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

ABoVE Science Definition Team

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Forword

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

Rapid changes that are presently occurring to Northern High Latitude terrestrial and aquatic ecosystems and the societal impacts of these changes have provided the impetus for significantly expanding research sponsored by a number of agencies. A key component of these studies is the collection and analysis of a wide range of remotely sensed data (both airborne and spaceborne) to help quantify and understand ongoing changes to the Earth surface and adjacent boundary layer of the atmosphere. Recognizing the importance of remotely sensed data, NASA's Terrestrial Ecology Program funded the development of a Scoping Study Report to provide the proof-of-concept demonstration of feasibility for a field campaign to study the vulnerability of Arctic and boreal social-ecological systems to environmental change. This report was reviewed by an expert panel, which made several recommendations. These recommendations were the focus of a subsequent workshop that resulted in a revised Executive Summary for the Arctic-Boreal Vulnerability Experiment (ABoVE)[1]. The document presented here, which is based on the outcomes from these previous activities, represents the ABoVE Concise Experiment Plan that will 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 field campaign and expresses the compelling rationale explaining the scientific and societal importance of the study. The experiment plan presents both the science questions driving ABoVE research as well as the study design that will address them. It defines ABoVE's science objectives, broadly focused on 1) developing a fuller understanding of ecosystem vulnerability to environmental change to Arctic and boreal ecosystems in western North America, and 2) providing the scientific basis for informed decision-making to guide societal responses at local-to-international levels. The ABoVE campaign will link field-based, process-level studies with geospatial data products derived from airborne and spaceborne sensors, providing a foundation for improving the analysis and modeling capabilities needed to understand and predict ecosystem responses and societal implications.

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

ABoVE Vision

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

1. Introduction

The western North American Arctic and boreal region (hereafter referred to as the ABoVE Study Domain) contains vast expanses of tundra and boreal forest – globally significant biomes whose unique properties make them particularly sensitive to environmental change. The sub-biome or ecoregion heterogeneity is considerable, ranging from densely forested lowlands to high Arctic deserts to flat, poorly drained terrain covered by ponds, small lakes, wetlands, and peatlands. With an average annual temperature less than 0°C, a significant portion of the ABoVE 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 carbon in thick surface organic layers and frozen mineral soils. The streams and rivers in this region not only provide fresh water and serve as a key transportation network, but deliver significant inputs of freshwater, sediment, and dissolved organic matter to coastal oceans, which in turn, contribute to the regulation of oceanic ecosystems and processes. The terrestrial and aquatic ecosystems of the ABoVE Study Domain provide habitat for a large number of fish, mammal, and bird species, with many migratory species using this region as their primary breeding ground. Although they are lightly populated and managed by humans, the terrestrial and aquatic ecosystems of the ABoVE Study Domain are critical to society in a number of ways. This area is a homeland to a number of ethnically and culturally distinct indigenous groups of people, all of which have unique and significant political relationships with state, territorial and federal governments. The ABoVE 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. There is recognition from decision-makers and land managers at all levels that improved scientific knowledge on the impacts of climate and environmental change, along with an understanding of how society is responding to these changes, is imperative to inform development of sound policies and management strategies.

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

At local to landscape scales, some social-ecological systems in the ABoVE Study Domain are resistant to the impacts of changes in press or pulse-disturbance regimes, while others are undergoing significant changes. *Resilience* is the capacity of a social-ecological system to maintain its function, structure and feedbacks in the face of a significant disturbance or perturbation. Resilient systems recover to a similar pre-disturbance state because the internal feedbacks that regulate system stability are robust. In other cases, internal, stabilizing feedbacks weaken or are disrupted, rendering social-ecological systems 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 them into new states as a result of transformations, where novel dynamics emerge.

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

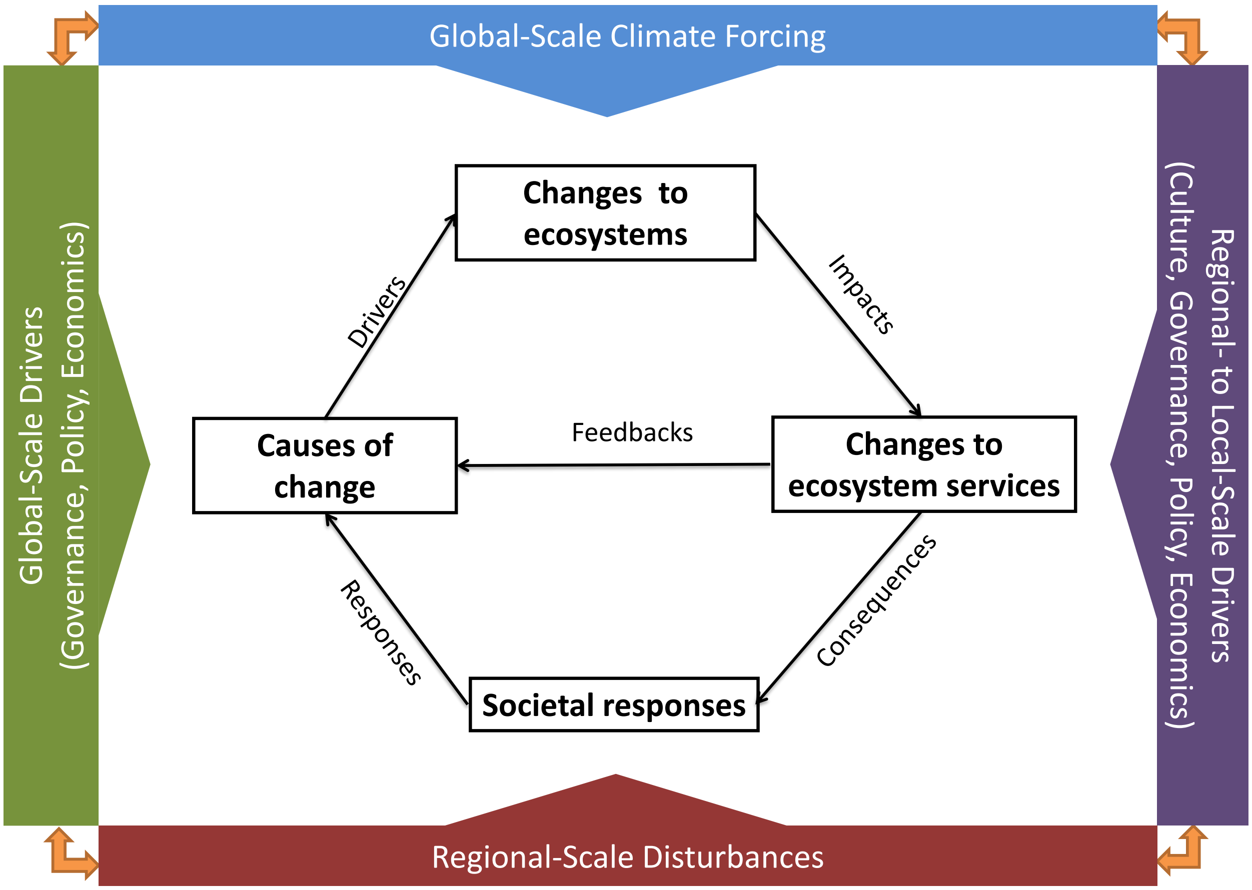
2. Research Framework and Overarching Science Question

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

The Vulnerability Research Framework

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

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



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

Substantial changes to the physical landscape and ecological functioning have been documented across the ABoVE 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 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). Also driven by climate change, both tundra and boreal forest ecosystems in the ABoVE Study Domain have experienced increased frequency and severity of wildfire and other biotic disturbances such as insect outbreaks.

The rapid changes observed in the structure and function of ecosystems in the ABoVE Study Domain have realized and potential impacts on key ecosystem services. The region's terrestrial and aquatic ecosystems supply important *provisioning services* to society, including freshwater, food, fuel, wood and fiber. The vast areas of wilderness found throughout the ABoVE Study Domain along with bird, fish, and wildlife species provide important *cultural services*, supporting a wide range of educational, spiritual, and recreational activities and are central to 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 in support of mineral, oil, and gas resource development. High Northern 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. Within the ABoVE Study Domain, flora and fauna represent important provisioning and cultural resources; both global-scale climate forcing and regional-scale disturbances are changing their habitat, abundance, health, phenology and migration patterns. Human infrastructure and transportation relies heavily on the supporting service of stable ground, which is threatened by warming-driven permafrost degradation and coastal erosion caused by sea ice loss and increasing storm surges. Carbon sequestration and storage in the vegetation and soils of ecosystems in the ABoVE Study Domain benefits global society through prevention of additional greenhouse gas release to the atmosphere. Carbon sequestration in the 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 may be expected to increase from increased 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 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 ABoVE 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.). Responses are also mediated by economic factors (cost of living, cost of moving, availability of jobs for cash) 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.

Overarching Science Question and Objective

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

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

To address this overarching question, research during ABoVE will be organized around six *focus areas* that represent critical and unique aspects of Arctic and boreal social-ecological systems: society, disturbance, permafrost, hydrology, flora and fauna, and carbon biogeochemistry These focus areas will address important second tier questions, which in turn, will require research on key processes and interactions that are driving changes to social-ecological systems in the ABoVE Study Domain. Addressing these questions requires an integrated research approach based upon the following *overarching research objective*:

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

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

3. Research Focus Areas

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

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

The demand for ecosystem services and natural resources is increasing throughout the ABoVE 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 ABoVE Study Domain are providing. For example, how do exploration activities that are dependent on winter roads impact wildlife populations? How will these impacts change if all-weather roads are constructed to provide access to exploration areas? Understanding the consequences of different land uses within the context of a landscape that is rapidly changing in response to environmental change presents a key challenge to decision makers in the ABoVE Study Domain.

Landscapes and their ecosystem services in the ABoVE 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 which are mandated by law to identify and protect cultural resources, many of which have deep-rooted ties to nearby communities. These agencies are also required to consult with Alaska Native entities regarding the protection of these 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 ABoVE Study Domain will have significant impacts at scales beyond the local and regional levels. The abundance of natural resources in High Northern Latitude regions creates opportunities for the use and distribution of additional ecosystem services both locally and beyond, but the potential substantial losses of carbon sinks in vegetation and soil 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 and/or not easily anticipated. Given these complexities and the rate of current environmental change in the ABoVE 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 ABoVE 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 that social-ecological systems are particularly vulnerable to the impacts of environmental change:

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

2. Direct and indirect effects on human health (e.g., disease vectors, food availability, air and water quality, mental health from intact culture and perceived ability for self determination);

3. Rapid direct and indirect effects on hydrology, permafrost, and ice which impact infrastructure and landscapes (buildings, roads, airports, frozen rivers) and cultural heritage (practices, traditions, language, historically important places); 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 ABoVE Study Domain, including changes to disturbance regimes, the cryosphere, hydrologic systems, and the flora and fauna endemic to northern high latitude ecosystems. These relationships provide a strong linkage to the research being conducted to address the other ABoVE science questions discussed in this chapter.

Key Research – Improving the understanding of the impacts of environmental change on provisioning, subsistence, natural resources, human health, infrastructure and culturally important places will require interdisciplinary research approaches integrating socio-economic data with data on relevant landscape patterns and processes. This research will 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 climactic 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 observations of landscape and ecological processes be coupled with socio-economic data at multiple scales to investigate how these changes are affecting human societies. Research on the impacts of climate change on landscapes and ecosystems will carried out through addressing the questions and objectives for the other focus areas discussed in this chapter.

Studies on the range of underlying processes and interactions that provide feedbacks to climate in Arctic and boreal ecosystems across the ABoVE Study Domain will be needed to determine changes to climate regulation. Research addressing climate feedbacks includes 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 discussed in the other focus areas in this chapter.

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

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

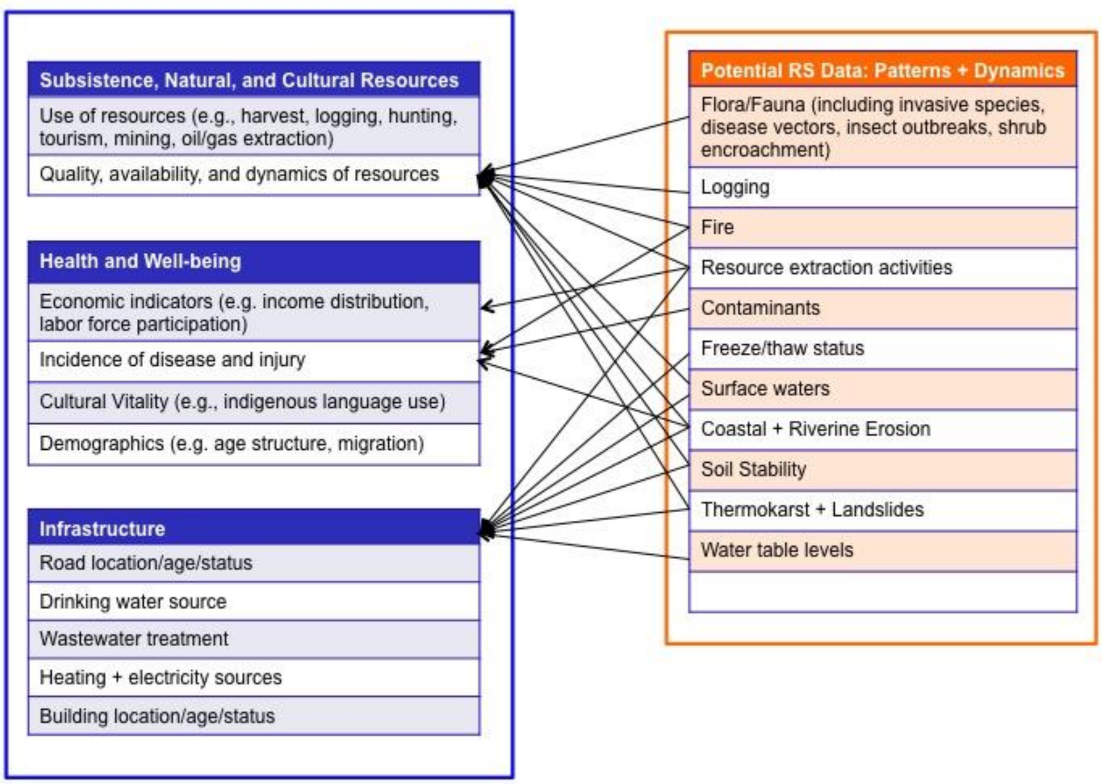


Figure 3.1. *The linkage of information provided through the analyses of remotely-sensed data to key ecosystem services in the ABoVE Study Domain that will be studied during ABoVE.*

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

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

Across the North American boreal forest, average annual area burned has increased over the past half-century. Late-season burning in Alaska has risen over the past decade, which in turn, has resulted in more severe fires. In particular, there has been an increase in deeper burning of surface organic soils, which in turn, reduces soil carbon stocks, causes more rapid warming of permafrost, and alters post-fire succession. The occurrence of large fires may also be increasing in tundra. While further climate warming is likely to increase potential for burning, changes in forests dominated by conifers to deciduous vegetation, at least in boreal forests, will have a negative feedback on fire activity. Based on current understanding, it is challenging to predict future changes to fire regimes in the ABoVE 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 ABoVE Study Domain. Unlike in 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 disturbances is particularly important in the southern boreal forest where harvesting of wood products represents an important economic driver for local communities.

In many regions of Alaska and northwest Canada rapid permafrost thaw is on the rise as shown by observations of increased observance of thaw slumps, formation of new thermokarst lakes and ice wedge ponds, collapse of peat plateaus, and rapid lake drainage due to permafrost loss or near-surface degradation. These changes are occurring across the Arctic at different rates controlled by variations in ground ice content, geomorphology, and vegetation, and are consistent with borehole-measured permafrost temperatures that have steadily increased in northern Arctic areas by several degrees Celsius 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 ABoVE 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 will include landscape- to regional-scale observations of disturbance area and severity derived from remotely sensed data, as well as from land-management records and paleo proxies. While information on the areas disturbed by fire and some biotic disturbance agents are available from records maintained by land management agencies, the use of remote sensing data provides improved information on actual area disturbed, the timing of disturbances events, and the severity of the disturbances. Additional research is needed to develop and validate remotely sensed disturbance products across the ABoVE 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 critical land characteristics (vegetation cover and condition, permafrost characteristics including temperature and ice content, active layer depth, soil moisture, surficial geology, topography, weather and climate). Ground-based observations at plot scales stratified across disturbance severity and the biotic and abiotic conditions at the time of disturbance are needed to quantify disturbance severity, the controls on severity, as well as understand the immediate impacts on ecosystems. Observations across sites and landscapes that differ in time after disturbance, as well as abiotic conditions (including remotely-sensed data), are needed to understand the consequences of past disturbances for ecosystem and landscape processes as well as to assess whether and how current disturbance regimes and their impacts differ from that occurred during past periods of rapid change. Ground-based observations are also needed to further develop and validate disturbance products from remotely sensed data. Long-term change in disturbance regimes can only be identified by comparing recent (i.e., the last 30 to 50 years) trends to historical records of disturbance, including regional stand age structure and paleo-ecological reconstructions from tree rings and sediment records. Analysis of paleo data can also provide critical information on the ambient conditions at the time of disturbance, but also on longer-term changes to community composition.

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

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

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

The vulnerability and resiliency of permafrost to rapid thaw has significant consequences for society – both within and beyond the ABoVE 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 ABoVE Study Domain. Frozen ground supports infrastructure, transportation and other services that local communities rely on. Pan-Arctic permafrost stores an enormous quantity of frozen soil organic carbon that is protected from release to the atmosphere – thus providing a critical climate regulation service for global society. The fate of the thawing permafrost landscape, along with associated changes in ecosystem structure and function, represents a critical uncertainty in projecting greenhouse gas feedbacks to future climate.

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

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

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

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

Rationale – The hydrologic cycle in High Northern Latitudes regions is dominated by winter water storage as snow, followed by high rates of runoff and stream and river flows in spring, and generally lower flows in summer and fall. Lakes, ponds and wetlands (that provide extensive habitat for fish, birds and other wildlife) are abundant on the landscape. Across the ABoVE Study Domain, annual precipitation (P) is nearly equally partitioned between rain and snow, with excess water above evapotranspiration (ET) being either stored as snow, surface water, and soil and groundwater or exported as stream and river flow to the Bering Sea and Arctic Ocean, where these inputs are particularly important in regulating coastal ocean processes. The hydrology of the ABoVE Study Domain also influences land-atmosphere and water-atmosphere interactions and feedbacks that involve water, carbon dioxide, methane, and energy exchange, and a range of ecosystem processes. Understanding the impact on plant productivity and mortality from increased evapotranspiration due to warmer temperatures without concurrent increases in precipitation is particularly important. Intensification in fluxes of P, ET, and runoff are expected manifestations of a warming climate. Warming is also projected to lead to a shift from a surface-water dominated to a more groundwater dominated system, a transition that may alter the timing and decrease the amount of runoff.

Changes to hydrology in the ABoVE 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 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 element of the hydrologic system in the ABoVE Study Domain is the widespread presence of permafrost, and the fact the permafrost is undergoing rapid warming will to a large degree control the vulnerability of hydrologic systems. Permafrost influences infiltration, lateral runoff, groundwater flow, and associated soil groundwater storage. It is hypothesized that thawing permafrost will lengthen hydrologic flow paths and residence times, thus affecting water quality and the rate of biogeochemical processing of carbon, nutrients, and contaminants. Decreased permafrost extent has been linked to increased infiltration and subsurface flow, increased organic carbon mineralization (carbon dioxide or methane production), decreased organic carbon export, and increased inorganic carbon export across boreal and Arctic regions. In most hydrologic systems, residence times are considered to be the travel times along surface and sub-surface flow paths; however, the 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, and is potentially critical to controlling ecosystem structure and function.

The unusual temporal-spatial distribution of water in the ABoVE Study Domain has thermal as well as hydrologic impacts, and provides strong feedbacks to and regulation of climate. The snow that covers the ground from October through May not only represents half of the annual surface runoff, but also is an efficient thermal insulator and reflector of shortwave radiation that controls the surface energy balance. Snow insulating properties have a major impact on winter soil freezing and permafrost temperature and distribution. In addition, local distribution and depth of snow, is influenced by the type and structure of vegetation. When the snow falls, how it falls, and how long it stays has profound implications for hydrology and ecosystem structure and function in the ABoVE Study Domain; therefore, patterns of snowfall have to be considered as an integral part of the hydrologic system. Finally, snow depth and duration, and patterns of mid-winter thawing and refreezing of snow are 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 ABoVE 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. In addition, erosion of thaw slumps from rapidly warming permafrost adjacent to streams and rivers also control patterns of material export. Surface waters also influence the carbon cycle through the exchange of gases between the land and atmosphere. Unlike terrestrial ecosystems that are spatially and temporally variable sources or sinks of carbon dioxide and methane, lakes, streams, and rivers are all net sources of these greenhouse gases (GHG) to the atmosphere, and commonly exhibit gas flux densities that far exceed terrestrial GHG fluxes.

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

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

Rationale – Long-term satellite remote sensing data records indicate that vegetation characteristics in undisturbed areas of the ABoVE Study Domain are undergoing directional change at regional and in some cases, pan-Arctic scales. In response to climate warming, some regions have been increasing in productivity (greening), while other regions have experienced reduced productivity and increased mortality (browning). The same satellite sensors are revealing that at the pan-Arctic scale, growing seasons are lengthening primarily because warmer springs alter freeze-thaw dynamics and advance spring snowmelt and onset of plant growth. Climate-sensitive disturbance regimes in the ABoVE 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, 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 ABoVE 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 ABoVE Study Domain's changing vegetation characteristics – and vice-versa – how this changing vegetation impacts fauna. Faunal influences on ecosystem form and function in the ABoVE Study Domain include, but are not limited to, rodents altering cycles of tundra productivity that are detectable from satellite greening records, insect infestations defoliating large areas of boreal forest, and large mammal grazing that inhibits woody shrub productivity, alters secondary succession following wildfire or inhibits northward treeline advancement. A wide range of resident and migratory fauna depend on the unique habitat provided by the ABoVE Study Domain for food and shelter. As a result of the aforementioned 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 ABoVE Study Domain, such as caribou, as the advancement of vegetation phenology in some areas outpaces the rate at which these animals are able to adjust the timing of their nutritional requirements, which may be contributing to the recent major decline in their reproductive success of some herds.

Satellite remote sensing records have also revealed significant and contrasting trends in surface water extent within the ABoVE 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 impacts the carbon and nutrient cycling. These changed patterns of ice cover, wetting and drying, and water composition are likely to alter habitat availability and quality for the aquatic and semi-aquatic fauna in the ABoVE Study Domain, including birds, fish, mammals, and invertebrates. Every spring, millions of shorebirds, ducks, geese, loons and swans migrate to the ABoVE Study Domain to breed, raise their young and feed in wetlands. Fresh water fish inhabit lakes and streams, and move between spawning and overwintering areas via stream networks. Beavers are a semi-aquatic and critical keystone species of the boreal forest, and thus changes in their habitat quality will likely have cascading impacts on ecosystem form and function

Humans, in addition to being drivers of change, are also responding to changes in the flora and fauna with respect to the ecosystem services they provide. People both within and beyond the ABoVE 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 aquatic ecosystems in the ABoVE Study Domain that will have a variety of cascading effects on the ecosystem services that society depends upon.

It is largely unknown which faunal species will be able to adapt and be resilient to the many biotic and abiotic changes occurring in the ABoVE Study Domain, yet the resulting changes in both plant-animal and fresh water-animal interactions will strongly influence the response of ecosystem form and function. Further, because 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 ABoVE 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.

Arctic and boreal terrestrial ecosystems play a particularly important role 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. Changes in vegetation cover and phenology have strong impacts on albedo, as well as the exchange of water between the land surface and atmosphere.

Key Research – Research to address this question will include landscape- to regional- to domain wide-scale observations of vegetation characteristics and surface water extent derived from remotely sensed data, as well as observations to assess changes in terrestrial and aquatic growing season length (e.g. visible, infrared, and microwave data). Satellite remote sensing data are needed to assess seasonal, inter-annual and longer-term variations in vegetation characteristics at scales of 30 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 data are 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 factors controlling vegetation characteristics, surface water extent, and growing season length will also require geospatial data on climate (air temperature, relative humidity, precipitation, climate indices), ice cover, burned area metrics, spatial distribution of biotic disturbance agents, resource extraction sites, active layer thickness, ground temperature, soil moisture, topography and soils, with many of these observations being provided using remotely sensed data. Regional-scale observations of spatial and temporal dynamics in wildlife habitat could include satellite (e.g. using ARGOS) and / or airborne and telemetry tracking of tagged or observed animals. Ground-based, plot level observations stratified across different tundra and boreal ecoregions/subzones, vegetation community types, burn scar properties, and wildlife habitats and migratory corridors will be required. Ground observations will also be necessary to gain a mechanistic understanding of the interactions and feedbacks among abiotic and biotic changes that together result in net changes in ecosystem form and function, including greenhouse gas fluxes and exchanges of energy and water. 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.

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

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

Rationale – There is considerable intra- and inter-annual and decadal variability in the exchanges of two key greenhouse gases (CO_2 and CH_4) between the land surface and atmosphere across the Arctic and boreal region. Ongoing data collections for NASA's CARVE mission are showing 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. Because of this uncertainty, the research previously presented for the different scientific focus areas identified for ABoVE specifically address many of the processes controlling carbon biogeochemistry and cycling. Here, additional research on processes regulating land/atmosphere exchange of soil carbon biogeochemistry is presented.

The ABoVE Study Domains contains a significant fraction of the Earth's soil organic carbon (SOC).. The processes resulting in the removal and storage of atmospheric CO_2 as SOCrepresent an important ecosystem service in terms of long-term regulation of the earth's climate through removal and storage of a significant amount of atmospheric carbon. Presently, longer-term changes in the climate are mobilizing deeper pools of SOC in the ABoVE Study Domain that have sequestered from the atmospherefor hundreds to thousands of years, as well as accelerating the rate of turnover of more labile SOC pools. This is particularly important in regions experiencing rapid permafrost warming and degradation, where SOC has previously remained stable due to low temperatures. However, destabilization of slow-turnover SOC is also an important feature of non-permafrost profiles, especially peatlands, where stabilization mechanisms of SOC may be more strongly linked to processes of formation of deep organic soil horizons. Finally, disturbance from fires plays an important role in SOC cycling either directly reducing organic soils through combustion or by changing ambient conditions. Understanding the complex interactions that contribute to the vulnerability of Northern High Latitude soil carbon stocks represents a major research challenge.

As the size of the High Northern Latitude soil carbon pool is estimated to be more than twice hat contained in the atmosphere, there is significant concern about its potential to feedback to climate through exchanges of CO_2 and CH_4 between the land surface and the atmosphere. Simultaneous with enhanced SOC destabilization, climate changes are driving changes in disturbance regimes along with shifts in vegetation, soil temperature, and the hydrological cycle that alter rates of heterotrophic respiration and SOC production. Which of these factors dominates the biogeochemical processes regulating C cycling in the ABoVE Study Domain, what are the processes that drive their 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 production, transformations, and fate of SOC in the ABoVE Study Domain.

In order to understand how variations in abiotic and biotic conditions regulate 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 High Northern Latitude ecosystems, spatial and temporal variations in CO_2 and CH_4 fluxes from soils are regulated by vegetation, 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, soil temperature and moisture, active layer depth, area of small lakes and ponds, and levels of inundation in wetlands.

A key challenge currently hindering progress in more accurate predictions of soil microbial gas fluxes using information derived from airborne and satellite remote sensing systems is the lack of mechanistic models validated against large-scale remote measurements of state variables in the ABoVE Study Domain. Research addressing SOC stabilization and destabilization must involve studies of the factors that control soil biogeochemistry at multiple temporal and spatial scales. The ultimate drivers of releases of soil organic matter carbon through heterotrophic respiration – enzymes secreted by microorganisms – function in accordance with the biochemical properties of substrates and enzymes, as well as the physical characteristics of the environment. The microbes that demand the resources liberated upon substrate decay produce these secreted enzymes in response to competitive dynamics among microbial populations. A fraction of the C they take up can is allocated to CO_2 or, for methanogens, CH_4.

In addition to gaseous efflux of C to the atmosphere, carbon also can be liberated from these ecosystems into water and transported as particulate organic carbon (POC), dissolved inorganic carbon (DIC), and dissolved organic C (DOC) to streams, ponds, lakes and eventually to the coastal regions, where it can be buried or become available for decomposition to a different microbial community and potentially emitted to the atmosphere.

Only recently have researchers begun to incorporate critical drivers of microbial activity such as nutrient availability and substrate stoichiometry into models. Any research strategy must promote the development of empirical and theoretical modeling studies that link disciplines as diverse as biochemistry, microbial ecology, and biogeochemistry to broader-scale observations made from remotely-sensed data. In addition, these modeling studies need to capture the complex interactions that drive variations in the abiotic environment that control soil 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 understanding of the factors controlling the vulnerability of organic carbon is needed. This research will employ landscape- and regional-scale observations of land cover classes, hydrological and C cycles, and other observations of state variables such as changes to permafrost. Where time series of state variables and ecological data are not obtainable, it will be necessary to include research based on space-for-time substitutions as a means of predicting future soil organic stabilization and destabilization trends. Biogeochemical and ecological data needed from spatially disparate scales. These include: (a) observations of critical microbial processes and edaphic and abiotic features at the plot scale (i.e. nutrients, quantity and stoichiometry of soil inputs, moisture, pH, stable isotopes of soil organic carbon, dissolved species and trace gases, hydrologic connectivity or transport); (b) flux tower data quantifying meso-scale energy and fluxes of CO_2 and CH_4 and the isotopic signatures of these gases' fluxes; (c) large-scale flux observations of CO_2 and CH_4 and their isotopic signatures using aircraft and tall towers; and (d) remotely sensed data at the landscape- to regional- scales to understand patterns of biogeochemical fluxes across land cover classes as a function of time since disturbance where needed. Isotopic signatures of relevant gases are particularly important, because they help constrain flux source. For example, radiocarbon measurements permit estimation of CO_2 age, and hence the age of its source, and ^{13}C, deuterium, and ^{18}O measurements help identify biotic vs. abiotic CO_2 and CH_4 production and consumption processes and transport pathways, and hydrologic influences on soil organic carbon destabilization.

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

Synthesis and Integration

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

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

Key Research – At the heart of addressing the ABoVE research objectives is the need to develop models of ecosystem structure and function that integrate and synthesize understanding on the dynamics of social-ecological systems that focused on people, permafrost, hydrology, disturbance regimes, and flora and fauna. In addition, some issues may also require the development of impact models and human consequence models. Research carried out as part of ABoVE needs to promote the development of a diversity of conceptual frameworks that are collectively capable of addressing a broad range of assessment issues relevant to the ABoVE Study Domain. The design of these conceptual frameworks must clearly identify their scope and intended use. Key issues that need to be addressed in the design of conceptual frameworks for integration and synthesis include: (1) connectivity among processes in the framework; (2) description of processes in the framework; (3) model parameterization; (4) model initiation; (5) model verification (reproducing data used in model development; (6) model validation (evaluation of model quality for independent data not used in model development); (7) model analysis (sensitivity/uncertainty analyses); and (8) collection and/or compiling the data needed to drive model application. The design of conceptual frameworks will need to elucidate how information that will be forthcoming from ABoVE research, as well as information available from other research efforts in the ABoVE Study Domain, will be used address each of these issues. There are challenges cutting across these issues that need to be addressed, including scaling and model-data fusion. Finally, a major challenge is to bring together a collaborative team with the expertise and focus to successfully bring an integration and synthesis conceptual framework to fruition through the design, implementation, and application phases within a defined time window.

Table 3.1. *Tier 2 Science Questions and Objectives*

Tier 2 Questions

How are environmental changes affecting critical **ecosystem services** - natural and cultural resources, human health, infrastructure, and climate regulation - and how are human societies responding?	What processes are contributing to changes in **disturbance regimes** and what are the impacts of these changes?	What processes are controlling changes in the distribution and properties of **permafrost** and what are the impacts of these changes?	What are the causes and consequences of changes in the **hydrologic system**, specifically the amount, temporal distribution, and discharge of surface and subsurface water?	How are **flora and fauna** responding to changes in biotic and abiotic conditions, and what are the impacts on ecosystem structure and function?	How are the magnitudes, fates, and land-atmosphere exchanges of **organic carbon pools** responding to environmental change, and what are the biogeochemical mechanisms driving these changes?

Underlying Process Objectives

Identify and map vulnerable and resilient **social-ecological** systems over space and time, with a focus on processes that control human responses and adaptation to changes in ecosystem services.	Determine the controls on the spatial and temporal patterns of the primary natural **disturbance** regimes (fire, biotic disturbances, rapid permafrost thaw).	Identify the primary factors driving **permafrost** vulnerability and resiliency to thaw.	Identify and understand the combination of factors driving longer-term temporal and spatial changes in **vegetation** characteristics, including **habitat** quality and extent, productivity, phenology, cover type and extent, as observed in the satellite data record.	Reduce uncertainties in destabilization rates of slow- to fast-turnover of **soil organic carbon** pools.

Complex Interactions Objectives - Ecosystems

Improve understanding of how landscape-scale variations in air temperature, snow cover, disturbance, surface hydrology, soil properties, and vegetation cover interact to control the distribution of **permafrost** and permafrost degradation.	Determine how the direct and indirect impacts of press and pulse disturbances interact to affect the **hydrologic** system.	Evaluate how changes to and interactions between disturbances, permafrost, and the hydrologic system are driving direct and indirect changes to **flora, fauna, and carbon fluxes**.	Assess factors controlling observed and projected changes in water discharge, storage, and hydraulic connectivity on **materials exports.**

Complex Interactions Objectives - Society

1. Assess how future climate warming is likely to affect **infrastructure and transportation**	2. Determine how changes to disturbance regimes, flora and fauna, permafrost conditions, and/or	3. Evaluate how changes to ecosystems will influence **subsistence**	4. Analyze how changes to natural and cultural resources will impact local communities as well as	5. Determine the sources of variations in climate feedbacks from Arctic and boreal ecosystems and assess the potential	6. Determine the degree to which the changing environment and altered human activities results in self-reinforcing/synergistic

networks.	hydrology influence **human health outcomes** in the ABR.	opportunities.	influence **land management** policies and practices.	for future changes to **climate regulating** services at regional to global scales.	and/or self-attenuating/ antagonistic changes in **ecosystem services.**

4. Overall Research Approach and Strategy

To address the science questions and objectives presented in Chapter 3, research during ABoVE will focus on studying to the response of social-ecological systems across the ABoVE Study Domain to environmental change, and the impacts and consequences of these responses. Projects sponsored by NASA should utilize an integrated strategy that includes field studies, analyses of remote sensing data (both airborne and spaceborne), and modeling. Where possible, NASA-sponsored research should be coordinated with studies being funded by other agencies and organizations within the ABoVE Study Domain.

To address the tier 2 questions and objectives summarized in Table 3.1, NASA should fund three broad categories of projects. Category 1 projects should include research to document and understand the causes and consequences of large-scale changes to land surface areas across the ABoVE Study Domain. Category 2 projects should include research to identify and quantify the underlying processes and complex interactions among them that drive changes at landscape to regional scales, as well as the impacts of these changes. Using the results from Category 1 and 2 projects, Category 3 should include research to assess the impacts of environmental changes on social-ecological systems through integration, synthesis and scaling of results across the entire ABoVE Study Domain. The timing of projects sponsored by NASA during the ABoVE field campaign should be sequential, initially focusing on Category 1 and 2 projects, followed by Category 3 during the latter years.

We recommend that all projects associated with ABoVE include research that employs remotely-sensed data, as well as field-based research and/or modeling. The modeling and field-based studies that are used with the collection, analysis and use of remotely sensed data, however, could be part of research activities funded by other agencies, particularly those that have agreed to collaborate with NASA on research about the impacts of environmental change on social-ecological systems in the ABoVE Study Region (see Chapter 5).

<u>Category 1:</u> *Document and understand the causes and consequences of changes to land surfaces areas across the ABoVE Study Domain over the past several decades (including the period of the ABoVE Field Campaign)*

Research for these projects should focus on using remotely-sensed data from across the entire ABoVE Study Domain to determine what ***large-scale changes*** are occurring to the land surface[2] and atmosphere, as well as identify areas where changes are not occurring. This information is critical for determining what portions of the ABoVE Study Domain are vulnerable to change as well as those portions that are resistant or resilient to the impacts of recent climate change. This research will focus on observations of changes that result from: (a) pulse disturbances such as fire, biotic disturbance agents, and changes in land use; and/or (b) the impacts of press disturbances such as climate change, including but not limited to longer-term changes to

[2] In this experiment plan, the term "land surface" not only includes terrestrial ecosystems, but the extensive aquatic ecosystems that found in Arctic and boreal regions

surface water extent, vegetation greenness, phenology, and biophysical structure, surface subsidence, and changes in seasonal patterns of snow cover, ice on/off dates, freeze/thaw periods, soil moisture, surface inundation, and active layer depth. Research should also emphasize the unique capabilities provided by spaceborne satellite remote sensing data products for studying seasonal and inter-annual variations in surface and atmosphere characteristics. Field-based studies will be used to collect data required for further refinement and validation of information products (Level 2 and 3 products) generated from satellite remote sensing data. Where appropriate datasets already exist (e.g., climate data, vegetation, weather station records, tree ring records, permafrost temperature and active layer depth, etc.), research on processes causing the observed changes should be carried out, but the focus of Category 1 projects should not be on the establishment of new field studies for understanding drivers of observed change. Research on the impacts on ecosystems and the services they provide that require large-scale observations of changes to land surfaces should also be carried out. Studies on the synergistic use of different satellite products to analyze factors contributing to variations in a specific land surface characteristic should also be carried out. For example, inter-annual variations in plant phenology can be caused by variations in soil moisture, surface temperature, and snow cover, and other characteristics that can be provided from satellite remote sensing data. Finally, high priority should be also given to research that includes model refinement, validation and analyses using the results from these studies.

Category 2: *Identify and quantify the underlying processes and complex interactions driving the responses of ecosystems at landscape to regional scales*

This category of research will focus on ***landscape- to regional-scale*** studies of underlying processes and complex interactions among abiotic and biotic factors that are being driven by pulse and press disturbances, including the consequences of these changing interactions to social-ecological systems in specific areas of the ABoVE Study Domain. This research will be focused on addressing the question and objectives defined for ABoVE, specifically focusing on understanding the vulnerability and resilience of social-ecological systems. High priority should be given to projects that focus on study sites where previous, ongoing, and new field-based research and data sets provide the foundation needed to study the underlying processes and complex interactions that are occurring in representative social-ecological systems. In particular, substantial research has already taken place or is being planned across the ABoVE Study Domain on the impacts of press and pulse disturbances and variations in exchanges of energy and materials between the land, aquatic systems and atmosphere. In addition, there are a number of watersheds with ongoing, interdisciplinary studies that are already examining and quantifying the impact of complex interactions among changing abiotic and biotic factors. High priority should be also given to studies that will be used to to refine and validate models. Where common datasets and measurements are to be acquired among individual projects, these projects should be asked collectively to agree upon common measurement protocols and data organization that will facilitate integration, synthesis and scaling activities to take place during Category 3 research. Finally, high priority should be given to research that uses remotely sensed data products to effectively scale and extrapolate the field-based observations as well as utilizes field-based observation to further develop and validate remotely sensed data products.

Category 3: *Category 3 – Assess the impacts of environmental changes on social-ecological systems through integration, synthesis and scaling of results from specific regions as well as across the entire ABoVE Study Domain*

This category of research would be phased to start near the conclusion of the previous two categories to maximize opportunities to synthesize and analyze results, and specifically focus on analyzing the vulnerability and resilience of social-ecological systems across the ABoVE Study Domain. Priority should be given to: (a) synthesis of the results of field based research across multiple sites to gain new insights and address key model uncertainties; (b) studies that focus on scaling issues, in particular linking domain-wide observations of changes to key land surface characteristics (Category 1 research) to field-based results describing the complex interactions inducing changes to social-ecological systems (Category 2 research); and (c) use of the results from (a) and (b) to further refine and validate extant and nascent models. Research should also be carried out on developing approaches with stakeholders and decision makers to develop a diverse suite of decision-making tools, including assessment of specific scenarios.

In this chapter, the research strategy for ABoVE research activities is further discussed in terms of the ABoVE Study Domain (Section 4.1), remote sensing studies (Section 4.2) field-based research (Section 4.3), modeling (Section 4.4), and synthesis, integration, and scaling (Section 4.5).

4.1 ABoVE Study Domain

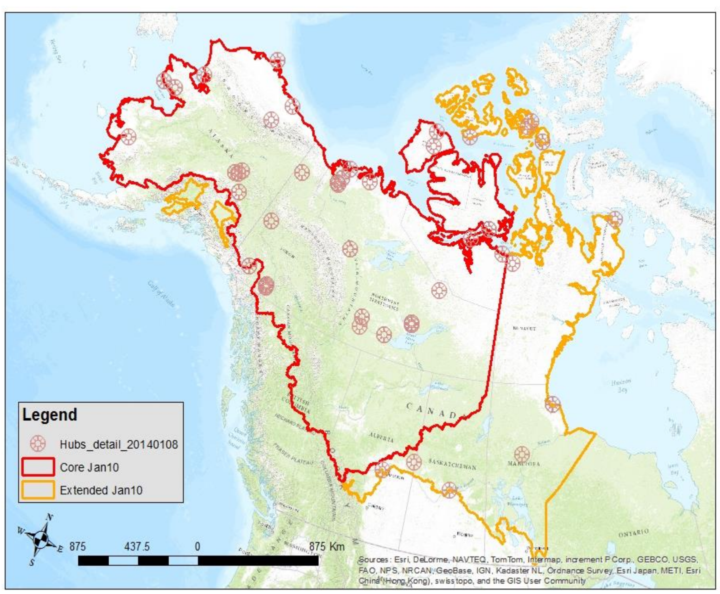


Figure 4.1. *Boundaries of the ABoVE Study Region*

The ABoVE Study Domain includes most of northwestern North America (north and east of the coastal mountain ranges) (Figure 4.1)[3]. The Domain reflects the variability in the key land surface features that are both unique to arctic and boreal ecosystems in North America as well as representative of the larger northern high latitude region. The Core Area of the ABoVE Study Domain is delineated to capture the regional-scale variations underpinning the six Focus Areas of ABoVE research (Chapter 3). The Core Area encompasses a range of landscapes that are rapidly changing in complex ways in response to global-scale climate warming and regional-scale disturbances. The ABoVE Study Domain also includes Contributing Areas outside of the Core Area that will provide opportunities to study a subset of important changes that are occurring in these regions (for example, insect outbreaks and forest dieback in the southern boreal forest), to provide areas where environmental conditions are considered to be antecedent to those in the Core Area, as well as to collaborate on research being sponsored by partner organizations. The variation in important land surface and socio-economic characteristics unique to arctic and boreal regions across the Core ABoVE Study Domain provides the opportunity to address the entire suite of questions and objectives presented in Chapters 2 and 3 through an integrated research program. Finally, the Study Domain includes a number of Research Sites identified as having existing research and/or transportation and logistics infrastructure.

The ABoVE Study Domain provides the opportunity to study the drivers of environmental change in arctic and boreal ecosystems. There is a distinct low-to-high gradient in both temperature and precipitation from north to south across the Domain. This gradient, along with recent changes to climate in this region, are the primary drivers to variations in disturbance regimes, both press and pulse. In general, disturbances from rapid permafrost warming are most prevalent in the northern portion of the Domain, disturbances from fires are most common in the central portion, and large-scale disturbances from biotic agents are found in the southern portion. At more localized scales, a range of human activities and socio-economic factors that are driving changes are found throughout the ABoVE Study Domain.

The ABoVE Study Domain provides opportunities to observe changes that are occurring to arctic and boreal ecosystems and to study the underlying processes and complex interactions that are controlling these changes. A key challenge in studying the impacts of climate change in arctic and boreal regions is to account for the underlying physiographic complexity of the landscape, which is a function of the geomorphic processes that produce variation in topography and soils. In particular, the ABoVE Study Domain encompasses a gradient in permafrost distribution (from continuous to discontinuous to sporadic) with a range of ice content (ice rich to ice poor), includes the major river watersheds of the region (that provide the majority inputs of freshwater particulate matter and DOC and DIC to the Arctic Ocean in western North America) as well as vast lowland areas dominated by ponds, lakes, wetlands, and peatlands. The Domain also contains the major terrestrial ecosystems common to arctic and boreal regions which are strongly controlled by variations in climate, physiography, permafrost, hydrology and disturbance regimes. The Domain contains substantial variability in soil carbon pools controlled

[3] For a more detailed discussion of the geographic aspects of the ABoVE Study Region, see Appendix __.

by permafrost and site drainage, including significant areas with frozen mineral soil as well as thick organic soil horizons in peatlands. The Domain provides critical habitat for bird, fish, and mammal populations, which are not only important drivers of changes to vegetation, but also provide the foundation for a range of ecosystem services. Additionally, the Domain encompasses significant variation in human communities with respect to size, culture, demographics, economic activities, and institutional structure.

The ABoVE Study Domain provides the opportunity to study the societal impacts of climate change in arctic and boreal regions at local, regional, and global scales. It contains significant populations of unique migratory and endemic fish and wildlife populations whose management is the responsibility of a range of land agencies and Aboriginal governments. The Domain is home to numerous tribes and groups of Aboriginal peoples whose culture and subsistence are basedo n the natural resources present in this region, as do the non-Native people who occupy and visit this region. This region has significant forest, oil, gas, and mineral resources that provide an economic foundation for the region, where the development of these resources not only is driving environmental change, but is dependent on the direct and indirect impacts of climate change. Finally, because the land surface within the Domain provides significant feedbacks to climate, this region provides an opportunity to study the impacts of climate change on regulating services at regional to global scales.

Figure 4.1 presents the locations of key roads and locations of airports near communities that provide the physical access to the different areas within the ABoVE Study Domain where field-based studies and observations are likely to take place. The locations of these airports also represent places where access to boats and charter airplanes and helicopters could be made available to access the remote study regions, and most of these locations provide access to food and shelter. Figure 4.2 also presents the location of research stations or facilities (for example at universities) that are available to provide some level of logistical support for research during ABoVE.

A key consideration in the delineation of the ABoVE Study Domain was the inclusion of key Environmental Observatories that provide a base of significant previous and ongoing field-based research that can be used to address the ABoVE questions and objectives. Most of Environmental Observatories have a history of interdisciplinary research and data that spans several decades, which is critical for developing an understanding of the factors controlling longer-term changes in arctic and boreal ecosystems. Another important characteristic of these Environmental Observatories is they are located in key landscapes that are undergoing change, and have significant research infrastructure, including instrumentation monitoring environmental characteristics, research focused on assessing changes to ecosystems, laboratory space and facilities, and housing and transportation needed to gain access to remote areas. Several of the Environmental Observatories include previous and/or ongoing research located along road networks that are easily accessible. Finally, in many cases, the work being conducted at the Environmental Observatories is being funded by organizations who have expressed a direct interest in collaborating or jointly sponsoring research activities with NASA during the time period of the ABoVE field campaign.

Table 4.1. *Summary of the types of research projects that should be NASA as part of the ABoVE Field Campaign*

Research Approach	**Project Goals**		
	Category 1 – Document and understand the causes and consequences of changes to land surfaces areas across the entire ABoVE Study Domain **Top Down**	**Category 2 – Identify and quantify the underlying processes and complex interactions driving the responses of ecosystems at landscape to regional scales** **Bottoms Up**	**Category 3 – Assess the impacts of environmental changes on social-ecological systems through integration, synthesis and scaling of results across the entire ABoVE Study Domain** **Cross-Scale Studies**
Field Studies	- Collect data to develop and/or validate algorithms to generate existing or new information products from satellite remote sensing data	- Studies focused on understanding the underlying processes and complex interactions that are resulting in changes to social-ecology systems on the impacts and consequences of environmental change - Data to develop/validate algorithms to generate new information products from airborne and spaceborne remote sensing	- Synthesis and integration of results from field research across individual Category 1 and 2 studies. - Development of information products needed by stakeholders and decision makers
Remote Sensing	- Analyses of domain-wide satellite remote sensing data to quantify variations in key land surface characteristics and to understand the causes of these variations	- Collection of airborne remote sensing data and development and validation of information products - Analysis and development and validation of products from fine and medium scale satellite remote sensing data for specific study areas	- Studies on scaling results from Category 2 studies using satellite remote sensing products from across the entire study domain - Development of information products needed by stakeholders and decision makers
Modeling	- Use of information derived from analyses of remotely sensed data products to refine and validate drivers of large-scale changes the impacts of these changes based	- Refinement and validation of models on the impacts of climate change on social-ecological systems based on using information and products from remote sensing and field-based studies	- Integration and synthesis of model results across Category 1 and 2 studies - Scenarios based on assessing the vulnerability of social-ecological systems - Development of products needed by stakeholders and decision makers

4.2 Remote Sensing Studies

Studies during ABoVE will use existing and new data products derived from spaceborne and airborne remote sensing observations in studies to address the key science questions and objectives presented in Chapter 3. These data products will be used to study and understand changes to important characteristics of the land surface and atmosphere that are either controlling or resulting from changes to important ecosystem processes across the ABoVE Study Domain. For example, growing season timing (and variance), snow melt, run-off, ground-water recharge rates, and CH_4/CO_2 evolution are all likely to show close temporal coordination at multiple time scales, but the details of these linkages have yet to be explored. Ensuring that the remote sensing data are compiled and co-regisitered 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 validated data products derived from multiple sensors that are seamlessly integrated to form the basis for investigations of ecosystem responses and drivers over the entire ABoVE Study Domain. These remote sensing data products are also needed at multiple time-scales (daily to seasonal to inter-annual).

Category I research projects focused on large-scale processes across the entire ABoVE Study Domain will utilize satellite remote sensing data products that have been or will be generated from existing or new systems, or new information products generated from historical archives. This research will focus on understanding the sources and consequences of variations in land surface and atmospheric characteristics over large spatial scales occurring over multiple-time scales. The data products used (and in some cases further developed) these studies will also be used to provide inputs for models, and information for model calibration and validation. In some cases, the same data products used for large-scale, domain wide research will also be used in research on understanding the underlying processes and complex interactions occurring at landscape to regional scales during Category II projects.

Data products for different land surface variables derived from satellite remote sensing data are summarized in Table A1[4]. In some cases, the effective use of some satellite data products in these large-scale projects will require further refinement and or validation of existing/new products for the unique conditions that are present in Arctic and boreal ecosystems. In other cases, additional data products will need to be generated using archived satellite remote sensing data using approaches that have been validated. A summary of data products that are of high importance for research over large scales that require further refinement/validation/ generation are presented in Table 4.1[5]. The information presented in Table 4.1 does not preclude research projects that generate and/or refine/validate other data products that address the ABoVE research questions and objectives. The different approaches and field data required for further refinement and validation of satellite remote sensing data products are presented in Table A1. Note that some of the approaches to refine and validate spaceborne

[4] Tables A1 and A2 are in Appendix A

[5] Data products may need to be generated for exisiting products if support for their continuous generation stops prior to the study period for ABoVE

data products will require the collection and analyses of data from airborne remote sensing systems.

Category II research projects focusing on landscape- to regional-scale studies will use a combination of data products generated from airborne and spaceborne remote sensors. This research should be closely integrated with field-based studies on the underlying processes and complex interactions driving changes to social-ecological systems in Arctic and boreal regions (Section 4.3). This integration is needed to support the scaling of field observations across time and space, provide meaningful inputs for driving models, and provide information for model calibration and validation. The data products for different land surface and atmospheric variables used in landscape- to regional-scale studies derived from satellite remote sensing data are also summarized in Table A1, while airborne remote sensing data products are summarized in Table A2. A list of the spaceborne data products that are of particular importance for landscape- to regional-scale research are presented in Table 4.1, while Table 4.2 summarizes the important airborne sensors and the variables they would provide. The information in these Tables 4.1 and 4.2 does not preclude research projects that generate and/or refine/validate other data products that address the ABoVE research questions and objectives. The different approaches and field data required for further refinement and validation of the airborne and satellite remote sensing data products are presented in Tables A1 and A2.

Research is also needed to develop derived products that specifically address information required by stakeholders and decision makers. The generation of these products often requires combining specific remote sensing data products with other geospatial data or information to create a product depicting the required information.

Research involving the development/validation/generation and use of remote sensing data products should be carried out in several phases. The research should initially focus on large-scale projects using using a single satellite data product and landscape to regional-scale studies using existing, validated spaceborne remote sensing data products. Research projects that require the use of airborne remote sensing data can be selected at the same time, the start of these projects may have to be delayed to accommodate the availability of airborne sensors as well as the need to coordinate data collections using the same system across different projects. Finally, research requiring multiple data products may require the further refinement/validation of specific projects before they can be carried out. Table 4.3 presents a strawman schedule for research involving remote sensing data products.

Table 4.1. *High-impact data products from satellite remote sensing data that require further refinement, validation, and/or generation*

Satellite data products for large-scale, domain-wide studies
• Freeze – thaw dynamics (seasonally and inter-annually), as well as winter-time thaw events
• Soil moisture
• Seasonal inundation and flooding (moderate- to coarse-resolution data)
• Annual maps of surface water extent (lake/pond) (medium-resolution data
• Snow extent time series (single product generated from integration of existing products)
• Snow depth
• Snow water equivalent
• Lake ice cover / extent / progression
• Land surface temperature
• Seasonal and inter-annual variations in primary productivity
• Seasonal and inter-annual variations in LAI/Fpar
• Seasonal and inter-annual variations in phenology
• Seasonal and inter-annual variations in spectral vegetation indices
• Daily, seasonal, inter-annual changes in atmospheric mole fractions of CO_2, CH4, and CO
Satellite data products for local- to regional-scale studies
• Area extent and severity of biotic disturbances
• Burn severity
• Distribution and extent of thermokarst features (e.g., active layer detachments, thaw slumps).
• Depth of thaw (active layer) dynamics, seasonally and interannually
• Inundation maps (seasonal to inter-annual from medium-resolution data
• Connectivity between water bodies (fine resolution)
• Wetland maps
• Time-series Landsat and SAR data products for studying processes and complex interactions controlling post-disturbance ecosystem recovery
• Land and lake surface temperature maps (time series from Landsat data)
• Annual changes in vegetation cover (time series from Landsat data)
• Dissolved organic matter, suspended sediments, and chlorophyll in terrestrial water bodies

Table 4.2. *Summary of important airborne sensors and key environmental variables needed to address ABoVE objectives.*

Variable	Sensor						
	Lidar (small/medium footprint)	SAR/ InSAR	Passive Microwave	Hyper-spectral	Spectrometer	Fourier Transform Spectrometer	EM resistivity
Surface elevation	X						
Surface Deformation	X						
Thermokarst	X	X					
Snow dynamics	X						
Biomass	X	X					
Canopy Structure	X	X					
Freeze-thaw		X					
Active layer depth		X					
Deep substrate properties							X
Soil moisture		X	X				
Snow water equivalent		X	X				
Canopy snow interception	X	X	X				
Vegetation composition				X			
Canopy chemistry				X			
Photosynthetic Capacity				X			
Light use efficiency				X			
Atmospheric CO2, CH4 and CO					X	X	

Table 4.3. *Schedule of remote sensing research activities*

<table>
<tr><th>Research Activity</th><th>Yr 1</th><th>Yr 2</th><th>Yr 3</th><th>Yr 4</th><th>Yr 5</th><th>Yr 6</th></tr>
<tr><td>Large-scale projects focused on further refinement/validation and use of a single spaceborne remote sensing data product</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Landscape- to regional-scale projects using spaceborne remote sensing data product</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Projects using airborne remote sensing data products</td><td colspan="5">3 years within a 5 year window</td><td></td></tr>
<tr><td>Projects involving use of multiple spaceborne remote sensing data products</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

4.3 Field-based research

4.3.1. Required field activities. Field-based research activities will explore historic, current and future states and trajectories of terrestrial and freshwater ecological systems in the ABoVE domain (Category 1 projects). These observations will provide quantitative information from which to identify baselines, rates and directions of change, and possible causes and consequences from landscape and regional to domain wide scales (Category 2 projects). A critical outcome of Category 1 and 2 activities should be insights into ecosystem resistence, resilience, and vulnerability of ecosystems to changing environmental drivers. Integration, synthesis and scaling of results across the entire study domain (Category 3 projects) will link patterns and consequences of change to social-ecological systems (Category 3 projects) (see Table 3.1). Two broad groups of field-based research activities will be required:

Field data inputs to remotely sensed data products and models. Field-based research activities, whether for development and validation of remotely sensed data products or benchmarking of models, will be required for both Category 1 and 2 research projects. The goal of this research should be to develop new or refine and integrate existing models and remotely sensed data products that can then serve as reliable proxies of the most important ecosystem/land surface changes occurring in the ABoVE study domain (see Table 3.1). Field verification and validation will be needed for models (see Section 4.4 Modeling Studies), as well as for remotely sensed products from satellite and airborne platforms (see Section 4.2 Remote Sensing Studies) that measure changes and differences in land surface/ecosystem properties at landscape and regional (Category 1 projects) to ecosystem and domain wide (Category 2 projects) scales.

Field research activites will require consideration of both the spatial and temporal dynamics of ecosystem form/land surfaces that are likely to impact the spatial and temporal extents over which any remotely sensed data product or model can be confidently utilized. The ABoVE study domain is vast, encompassing a wide range of communities, ecosystems, and landscapes that differ significantly in their physical structure, composition and functioning. This high degree of spatial heterogeneity within the ABoVE study domain will necessitate spatially explicit and representative field validation in order to develop and verify reliable and well-understood data products as well as realistic models (see section 4.3.3. *Location of field activities* for guidelines on the location of field-based research). In order to facilitate integration, synthesis and scaling across the ABoVE domain, field based research projects will be required to collect a suite of common and standardized datasets (see section 4.3.2 *Synthesis and integration of field research*).

Similarly, because portions of the ABR are changing very rapidly as result of climate warming, and because the snow-free season is so short, there is significant temporal variation in environmental conditions, atmospheric conditions, and land surface characteristics that will require temporally explicit refinement and validation of remotely sensed data products and models, especially for those that are be applied on a pan-seasonal basis.

Improve understanding of the processes and complex interactions. Both Category 1 and 2 research projects will require field-based studies to quantify ecological stasis and change at ecosystem, landscape, and domain-wide scales. Additionally, field studies, combined with remote sensing and modeling, will be required to identify sources of resilience and drivers of change, and to directly test causal hypotheses. Previous field studies have demonstrated that dynamics of the ABR are driven by highly-coupled processes that together determine the ABR's resilience and vulnerability to climate change. There is therefore a need to conduct studies and gather data that support an integrated understanding of change, which will require interdisciplinary approaches to field-based research. To this end, ABoVE field studies are encouraged to contribute towards an improved mechanistic understanding of the most critical interactions (see Table 3.1), characterize and quantify how these interactions are changing, and determine the ecological and societal impacts of the changes. Similar to the field activities required to validate remotely sensed data products and benchmark models, collectively, field studies focused on understanding complex interactions will need to be spatially and temporally representative of the ABoVE Study Domain. Please refer to section 4.3.3. *Location of field activities* for guidelines on the location of field-based research. All field based activities will be required to include a remote sensing component, either via near-surface, airborne or spaceborne sensing.

4.3.2. Synthesis and integration of field research. ABoVE seeks an integrated, systems level understanding of historic, current and future ecological states and trajectories that will enable understanding of the ABR's resiliency and vulnerability to change with application information products needed by stakeholders and decision makers. To this end, synthesis and integration of results from field-based research across individual Category 1 and 2 studies will be required. Separate field studies will therefore be required to produce intercomparable results that can be used Category 3 projects (and see section 4.4 *Modeling*, and, 4.5 *Synthesis, integration and scaling*). This will be accomplished in the following two ways:

(a) Where common observations and spatially co-located studies are proposed to be acquired among individual Category 1 and 2 projects, once funding decisions have been made, project leaders will be required to collaborate formally in order to agree upon a common set of measurement protocols and data organization templates that will facilitate integration, synthesis and scaling activities to take place during Category 3 research. Collaboration will be required both to systematize the collection of common observations, and to connect very different types of observations within the watershed unit.

(b) Here is where we need, as a full SDT, to decide on how/if we want to include an additional way (to the one listed in 'a' above that I don't think will cut it alone) to ensure excellent coverage for RS and Modeling validation purposes that will really give the ABoVE Field Campaign a way of achieving something truly cohesive in space – a domain wide coverage of a few critical, 'CORE/BASELINE' variables. Here are the two end-member/extreme approaches we could take to get these core/baseline variables covered:

<u>Approach 1:</u> Regardless of each individual field-based project's specific objectives, each funded project will be required to make the following set of core measurements/observations of physical properties/variables collected in a pre-determined standardized way (ie. prescribed protocols/equipment) that will be used by Category 3 projects, and for refinement and validation of remotely sensed data products or modeled data , as well as any other synthesis activities:

INSERT list of ~ 3 TBD core measurements here

<u>Approach 2</u>: In contrast to Approach 1, the responsibility to collect a domain wide set of core variables falls on a group of dedicated observers (ie. ABoVE Core Variables Team), that might be a group of hired technicians or grad+undergrad students, or some combo of these people. This group would travel to all the TBD Research Access Points and make the same set of standardized measurements that will be used by Category 3 projects, and for refinement and validation of remotely sensed data products or modeled data , as well as any other synthesis activities:

INSERT suite of TBD core measurements here

4.3.3. Locations of field activities

The core ABoVE domain is comprised of 12 ecoregions as designated by the EPA level-2 classification system. The extended domain contributes additional southern and eastern ecoregions where current socio-ecological systems may provide insight into future conditions in the core domain. To facilitate domain-wide scaling, field studies will need to be conducted in each of the 12 ecoregions within the ABR domain. Larger domains that cross many degrees of latitude or longitude will need core data collected at multiple field sites to adequately represent climatic and biogeographic gradients. This will ensure that spatial variability in climate, and ecosystem form and function is well represented. The SDT may identify 'research hubs' - established research stations where historical and ongoing dataset collection is available for key variables, and where critical infrastructure and science support are already in place. At this time, however, the SDT has limited identification to research access points pending clarification of goals. These research access points, when arrayed across the region, should yield adequate coverage of ecoregions and north south gradients for the purposes of scaling to the Domain.

While the concept of ecoregions was introduced above for the purpose of illustrating the 'research hub' concept, investigators will be expected to present a rationale or strategy for how site selection facilitates spatial or temporal scaling for the ABR. Investigators are not limited to the ecoregion concept, but must provide evidence of intercomparable, scalable measurements (??).

Table x (Excel file: Ecoregions_research_access_points_1252014). Potential research access points in the ABoVE core and extended domain. When domains are arrayed across several degrees of latitude, northern, middle and southern sites are identified. Note that domains at the southern edge of the core region may only contribute northern sites.

4.4 Strategy for modeling studies

4.4.1 The role of modeling in ABoVE (integration, diagnosis & prediction)

As indicated in Table 4.1, modeling activities during ABoVE should focus on research on (1) large-scale changes to ecosystems across the ABoVE Study Domain and (2) complex interactions at landscape to regional scales. Models by design, provide an opportunity to test and improve conceptual frameworks for integrating observations at multiple scales. However, the successful integration of research results from both field-based (local scales) and remote sensing studies (landscape to regional to large scale) into a model requires careful consideration from the beginning of any investigation. For example, it is a good practice to analyze and quantify model sensitivities and uncertainties first, in order to provide direction for field- and remote sensing based studies and clear traceability to the often stated contention that proposed measurements have helped to improve models and to reduce the uncertainty of their estimates and predictions. Typically, field-based studies are more likely to provide calibration and validation for models, while remote sensing studies are more likely to provide initialization the data needed to drive models, and to provide the mechanism by which site-based field studies can be extrapolated to larger spatial scales. A particularly strong interest of ABoVE are models that enable decision support relevant to the impacts of ongoing and future environmental change.

4.4.2 Overall modeling strategy

4.4.2.1 A 'portfolio' approach

Models which simulate ecological processes that impact ecosystem services can be broadly categorized into terrestrial biosphere models (TBMs, including Dynamic Global Vegetation Models, DGVMs); disturbance models; soil thermal/permafrost models; hydrologic models; soil carbon models; and fauna models. There is considerable overlap in the variables required to parameterize, drive, calibrate, or validate these model types, and these variables should be the focus of field-based and tower/aircraft/remote sensing measurements. Many of these land-based models form important boundary conditions for atmospheric-based models such as atmospheric flux inversion models or atmospheric tracer transport models that enable fluxes from land based models to be compared to remote observations of atmospheric trace gases like CO2 and CH4. These model types are often linked together in more generalist, or "community", land surface models that themselves can be coupled with ocean, sea ice and atmosphere models to represent global-scale feedbacks in the Earth system and project future climate trajectories.

TBMs encompass any combination of 4 general features: 1) biogeography (plant distribution); 2) biogeochemistry (carbon, water, and nutrients cycling); 3) biophysics (land-atmosphere exchange of energy, water vapor, and momentum); and, 4) vegetation dynamics (establishment, succession, mortality, competition). TBMs are in great need of development for Arctic processes, particularly with accurate simulation of soil carbon dynamics and emissions, and plant functioning and migration with changing climate. Moreover, sub-grid scale processes that are important in the Arctic are not well captured in TBMs. TBMs encompass and include links to other models described here--i.e., disturbance, permafrost, and hydrologic.

Hydrologic models range from simple water balance models to lumped parameters models and large-scale distributed 3-D models. Many hydrologic models also include elements of the carbon cycle. To capture the high prevalence of wet surficial soils and surface water, hydrology models operating across the high northern latitudes typically include the seasonal thawing and freezing of soils. At fine spatial scales local landscape factors become essential parametrizations in hydrological modeling. Given the expected degradation of permafrost, hydrologic models will be required to increasingly focus on the complex interactions linking soil thaw, talik formation, and subsurface flow paths.

High priority hydrologic modeling activities in support of ABoVE goals and objectives include the quantification of surface water extents and their connections with surface meteorology; linkages between surface and subsurface flows; and the amount and timing of lateral transports of water-borne materials across the region. Prognostic modeling of the temporal and spatial dynamics in surface waters will best be advanced with scaling studies which leverage coincident observations from airborne and satellite overpasses using both active and passive microwave instruments. Field measurements of organic matter, major ions, and sediment load are research priority for the parameterization and validation of models which simulate biogeochemical fluxes.

Models which simulate soil temperatures range from one-dimensional models of the temperature profile with depth to large-scale, 3-D models. An explicit accounting of spatial variations in vegetation, soil type, slope/aspect along with accurate meteorological forcings are essential to many such models. Soil thermal models will be a critical link to the hydrology, soil carbon and dynamic vegetation models given their dynamic depiction of soil temperature variations with depth, the seasonal active layer development, and seasonal frost penetration in non-permafrost areas. High priority research in support of these model includes the gathering and development of high-resolution data sets of landscape parameters and 3-D maps of soil ice and carbon content with depth. The full expression of these models will require these and other similar initial conditions and meteorological forcings to accurately describe contemporary states and project future changes. These models will be calibrated over different land types within the ABoVE domain to accurately model snow, ground cover, soil and permafrost thermodynamics in each domain with the expectation of changes in soil carbon and soil moisture. They will be validated against borehole and other in situ data of soil temperature with depth.

The two most important categories of natural disturbance in the ABoVE study domain are forest fire and biotic disturbances, typically insects or plant pathogens. Modelling needs for these two types of disturbance share commonalities in that both require estimates of area affected, its impact, for example, on the re-distribution of biomass or C within an ecosystem, resulting emissions of C and other GHGs to the atmosphere, as well as on post-disturbance ecosystems trajectory, either in terms of reduced productivity, increased mortality, or a shift to a different ecosystem type. The two disturbance types differ in the temporal nature of their risk profiles. Fire may occur every year, depending on fire weather conditions, and is thus an annual risk agent, and it presently already occurs throughout much of the ABoVE domain, with regional variation depending on vegetation (decidious forest vs.coniferous forest vs. tundra) and past climatic conditions. Biotic disturbances (particularly insects), on the other hand, often exhibit cyclical behaviour, whereby there are outbreaks of variable length where ecosystems susceptible to a particular agent are at risk, as well as periods of time between outbreaks where a particular agent is unlikely to occur. Plant pathogens are different still, in that they may be characterized as chronic risk agents, having an annual probability of infestation, with effects on productivity and mortality that then continue for long periods of time into the future once it occurs. An additional complication with biotic disturbance relative to fire is that each particular biotic disturbance agent has a certain susceptible host plant species (e.g. for mountain pine beetle, mainly trees of the genus *Pinus*, particularly *Pinus contorta*, or for aspen defoliators, *Populus tremuloides* or *balsimifera*). Many remote-sensing based vegetation maps do not classify forests at the species level. A further complication with biotic disturbance is that one of the main risks associated with warming is the northward spread of agents that may presently occur outside or only at the southern edges of the ABoVE study domain.

Another class of models are atmospheric flux inversion approaches. Inverse approaches can be used to derive parameterizations for process models. They can also be applied in scaling studies which leverage data and models developed during ABoVE. For example Geostatistical or Baysian inversions can be used to scale ground-based measurements or point models of carbon dioxide or methane fluxes to scales resolved using tower, aircraft or satellite platforms. Flux inversion models are particularly useful because they can directly assimilate atmospheric measurements from remote sensing instruments.

Scaling and projecting scientific understanding on the vulnerability of ecosystem services dependent on wildlife resources requires the ABoVE portfolio to include models of faunal population dynamics. Fauna population models generally include a wide variety of approaches and information content at different scales; for ABoVE, the priority is on the use of geospatial models of current and projected wildlife population dynamics at landscape-to-regional scales. At this spatial scale, and over annual to decadal time scales, fauna demographics are primarily a function of the distribution of habitat over the landscape. At the fundamental level, this is essentially a mapping exercise that remote sensing studies are ideally suited for, and data from field studies (e.g. population counts) can be linked spatially by these maps. Predicting future changes in populations of key fauna species largely depends, then, on predicting habitat change. Projecting habitat change requires linkage between models of vegetation dynamics, hydrology, permafrost, and disturbance. Key variables driving the variability in populations over the landscape and through time include weather, forage availability and quality, populations of predator and prey species, and harvesting, regulation and management by humans. For each variable, both seasonality (timing) and inter-annual variability and trends are important metrics to assess through model frameworks that incorporate this information from field and remote sensing studies. In addition to the impacts of changes in these key drivers, fauna models will also require representation of the critical internal feedbacks related to resource use versus availability that govern population dynamics.

4.4.2.2 Multi-phase modeling timeline

To be successful, ABoVE will need to foster a diversity of models and modeling approaches to support the various research categories depicted in Table 4.1. Because environmental change affects a number of ecosystem services (e.g., climate regulation, food security, subsistence lifestyles, natural resources, cultural resources, infrastructure, and transportation), a “portfolio” approach should be adopted so that the diversity of ecosystem services are addressed by a variety of modeling efforts across the ABoVE Field Campaign. One way of fostering integration and synthesis is to provide support for approximately two-year “incubation” studies at the beginning of the ABoVE campaign that would later be developed into full proposals to integrate and synthesize funded remote sensing and field-based research of research categories 1 and 2 in the context of what is depicted in Figure 4.1. The notion is that the successful full proposals would lead to a diversity of integration and synthesis modeling activities throughout the remainder of the ABoVE Field Campaign.

4.4.3 General categories of model types that simulate the ecological processes that impact ecosystem services, across which there are generic needs for data (Figure 4-X).

To fully realize the linkage from remote sensing and field studies to social-ecological decision support with diagnostic and prognostic models, ABoVE will need to support the development of “ecological” (in the broad sense) models and social (people) models (Figure 4.X). Ecological models include models of the physical and biological environment and may include models of animal (fauna), vegetation, biogeochemistry, hydrology, soil temperature, and disturbance dynamics. Social models in the context of social-ecological systems include any models that incorporate dynamics of human behavior or social systems (e.g., economic, policy, and governance decisions) that influence the impacts of environmental change on ecosystem services.

4.4.4 Data needs across model types (Table 4-X)

4.4.4.1 Driver / initialization data

4.4.4.2 Cal / val data

4.4.4.3 RS and field data requirements (spatial / temporal resolution & extent; process-level resolution)

RS and field data will help support scaling approaches across both spatial and temporal scales.

4.4.5 Summarize the status of each model type application and qualify its uncertainty in simulating the key variables

4.4.6 Model intercomparisons (MIPs) and model-data benchmarking requirements

Model Intercomparison Projects (MIPs), or comparing models to models, have been used as a starting point to understand uncertainty or confidence in the model estimates. The spread of model results is an indicator of structural uncertainty. MIPs can also be used to better inform comparisons across models by eliminating as many of the controllable differences across models as feasible (e.g., choice of driver data, process inclusions, flux definition). MIPs are important activities for understanding (1) the differences in dynamics and (2) reasons for differences in dynamics among models to are used to predict similar responses (e.g., changes in carbon storage across the ABoVE study domain in response to environmental change.

To be successful at identifying reasons in differences, it is important for models to be compared against "benchmarking" data sets that are appropriate for evaluating the dynamics of model responses to past environmental change. In the past, benchmarking activities have overemphasized modeling of the mean state rather than changes in the mean state, the latter of which is more appropriate for modeling social-ecological change over the next century. Thus, it will be important for ABoVE to develop benchmarks that can evaluate model responses on multi-decadal time scales. Benchmarks must have rigorous uncertainty quantification. Modelers should develop radiative transfer processes to simulate more directly what satellites observe so that any modeling uncertainty on the part of the remote sensing datasets can be eliminated.

4.4.7 Set priorities for improving existing model types and developing new types and/or applications

4.4.8 Optimal schedule of modeling activities (may go to Chap 5)