be used to conduct the research for **Investigator Studies**.

Investigator Study: An individual research project selected for **ABoVE** based upon peer review of solicited proposals submitted to NASA and its **Partners.**

Partner: Any organization that is participating with NASA in providing support to the **Field Campaign** in any capacity.

Remote Sensing Site: Investigator Sites where data for refinement and validation of remote sensing data products will be collected.

Research Area: An area located in the **Core Region** where the majority of **Investigator Sites** will be concentrated.

Science Team: All researchers involved in Investigator Studies funded by NASA and its Partners, or researchers carrying out activities within Partner organizations that are contributing to ABoVE research.

Science Themes: The disciplinary focus areas for research during ABoVE: society, disturbance, permafrost, hydrology, flora and fauna, and carbon biogeochemistry.

Study Domain: The regions of Alaska and western Canada that will be studied during the **Field Campaign**.

Vulnerability/Resilience Framework: The conceptual foundation for studying the impacts of environmental change on social-ecological systems during the **Field Campaign.**

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[10] Terms in bold are defined in this Glossary

Appendix A: Maps of Key Surface Characteristics for the ABoVE Study Domain

This appendix presents and discusses a set of figures that depict important characteristics of the Study Domain, including the locations of sites that provide access to transportation, existing facilities that provide logistical support, and research stations with established and ongoing studies. Also presented are the locations of sites within important environmental monitoring networks that will provide data for the Field Campaign. The information and figures presented in this appendix were derived from an extensive geospatial data set developed by the CCE Office to support planning activities for ABoVE. These data were used in identifying the fifteen Research Areas that will be used for the ABoVE Field Campaign (Figure 4.1 in the Experiment Plan). Key features of these Research Areas are summarized in Table A1.

The Core and Extended Regions within the Study Domain provide the opportunity to carry out research needed to address key research questions and objectives for understanding how environmental change is impacting social-ecological systems across the Arctic and boreal region of western North America. This research requires making observations in specific locations and landscapes that represent a number of key land and atmospheric characteristics unique to this region. The study design developed for ABoVE is based on the ability to gain access to research sites using existing road networks, commercial flights to major regional transportation hubs (e.g., Anchorage, Fairbanks, Whitehorse, and Yellowknife) and smaller airports located to communities throughout the region, boats (on rivers), and charter air flights (Figure A1). The study design also builds on a number of research stations and support facilities located across the Study Domain that can provide significant logistical support (Figure A1). Finally, the research design is based on building from research and monitoring activities that have taken place or are being planned. These activities include longer, interdisciplinary studies at specific sites (e.g., field stations in Figure A1) and monitoring networks collecting data to study specific processes, including Ameriflux and NEON (Figure A3) Global Terrestrial Network for Permafrost (GTN-P) with its two components on the Thermal State of Permafrost (TSP) and the Circumpolar Active Layer Monitoring (CALM) (Figure A8).

There are significant gradients in temperature and precipitation across the Study Domain controlled by north to south variations in the surface energy budget and the movement of precipitation from the Pacific Ocean across the region by the movement of weather systems. There is a significant modification of climate by topography, in particular by the major mountain ranges found throughout the region that have a strong influence on precipitation patterns. A cluster analysis of temperature and precipitation data from 1960 to 1999 reveals a number of regions with similar climatic conditions (Figure A2).

The Study Domain contains all the major vegetation types common to Arctic and boreal regions, including a range of tundra and boreal forest ecosystems, peatlands and wetlands, and important aquatic systems (Figure A3). Vegetation cover combined with climate and topographic data provide the basis for the boundaries of the major ecoregions found in this region (Figure A4). An important research focus for ABoVE will be on factors controlling patterns of vegetation greening and browning observed from the longer-term satellite remote sensing data record (Figure A5).

The Study Domain encompasses the two major watersheds (Yukon and McKenzie River Basins[11]) as well as smaller watersheds that provide most of the freshwater inputs to the western Arctic Ocean and Bering Sea (Figure A6). Research in these watersheds provides the opportunity to study how changes to terrestrial and freshwater systems in Arctic and boreal regions control variations in the extent of surface water (Figure A7) and the deliveries of fresh water, dissolved organic matter, and suspended particulate matter to coastal oceans.

The Study Domain spans the major permafrost zones of North America (Figure A8), where there is also significant variation in ground ice content (Figure A9).

Over the longer term, variations in topography, surface drainage, permafrost conditions, vegetation, and disturbance regimes have contributed to significant reservoirs of carbon in surface organic layers and frozen mineral soils (Figure A10). When combined with studies on understanding causes of changes in aboveground carbon pools, research during ABoVE will provide important insights on exchanges of carbon between the land surface and atmosphere across the Study Domain.

Disturbances play an important role in controlling changes in Arctic and boreal ecosystems across the Study Domain (Figure A11). Fire is common in boreal forests, with insect and disease being important in more southern forests. Thermokarst is common to northern and western tundra within areas with high ice content (Figure A9), and also occurs in other ecosystems (forests, peatlands, and wetlands). Large areas in the Study Domain have also been impacted by activities associated with the exploration and development of mineral, oil, and gas resources, as well as the management of forest resources.

Finally, the Study Domain contains important habitat for fish and wildlife, illustrated by the number of major caribou herds found across the region (Figure A12).

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[11] The boundaries for the major watersheds such as the Yukon and McKenzie Rivers vary depending upon the source map. The boundaries presented in Figure A6 are based on the maps provided in North American Environmental Atlas (http://www.cec.org/Page.asp?PageID=924&ContentID=2866).

Table A1. *Key features of the Research Areas to be used during ABoVE*

Research Area	Ecoregion/CAVM Subzone	Permafrost Conditions	Major Ecosystems	Major Disturbances	Research Activities*
A	Boreal Plain	None	Boreal Forest, Peatlands, Lakes/Ponds	Biotic Agents, Fire, Oil/Gas Exploration/ Extraction, Forestry	a,b,e,f
B	Taiga Plain	Sporadic/Isolated, Low Ice Content	Boreal Forest, Peatlands, Lakes/Ponds	Fire, Thermokarst, Oil/Gas Exploration/ Extraction, Forestry	a,b,f
C	Taiga Shield	Discontinuous, Medium Ice Content	Boreal Forest, Peatlands, Lakes/Ponds	Fire, Thermokarst, Mineral Extraction	a,d,e,f
D	E - Low Shrub	Continuous, Low Ice Content	Tundra, Lakes/Ponds	Mineral Extraction	a,e,f
E	C - Hemi-prostate Low Shrub, D - Erect Low Shrub	Continuous, High Ice Content	Tundra	Thermokarst	a,b,e,f
F	Taiga Plain	Discontinuous, Low to Medium Ice Content	Boreal Forest, Peatlands, Lakes/Ponds	Fire, Thermokarst, Oil/Gas Exploration/ Extraction, Forestry	a,b,d,e,f
G	Taiga Plain	Continuous, Medium to High Ice Content	Boreal Forest, Peatlands, Lakes/Ponds	Fire, Thermokarst, Thaw Slumps	a,b
H	Taiga Plain, E - Low Shrub	Discontinuous, Medium to High Ice Content	Boreal Forest, Tundra, Lakes/Ponds, Wetlands	Fire, Thermokarst, Thaw Slumps	a,b,d,e,f
I	Boreal Cordillera	Sporadic/Isolated, Low Ice Content	Boreal Forest, Alpine Tundra	Fire, Biotic Disturbances	a,b,d,e,f
J	Boreal Cordillera	Discontinuous, Low Ice Content	Boreal Forest, Alpine Tundra	Fire, Biotic Disturbances	a,b,c,e,f
K	Alaska Boreal Interior	Discontinuous, Low to Medium Ice Content	Boreal Forest, Alpine Tundra, Lakes/Ponds, Wetlands	Fire, Biotic Disturbances, Thermokarst, Thaw Slumps	a,b,c,d,e,f

L	E - Low Shrub	Continuous, Low Ice Content	Tundra, Lakes/Ponds	Fire, Thermokarst, Oil/Gas Exploration/ Extraction	a,b,c,d,e,f
M	C - Hemi-prostate Low Shrub, D - Erect Low Shrub	Continuous, High Ice Content	Tundra, Lakes/Ponds	Thermokarst, Oil/Gas Exploration/ Extraction	a,b,c,d,e,f
N	E - Low Shrub	Sporadic/Isolated, Low Ice Content	Tundra, Lakes/Ponds, Wetlands	Thermokarst	a
O	E - Low Shrub	Discontinuous, Medium Ice Content	Tundra	Thermokarst, Fire	a, f

*Level of previous, ongoing, and planned research activities within the Primary Study Area

a. Has research sponsored by an ABoVE Partner, including the Canadian High Arctic Research Network, the Department of Energy Next Generation Ecosystem Experiment – Arctic, Department of Interior Landscape Conservation Cooperatives, and Natural Resources Canada.

b. Has sites associated with monitoring networks such as NEON, Ameriflux, Circumpolar Active Layer Monitoring network, Thermal State of Permafrost Monitoring Network.

c. Has research carried out at part of long-term research projects (LTER, NGEE, etc.).

d. Has well-instrumented watershed studies, including Water, Ecosystem, Cryosphere and Climate (WECC) Observatories that are part of the Changing Cold Regions Network (http://www.ccrnetwork.ca/).

e. Has research stations or organizations/facilities dedicated to research support.

f. Has a significant number of PI-led research activities, both past and present.

Figure A1. *Major roads, airports, research stations and logistics centers in the Study Domain. Research stations include locations at which field-based research activities are currently being conducted, while logistics centers include labs, facilities, and organizations at Universities and Colleges and other locations that are available to provide support for field-based research activities.*

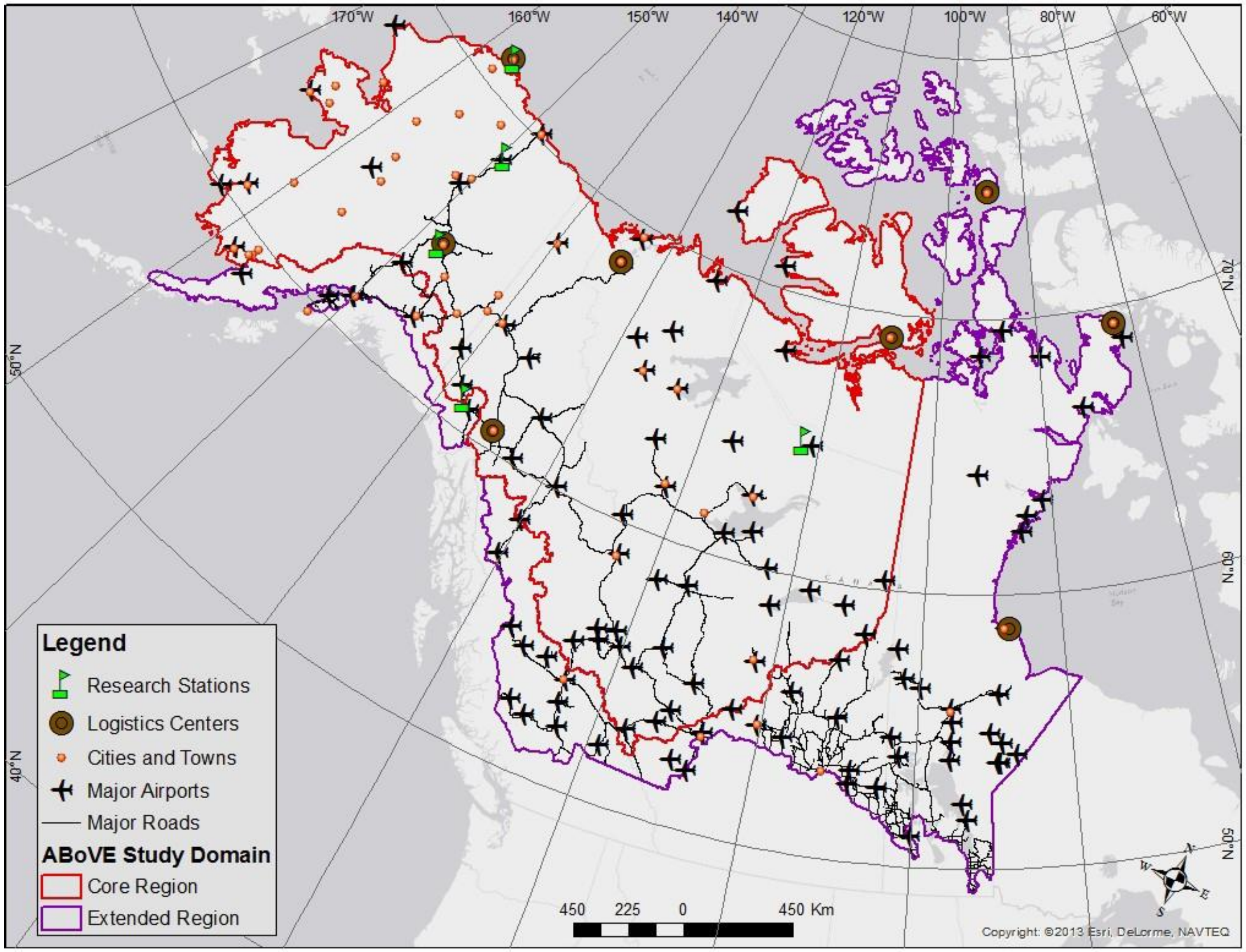


Figure A2. *Principal climatic zones for the Study Domain and locations of weather stations* (climatic zones from **Predicting Future Potential Climate-Biomes for the Yukon, Northwest Territories, and Alaska**, prepared by the Scenarios Network for Arctic Planning and the EWHALE lab, University of Alaska Fairbanks, 2012: http://www.snap.uaf.edu/attachments/Cliomes-FINAL.pdf ; weather station data from http://weather.rap.ucar.edu/surface/).

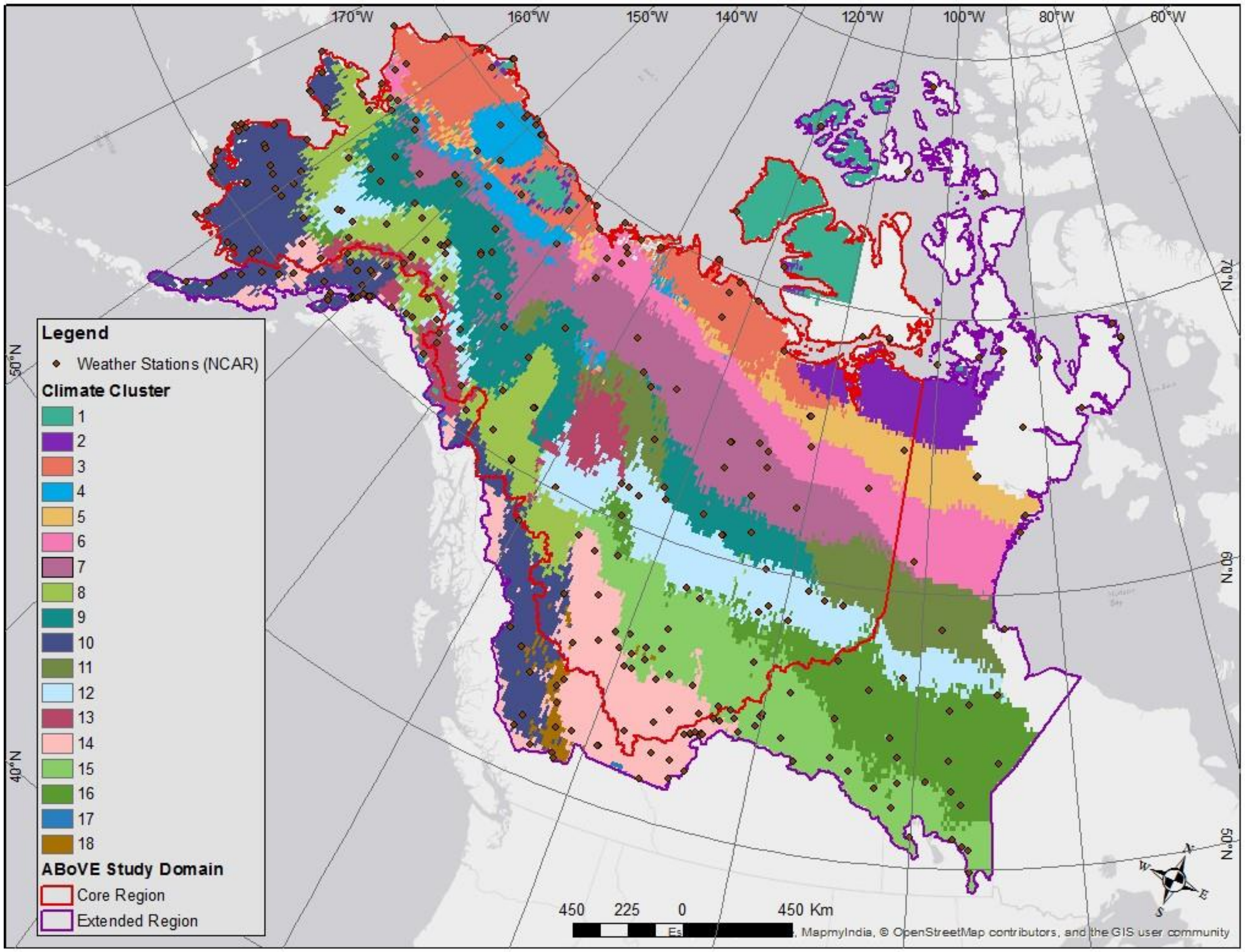


Figure A3. *Major land cover types in the Study Domain and the location of (a) eddy covariance flux towers used to monitor exchanges of CO_2 and CH_4 and (b) planned NEON sites* (Major land cover types from the North American Land Change Monitoring System (NALCMS) 2005: http://www.cec.org/Page.asp?PageID=924&ContentID=2819&AA_SiteLanguageID=1).

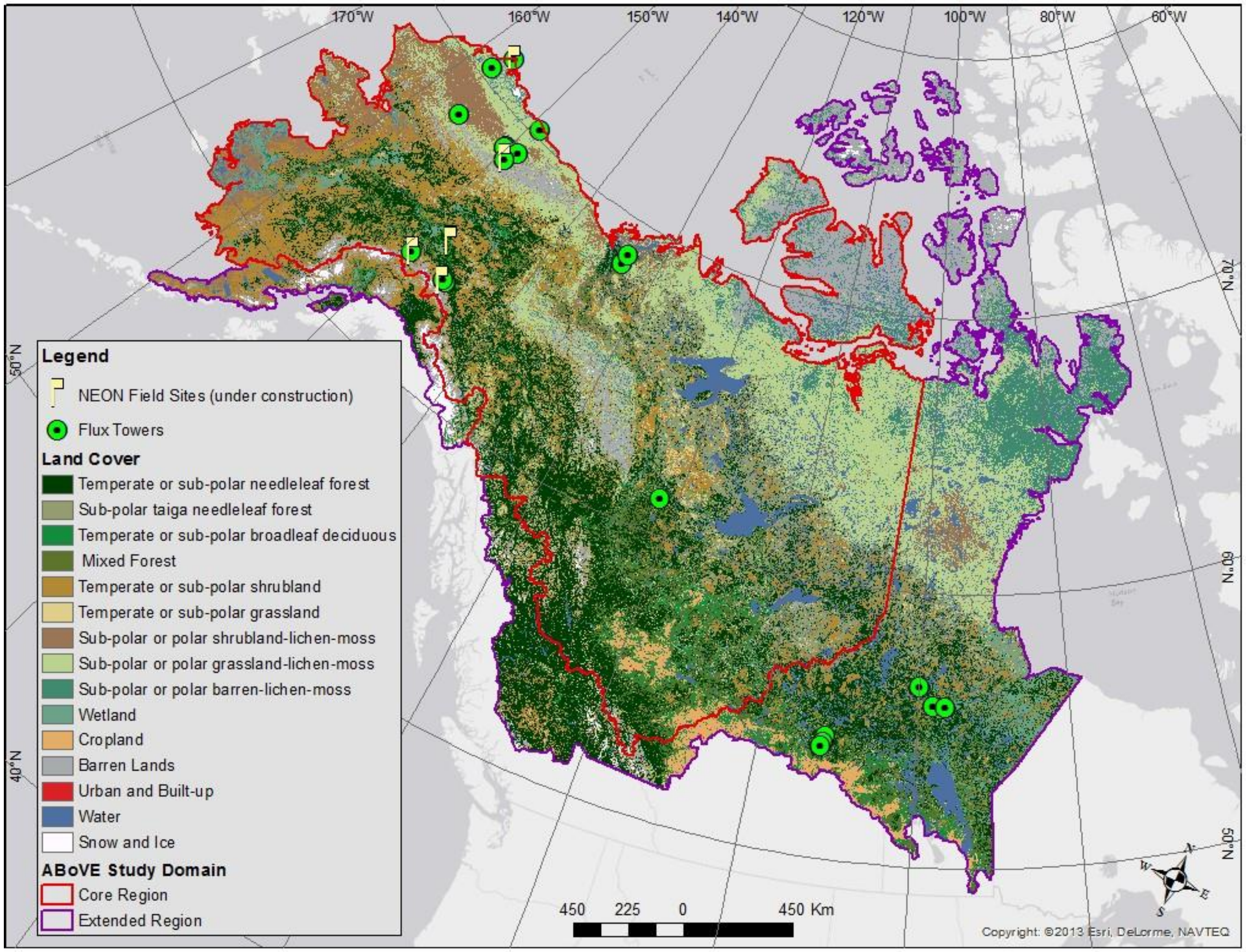
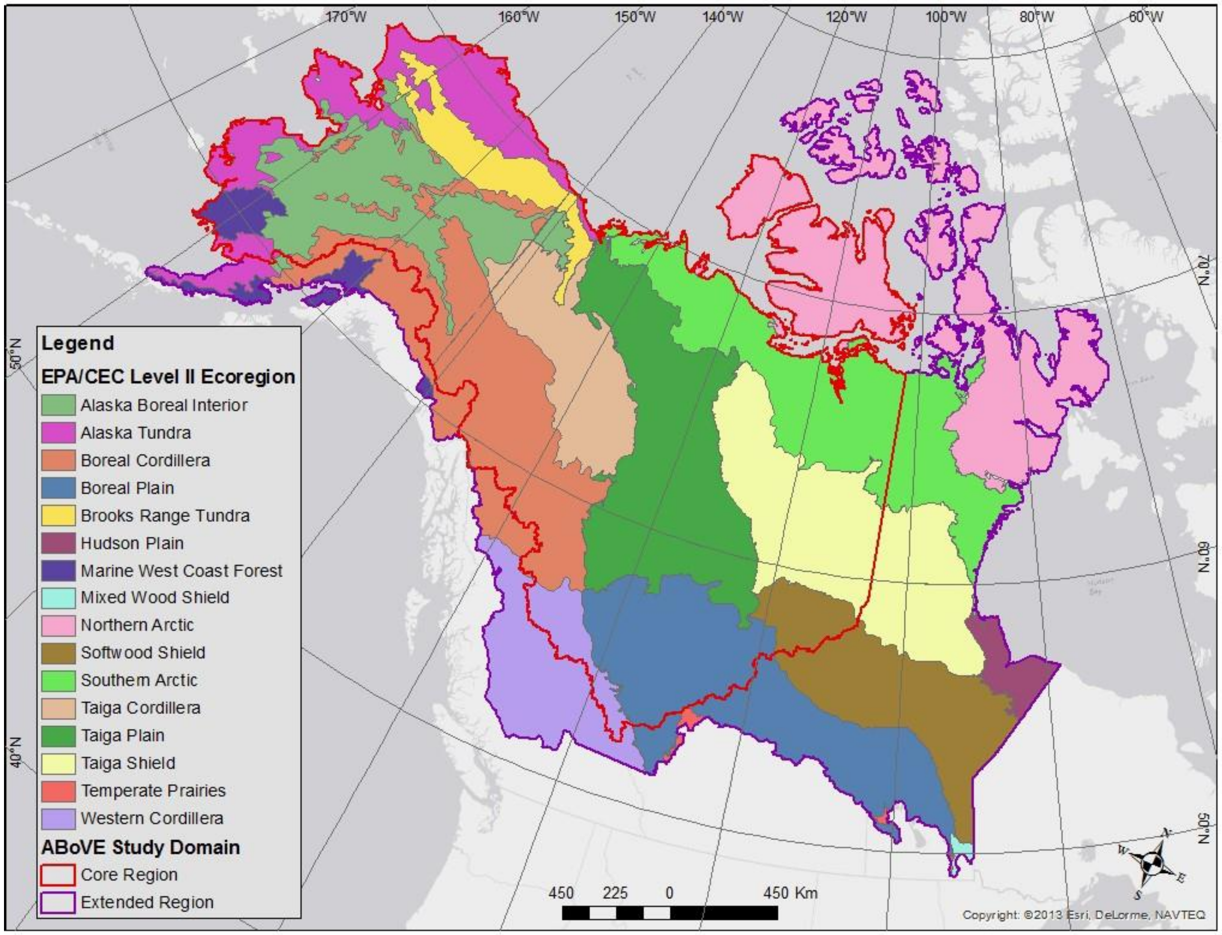


Figure A4. *(a) Level II Ecoregions for the Study Domain and (b) tundra vegetation types* (Level II Ecoregions are after Commission for Environmental Cooperation. 1997. **Ecological regions of North America: toward a common perspective.** Commission for Environmental Cooperation, Montreal, Quebec, Canada. 71p. Map (scale 1:12,500,000). Revised 2006: http://www.epa.gov/wed/pages/ecoregions.htm; and Circumpolar Arctic Vegetation Map from http://www.geobotany.uaf.edu/cavm/).

(a) Level II ecoregions



(b) Tundra vegetation types

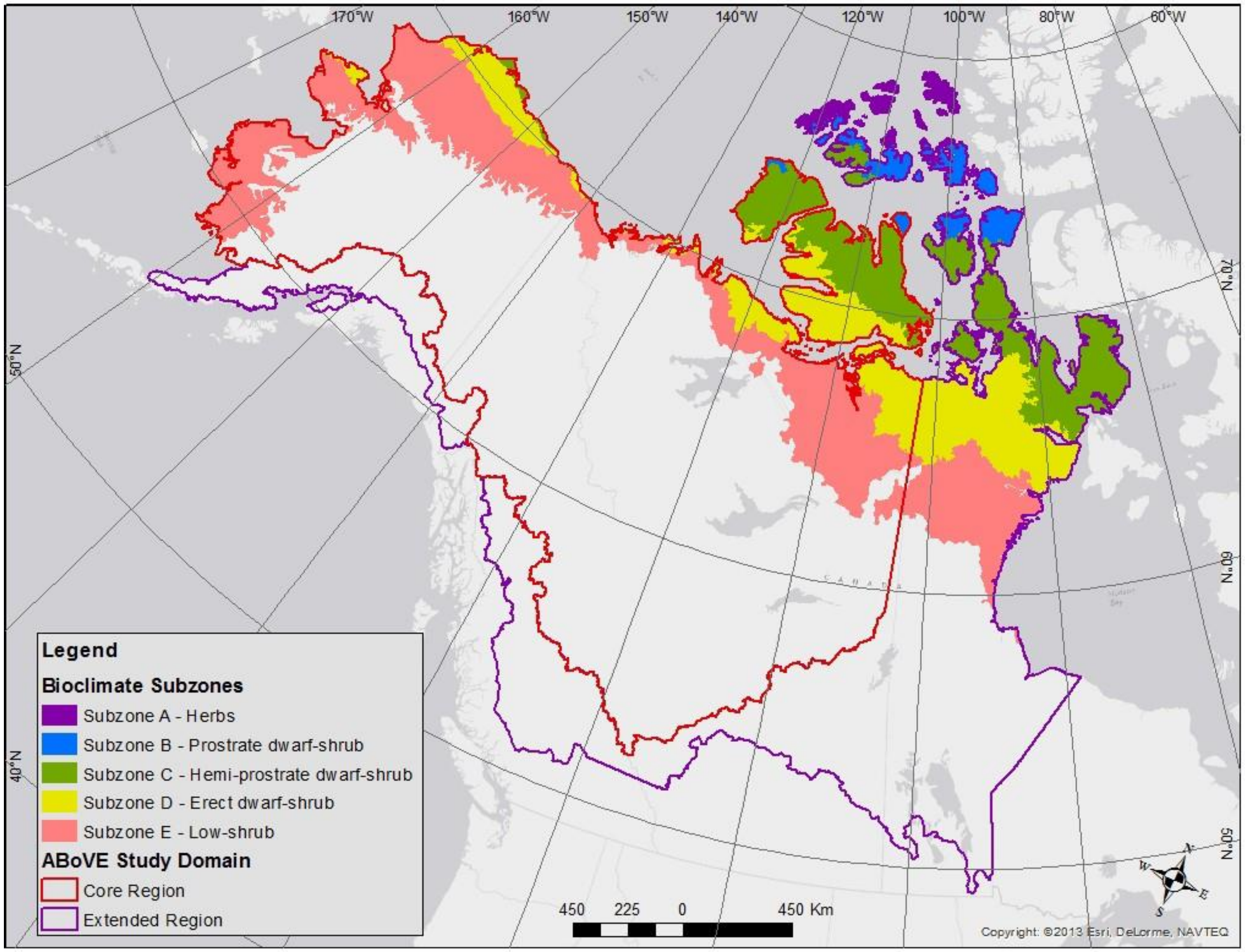


Figure A5. *Trends in vegetation greening and browning across the Study Domain based on examination of growing season satellite Normalized Difference Vegetation Indices (NDVI) for the period of 1982 to 2010* (data provided by Scott Goetz of the Woods Hole Research Center and is based on an analysis of per-pixel averages of June, July and August bi-monthly, 8km resolution GIMMS 3g NDVI).

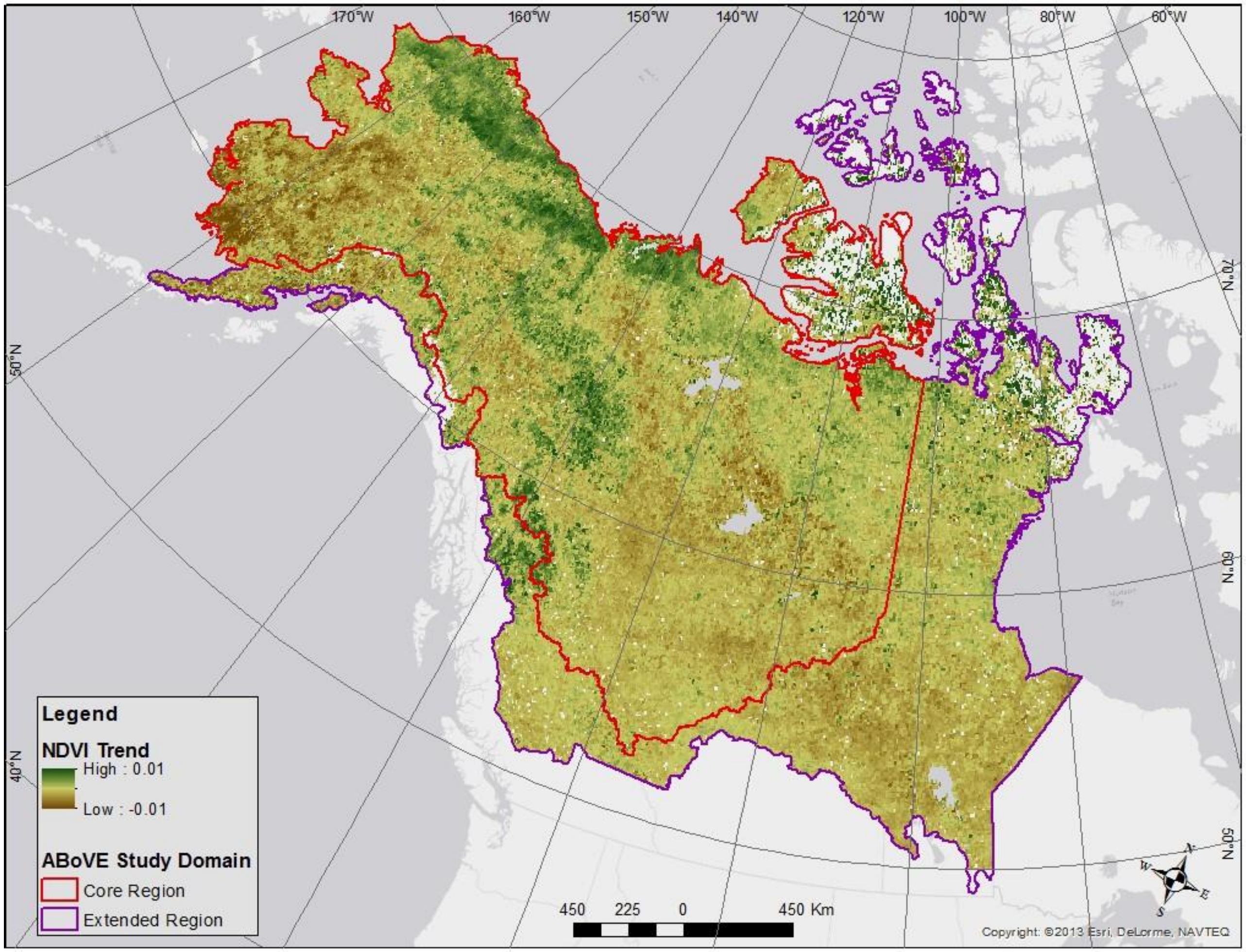


Figure A6. *Boundaries of major watersheds for the Study Domain and location of stream gauges* (watershed boundaries are from the North American Environmental Atlas: http://www.cec.org/Page.asp?PageID=924&ContentID=2866; hydrology data are from NOAA: http://www.nws.noaa.gov/oh/hads/and Environment Canada: http://www.ec.gc.ca/rhc-wsc/).

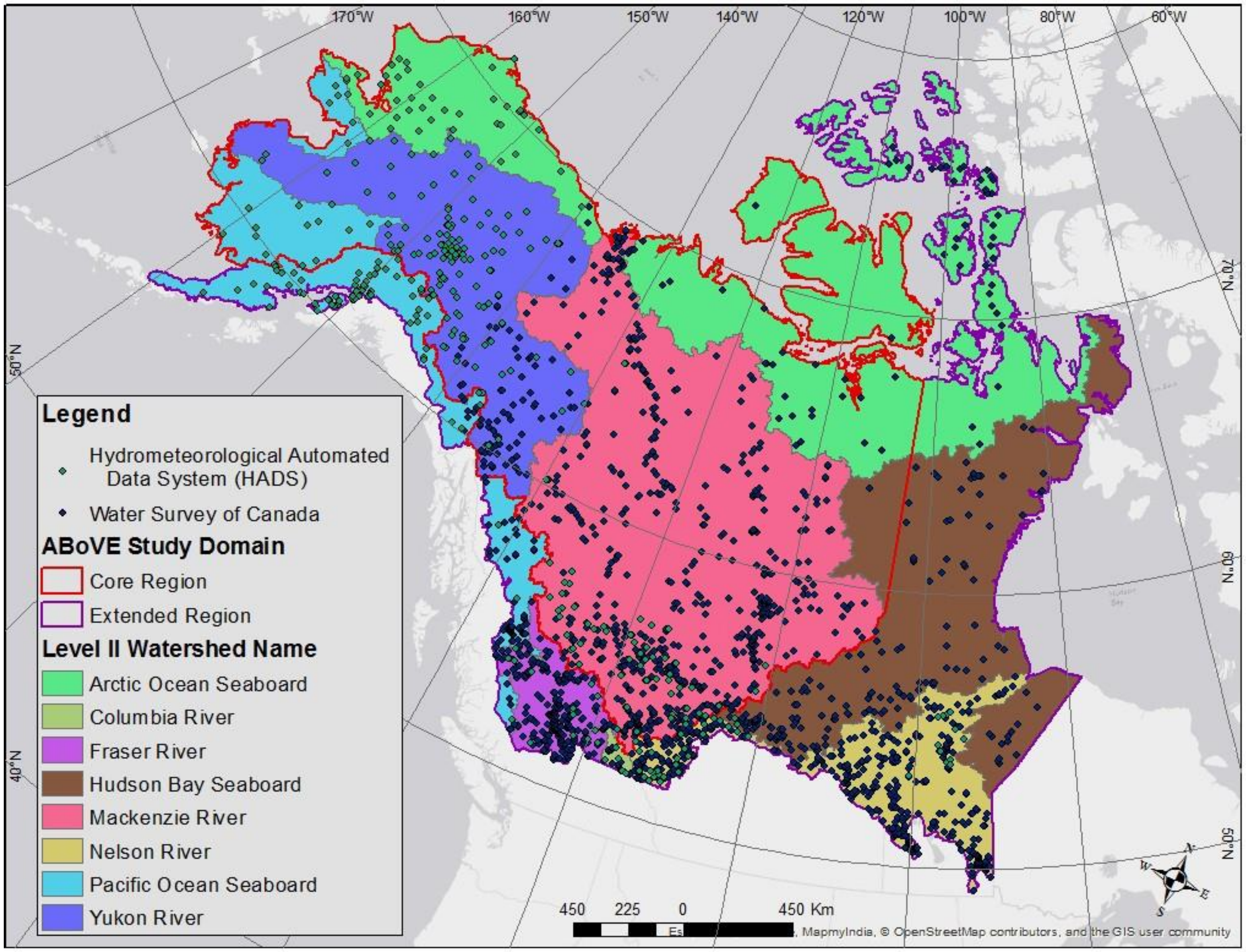


Figure A7. *Map of surface water extent across the Study Domain* (based on MODIS 250 m water mask product: 250m MODIS available at: http://glcf.umd.edu/data/watermask/ and provided by Mark Carroll).

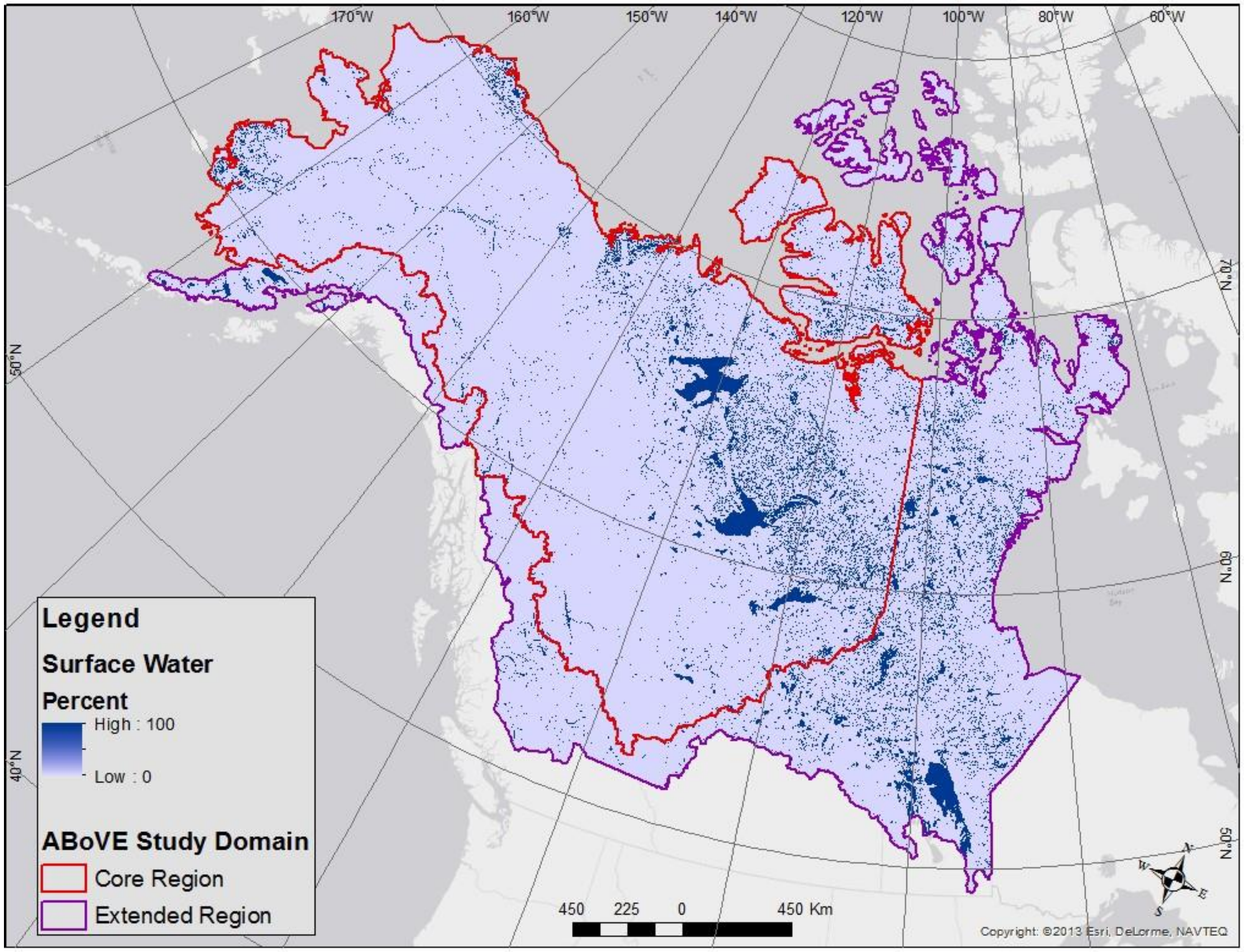


Figure A8. *Major permafrost zones in the Study Domain* (after Brown et al., Circum-Arctic Map of Permafrost and Ground-Ice Conditions. Version 2. Boulder, Colorado USA: National Snow and Ice Data Center 2002: http://nsidc.org/data/docs/fgdc/ggd318_map_circumarctic/index.html), along with the location of sites that are part of the Global Terrestrial Network for Permafrost (GTN-P; http://gtnp.arcticportal.org) with its two components of the Circumpolar Active Layer Monitoring Network (CALM; http://gtnpdatabase.org/activelayers) and the Thermal State of Permafrost monitoring network (TSP; http://gtnpdatabase.org/boreholes).

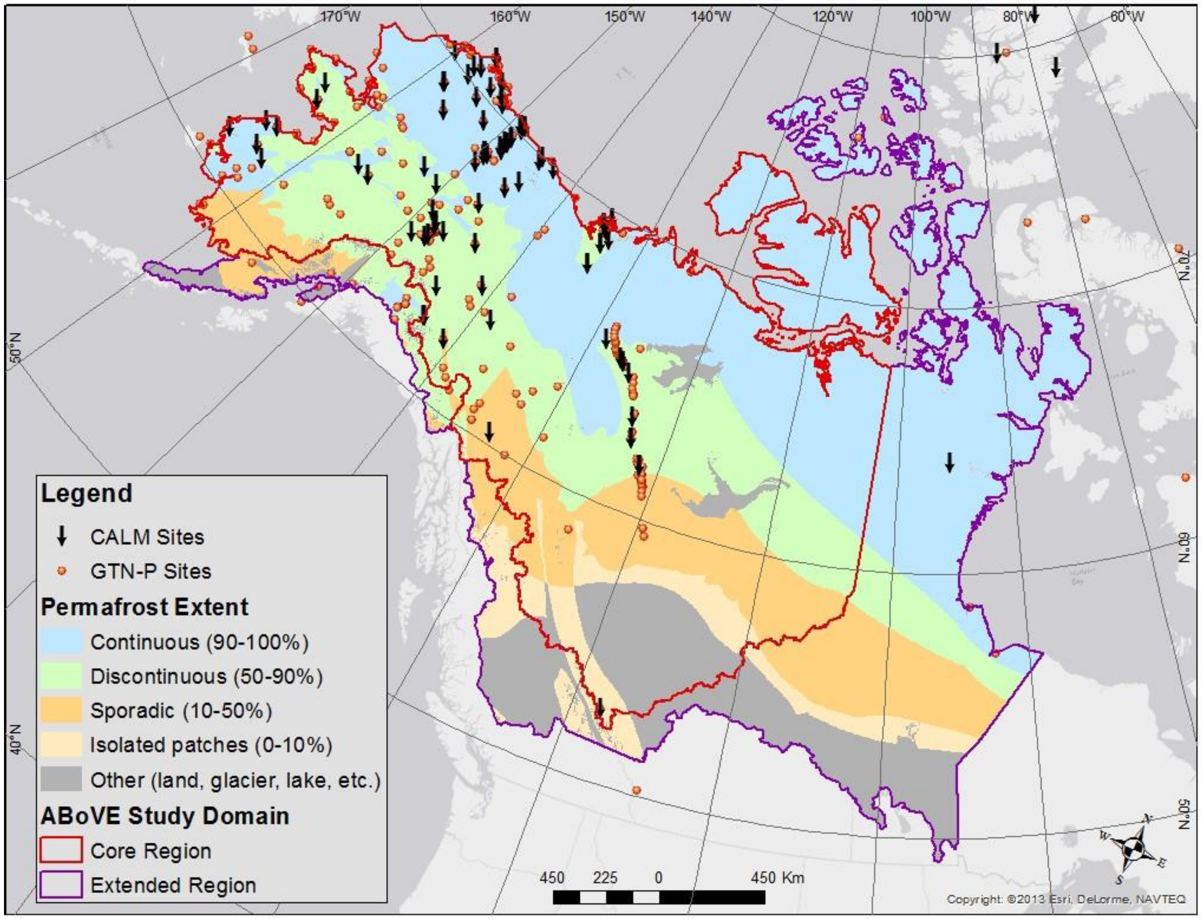


Figure A9. *Location of areas with different ground ice content within the Study Domain* (after Brown et al., 2002: http://nsidc.org/data/docs/fgdc/ggd318_map_circumarctic/index.html).

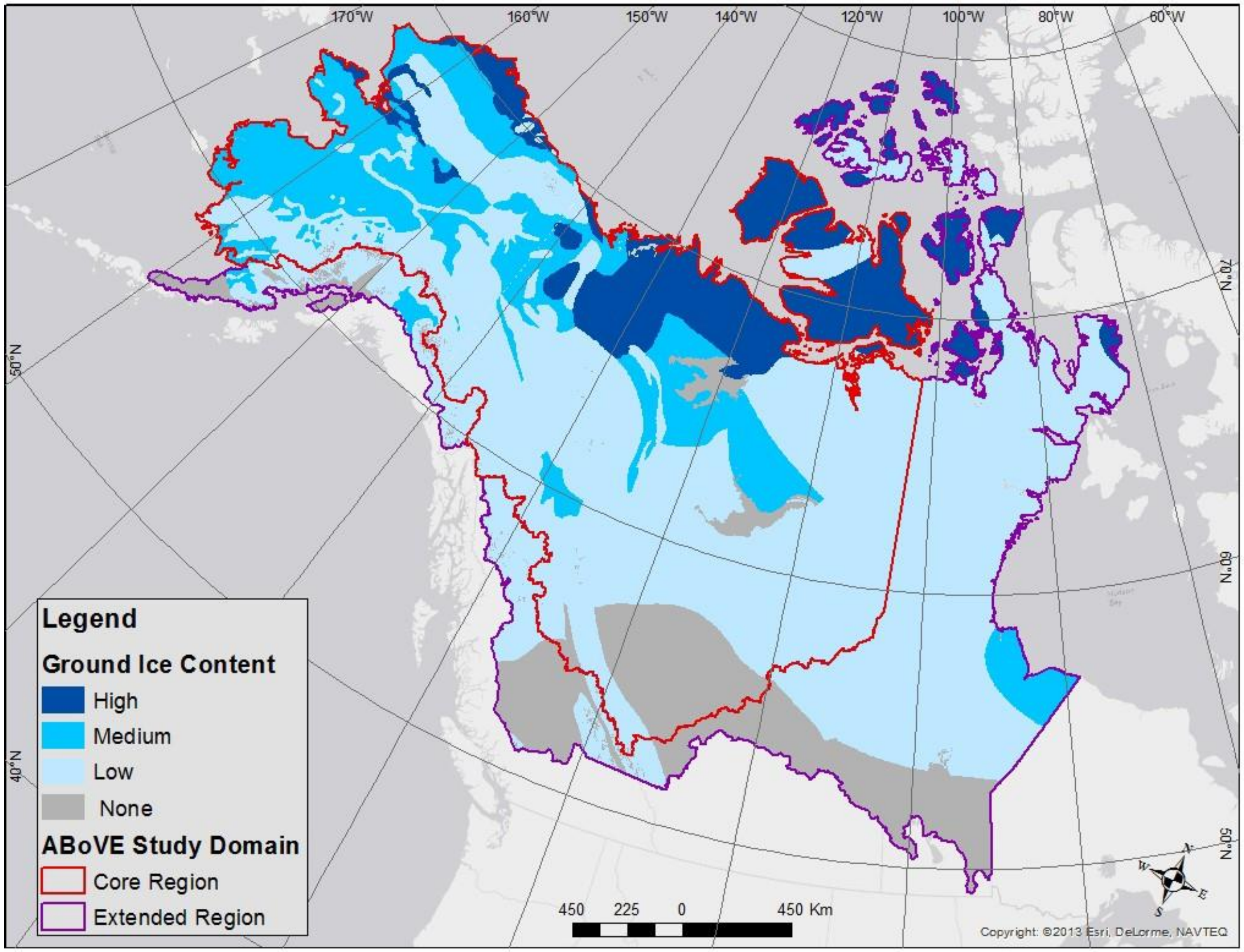


Figure A10. *Soil carbon concentrations for the Study Domain, including soil carbon present in organic soils and the top 100 cm of soil* (from Hugelius et al. (2013) The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions, *Earth Syst. Sci. Data, 5*, 3-13, doi:10.5194/essd-5-3-2013; *data obtained from* Northern Circumpolar Soil Carbon Database: Bolin Centre Database: http://bolin.su.se/data/ncscd/.)

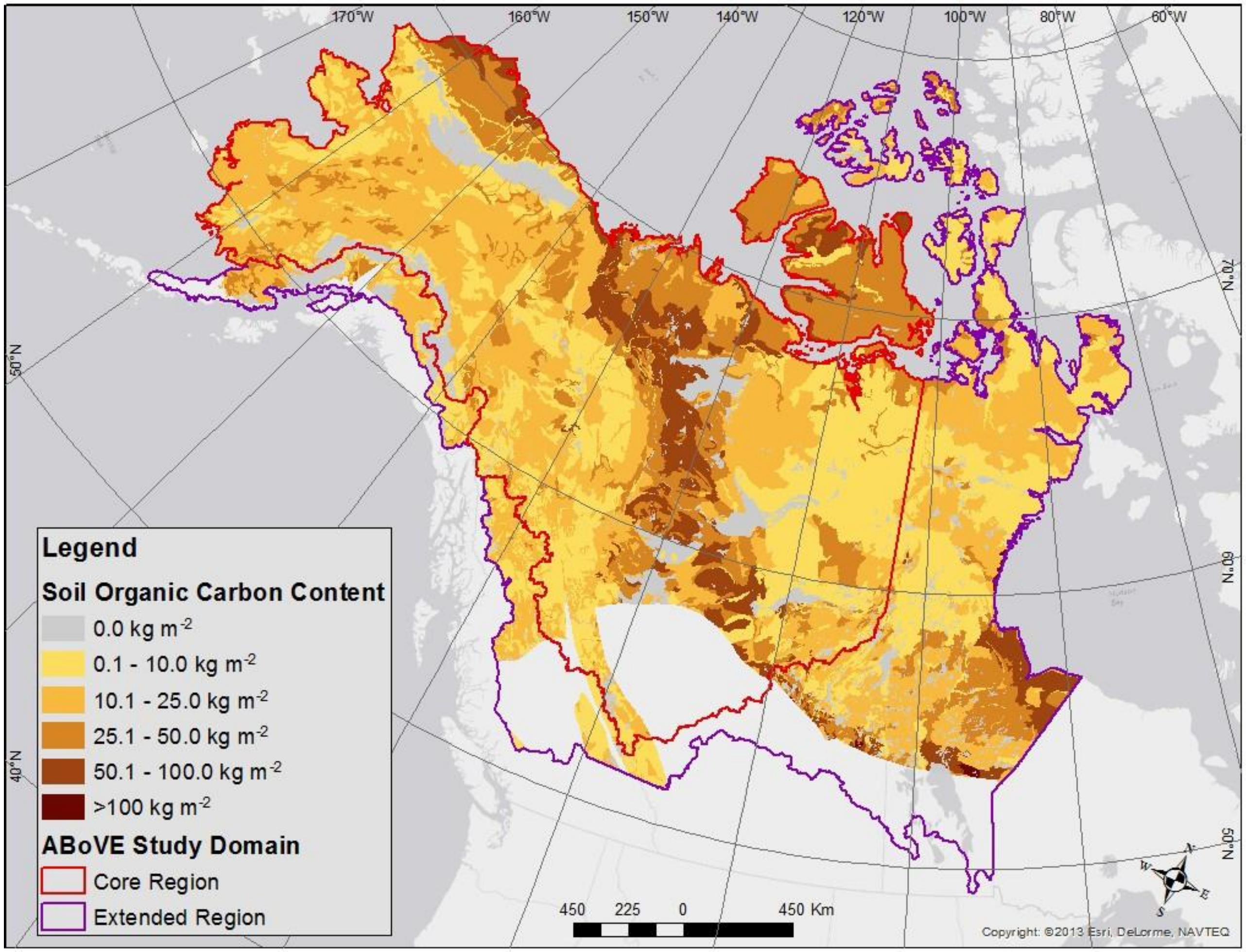


Figure A11. *Location of the perimeters of large fires in the Study Region and location of areas with mineral, oil, and gas exploration and development* (data from the Alaskan Large Fire Database: http://www.frames.gov/rcs/10000/10465.html, and the Canadian National Fire Database: http://cwfis.cfs.nrcan.gc.ca/ha/nfdb?type=poly&year=9999).

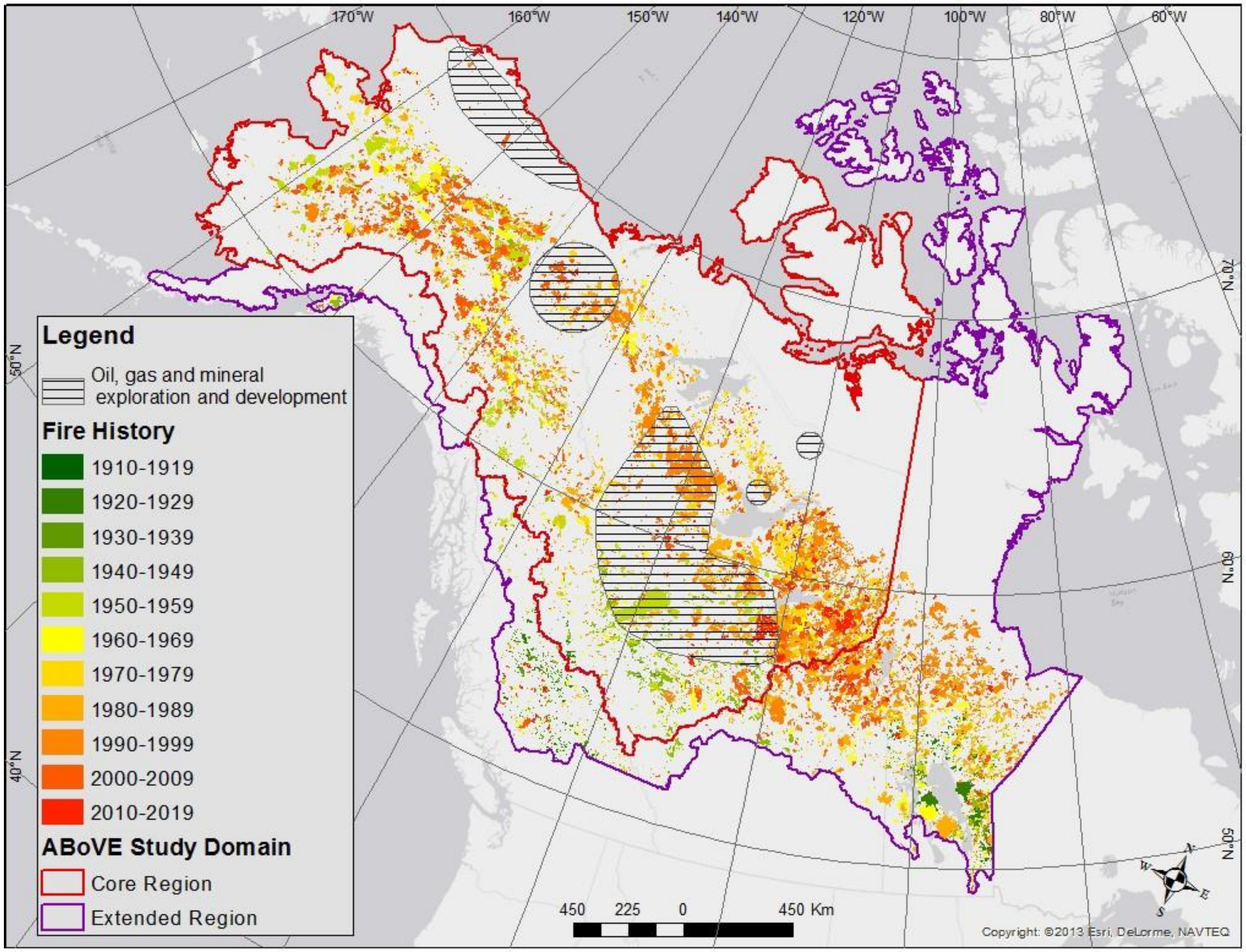
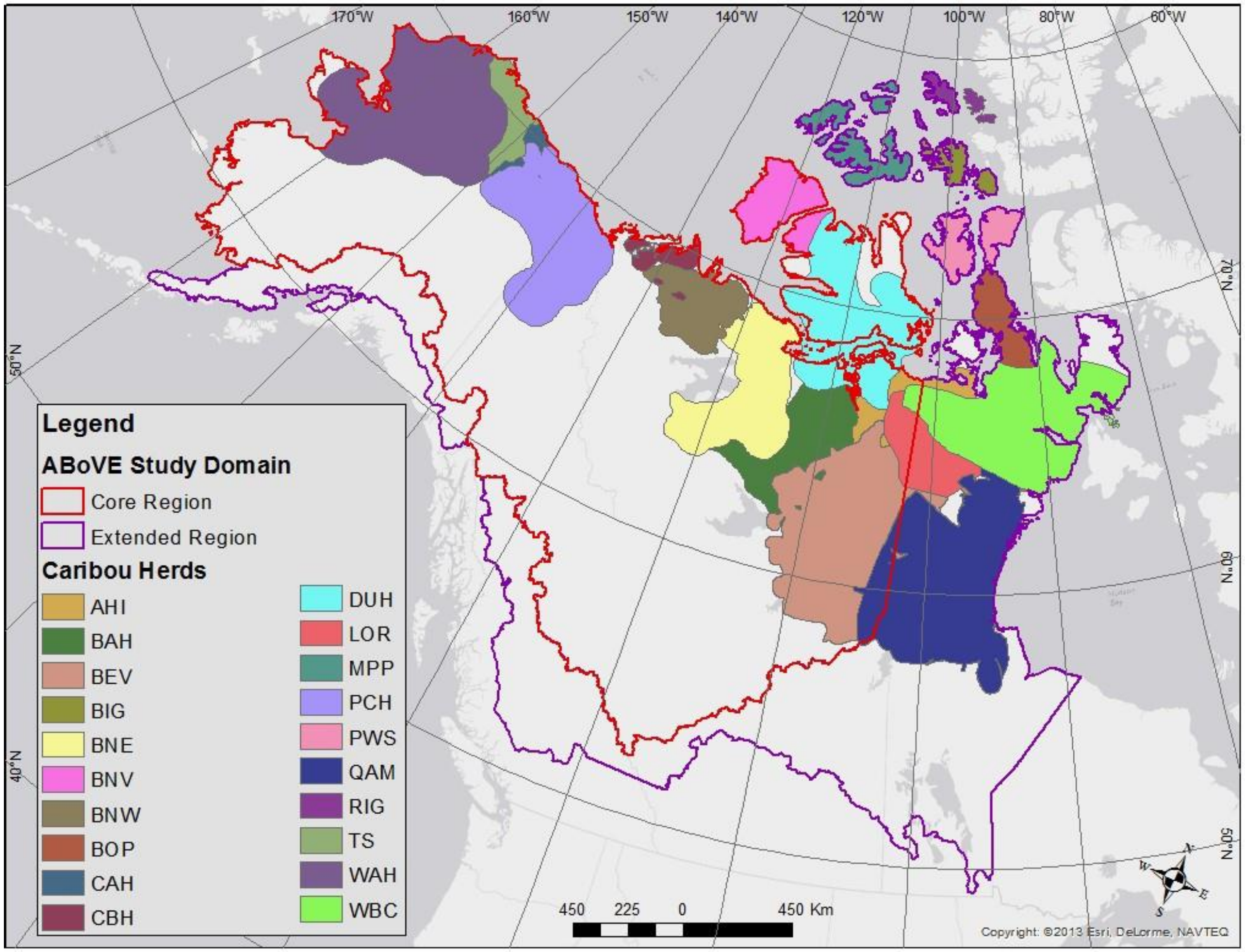


Figure A12. *Location of the boundaries of major caribou herds in the Study Domain* (map data provided by the CircumArctic Rangifer Monitoring and Assessment Network (CARMA): http://carma.caff.is*).*



Appendix B: Core Variables and Important Datasets

As discussed in section 4.2., there are a number of datasets that are central to the research for the ABoVE Field Campaign, including data from monitoring networks that should be made readily available, which also represent Core Variables that should be collected in Investigator Sites in each Research Area (B1), datasets that should be integrated and synthesized from multiple sources for research on social systems (Table B2), ecological systems (Table B3), and datasets based on surveys of local and traditional knowledge (Table B4).

Table B1. *Summary of variables available from data networks that should be made available for ABoVE. These also represent the Core Variables that should be collected from at least one Investigator Site in each Research Area, when appropriate.*

1. **Weather Station Records**

2. **Hydrometric Data** (stream flow and water level) from streams and rivers from the U.S. Geological Survey and Environment Canada

3. **Water Quality Data** from the U.S. Geological Survey and Environment Canada

4. **Borehole Temperature Data** from the Thermal State of Permafrost monitoring network within the Global Terrestrial Network for Permafrost (GTN-P)

5. **Active-Layer Thickness Data** from the Circumpolar Active Layer Monitoring Network (CALM) within the Global Terrestrial Network for Permafrost (GTN-P)

6. **CO_2 and CH_4 Eddy Covariance Flux Data** from the AMERIFLUX Networks

Table B2. *Important regional and domain-wide societal datasets for addressing Tier 2 science objectives that should be compiled and integrated.*

1. **Quality, Availability, Dynamics, and Use of Natural Resources**

2. **Subsistence Harvest Data**

3. **Demographic Data** (age structure, migration)

4. **Economic Indicators** (income distribution, labor force participation)

5. **Incidence of Disease and Injury**

6. **Cultural Vitality** (e.g., indigenous language use)

7. **Road Location/Age/Status** (including winter roads)

8. **Length of Season for Winter Transportation and Exploration**

9. **Location of Mineral Oil, and Gas Exploration and Extraction Activities**

10. **Drinking Water Sources**

11. **Location and Use of Wastewater Treatment Facilities**

12. **Heating and Electricity Sources**

13. **Building Location/Age/Status**

14. **Historically Important Places**

15. **Climate Mitigation Activities**

Table B3. *Important regional and domain-wide environmental datasets for addressing Tier 2 science objectives that should be compiled and integrated.*

1. **Fire Maps and Fire Statistics**

2. **Maps of Outbreaks of Insects and Pathogens and Associated Data**

3. **Location of Mineral, Oil, and Gas Exploration and Extraction Activities**

4. **Forest Harvest Data**

5. **Forest Inventory Data**

6. **Data from Canadian CIPHA (Climate Impacts on Productivity and Health of Aspen) Plots**

7. **Dendrochronological Data** (tree cores from canopy trees across forested sites, shrub core disks from tundra and taiga across study domain)

8. **Fish and Wildlife Population Data**

9. **Wildlife Radio Collar Position Data**

10. **Soil Survey Data** (including deep soil cores and cryostratigraphies)

11. **Snow Depth Transect Data**

Table B4. *Summary of important datasets on changes to landscape characteristics based on local and traditional knowledge that would be used to address Tier 2 science objectives.*

1. **Climate**
2. **Distribution of key flora and fauna**
3. **Abundance and locations of subsistence resources**
4. **Areas used for fishing and hunting**
5. **Travel corridors and routes**
6. **Water resource availability and use**

APPENDIX C: Identification of Important Data Products from Spaceborne and Airborne Remote Sensing Data

In determining what types of remote sensing activities needed to be supported during ABoVE, data products related to specific land and atmospheric characteristics that are presently available or could be generated from spaceborne and airborne remote sensing were identified (Tables C1 and C2). The maturity of the remote sensing data products was determined using the six maturity levels defined by NASA[13], which were then divided into three groups for further review and assessment:

A. Products with Stage 2 to 4 validation.

B. Products with Stage 1 validation.

C. Provisional Products.

In summary, the accuracy for products with Stage 2 to 4 validation is known, and has been assessed over a number of locations and times by comparison with reference *in situ* or other data. These products can be used without further refinement and validation. In contrast, products with Stage 1 validation or Provisional Products have not undergone validation using data collected from a large number of locations and times, and thus require resources for further refinement and validation for the land and atmospheric characteristics that are common in Arctic and boreal regions.

The data products listed in Tables C1 and C2 were reviewed and those products in the above three areas that were judged to be important for addressing the Tier 2 science objectives (Table 3.1 in the Experiment Plan) were identified. The relative importance of each variable was then evaluated based on their use: (a) from a strictly remote sensing perspective based on their utility for studying the spatial and temporal variations in important characteristics of the land surface and atmosphere over space and time; (b) for addressing the Tier 2 Ecosystem Dynamics Objectives in Table 3.1; (c) for addressing the Tier 2 Ecosystem Services Objectives in Table 3.1; and (d) for use as model drivers, or to initialize, calibrate, or validate models. The importance for each of these areas for each variable was ranked as 0 or 1, and the rankings for the four areas summed to create an overall ranking for each variable. For each area and variable level, these rankings were used to identify data products with the highest importance (rated 1 in Table 4.2 in the Experiment Plan) to lowest importance (rated 3). Some of the overall importance in areas (b) and (c), landscape to regional satellite and airborne data products, were increased if they were required for further refinement and validation of the highest importance Level B products. The importance rankings for the identified data products are presented in Table C3.

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[13] http://science.nasa.gov/earth-science/earth-science-data/data-maturity-levels/

Table C1. ***Information products from satellite remote sensing data***[14]

Sub-variable	**Existing/ Future Products with Stage 2-4 Validation (A) or Stage 1 Validation (B)** [15]	**Products with Stage 2-4 Validation Requiring Generation from Data Archives**	**Provisional Products**	**Validation Requirements**
		MATERIAL FLUXES/ENERGY BALANCE		
CO_2/CH_4	a. Column maps from GOSAT, OCO2, TES, S5-P (B).	b. SCIAMACHY monthly, seasonal, annual column CO2 and CH4 maps.		a.-b. Atmospheric carbon observation from TCCON (Total Carbon Column Observing Network) sites; AirCore vertical profile data with ~1 km vertical resolution a.-b. Continuous, in situ measurements from tall towers. a.-b. Eddy flux tower measurements.
CO (carbon monoxide)	a. Column maps from MOPITT, TES, S5-P (B).	b. SCIAMACHY monthly, seasonal, annual column CO maps.		a.-b. Atmospheric carbon observation from TCCON (Total Carbon Column Observing Network) sites; AirCore vertical profile data with ~1 km vertical resolution. a.-b. Continuous, in situ measurements from tall towers.

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[14] Resolution for satellite systems in this table are defined as follows: Fine resolution – pixel sizes < 2 m common to commercial satellite systems such as Quickbird, IKONOS, etc.; Medium resolution – pixel sizes between 10 and 100 m common to Landsat and similar satellites; Moderate resolution 200 to 5000 m common to MODIS, AVHRR and similar systems; Coarse resolution – pixel sizes greater than 10 km common to microwave radiometers, scatterometers, and atmospheric sensors.

[15] It is assumed that where products already exist, they can be generated in the future when suitable satellite data are available, and the products are required to address specific questions and objectives.

Net Radiation	a. GEWEX/SRB products (A). b. CERES ABAF (A).			
Up- & Down-welling Short- & Long-wavelength radiation	a. MODIS Clear sky products (A).			
Albedo	a. Shortwave and PAR albedo (A).	b. MODIS atmospherically corrected surface reflectance.	c. Albedo from Landsat data.	b.-c. Tower-based measurements of components of surface energy budget. a.-c. Aircraft measurements of surface reflectance to refine/validate albedo products.
Surface Emissivity	a. MODIS Clear sky products (A).			
Land and water surface (skin) temperature	a. Surface land and water temperature (skin temperature) maps (weekly) from spaceborne thermal IR data at moderate (1 to 5 km) resolution for entire Domain (A).	b. Surface land and water temperature (skin temperature) maps for specific regions/times from spaceborne thermal IR data at medium (60 to 100 m) resolution.		
PERMAFROST, SNOW & ICE				
Seasonal snow extent/area	a. GlobSnow (A). b. NOAA IMS (A). c. MODIS Snow Cover (A).	d. A single snow cover product for ABoVE Study Domain based on integration of existing products.		d. An evaluation of the various snow cover products needs to be carried out, including comparisons to medium resolution (30 m) products developed from Landsat imagery. Snow course data should be tabulated for key areas for further validation.

Snow thickness/snow water equivalent			a. Snow thickness/ snow water equivalent maps from SAR, Scatterometer, and MW radiometer data.	a. See airborne data products in Table C2. Snow course data should be tabulated for key areas.
Active layer thickness			a. Map available for selected areas and time periods based on processing and analysis of InSAR data.	a. Field geophysical resistivity measurements observations of active layer thickness, as well as soil moisture content, ground ice content, soil and vegetation characteristics.
Winter snow thaw length			a. Thaw events based on analyses of MW remote sensing products used for freeze/thaw assessment.	a. Weather station temperature data for development and validation of algorithm.
Thermokarst/ thermokarst lake area			a. Maps of thermokarst/ thermokarst lakes from Landsat and SAR, fine resolution satellite data and historical aerial photography in key regions where these features are present and data are available.	a. Field-based observations of thaw subsidence, thaw-related vegetation and soil disturbances, lateral erosion, ground temperature, active layer depths, talik dimensions, ground moisture, and inundation.
Thaw slump area	a. Maps of thaw slump area and progression have been developed from SAR and VIS/IR satellite imagery for some regions(A).	a. Further maps should be developed in key regions in support of specific research projects.	a. Maps of thaw slumps from fine resolution satellite imagery.	
Surface deformation			a. Maps using InSAR have been developed and applied in some regions. Further development and validation of approaches to maps are needed as is coverage of additional regions, coordinated with mapping of thermokarst.	a. Field-based observations of thaw subsidence, thaw-related vegetation and soil disturbances, lateral erosion, ground temperature, active layer depths, talik dimensions, ground moisture, and inundation.

Lake ice thickness		a. Maps based on C-band SAR imagery.		a. Lake and river ice thickness measurements with mechanical probing or geophysical surveys.
River/lake/pond ice cover extent/ progression		a. Maps based on analysis of time-series SAR and Landsat/SPOT data.		
Ice jam location/ thickness			a. Potential exists for using SAR data.	a. Ice jam characteristics (thickness, height, width, grounding).
HYDROLOGIC VARIABLES				
Surface water extent	a. Landsat product for 1990, 2000, 2010 for entire Domain (A). b. MODIS product for entire Domain (A). c. SAR-products for smaller region (A).	d. Annual maps from Landsat data or SAR data.	e. Historical aerial photography in key regions where these features are present and data are available.	
Surface water and lake/river ice elevations	a. Product for large bodies from altimeters (B). b. Products for large bodies from LiDAR (B).			a. and b. Water level gauges and differential GPS.
Small lake/pond depths		a. Product for specific areas/times based on analysis of SAR data.		a. Ship based bathymetric surveys.
Surface water body connectivity		a. Maps based on analysis of fine resolution satellite imagery.		
Wetland inundation	a. Single to multiple date maps from SAR for specific sites (A). b. Weekly/ monthly AMSR-E products for entire Domain (B).	c. Seasonal and inter-annual maps of inundation for specific sites based on SAR data.		c. Seasonal variations in water depth across wetland types. b. Use of SAR product for algorithm validation.

River flooding		a. MODIS based products for specific areas. b. SAR based product for specific areas.		
Wetland type	a. Map available for entire study region (B). b. Validated maps exist for some regions (A).			a. Development of wetland map for entire study domain requires extensive validation.
Soil moisture	a. Maps from existing and future spaceborne MW radiometers (B). b. Soil moisture maps from SMAP (B).		c. Maps from time-series SAR data.	a., b., and c. Field measures of surface soil moisture via point measurements (continuous) and collected over a grid at time of satellite overpass. Use of spaceborne SAR and Airborne MW data to calibrate moderate to coarse resolution satellite products (see Airborne products in Table C2).
Water quality			a. Water quality based on Landsat data.	b. Water quality data for algorithm development and validation.
Surface elevation	a. Data from a single point in time based on SRTM for areas south of 60 degrees N Latitude (A). b. Fine resolution data derived from imagery from the National Geospatial-Intelligence Agency (B).	c. InSAR derived elevations.		

DISTURBANCE VARIABLES				
Burned area extent	a. Burned area product from MODIS/ATSR exist for period of 1997 to present (A). b. Burned area product from Landsat/SAR being generated through pre-ABoVE Project for ABoVE Study Region above 60 N latitude (A). c. Burned area product for Canada based on SPOT Vegetation and Landsat (A).	b./c. Fill in the gaps for burned area product using existing Landsat data archives back to 1972 where possible.		
Seasonal fire activity	a. MODIS daily burned area products (B).	b. Methods to generate seasonal fire activity based on medium resolution hotspot data exist.		
Fire severity			a. MTBS dNBR product exists for Alaska, but has been shown to provide inaccurate or incomplete information on fire severity. Other approaches using Landsat TM data have been demonstrated. Product development and validation required. b. FRP/FRE based products of fuel consumption from MODIS and similar thermal IR sensors.	a. Field-based observations of key measures of fire severity across ecosystem types. b. Field measures of fuel consumption across ecosystem types.
Fuel type/fuel load map	a. Fuel type maps based on MODIS and Landsat data are available across study region (A).			

Insect/disease area impacted and severity			a. Maps of insect/disease extent and severity have been generated for specific biotic agents in some regents. Development of maps to study specific outbreaks should be conducted in support of specific research projects.	a. Airborne and field observations of insect outbreak extent and severity.
Coastal/river erosion	a. Maps of coastal change based on Landsat TM data are being generated for western Alaska by the Western Alaska LCC (B).	a. Generation of maps for additional coastal areas b. Maps of coastal/river erosion in key study areas based on collection and historical/current aerial photography.		
Land cover change			a. A variety of approaches have been demonstrated to use medium resolution satellite data to map land cover change over broad areas. Specific products could be developed to support research in specific areas.	a. Field observations of land cover type to support development and validation of products.
Forest clearing	a. Forest loss maps for entire study region available for 2000 to 2012 period (B).	b. Maps for additional years could be developed to support specific research projects.		

VEGETATION VARIABLES				
Biomass	a. Biomass product from MODIS products and ancillary datasets, circa 2001 at nominal 250m resolution (B). b. Biomass products of Canada at 250m from Canadian Forest Service efforts (B). c. Biomass maps for Alaska from NASA CMS projects (ca 2005 and 2010) (B).		d. Biomass product based on processing of MODIS, VIIRS, SAR, and ancillary datasets.	a-d. Field observations of aboveground biomass.
Canopy Structure			a. Aboveground canopy structure, including height, has been generated from waveform LiDAR (e.g. GLAS) and might be possible from ICESat-2 photon-counting LiDAR.	d. Field observations of canopy height and structure.
Productivity	a. Gross primary productivity capacity at 1km from standard MODIS products (2000s) (A). b. Gross primary productivity capacity for Canada at 250m-1km from MODIS, AVHRR and forest inventory datasets (Canadian Forest Service) (A).		c. Gross and net primary productivity product based on processing of MODIS, VIIRS, and ancillary datasets.	c. Field observations for assessing ecosystem productivity, in particular flux tower data.
Leaf Area Index	a. Leaf area index and fPAR at 1km from standard MODIS products (2000s) (A). b. Leaf area index and fPAR of Canada at 250m-1km from MODIS, AVHRR and field datasets (Canadian Forest Service) (A).		c. LAI/ fPAR product based on processing of MODIS, VIIRS, and ancillary datasets.	c. Field observations of LAI and fPAR.

Light Use Efficiency, PAR, fPAR			a. Multi angle MODIS data to estimate photochemical reactive index (EPI).	a. Tower observations of GPP and light use efficiency.
Phenology / Seasonality	a. Phenology at 1km from standard MODIS products (2000s) (A). b. Phenology of Canada at 1km from MODIS and field datasets (Canadian Forest Service) (A).		c. Phenology product based on processing of MODIS, VIIRS, and ancillary datasets.	c. Observations of phenological patterns across ecoregions.
Inter-annual variability (spectral veg. indices)	a. Inter-annual variability of NDVI and EVI from standard MODIS products (250m-1km) (A). b. Range of AVHRR-based NDVI products (8km+) (A).		c. Inter-annual variability of NDVI and EVI product based on processing of MODIS, VIIRS.	
Growing season length / Surface thaw duration	a. Growing season length from standard MODIS phenology products (500m-1km) (A). b. Duration of the freeze-thaw period(s) from coarse resolution passive microwave (SSMR/SSMI) (A). c. SMAP based freeze/thaw maps (A).	d. Duration of the freeze-thaw period(s) can generated from medium to moderate resolution passive and active microwave data (e.g. AMSR-E, SARs).		c. and d. Weather station temperature data for validation of algorithms.
Community / Cover Type / Habitat types	a. Maps from various efforts, both Canadian and US from Landsat data (A). b. Maps from various efforts, both Canadian and US from MODIS data (A). c. Maps from various efforts, both Canadian and US from AVHRR data (A).	d. Updating existing land cover maps using information on the location and areas of recent disturbances using a number of disturbance products (burned area, forest loss).	e. Maps based on fine resolution satellite imagery.	

Post-disturbance recovery	a. Vegetation recovery based on assessment of variations in NDVI, albedo, and NPP can be carried out using existing products based on moderate resolution satellite data (B).		a. Several approaches have been developed to assess vegetation recovery based on assessment of time series, medium resolution satellite data. Additional product development and validation needed for different disturbance agents and vegetation types to support specific research projects.	a. Observations of differences in vegetation cover, disturbance severity, and site conditions as a function of disturbance type and vegetation type.

Table C2. ***Information products from airborne remote sensing data***

Sub-variable	Existing products	New products	Validation requirements
	MATERIAL FLUXES/ENERGY BALANCE		
CO_2/CH_4	a. Column CO_2 and CH_4 data over Alaska (A). b. Airborne Fourier Transform Spectrometer (FTS) (e.g., airborne eddy covariance data) (A) over Alaska.	a. Column CO_2 and CH_4 (A). b. Airborne FTS (A). c. CO_2 & CH_4 LiDAR (A).	
CO (carbon monoxide)	a. Column CO over selected areas (A).	a. Column CO (A). b. Vertical profiles of CO (A).	
	PERMAFROST, SNOW & ICE		
Land and water surface (skin) temperature		a. Day/night thermal IR data (B) to test thermal inertia as an indicator of land surfaces characterized by different permafrost types, ground ice contents, active layer depths, and talik dimensions.	a. Field-based observations of subsidence, thaw-related vegetation and soil disturbances, ground temperature, active layer depths, talik dimensions, ground moisture, and inundation.
Snow thickness/snow water equivalent		a. Airborne LiDAR data, stereo aerial photography (A), SAR and MW radiometer data (B) to aid in the development of snow thickness/snow water equivalent maps for specific watersheds.	a. Snow depth and snow water equivalent measurements along transects.
Active layer thickness		a. Airborne electromagnetic resistivity data over areas with different permafrost conditions, including thermokarst-affected sites in various stages of thaw (B).	a. Field-based observations of subsidence, thaw-related vegetation and soil disturbances, ground temperature, active layer depths, talik dimensions, ground moisture, and inundation.

Thermokarst/thermokarst lake area	a. Airborne LiDAR data exist for some regions (A).	a. Collect additional LiDAR data (A) in areas previously mapped for detection of surface elevation changes, as well as data in key regions to study thermokarst processes. Coordinate with satellite product development.	
Surface deformation	a. Airborne LiDAR data exist for some regions (A).	a. Collect additional LiDAR data (A) in areas previously mapped for detection of surface elevation changes, as well as data in key regions to study thermokarst processes. Coordinate with satellite product development.	
Lake ice thickness		a. Airborne electromagnetic resistivity data (B).	a. Lake and river ice thickness measurements with mechanical probing or geophysical surveys.
Ice jam location/ thickness		a. Airborne electromagnetic resistivity data (B).	a. Ice jam characteristics (thickness, height, width, grounding).
HYDROLOGIC VARIABLES			
Small lake/pond depths		a. Maps for specific sites/areas based on LiDAR /VIS-IR data (B).	a. Ship based bathymetric surveys.
Surface elevation	a. Surface elevation data for selected areas/watersheds based on LiDAR data. b. Surface elevation data from airborne InSAR.	c. Super-high resolution (cm scale) from UAV stereo photography for specific sites (A).	
Soil moisture		a. Airborne MW radiometer data (C) and SAR data (C) over selected study sites.	a. Field measures of surface soil moisture via point measurements (continuous) and collected over a grid at time of overpass.
DISTURBANCE VARIABLES			
Fire severity	a. Hyperspectral data over 2004 burn in Alaska (USFS collection) (B).	a. Hyperspectral data (C) over burned areas in different vegetation types.	a. Field observations of surface characteristics used to map severity.
Insect/disease area impacted and severity		a. Hyperspectral data (C) over areas experiencing different insect/disease disturbances.	a. Airborne and field observations of insect outbreak extent and severity.

VEGETATION VARIABLES			
Biomass	a. LiDAR datasets (B) exist for some areas in Canada; data are being collected in Alaska as part of NASA CMS project, and for ongoing NASA TE project in tundra.	a. Collection of LiDAR data (C) over and SAR data (C) sites in different vegetation types (coordinate with canopy structure and disturbance recovery - vegetation).	a. Field observations of aboveground biomass.
Canopy Structure	a. LiDAR datasets (B) exist for some areas in Canada; data are being collected in Alaska as part of NASA CMS project, and for ongoing NASA TE project in tundra.	a. Collection of LiDAR data (B) over sites in different vegetation types (coordinate with biomass and disturbance recovery - vegetation).	a. Field observations of canopy height and structure.
Disturbance recovery – vegetation	a. LiDAR datasets (B) exist for some areas in Canada; data are being collected in Alaska as part of NASA CMS project. b. Some hyperspectral data (C) being collected in Alaska as part of NASA CMS project.	a. Collection of LiDAR data (C) over sites in different vegetation types experiencing different disturbances at different stages of recovery (coordinate with biomass and canopy structure). b. Collection of hyperspectral data (C) over sites in different vegetation types experiencing different disturbances at different stages of recovery.	a. and b. Observations of differences in vegetation cover, disturbance severity, and site conditions as a function of disturbance type and vegetation type.

Table C3. *Priority for products generated from satellite and airborne satellite data (where 1 are products with the highest overall importance and 3 the lowest).*

a. Domain-wide products (satellite remote sensing data)

	Maturity Level*	Importance Ranking
Snow depth	A	1
Snow water equivalent	A	2
Ground surface temperature	A	2
Annual maps of surface water extent (lake/pond) (medium-resolution data	C	1
Forest cover change (Landsat-based product)	C	1
Daily, seasonal, inter-annual changes in atmospheric mole fractions of CO_2	B	1
Land surface temperature	B	1
Seasonal inundation and flooding (moderate- to coarse-resolution data)	B	1
Snow extent time series (single product generated from integration of existing products)	B	1
Soil moisture	B	1
Wetland maps	B	1
Winter thaw events	B	1
Daily, seasonal, inter-annual changes in atmospheric mole fractions of CH4	B	2
Aboveground biomass	B	3
Daily, seasonal, inter-annual changes in atmospheric mole fractions of CO	B	3

*A. Provisional products B. Products with Stage 1 validation
C. Products with Stage 2 to 4 validation

b. Landscape- to regional-scale products (satellite remote sensing data)

	Maturity Level	Importance Ranking
Area extent and severity of biotic disturbances	A	1
Burn severity (organic layer consumption, mortality, etc.)	A	1
Depth of thaw (active layer) dynamics, seasonally and inter-annually	A	1
Distribution and extent of thermokarst features (e.g., active layer detachments, thaw slumps).	A	1
Inundation maps (seasonal to inter-annual from medium-resolution data)	A	1
Post-disturbance soil moisture	A	1
Post-disturbance vegetation recovery (Landsat time series)	A	1
Dissolved organic matter, suspended sediments, and chlorophyll in terrestrial water bodies	A	2
Land cover change (annual)	A	2
Anthropogenic disturbance	C	1
Seasonal and inter-annual variations in river, lake/pond ice cover	C	2
Connectivity between water bodies (fine resolution)	C	3
Land and lake surface temperature maps (time series from Landsat data) model validation	C	3
River flooding	C	3

c. Landscape- to regional-scale products (airborne remote sensing data)

	Maturity Level	**Importance Ranking**	**Airborne Remote Sensing Systems**
Active layer depth	A	1	Small Footprint LiDAR, InSAR
Biomass/canopy structure	A	1	Large Footprint LiDAR, SAR
Deep substrate properties (permafrost depth, ice content, talik)	A	1	Electromagnetic Resistance Imager, Ground Penetrating Radar, P-band SAR
Soil moisture	A	1	Microwave Radiometer, SAR
Vegetation composition	A	1	Hyperspectral Imager
Snow water equivalent	A	2	
Canopy chemistry	A	3	
Canopy snow interception	A	3	
Light use efficiency	A	3	
Atmospheric CO_2, CH_4 and CO	C	1	CARVE Payload, Airborne Fourier Transform
Seasonal snow depth dynamics	C	1	Small Footprint LiDAR, Microwave Radiometer, SAR
Surface Deformation (seasonal)	C	1	Small Footprint LiDAR, InSAR
Thermokarst distribution (annual)	C	1	Small Footprint LiDAR, InSAR
Surface elevation	C	2	
Photosynthetic Capacity	C	3	