Arctic-Boreal Vulnerability Experiment

ABoVE

The Arctic-Boreal Vulnerability Experiment (ABoVE):

A Concise Plan for a NASA-Sponsored Field Campaign

Authors:

Eric S. Kasischke (University of Maryland)

Scott J. Goetz (Woods Hole Research Institute)

John S. Kimball (University of Montana)

Michelle M. Mack (University of Florida)

Final Report

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Foreward

NASA's Research Opportunities in Space and Earth Sciences released in 2008 called for proposals to conduct scoping studies to identify the scientific questions and develop the initial study design and implementation concept for a new NASA Terrestrial Ecology field campaign or related team project. In the spring of 2009, NASA selected two projects for funding, including a project entitled: "*Vulnerability and Resiliency of Arctic and Sub-Arctic Landscapes (VuRSAL) - the Role of Interactions between Climate, Permafrost, Hydrology, and Disturbance in Driving Ecosystem Processes*" (NASA Grant NNX09AH57G to the University of Maryland). This report contains the recommendations from this scoping study, which presents the **Arctic-Boreal Vulnerability Experiment (ABoVE).**

NASA outlined eight expectations for each scoping study:

1. The science questions and issues to be addressed must be identified;
2. The current state-of-the-science must be addressed;
3. The potential for a major, significant scientific advancement must be described;
4. The central, critical role of NASA remote sensing must be explained;
5. The essential scientific components of the study must be described and why coordinated teamwork is required in their implementation. An overall study design identifying the required observational (e.g., spaceborne, airborne, and/or supporting *in situ* observations) and analytical (e.g., models, data, and information system) infrastructure must be developed;
6. The feasibility of the proposed project, both technical and logistical, must be assessed;
7. The broader research community must be engaged, in order to seek feedback on the ideas and to assess interest; and
8. The disciplinary skills needed to conduct the study and engage potential partners in their planning activities must be identified.

The investigators funded through this scoping study were aided by five collaborators: Jennifer Harden of the U.S. Geological Survey; Larry Hinzman and Masami Fukuda of the International Arctic Research Center, and Roger Ruess and Scott Rupp of the University of Alaska. To conduct the scoping study, a workshop was organized and conducted in August of 2009. This workshop was hosted by the International Arctic Research Center on the campus of the University of Alaska-Fairbanks, and was attended by 64 researchers and managers involved in climate change research in Arctic and Boreal ecosystems. These researchers were from Canada, Japan, Russia, and the United States, and represented an interdisciplinary cross-section of the terrestrial science community active in Arctic and Boreal research in North America. The attendees at this workshop provided critical insights on the key science questions and issues to be addressed by ABoVE, and identified the different approaches and components of studies needed to address these questions and issues, including the further development and integration of models.

Based upon the recommendations from this workshop, a draft report was prepared. This report was distributed to a limited group for comments in the late spring of 2010, and revised during the early summer of 2010. The revised draft report was then distributed for review to the broad scientific community in July 2010. The draft report was not only sent to over 150 scientists and managers identified by the investigators for this scoping study, but to over 300 researchers on NASA's Terrestrial Ecology email list. The comments and suggestions provided by 65 respondents were taken into consideration in generating the final draft of this report.

The organization of this report follows an outline provided by NASA in order to facilitate the review of the recommendations made by the two scoping studies. This report is not intended to serve as a proposal *per se*, but to present a broad outline of a large-scale, interdisciplinary study (ABoVE) that addresses important scientific uncertainties through the integration of information derived from the synthesis and integration of satellite and airborne remote sensing with observations made through ground-based research and monitoring. As such, specific details of the analysis of remote sensing data, field-based research, and modeling are not presented.

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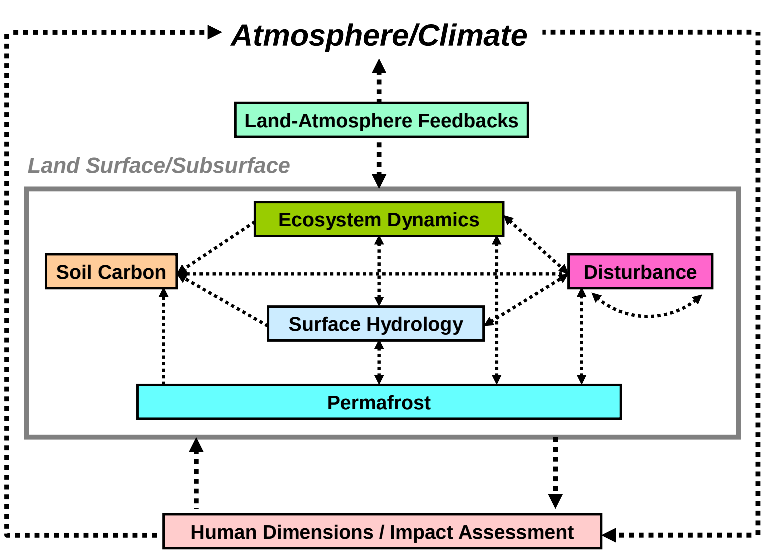
Summary

The Arctic-Boreal Vulnerability Experiment (ABoVE) will be an international research initiative led by NASA. ABoVE is designed to produce new knowledge needed to understand how climate change impacts ecosystems in the High Northern Latitude region, and how these changes produce feedbacks to climate and are influencing ecosystem services. Through research that integrates and synthesizes geospatial information products generated from airborne and spaceborne remote sensors with data from field studies and ground-based monitoring, ABoVE will focus on addressing three key questions:

- *What patterns of changes in ecosystem dynamics and land surface characteristics have occurred over the past 25-50 years and are likely to occur in the near future (5 to 25 years) and over the longer term (25 to > 100 years)?*
- *What processes, interactions, and feedbacks control the vulnerability of Arctic and Boreal ecosystems and landscapes to structural and functional change in a changing climate?*
- *How will potential future changes to the land surface in Arctic and Boreal regions contribute to positive and negative feedbacks to local, regional and global climates?*

To address these questions, ABoVE will emphasize observations, analyses, and synthesis across seven science themes: Disturbance, Permafrost, Surface Hydrology, Ecosystem Dynamics, Soil Carbon, Land-Atmosphere Feedbacks, and Human Dimensions / Impacts Assessment. The questions for each of these science themes will address the key uncertainties on the processes that are driving changes to ecosystems in the High Northern Latitude (HNL) region, as well as the impacts of these changes. The studies conducted for ABoVE will focus on identifying thresholds and tipping points that can produce state changes in how Arctic and Boreal ecosystems in response to variations in climate, providing the basis for improving the reliability of the process models required to predict how these ecosystems are likely to change in the future based on different climate change scenarios.



Each of the seven science themes for ABoVE include processes that are not only impacted by climate change, but in turn, interact with other processes to regulate ecosystem characteristics that are unique to Arctic/Boreal systems. These include the presence of permafrost and the existence of high levels of soil carbon in peatlands and frozen soils. At local scales, some Arctic and Boreal ecosystems are resistant or resilient to longer-term changes in climate and episodic perturbations; however, ongoing climate change in the HNL region may be crossing important threshold points that push or tip ecosystems and landscapes into new states. A key focal point for ABoVE is to conduct the research necessary for identification of vulnerability and tipping points that produce state changes in ecosystems and key ecosystem functions.

Studies for the Disturbance Theme will focus on understanding the controls on the natural disturbance regimes common to the HNL regions, including fire, insects and disease, and the formation of thermokarst and other land features associated with thawing of permafrost. Information products derived from satellite remote sensing data will be used to study the spatial and temporal distribution and impacts of disturbances across different biomes and regions experiencing different permafrost and surface hydrologic regimes. This information will be used to develop improved disturbance probability models. The analyses of satellite information products will be linked to field-based research quantifying the impacts of disturbances on vegetation dynamics, permafrost, surface hydrology, and soil carbon.

Research for the Permafrost Theme will focus on understanding how variations in climate, surface characteristics (e.g., topography, soils, vegetation type and structure, organic soil depth, surface hydrology) and disturbance history, interact to control the distribution of permafrost. Information products derived from satellite remote sensing data will be used to quantify spatial/temporal variations in key surface characteristics that influence permafrost, including vegetation type and structure, snow cover, surface temperature, seasonal patterns of freezing and thawing, soil moisture, and surface water coverage. Field research and experiments will be conducted to study how variations in surface characteristics control permafrost and to collect the data needed to improve models that predict formation and loss of permafrost.

Under the Surface Hydrology Theme, investigations will be carried out on the processes and factors controlling landscape and regional variations in the patterns of surface and subsurface water (including soil moisture) over multiple time scales. Remotely-sensed information products will not only be used to analyze the spatial variations in surface hydrology (soil moisture, surface water extent), but also land surface characteristics important in modeling hydrologic regimes (vegetation cover and structure, disturbances, snow and ice cover, surface temperature, freeze/thaw). Because permafrost and seasonal thawing of frozen grounds are important to surface hydrology, the field studies and experiments for this science theme will be closely linked to those being carried out for the Permafrost Theme. A number of field data (including tower eddy covariance measures of land-atmosphere exchanges energy and water) will be collected to provide the basis for improvement of hydrologic models.

Research for the Ecosystem Dynamics Theme will include investigations on the responses of vegetation to changes in climate, disturbance regimes, surface hydrology and permafrost. Long-term satellite data records show that the HNL region has experienced complex changes to vegetation productivity over the past three decades; however, the underlying processes driving these changes are not well understood. Field-based research will focus on collecting data needed to understand, quantify, and model the processes responsible for these large-scale changes in vegetation. At landscape and regional scales, vegetation changes are also being driven by complex interactions between disturbances, surface hydrology, and permafrost. Research will focus on developing new information products from satellite and airborne remote sensors to map post-disturbance changes in vegetation that are being driven by variations in disturbance regimes. Field-based research will be conducted to develop a better understanding of how different processes interact to control post-disturbance vegetation succession.

Studies for the Soil Carbon Theme will investigate the responses of carbon stocks in organic and mineral soil layers to the direct and indirect impacts of climate change. Research will focus on linking surface-based inventories of soil carbon stocks with land surface features that can be mapped using remote sensing (vegetation cover, locations of wetlands and peatlands, disturbance location and severity, surface hydrology, topography and microtopography) that correlate with variations in soil carbon. Field research will also focus on collection of measurements to quantify CO_2 and CH_4 emissions (including airborne measurements collected during the NASA Venture Mission CARVE) and on surface characteristics and processes that control emissions of carbon-based trace gases from the land surface (disturbance, anaerobic and aerobic respiration, ebullition from lakes and ponds) or drive longer-term storage of soil carbon). Again, these field processes will be linked via models to surface characteristics that control emissions that can be monitored via remote sensing. These processes include those that will be investigated under other ABoVE Science themes, including Disturbance, Permafrost, Surface Hydrology, and Vegetation Dynamics.

Under the Land-Atmosphere Feedbacks Theme, the role that processes occurring on the land surfaces have on regulating key characteristics of the atmosphere and climate will be investigated. An important forcing of the earth's climate in HNL regions occurs from changes in surface albedo. A variety of satellite data products that produce maps of surface albedo will cross-calibrated during ABoVE, and then correlated with other surface characteristics derived from remote sensors (surface water cover, snow cover, characteristics of surface vegetation, disturbances) to analyze the sources of variation in albedo. Studies carried out for other science themes will provide understanding of the processes driving changes in these surface characteristics, and can be incorporated into models for predicting changes in surface albedo and associated energy budgets. Another important feedback that will examined as part of studies for other science themes (e.g., Disturbance, Soil Carbon, Ecosystem Dynamics) are the processes responsible for exchanges of carbon between the atmosphere and land surface. The results from these studies will provide the basis for further development and refinement of models that can predict factors contributing to changes in the radiative forcing of the atmosphere.

Finally, studies for the Human Dimensions / Impact Assessment Theme will investigate the role that humans play in altering HNL ecosystems and landscapes and explore how climate warming will impact ecosystem services and society. Using geospatial data sets generated as part of the activities conducted for the Disturbance Theme, research will be conducted on how human activities influence disturbances, including human impacts as a result of oil and gas exploration. Using satellite information products derived for other science themes, research will focus on how changes to land surface characteristics have altered terrestrial and aquatic habitats and key fish and wildlife populations. Research will also focus on how climate change impacts human societies. Research conducted on further refinement and development of decision support systems will provide information products on the impacts of climate change in the HNL region to a variety of users.

Research and analysis activities for ABoVE will be carried out in study sites located across western Canada and Alaska (the ABoVE Study Region). Research will be carried out over a range of spatial scales, including within the different ecoregions, within Primary and Secondary Research Areas, within Discrete Landscape Units (such as a watershed or disturbance event), and within small plots (at a scale of 10 m to 1 km). The research for the different science themes will be carried out during a five-year Intensive Study Period. The projects funded by NASA as part of the intensive study period will be involved in a variety of activities, including the collection and analyses of airborne remote sensing data, development of new information products from remote sensing data, collection and analysis of field data, and refinement and validation of process models.

An activity that will occur in each Science Theme is the refinement and validation of process models based on the studies and analyses being carried out for ABoVE, including the use of information products derived from analyses of remotely sensed data either as model inputs or a means to validate the models. In order to understand the impacts of the processes that are affected by climate change requires that different process models be linked. The Integrated Modeling Framework component of ABoVE will provide the mechanisms for developing these model linkages. Compiling regional and global information products will be conducted as part of the activities associated with conducting assessments using the Integrated Modeling Framework. An additional activity for ABoVE will be to synthesize the results from research being carried out in other HNL regions. The results from this synthesis will be used to make further refinements to the Integrated Modeling Framework. This framework will then be used to conduct a pan Arctic/Boreal assessment of the impacts of climate change.

The development of a data and information system will be another important component for ABoVE. The ABoVE Information System will serve as the repository for all data sets collected and data products produced as a result of ABoVE research. It will provide access to other datasets that will be used during ABoVE that were generated from other HNL research projects, products from land management agencies, and from long-term monitoring efforts. The ABoVE Information System will provide access to the results and assessments being produced through modeling and other analyses to a wide range of end users, and will provide support for experiment planning during ABoVE. Representatives of end users for information from assessments of the impacts of climate change will be involved in the determining the products that will be generated during ABoVE and made available through the ABoVE Information System.

ABoVE will provide coordination with scientists in research and land management agencies in Japan and Canada who are studying the impacts of climate change in HNL regions, as well as those in similar agencies in the U.S., both at the state and federal levels, and with non-government organizations. Within these organizations, there is a substantial level of research, monitoring, and assessment activities that focus on the questions and issues being addressed by ABoVE. Discussions with scientists and managers across a range of organizations in Canada, Japan, and the U.S. revealed there is strong support for ABoVE, especially in carrying out coordinated, collaborative research activities. A key activity for ABoVE will be the creation of a management framework to facilitate this coordination and collaboration.

Finally, the Arctic-Boreal Vulnerability Experiment (ABoVE) will build upon foundational information and lessons learned from the Boreal Ecosystem-Atmosphere Study (BOREAS), a previous NASA led, large-scale field campaign conducted in central Canada from 1993 to 1996. Areas that were not addressed in BOREAS but will be during ABoVE include studies of tundra ecosystems, disturbance (fire, insects) and permafrost impacts on ecosystem processes and the carbon cycle, and human dimensions of climate change in HNL systems. ABoVE will also build upon more than a decade of subsequent research and technology development, and information from field studies, observations, modeling activities and satellite remote sensing that have occurred since BOREAS.

ABoVE VISION

Over the past 100 years, the High Northern Latitudes (HNL) have experienced more rapid climate warming than anywhere else on Earth. 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 thawing of frozen ground (permafrost) and changes to disturbance regimes and surface hydrology. In turn, changes to the land surface can feedback strongly to regional and global climate as well as impact the goods and services ecosystems provide. While there is a considerable legacy from previous research (including that sponsored by land management agencies) in the HNL region on the causes and impacts of climate change, there are still significant gaps in knowledge that provide the basis for additional research. ABoVE will provide the opportunity to expand and coordinate this focused, interdisciplinary research to further understand the drivers and consequences of climate change in HNL regions. The unique geographic perspective of data collected by remote sensing systems provides a practical means to extend field-based measurement, as well improve capabilities for monitoring and modeling processes that are causing changes in HNL regions as well as the responses of ecosystems across multiple spatial and temporal scales. When interpreted synergistically with the results from field-based observations and monitoring, the use of information derived from analyses of remotely-sensed data that will take place during ABoVE will substantially and measurably increase our ability to project realistic scenarios of environmental change in Arctic and Boreal regions and assign probabilities of risk to those scenarios.

1. INTRODUCTION

Since 1960, the Earth's High Northern Latitude (HNL) region (above 50º N) has experienced temperature increases of 0.3 to 0.4º C per decade. This rapid climate warming has been caused in part by physical feedbacks within the Arctic/Boreal system – decreases in sea ice and snow cover have lowered surface albedo, enhanced absorption of shortwave solar radiation, and amplified regional warming. The biological responses of HNL landscapes to climate warming are also driving feedbacks to global and regional climate warming. Positive, amplifying feedbacks include changes in vegetation albedo associated with northward migration of tree line and increased growth of shrubs in tundra, as well as carbon dioxide and methane emissions from fire and warming-driven losses of soil carbon from large terrestrial reservoirs. Negative, stabilizing feedbacks emerge from increased plant growth and carbon uptake, and changes in dominant growth forms which cause changes in albedo forcings.

Arctic and Boreal regions are one of the primary terrestrial carbon pools because of high carbon concentrations in organic and mineral soils. Recent research has shown that carbon stocks in permafrost soils are much higher than previously estimated, and the warming and thawing of permafrost and changes to surface hydrology in peatlands in HNL regions have raised concerns about rapid releases of soil carbon in response to climate warming. Specifically, the freezing point of permafrost soil represents a threshold that, when crossed, will increase the vulnerability of soil organic carbon stocks to decomposition, resulting in release of carbon dioxide and methane into the atmosphere. Because permafrost carbon stocks are estimated to be more than twice the size of the atmospheric carbon pool, decomposition and release of permafrost carbon to the atmosphere could be substantial. Peatlands and wetlands contain deep organic soils, and this reservoir is vulnerable to both the direct impacts of climate change (changes in temperature, precipitation, and evaporation which affect surface hydrology and patterns of net primary production, and aerobic and anaerobic decomposition) and indirect climate change (in particular changes in the frequency and severity of fire which leads to increased combustion and release of organic soil carbon).

At local scales, some Arctic and Boreal ecosystems are resilient to longer-term changes in environmental drivers, such as unprecedented climate warming, and episodic perturbations, including fire or permafrost thaw. ***Resilience*** is the capacity of an ecosystem to maintain its function, structure and feedbacks in the face of a perturbation. Resilient ecosystems recover to their pre-disturbance state because the internal ecological feedbacks that regulate system stability are robust and recover following the perturbation. In other cases, internal, stabilizing feedbacks weaken or are disrupted, rendering ecosystems vulnerable to directional changes in structure and function. ***Vulnerability*** is the degree to which a system is likely to suffer harm and change in structure and function following a specific perturbation. These changes may tip ecosystems and landscapes into ***new states***, where novel dynamics emerge. Identification of these vulnerabilities and ***tipping points*** is needed for predicting how changes in climate and disturbances will alter Arctic and Boreal ecosystems and landscapes and their role in the earth system.

At larger spatial scales, Arctic and Boreal landscapes are experiencing gradual change due to the direct effects of climate, and rapid change due to climate-driven modification of disturbance regimes. The gradual changes occurring across large regions include more frequent droughts, both expansion and contraction of surface waters (depending on underlying substrates), changes in runoff and streamflow, deepening of the active unfrozen soil layer, thawing of permafrost, and alteration of the timing and rate of biological processes (e.g., seasonal plant growth, soil microbial activity). Increasing frequency, intensity and size of disturbances such as fire, insect and pathogen outbreaks, and thermokarst – ground subsidence following permafrost thaw – are causing more rapid changes in landscapes than the gradual direct effects of climate change. These climate-driven disturbances often occur as a series of discrete events over a large region in relatively short time period. As a result, these episodic disturbances alter landscape heterogeneity of many important surface characteristics (e.g., permafrost distribution, vegetation composition and structure) at local as well as regional scales, and over annual to decadal time scales. At these time-scales, the impacts of climate-driven episodic disturbances on landscapes may far surpass the slower and longer-term direct response of landscapes to climate change.

The tundra, peatland, wetland, forest, riparian and aquatic ecosystems found in Arctic and Boreal regions provide important and unique goods and services to human populations. Communities of Indigenous/Native Peoples occupy and manage the natural resources of large portions of Alaska and Canada, and these societies rely heavily upon Arctic and Boreal ecosystems for subsistence and economic well being. This subsistence culture is possible because HNL ecosystems provide habitat for an abundance of fish, mammal, and bird species, and are particularly important habitats for migratory species. Vast areas of wilderness and abundance of fish and wildlife species also provide for highly-valued recreational opportunities. In the southern Boreal region, forests are a major source for commercial wood products. In addition, the presence of extensive hydrocarbon and mineral resources in this region will provide for continuation of a wide range of resource-extraction activities, and the pursuit of these resources contributes to changing disturbance regimes in many Arctic and Boreal regions. The services that HNL ecosystems provide will undergo significant changes in a changing climate, in particular to the habitat of key plant and animal species. Climate impacts on permafrost and surface hydrology will have wide-ranging impacts on the infrastructure needed for exploitation of these resources, as well as the infrastructure of communities located in HNL regions.

1.1 Science Questions and Objectives

These observations justify the need for continuation and expansion of research in HNL ecosystems that would occur as part of an ***Arctic-Boreal Vulnerability Experiment (ABoVE).*** While an understanding of the linkages between climate and ecosystems for HNL biomes is now emerging, there are significant knowledge gaps that limit the ability to predict the manner, magnitude and rate of change that will result from additional climate change. These knowledge gaps provide the focus for research that would be conducted during ABoVE. The three overarching science questions to be addressed by ABoVE are based on developing a more clear understanding of how and why Arctic and Boreal ecosystems are responding to climate change in order to be able to predict future changes and feedbacks to climate from the HNL region:

A. What patterns of changes in ecosystem dynamics and land surface characteristics have occurred over the past 25-50 years and are likely to occur in the near future (5 to 25 years) and over the longer term (25 to > 100 years)?

B. What processes, interactions, and feedbacks control the vulnerability of Arctic and Boreal ecosystems and landscapes to structural and functional change in a changing climate?

C. How will potential future changes to the land surface in Arctic and Boreal regions contribute to positive and negative feedbacks to local, regional and global climates?

To address these three overarching questions, the objectives for ABoVE are to:

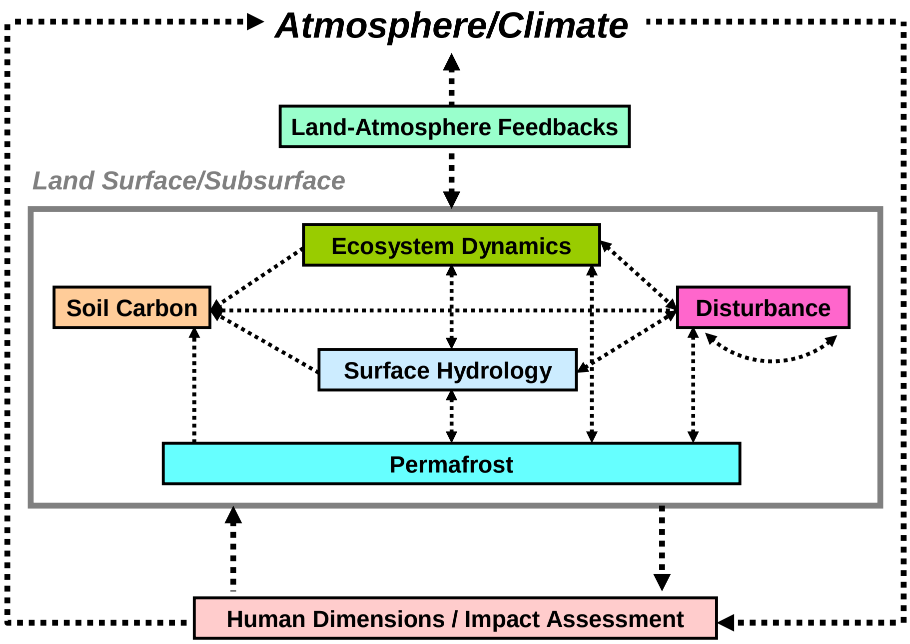
1. ***Quantify and model (i) the processes and interactions controlling natural disturbances, permafrost, and surface hydrology and (ii) the responses of ecosystems, changes in carbon stocks, and feedbacks between the land surface and the atmosphere that influence global climate.***
2. ***Identify and quantify the critical tipping points where changes in state occur, and the processes underlying these state changes.***
3. ***Understand how potential future changes to Arctic and Boreal ecosystems and landscapes will impact ecosystems services, resource exploitation, and land management activities.***

1.2 ABoVE Science Themes

Research to address these research questions and objectives will be organized around seven Science Themes (Figure 1):

- ***Disturbances*** are common across all HNL biomes and landscapes, and the primary disturbances (fire, insects/disease, thermokarst, thermal erosion, and mass wasting) are strongly regulated by climate. Disturbances trigger significant changes to ecosystems beyond the effects of climate change alone, and are important drivers of landscape heterogeneity.
- ***Permafrost,*** or permanently-frozen ground, occurs widely because the average air temperature is below freezing across the HNL region. Cold and frozen ground conditions in turn regulate many important ecosystem characteristics and functions, including drainage, rates of nutrient turnover and plant growth, heterotrophic respiration, and carbon cycling and storage. Climate warming will change the distribution of permafrost across the HNL region.
- ***Surface hydrology*** plays an important role in controlling ecosystem and landscape processes across most of the HNL region, and is a key factor in producing and maintaining large carbon reservoirs in HNL peatlands. Frozen ground layers combined with poorly-drained mineral soils and vast areas of flat topography have produced large areas dominated by ponds, lakes, wetlands, and peatlands. Climate change has historically resulted in changes to surface hydrology in HNL regions, where recent changes in precipitation, evapotranspiration, runoff, permafrost and terrestrial water storage (including snow cover, soil moisture and the location and extent of small lakes and ponds) have already occurred in some regions. Water cycle intensification under global warming and potential trajectories towards wetter or drier conditions will have dramatic and variable impacts on ecosystem processes and associated climate feedbacks.
- ***Ecosystem dynamics*** in the HNL region respond to the combined impacts of climate change, disturbance, and changes to surface hydrology and permafrost at a variety of spatial and temporal scales. These range from directional changes in growth rates observed in individual trees to changes in trajectories of secondary succession at plot and landscape scales to continental and global-scale variations in seasonal phenology and long-term patterns of vegetation productivity inferred from satellite imagery (e.g., vegetation indices). These changes to ecosystems have a variety of feedbacks to disturbance, permafrost and hydrology.

Figure 1. Inter-relationships between the ABoVE Science Themes.



- ***Soil carbon*** in the HNL region accounts for more than half of global soil carbon (C) stocks. Organic C has accumulated over century to millennial time scales in the soils and sediments of Boreal and Arctic ecosystems because cold ground temperatures combined with saturated soils has limited decomposition. Large soil carbon reservoirs exist in the organic soils of peatlands, wetlands, and tundra and as well as relic carbon in mineral soils that are frozen in areas with permafrost. Climate warming and resultant changes in disturbance regimes and permafrost extent together have the potential to initiate the release of large amounts soil carbon to the atmosphere over relatively-short (decadal) time scales.
- ***Land-atmosphere feedbacks*** across Arctic and Boreal biomes are important regulators of regional and global climate. Recent changes to HNL land areas have already demonstrated a positive feedback to climate through warming induced snow cover decline and resulting changes in surface albedo and land-atmosphere energy exchange. Continued warming and resulting climate change will likely result in additional feedbacks, where both positive and negative (release of soil carbon, changes in vegetation albedo, changes in carbon uptake by vegetation, etc.) are likely.
- ***Human dimensions*** and ***impact assessment*** represent the final ABoVE science theme. Human societies located in HNL regions, especially Indigenous or Native Peoples, are being impacted to a great extent by climate-driven changes in this region, in particular by changes to the landscape that impact the ecosystem services and key landscape features that are controlled by disturbances, permafrost and surface hydrology. The ecosystems and landscapes of HNL regions provide a number of important services. Because of this,

the ability to conduct impact assessments with respect to both natural systems and their human dimensions are critical areas for research.

While the ABoVE Science Themes are discussed as separate entities in this report, there are in fact important interactions and feedbacks between all of them, as depicted by the dashed lines in Figure 1. Five of the themes encompass key land surface / subsurface characteristics and processes, with several of these (permafrost and soil carbon) being unique to the Arctic/Boreal region. It is difficult, if not impossible, to identify the impacts of climate change associated with any one of these science themes without addressing the linkages to the others. Human activities affect land surface characteristics in a variety of ways, including altering vegetation and surface hydrology, which can in turn, impact permafrost. Land-atmosphere feedbacks can occur as a result of numerous changes to physical and biophysical processes involving the land surface/subsurface. In many instances the interactions and feedbacks that occur in Arctic/Boreal systems are complex – for example, the burning of organic soils not only releases large amounts of carbon to the atmosphere and particulate matter that can affect human health, but can cause thawing of frozen ground and changes to permafrost, which in turn, can change surface hydrology. Changes in vegetation growth and succession are influenced by the frequency and severity of prior disturbance and associated changes to soil temperature and surface hydrology. One of the key challenges for ABoVE is to conduct the research needed to identify and quantify the linkages that occur between land surface processes, human systems, and the atmosphere.

1.3 Role of Remote Sensing Observations

The legacy from NASA-sponsored research provides for a much different setting from previous experiment plans and major field campaigns, including the Boreal Ecosystem-Atmosphere Study [BOREAS] in 1993 and the Large-Scale Biosphere-Atmosphere Study in Amazonia [LBA] in 1996. Not least, the number of satellite systems in existence today and planned over the next decade is greater than for previous field campaigns. Many important satellite systems currently used in HNL research have been developed not only by NASA and NOAA, but by the space agencies of Canada, Japan, and the European Community. Over the past decade, data processing and data distribution technologies have advanced to the stage where a broad array of land-surface and atmospheric information products generated from satellite remote sensing systems are routinely available at continental and global scales. The availability of many these products spans 10 years and more and, as a result, they have become a central component for research focused on monitoring, modeling, and studying critical land surface processes and land-atmosphere interactions at a pan-Arctic/Boreal scale (Table 1).

Because of these advances, the primary science questions for the ABoVE Science Themes are based to a great extent on the availability of observations made from airborne and satellite remote sensing observations. The answers to these questions depend not only on information products that are currently available, but also on those from additional remote sensing systems that are scheduled to be launched over the next few years. ABoVE will thus provide the opportunity to evaluate new data products developed from continuity programs (e.g., Landsat Data Continuity Mission, NPP/NPOESS VIIRS) and from non-U.S. satellite remote sensing systems (e.g., GOSAT, GCOM, Radarsat, PALSAR, ENVISAT, etc). It will also provide the opportunity for further refining and validating land and atmospheric information products

Table 1. Summary of information products derived from satellite remote sensing data that provide the foundation for the ABoVE Science Theme questions. These information products include those from previous and existing satellite remote sensors, or those scheduled for launch in the near term (by 2015), and are not intended to be comprehensive or exclusive.

Science theme	Satellite remote sensing information products
Disturbance	Hotspot locations and fire radiative energy (AVHRR, MODIS, ASTER) Burned area (AVHRR, MODIS, SPOT Vegetation, Landsat, MODIS, VIIRS, GCOM, LDCM) Disturbance severity (Landsat, ASTER, LDCM) Vegetation change (Landsat, MODIS, LDCM, RADARSAT-2, ERS-2, ENVISAT, TERRASAR-X, PALSAR) Insect disturbance (MODIS, Landsat, LDCM, Ikonos/WorldView, Quickbird/GeoEye) Thermokarst and thermal erosion (Ikonos/WorldView, Quickbird/GeoEye, CORONA)
Permafrost	Surface/vegetation freeze/thaw status (ASCAT, SMAP) Snow cover (MODIS, AVHRR, VIIRS, SSM/I, AMSR-E) Vegetation cover and dynamics (MODIS, AVHRR, Landsat, LDCM, MISR) Surface temperature (MODIS, AVHRR, ASTER) Surface subsidence (Interferometric SAR: ERS, Envisat, Radarsat, TerraSAR-X, PALSAR)
Surface Hydrology	Surface water extent (MODIS, Landsat, LDCM) Precipitation (GPM, AMSR-E, AMSR2) Snow cover (MODIS, VIIRS, AMSR-E, AMSR2) Water storage (GRACE) Soil moisture (SSM/I, NSCAT, Radarsat, ERS, Envisat, PALSAR, SMAP, AMSR-E, AMSR2, SMOS) Wetland inundation (Radarsat, ERS, Envisat, PalSAR, AMSR-E, AMSR2)
Ecosystem Dynamics	Seasonal phenology (AVHRR, MODIS, VIIRS, AMSR-E) Shrub cover (AVHRR, MODIS, Landsat, ASTER, MISR) Vegetation biomass (Landsat, LDCM, ICESat-II, DESDynI) Post-disturbance vegetation characteristics (AVHRR, MODIS, Landsat, LDCM, ASTER, MISR, PALSAR)
Soil Carbon	Changes in frozen ground (see Permafrost) Disturbance impacts (see Disturbance) Impacts of inundation/soil moisture (see Surface Hydrology) Changes to soil carbon (see Ecosystems Dynamics)
Land-Atmosphere Feedbacks	Atmospheric greenhouse gases (GOSAT, OCO-2, SCHIAMACHY, MOPPIT, AIRS-AMSU) Surface albedo (AVHRR, MODIS, MISR, CERES, NPOESS VIIRS, GCOM) Disturbance impacts (see Disturbance) Vegetation dynamics (see Ecosystem Dynamics) Surface water extent and soil moisture (see Surface Hydrology) Surface temperature (see Permafrost)
Human Dimensions / Impacts Assessment	Changes to disturbance regimes (see Disturbance) Changes in frozen ground (see Permafrost) Changes in soil moisture and extent of surface water (see Surface Hydrology) Changes to vegetation cover (see Ecosystems Dynamics)

from NASA missions that will be launched over the next few years, such as OCO-2 and SMAP. The research that will be part of ABoVE will provide opportunities to continue to develop approaches to use these new satellite-based products in modeling (e.g., as inputs or for validation). ABoVE will build upon and expand the research that is being undertaken as part of the airborne remote sensing studies that are part of NASA's Earth Venture-1 Missions (CARVE and AirMOSS). ABoVE will also include collecting, processing, and analyzing remote sensing data from airborne systems that serve as test-beds for future satellite missions, such as DESDynI and HyspIRI, or that are needed to improve or calibrate existing satellite data products (e.g., surface albedo, atmospheric greenhouse gases). Finally, while NASA's Terrestrial Ecology Program will likely be the principal sponsor of ABoVE, the focus of this study is broad enough to be of interest to scientists from other NASA program areas, including the Cryospheric Science, Hydrologic Science, Land Use/Land Cover Change and Applied Sciences programs. Thus, ABoVE will offer significant opportunities to foster inter-disciplinary earth system science research across many of NASA's earth system science programs.

The unique spatial and temporal perspectives afforded by satellite remote sensing data will allow for integration across the ABoVE Science Themes. Integrating satellite-based information on specific land surface characteristics (e.g., disturbances, extent of surface water, variations in albedo) and ecosystem dynamics will allow for a more comprehensive understanding of the interactions among processes regulating HNL biomes, and their impacts on critical features of these biomes (e.g., extent of permafrost, variations in soil carbon, land-atmosphere feedbacks). This understanding will be central to improving models needed to diagnose ecosystem changes, underlying processes and feedbacks, and predict future impacts of climate warming across the Arctic/Boreal region.

For most Science Themes, understanding the underlying drivers of the satellite-based observations requires addressing important process-driven questions as well. The experimental design for ABoVE is based on the fact that in many cases, the process-based questions can be addressed using the results of ongoing and planned research in Arctic and Boreal regions, with many studies involving long-term monitoring through surface observations. ABoVE will thus provide a unique opportunity for collaboration between field-based research and monitoring programs being sponsored or planned by U.S. and international funding agencies (e.g., in Canada and Japan). These include agencies who traditionally fund basic research (e.g., NSF, NOAA, DOE, USDA, NSERC, JAXA, JAMSTEC), as well as agencies sponsoring applied research (CFS, DOI, USFS, USGS, NPS, FWS, State of Alaska). Agencies within this latter group represent important participants in ABoVE for several reasons. First, these agencies are generating key information products through the analysis of remotely sensed imagery or the collection of other geospatial data. Second, in some cases they have carried out and will continue to conduct field-based research and data collection. Third, many of these agencies are in the process of establishing climate change assessment programs involving the development of approaches to integrate many different classes of models as well as infrastructure to access the data sets required to carry out their integrated assessments.

1.4 ABoVE Study Domain

The initial focus on ABoVE will be on the sub-continental region that includes Alaska and northwestern Canada. The ABoVE Study Region (ASR) contains many of the major ecosystem and landscape types found in the circumpolar Arctic and Boreal regions, and provides the spatial scale required to address the primary questions in the seven science themes. Additional questions for each science theme will address critical knowledge gaps that need addressing in order to improve process models. Research to address these questions will take place in ~12 Primary Research Areas located along three North-South transects. The location of these Primary Research Areas will be based on opportunities to conduct integrated research across science themes as well as the existence of ongoing or planned research funded by other agencies, including Canadian and Japanese organizations. Upon the completion of an Intensive Study Period that includes the collection and analysis of airborne and spaceborne remote sensing data, field studies, and the refinement and validation of models, the final phase of ABoVE will include a synthesis of results of satellite and field-based research and observations from across the HNL regions of Alaska, Canada and Eurasia. This synthesis will provide for a pan-Arctic/Boreal assessment of the impacts of climate change on HNL ecosystems and landscapes, informed by improved understanding of processes and critical thresholds and tipping points from modeling studies.

2. ABoVE SCIENCE THEMES

By their very nature, each of the ABoVE science themes requires strongly linked and integrated studies, including satellite and land-surface observations, the experiments and research that are required to address knowledge gaps, and improvements of the models needed to assess the impacts of future climate change on Arctic/Boreal regions at multiple spatial and temporal scales. Not only must this integration occur for studies within each science theme, but across science themes as well. The key questions for each Earth Science theme will be addressed primarily through the use of specific remotely-sensed information products. The integration of information derived from remote sensing data products with that obtained from field-based research, in turn, will provide the geospatial perspective needed to study the interactions of processes across and between the themes, and provide the information needed to understand the human drivers of change and assess the impacts of HNL climate warming.

2.1 Disturbance

This ABoVE Science Theme will investigate the controls on the spatial and temporal patterns of the primary disturbances in Arctic and Boreal regions, and their immediate (or short term) impacts across ecosystems and landscapes.

Disturbances are important processes in all Arctic and Boreal regions. Climate controls many components of natural disturbance regimes, including the types, intensities, and frequencies of disturbance to which ecosystems have become adapted. Over the past decade, fires have burned >15% of the land area in interior Alaska, while insect outbreaks have damaged some 25% of the forests in British Columbia. Because of the large areas impacted by disturbances and the rapidity of their effects, they are in many cases the most important agent for initiating changes to Arctic and Boreal ecosystems and landscapes. Discrete disturbance events across different years create landscape heterogeneity at ecoregion scales. Within discrete disturbance events, heterogeneity at scales of 10 m to ~1000 m is regulated by variations in disturbance severity controlled by vegetation cover, topography, drainage, and freezing and thawing, which in turn control the manner in which vegetation, permafrost, and surface hydrology respond to the disturbance. Even within individual stands of similar vegetation, disturbance severity often varies at scales of 1 to 10 m, imparting fine-scale heterogeneity. This is particularly true in the high arctic where patterned ground formations including ice wedge polygons, pingos, sorted circles, frost boils, hummocks, and other features interact strongly with permafrost, surface hydrology and vegetation (Figure 2). Ultimately diturbances have a major influence on soil carbon and land-atmosphere exchange of energy, water, and carbon (CO_2 and CH_4). 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 disturbance.

Research during ABoVE will investigate three categories of disturbance agents: physical (fire and thermokarst), biological (insect and pathogens; Box 3), and anthropogenic (those associated with land management and mineral/oil/gas exploration – see section 2.7 below). Disturbances trigger a variety of responses in ecosystems and landscapes, and the degree to which disturbance regimes influence the vulnerability (e.g., susceptibility to change) and resilience (e.g., resistance to change) of ecosystems and landscapes is central to determining how high northern latitude biomes respond to climate change.

Figure 2. Warming permafrost resulted in this retrogressive thaw slump adjacent to a lake on Alaska's North Slope.

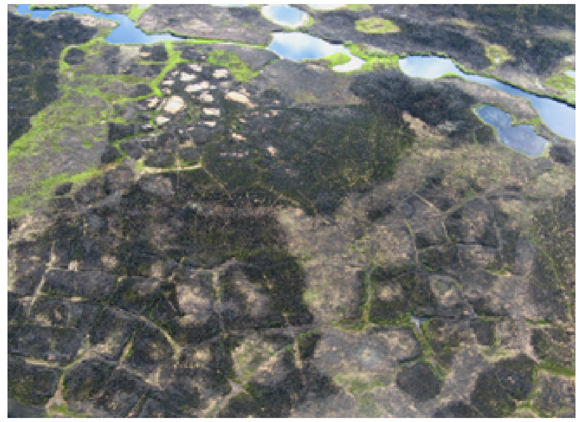
The overall goal for the research carried out for this science theme will be to develop disturbance probability models. These models are needed not only to assess how future changes in climate will drive disturbance regimes, but they are also critical to the modeling of a number of processes that are impacted by disturbance. The study of disturbance during ABoVE will be driven by answering the following questions:

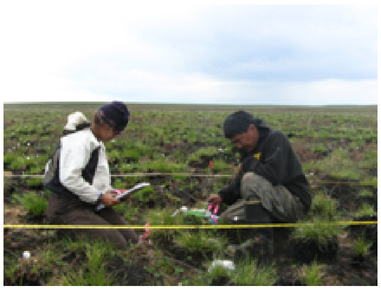
- ***What patterns and frequencies of disturbance have occurred on Arctic and Boreal landscapes during the satellite data record (past 35 to 40 years), and what regional disturbance regimes can be characterized using these data in combination with other sources of information?***
- ***What factors control the susceptibility of landscapes to disturbance?***
- ***How are natural disturbance regimes likely to change in a warming climate?***

The primary means for studying patterns of disturbance that have occurred over the past century has been through the use of data sets and disturbance perimeter maps collected by land management agencies. Analyses of paleo records (tree rings and lake-bottom sediments) provide a longer-term perspective on disturbance occurrence and frequency. Information derived from satellite remote sensing data since the 1970s provides a more accurate depiction of the distribution of different disturbances across ecosystems and landscapes. For fires, thermal IR hot spot products present information on seasonality of burning, while surface reflectance products can separate burned from unburned landscapes and have great potential for mapping of fire severity (Box 1). Similarly, approaches are now being developed to use satellite data to map the location and severity of insect outbreaks using moderate- (e.g., MODIS) and medium- (e.g., Landsat TM) resolution remote sensing systems. Studies of other common disturbances (thermokarst, oil exploration corridors, damage to tundra from exploration) have been carried out using high-resolution satellite imagery (e.g., IKONOS, Quickbird) in combination with micro-topography information from airborne LIDAR. Other surface characteristics mapped using satellite remote sensing data can provide information on key landscape characteristics at the time of disturbance (e.g., vegetation type and physical structure, soil moisture, presence or absence of water).

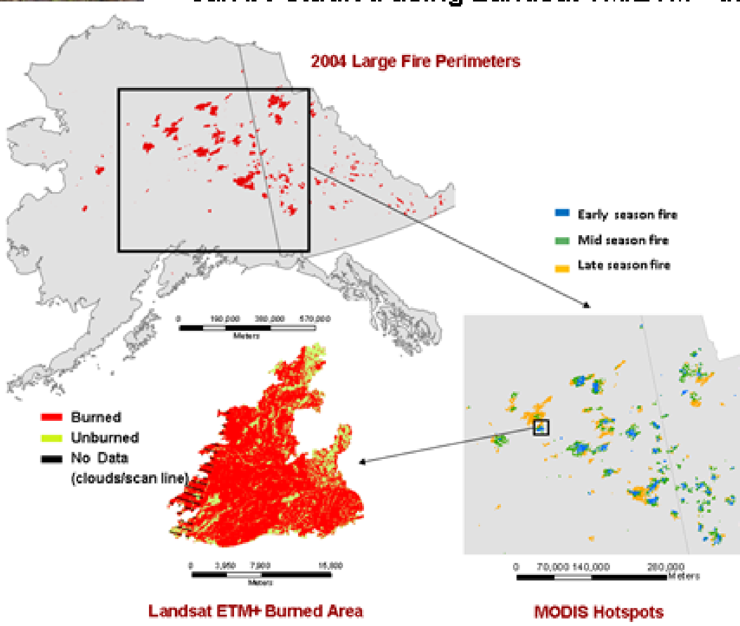
Integration of the remotely-sensed products with other geospatial data (e.g., topographic maps, weather data, insect population data, ignition data, etc.) during ABoVE will be used to assess variations in disturbances and the underlying landscape and climatic features that control susceptibility to disturbance across the entire ABoVE Study Region. Studies of the patterns of disturbance will be conducted at an ecoregion scale. Within the individual ecoregions of the ABoVE Study Region, analyses will further be stratified by primary land-cover type (forest,

Box 1 – Fires in the Boreal and Arctic Region





Fires are a common disturbance across the Boreal zone and may becoming more frequent in the Arctic. Fires occur in all vegetation types, and variations in severity can alter many important ecosystem characteristics. Geospatial data sets are central to the study of all disturbances in the HNL region, and remotely-sensed data products provide unique perspectives for studying disturbance regimes. While large fire databases provide information on fire locations back to the 1950s, MODIS hotspot data provide information on the geospatial patterns of burning, while landscape scale patterns of burning can be studied using Landsat TM/ETM+ data.



tundra, peatland), and further divided by ecosystem and vegetation type, topography, and drainage classes within individual disturbance events, as necessary.

Measurement and monitoring of disturbance severity is challenging because the specific vegetation/land surface characteristics used to quantify the impacts of disturbance depends to a large extent on the ecosystem and process being studied. For example, the changes to surface characteristics controlling post-fire regeneration of vegetation may be different than those regulating post-fire degradation of permafrost. Studies of the vulnerability of ecosystems/ landscapes to disturbance will require a more detailed understanding of a number of underlying ecosystem/landscape characteristics and processes that cannot be completely assessed using remote sensing data alone. Because of this challenge, ABoVE will also include research to address additional process-based questions concerning disturbance:

- ***How do climate, vegetation, site physiography (including permafrost and hydrology), and anthropogenic activities interact to control susceptibility to disturbance at landscape scales, and regulate the severity of disturbance across ecosystems and landscapes?***
- ***How do variations in disturbance regimes and their interactions with surface hydrology and permafrost influence the vulnerability of ecosystems and landscapes to changes in state?***
- ***How have humans modified the landscape and how do human activities influence natural disturbance regimes?***

To answer these questions, field-based research will be conducted to investigate the factors that control spatial and temporal variations in disturbance occurrence and severity. These observations will also support studies to further develop and validate severity maps derived from satellite remote sensing data. Research will focus on the systematic collection of data of the same disturbance type across different ecosystems and landscapes, including research on how variations in vegetation, surface hydrology and permafrost influence occurrence and severity. A systematic sampling design will be developed within individual disturbance events to collect data in plots that represent the full range in disturbance severity across the range of landscape characteristics (e.g., vegetation/ecosystem type, topography, human modifications, site drainage and climatic conditions) that are expected to control occurrence and severity.

The field-based studies on disturbance will be directly linked to research from other Science Themes investigating the impacts of disturbance on ecosystem dynamics, soil carbon, land-atmosphere feedbacks, and human dimensions. These connections are needed because determining which ecosystem and surface characteristics are needed to quantify disturbance (e.g., the cause) requires an understanding of how variations in severity cause changes to ecosystem processes (e.g., the effects). Such linkages are needed to determine which vegetation and land surface characteristics are the most meaningful measures of severity, as well as understanding how disturbance occurrence and severity influence the vulnerability of ecosystems and landscapes.

2.2 Permafrost

This ABoVE Science Theme will investigate the processes and landscape characteristics controlling the spatial distribution and dynamics of permanently frozen ground, in particular factors controlling its degradation and loss.

Permafrost is common across all Arctic and Boreal biomes, most of it having been formed during the Holocene and Pleistocene. Permafrost type varies according to the lateral continuity, depth and ice content of frozen ground. The presence or absence of permafrost at landscape scales is controlled by the site microclimate, slope and aspect, and by disturbance history and vegetation cover. The depth and soil texture of the seasonal thaw layer above the permafrost regulates site drainage, surface hydrology, ecosystem dynamics, and over the longer term, storage of soil carbon. Finally, dynamics of the materials within the seasonal thaw layer give rise to ground patterning unique to permafrost systems – ice wedge polygons, sorted and unsorted stone circles, pingos, stripes and hummocks – which exert strong controls over ecosystem processes that are likely to change dramatically as soils warm.

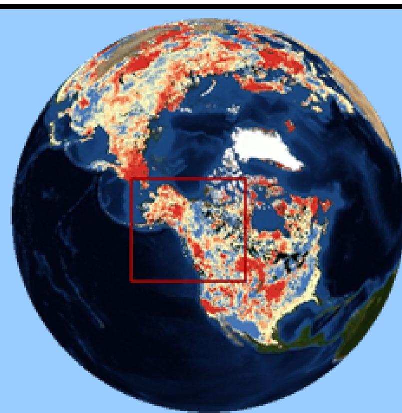
The broad zones of permafrost types (continuous, discontinuous and sporadic – Box 6), and the basic processes regulating the formation and degradation of permafrost are relatively well understood. In general, permafrost may form in regions where the average annual air temperature is $< 0^{o}$ C. With climate warming occurring across the HNL region, key characteristics of permafrost (e.g., temperature, active layer depth) are already changing and are expected to continue to change. In some regions, loss of permafrost is already occurring and is expected to be more widespread in the near future. However, changes to permafrost are difficult to predict because there are many non-linear responses associated with surface energy exchange and the vertical and horizontal transfer of energy with flowing water. The study of permafrost during ABoVE will be driven by studying the key surface characteristics that are responsible for regulating the surface energy budget in HNL regions, specifically answering the following question:

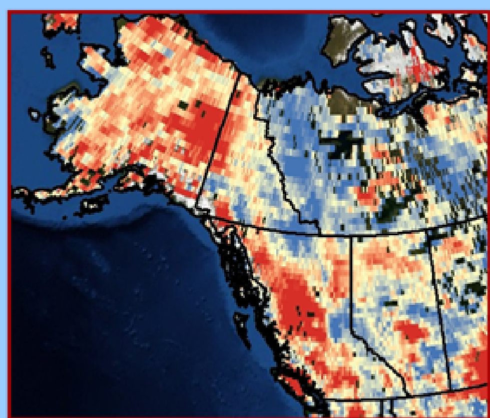
- ***How do variations in air temperature, snow cover, disturbance, surface hydrology, organic layer depth, and vegetation cover interact to control the distribution of permafrost and permafrost degradation?***

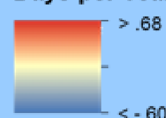
While recent studies have shown a gradual increase in the permafrost temperature in HNL regions over the past two to three decades, the rates of warming have not been uniform in time and space. During ABoVE, observations from satellite remote sensing systems will be used to monitor and quantify key land surface characteristics that regulate permafrost dynamics. In particular, satellite remote sensing data will be used to measure seasonal and inter-annual variations in freeze/thaw cycles (Box 2), albedo, snow cover, patterns of vegetation cover and vegetation change, disturbance occurrence and severity, variations in surface water coverage, and variations in soil moisture. Studies of the impacts of permafrost warming on thermokarst and thermal erosion (Figure 3) will be carried out using high-resolution satellite imagery and airborne LIDAR.

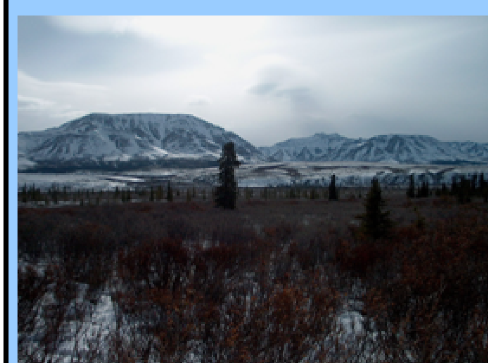
These observations will be used with field-based measurements to understand driving processes and as agents for the development of and inputs for physical models to predict spatial and temporal patterns and future conditions for soil active layer depth and permafrost status. The permafrost models will be validated using existing longer-term records of permafrost temperature, as well as new observations of ground layer temperature and moisture.

Box 2 – Freeze/Thaw Changes in the Boreal and Arctic Region









Research for ABoVE will investigate changes in HNL freeze/thaw dynamics at different spatial scales and linkages to ecosystem and hydrological processes. The freeze/thaw signal from satellite microwave remote sensing is sensitive to the predominant phase of water in the landscape. Satellite microwave (SSM/I) remote sensing records show a general lengthening non-frozen season (in red), with increases of more than two weeks for many areas since 1988 (top). Changes in HNL freeze/thaw dynamics not only affect permafrost but a number of biophysical processes including the snow cover regime, vegetation dormancy and the potential growing season (left), land atmosphere energy and trace gas fluxes, and availability of suitable habitat for Caribou (upper).

Improving the representation of fundamental processes incorporated in ground-layer thermodynamic and permafrost models will require answering key process-based questions:

- ***What are the causes and distribution of different permafrost thaw mechanisms across the landscape?***
- ***What is the heterogeneity of permafrost across the landscape within discontinuous permafrost areas and what controls this heterogeneity?***
- ***How will the area extent of permafrost that is vulnerable to thawing vary as a function of climate warming and climate change?***
- ***What is the influence of summer versus winter warming for causing permafrost temperatures to increase?***
- ***How important is air temperature change versus change in snow depth/timing for permafrost stability?***

Addressing these questions will require field-based studies in different land-cover types (tundra, forest, peatlands) located across the major permafrost zones (continuous, discontinuous, and sporadic). These sites will also be selected to encompass variations in ice content and disturbances. The field-based studies will include measurement of depths and bulk densities of organic and mineral soils (in both the active layer and frozen ground), permafrost depth and temperature, vegetation cover, seasonal snow depths and snow water content, ground ice content, seasonal ground temperature and moisture profiles, and seasonal active layer depths. Sampling of permafrost soils will be intrinsically linked to the study of soil C pool size and lability described below in the Soil C Theme. These field-based studies will also include seasonal mapping and monitoring of thermokarst, areas experiencing thermal erosion, and areas where permafrost thawing is causing mass wasting. These field-based observations will provide the means to address the process-based questions and key knowledge gaps, including the coupling of processes and feedbacks (e.g., hydrology, vegetation, thermokarst, etc.; Figure 2), non-linearity in controls on permafrost and feedbacks on permafrost, and impacts of disturbance.

To test specific hypotheses, field-based research will include both natural and manipulative experiments to study controls on permafrost. Natural experiments will occur within watersheds to study how natural variations in mineral soil, slope, soil moisture, vegetation, and organic layer control permafrost and its seasonal dynamics. Manipulative studies will focus on determining how variations in warming, snow depth, water table, and organic layer thickness control permafrost. Remote sensing and physical models will be used for spatial and temporal scaling and extension of these relationships over the larger ABoVE domains.

Figure 3. Thermal erosion of permafrost is one of the processes causing the shrinkage of lakes and ponds in some HNL regions

2.3 Surface Hydrology

This ABoVE Science Theme will investigate processes and factors controlling the spatial and temporal patterns of surface and subsurface water (including soil moisture) across different ecosystems and landscapes.

In HNL ecosystems, precipitation (P) occurs as both rainfall and snowfall and is stored as permanent ice, seasonal snow cover, soil moisture, ground water, and surface water. Terrestrial water is lost to the atmosphere through evapotranspiration (ET) (including sublimation), redistributed across the landscape through runoff, and groundwater and stream flow and ultimately transported to the ocean. The terrestrial water balance represents the difference between precipitation and evapotranspiration and determines the amount of water available for storage, runoff and ecosystem processes. Annual precipitation in Arctic and Boreal biomes tends to be much lower than in temperate, sub-tropical, and tropical regions outside of deserts. Because of lower temperatures and solar illumination, the rates of ET in HNL regions are low relative to other biomes, though sublimation of winter snow cover can be substantial in some areas. As a result, the combination of poorly drained mineral soils, permafrost, and vast areas with low relief has produced extensive areas with ponds, small lakes, wetlands, and peatlands (Figure 4). Global warming is causing water cycle intensification, changes in the terrestrial water balance (P-ET) and the distribution and storage of water in the landscape. The distribution, state and variability of water storage across the landscape influences land-atmosphere feedbacks (including water, carbon and energy exchange), permafrost formation and degradation, disturbance regimes, vegetation dynamics, and soil carbon. Surface hydrologic processes also represent a key linkage between the land surface and the coastal oceans (Figure 5). Land surface hydrology studies for ABoVE will answer the following questions:

- ***What are the long- and short-term variations in pond and lake area extent, surface water inundation, and soil moisture, and what controls this variability?***
- ***What are the processes regulating runoff and the flow of freshwater from the land surface to the Arctic Ocean and Bering and Beaufort Seas?***
- ***How do land surface hydrology patterns interact with vegetation, topography and permafrost to influence ecosystem dynamics, disturbance and the vulnerability and resiliency of Arctic/Boreal ecosystems to recent climate change?***
- ***How do disturbances (thermokarst, fire, insects) affect the hydrologic regime?***

Recent research has shown that the capabilities to monitor spatial and temporal variations in land surface hydrology are already available from existing satellite remote sensing systems or will be available from soon-to-be deployed systems. Surface hydrological characteristics available through the analysis of satellite remote sensing data include longer-term patterns of the number of small ponds and lakes and their area (using Landsat TM), mapping of surface water extent and inundation (using data from spaceborne SARs, MODIS, AMSR-E), detection and mapping of floods (using MODIS and SAR data), and mapping of soil moisture (using data from airborne and spaceborne SARs, microwave radiometers, and SMAP). During ABoVE data from all these remote sensing systems will be brought together and integrated to study variations in surface hydrology in Arctic and Boreal biomes. Information products derived from remote sensing data will also be used to investigate factors that control variations in surface hydrology. These additional products will include maps of vegetation type (particularly improved maps of peatlands and wetlands), micro-topography in areas with low relief, seasonal and inter-annual

Figure 4. Permafrost combined with variations in soil drainage result in complex landscapes in Boreal and Arctic regions. This aerial photograph was taken over a complex of forested permafrost plateaus, peatlands, and lakes in the southern Northwest Territories.

variations in snow and ice cover, seasonal and inter-annual variations in water surface temperature, and landscape freeze/thaw status. Research will be carried out in a number of Primary and Secondary Research Areas that provide the needed gradients to understand how surface hydrology is controlled by a number of critical factors, including climate, permafrost, and land cover type, ecosystem dynamics and disturbance. The satellite observations will be used as inputs for or a means to validate models that study the distribution and runoff of surface water in Arctic and Boreal regions. These include watershed and regional-scale water budget models that involve all components of the water balance, stream flow and river discharge models, lateral flow models in regions of low topography, and land-atmosphere water exchange models.

ABoVE will also include research to address key knowledge gaps in these models by answering the following process-based questions:

- ***What factors control the probability distribution of water storage in watersheds (i.e the likelihood of being wet)?***
- ***How do surficial flow regimes (direction, timing, connectivity and discharge) change seasonally and inter-annually?***
- ***What are the temporal dynamics of and physical controls on transitional phenomena and extreme events (e.g. flooding, freeze/thaw, ice break-up, etc.)?***
- ***What are the feedbacks between surface and sub-surface hydrology, landforms, permafrost and vegetation?***
- ***How are hydrological patterns and processes influencing and responding to regional water cycle intensification under recent global warming?***

Figure 5. Runoff from large rivers in the HNL region provide a linkage between the lands and oceans.

Field based research will be carried out at the watershed scale to address key knowledge gaps on processes and conditions that influence surface hydrology, including: (1) the effects of soil moisture and sub-surface hydrology on evapotranspiration by plant communities; and 2) factors controlling soil moisture and surface water storage across ecosystems, particularly in wetlands and peatlands and areas underlain by permafrost; (3) factors controlling the vertical and lateral fluxes between ground water and surface waters; (4) the pattern, rates and seasonality of lateral water movements; (5) hydrologic connectivity between upland and lowland ecosystems in relatively flat terrain; and (6) how variations in surface hydrology influence biogeochemical cycling.

Critical measurements collected during ABoVE will include soil moisture, precipitation, snow depth and snow water equivalent; tower eddy covariance measurements of land-atmosphere water and energy fluxes; water isotope measurements for diagnosing rates of transfer and storage residence times; stream flow data; fine scale topography; vertical and lateral runoff and groundwater flows sufficient to characterize flow pathways within relatively flat boreal and tundra landscapes; and measurement of water chemistry. The opportunity exists to extend the geographic domain of the AirMOSS NASA Earth Venture-1 Mission through overflights of test sites instrumented for ABoVE.

As with the permafrost studies, to test specific hypotheses, ABoVE research will include both natural and manipulative experiments. Because many of the factors controlling permafrost are also important in the understanding of surface hydrology (Figure 2), the experiments used for permafrost will also be used to inform studies of factors controlling surface hydrology. The natural experiments will also include investigations on the role of disturbance on surface hydrology through direct comparisons between disturbed and undisturbed areas.

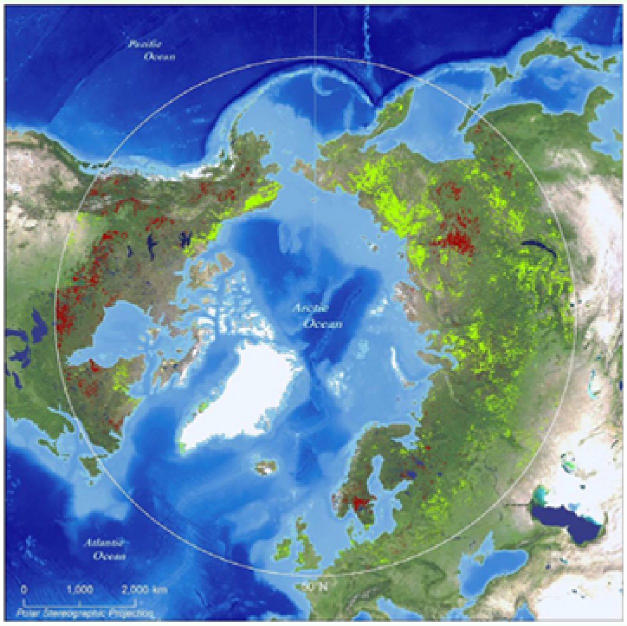
2.4 Ecosystem Dynamics

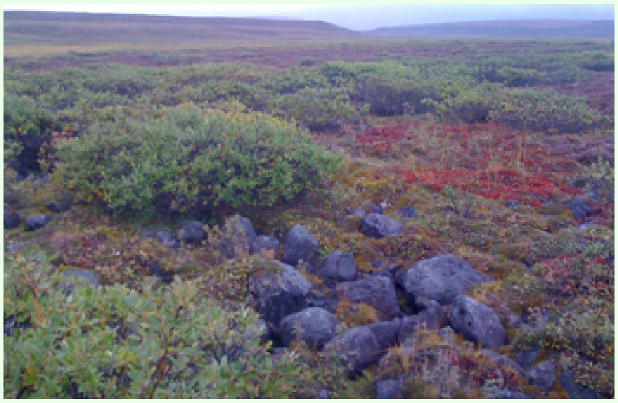
This ABoVE Science Theme will investigate the integrated responses of ecosystems to changes in climate, disturbance regimes, surface hydrology, and permafrost.

There is little doubt in the scientific community that recent climate change has resulted in changes to terrestrial ecosystems in the pan Arctic-Boreal region. Warming and changes to precipitation and snowfall patterns have caused a lengthening of the growing season and changes in plant phenology. While plant growth has increased in response to warming in some regions, drought-induced stress has decreased growth in some places (Box 3). Plant biodiversity is changing, with new species invading some regions and species becoming locally extinct in others. As a result, community composition and structure are changing, especially during secondary succession following disturbance. Species composition, including vegetation change, have important effects on ecosystem functioning and modify feedbacks to climate, while also being important for human use of natural resources. Variations in ecosystem dynamics, whether associated with changes in species composition or range distributions, are in many instances regulated by availability of key nutrients (particularly nitrogen) and soil temperature and moisture. Permafrost and surface hydrology are thus also particularly important in understanding ecosystem dynamics in HNL regions, even in the absence of vegetation composition change. Ecosystem dynamics studies for ABoVE will answer the following questions:

- ***What are the factors driving longer-term patterns of productivity observed in the satellite data record?***
- ***What is the seasonal and inter-annual variability in growing season timing and length based upon observations of surface temperatures and plant phenology?***
- ***To what degree are variations in disturbance regimes driving changes in secondary succession?***
- ***How do changes in species composition influence ecosystem processes and net feedbacks to climate?***

Box 3 – Productivity Changes in the Boreal and Arctic Region





Research for ABoVE will investigate changes to ecosystems and vegetation in HNL regions that are being observed at a variety of spatial and temporal scales. Vegetation indices derived from satellite imagery (top) show changes in productivity, with most tundra areas increasing (green) and some forest areas decreasing (red) over the past 27 years. These trends have been linked to forest decline (right) but not unambiguously to either tundra shrub expansion (above) or herbaceous plant growth (above right). The responses of trees and shrubs to climate change are also being derived from analyses of growth rings (bottom right) at longer time scales.

Since the late 1990s, a number of studies have used satellite remote sensing measurements of vegetation productivity to study vegetation dynamics on a global scale (Box 3). Observations are being used to investigate patterns of plant phenology related to seasonal variations in temperature and precipitation as well as identify areas with enhanced or suppressed plant growth. Because of strong seasonal variations in climate as well as recent climate warming, much of this research has focused on the HNL region, and there are still unanswered questions with respect to how the vegetation changes are influencing the satellite observations.

ABoVE will carry out research to further develop approaches to use satellite remote sensing data to monitor spatial and temporal variations in ecosystem dynamics in HNL regions, and to understand the processes that are responsible for these variations. To achieve this goal, ABoVE will carry out comparisons of variations in satellite remote sensing derived measures of land-surface gross and net productivity from different moderate-resolution satellite systems, including AVHRR (both GAC and LAC data), MODIS, and NPP/NPOESS/VIIRS. Medium-resolution satellite imagery (Landsat TM/ETM+, LDCM) will inform these assessments, as well as advanced technologies such as lidar and SAR that are useful for characterizing vegetation structure and biomass. The causes of the variations in satellite-observation of vegetation dynamics, including productivity, composition and structure, will be investigated through comparisons with ecosystem models that simulate these same properties and processes as well as with a variety of geospatial data, including, for example: (a) satellite maps of the extent, timing, and severity of disturbance; (b) seasonal variations in surface temperature and precipitation; (c) observations of canopy and ground layer phenology and snow cover; (d) satellite freeze/thaw maps; (e) satellite snow cover maps; (f) satellite maps of soil moisture and surface water extent; and (g) maps of canopy structure and aboveground biomass derived from data collected by airborne and spaceborne remote sensors.

Field-based studies will be carried out to further develop, assess and validate approaches to use satellite-remote sensing to monitor specific changes to ecosystem dynamics in HNL regions, including: (a) approaches to use remote sensing data to monitor changes in community structure and plant productivity associated with differences in secondary succession across different land-cover types (forests, tundra and peatlands) and ecosystems that result from variations in disturbance severity; (b) assessment of surface characteristics (e.g., soil moisture, disturbance severity) that control post-disturbance regeneration; (c) evaluation of the degree to which insect defoliation and aspen mortality in the southern Boreal forest drives variations in productivity; (d) examination of the links between satellite productivity metrics and wood growth increments derived from dendrochronology; and (e) further assessments of the degree to which satellite remote sensing data can be used to detect increased shrub growth and cover in tundra.

To understand the fundamental causes of changes to ecosystem dynamics, ABoVE research will also be directed towards answering the following process-driven questions:

- ***How are ecosystem dynamics responding to temporal and spatial variability and systematic shifts in forcing processes (disturbance regimes, surface hydrology, permafrost, site physiography) and more directly to climate?***
- ***How are HNL ecosystems responding to CO_2 and nitrogen fertilization relative to changes in climate (temperature, precipitation, insolation)?***

- ***What has been the magnitude, direction, and rate of change in ecosystem dynamics over the recent past (last 30-100 years), and how do they compare to longer-term (Paleo) records and climate proxies?***
- ***Are some ecosystem components (vegetation, fauna, etc.) more vulnerable or more resilient than others to state changes, and how much plasticity is there in these responses?***

To address these questions, ABoVE research will be carried to study variations in post-disturbance vegetation community composition, structure, and growth as a function of ecosystem and disturbance type, including chronosequence studies. These will make use of advanced remote sensing technology such as LIDAR and SAR that are useful for characterizing vegetation structure and biomass changes following disturbance (Figure 6). Paleoecological studies using lake-bottom sediments will provide opportunities to examine vegetation community change as a function of fire frequency. Field measurements and experiments will also be carried out to study factors controlling spatial and temporal variations in plant community structure and response rates to variations in permafrost and surface hydrology. Examination of tree rings will provide information on how local weather/climate variations have impacted plant growth. This research will be coordinated with studies being carried out for the disturbance, permafrost, and surface hydrology themes, and also include studies on how variations in biogeochemical cycling influence ecosystem dynamics, in particular nitrogen cycling.

Figure 6. Increased fire severity and northward migration of tree species are leading to complex patterns of succession in black spruce forests across the western North American boreal region. In interior Alaska (left), aspen seedling recruitment is occurring following fires that completely burn deep organic layers. In central Yukon (right), the northward migration of lodgepole pine is leading to the forests dominated by multiple species – in this case, pine, spruce, and aspen.

2.5 Soil Carbon

This ABoVE Science Theme will investigate the responses of carbon stocks in organic and mineral soil layers to the direct and indirect impacts of climate change.

Recent studies estimate as much as 1,672 Pg of organic carbon (C) resides in the soils and sediments of Arctic and Boreal regions (Box 4, Figure 7). Cold or frozen soils and poor drainage have driven net accumulation of soil C over millennial time scales, but recent studies suggest that these historic sinks for atmospheric CO_2 may be transitioning into net sources as climate warms and the frequency of disturbance, such as fire or thermokarst, increases. There is also much uncertainty on the factors responsible for recent variations in methane emissions in HNL regions. Because these soil C stocks are more than twice the size of the atmospheric C pool, there has been considerable interest in understanding how they will respond to observed and predicted changes in climate. Indeed, thaw, decomposition and release of C from northern latitude permafrost soils has been identified as a tipping point that could drive accelerated warming of global climate and associated ecosystem changes and feedbacks. Organic soil stocks in peatlands, wetlands, tundra and forests growing on permafrost and poorly-drained sites are regulated by rates of inputs from moss and lichen growth and rates of loss by aerobic and anaerobic respiration and combustion during fire. Additional research is needed to accurately quantify the impacts of climate change on this large soil carbon pool.

Soil carbon studies for ABoVE will address the following question:

- ***How vulnerable are both surface and deep soil carbon pools to changes in climate, disturbance, surface hydrology, permafrost and ecosystem dynamics?***

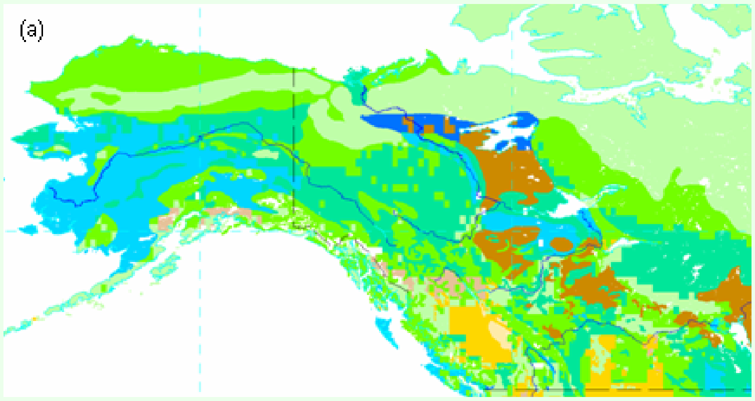
Research for ABoVE will compile and analyze information derived from airborne and satellite remote sensing data that are central to the study and modeling of soil carbon stocks in Arctic and Boreal ecosystems. Improvement of estimates of soil carbon stocks requires linking surface-based inventories with maps of land surface features that correlate with variations in soil carbon. Towards this end, ABoVE will provide maps of vegetation types (especially improve maps of wetlands and peatlands), disturbance location, type and severity, and topography and microtopography.

Research will also focus on providing spatial and temporal information on surface characteristics that control emissions of carbon-based trace gases from soils or landscapes (e.g., disturbance, aerobic and anaerobic heterotrophic respiration as a result of variations in surface hydrology, and ebullition from lakes) or drive the longer-term storage of soil carbon. Satellite remote sensing will be used to provide information on patterns of disturbance, soil moisture, surface water extent and surface temperature, lake ice extent, and inundation levels in peatlands and wetlands. These observations will be used as inputs into process models that estimate carbon fluxes from Arctic and Boreal organic and mineral soils. These studies will be coordinated with those being carried out for the Land-Atmosphere Feedbacks Science Theme.

To address key knowledge gaps in understanding the processes controlling both surface and permafrost soil carbon, research will be carried out to answer the following process-driven questions:

- ***How is climate variability altering patterns of soil carbon storage, and what are the primary mechanisms driving these changes?***
- ***Which ecosystem types and landscape components are most vulnerable to abrupt loss of soil C in a changing climate, and which are resistant to abrupt loss and why?***

Box 4 –Soil Carbon Dynamics



ABoVE will investigate the distribution and dynamics of soil carbon (C) stocks within the HNL region. Soil carbon maps based on historic surveys (a) will be combined with studies of disturbance via thermokarst (b) and fire (c) and dynamic models to predict the vulnerability of surface soil C stocks to changing climate. ABoVE scientists will also survey deep permafrost C stocks (d) and use laboratory studies to develop a mechanistic understanding of permafrost soil C stability.

- ***What is the net change in regional soil C stocks in response to the last several decades of warming, and how are stocks likely to change over the next century in response to predicted changes in climate and disturbance?***

To quantify the amounts and condition (e.g., age class, vertical distribution, chemistry) of soil C in different ecosystems and landscapes, ABoVE will contribute to ongoing regional soil mapping efforts by the USGS, USDA and Agriculture and Agri-Food Canada by inventorying soils in key areas known to have large soil C stocks. Soil C stocks will be mapped based on stratifying the landscape by parent material, vegetation cover, topography, surface hydrology, permafrost distribution and disturbance history. The covariation between soil C and these features will provide insight into controls over spatial heterogeneity in soil C storage. To understand how disturbance affects temporal heterogeneity in soil C storage, nested chronosequences will be constructed by assembling a series of mapped sites that vary in time since disturbance on different landscape positions, where other state factors remain constant. While surface soils in our study regions are relatively well-represented in current soil mapping efforts, few data exist for soil C stocks in permafrost soils. ABoVE soil C mapping will place particular emphasis on inventory and mapping of carbon stocks and ice content – which will determine the degree of surface subsidence upon thaw – of deep permafrost soils.

Upon thawing, the rate of C release from permafrost soils will depend upon C pool size, environmental conditions such as moisture, temperature and oxygen availability, and the lability (or relative decomposability) of soil C during ABoVE, including dissolved organic carbon (DOC) residing in soil water. The inventory of deep permafrost C stocks will also provide materials for laboratory incubation experiments that will examine the response of CO_2 and CH_4 release from newly-thawed permafrost soils to variation in temperature and moisture under oxic and anoxic conditions. Remote sensing will be employed to quantify linkages between *in situ* soil C patterns and overlying vegetation, terrain and microclimate conditions. Remote sensing derived parameters that are directly relevant to soil C studies include surface temperature and freeze-thaw status, vegetation cover and productivity, microtopography, surface soil moisture and inundation. Data from these laboratory and remote sensing studies will be used to develop models of soil C dynamics in newly-thawed permafrost soils.

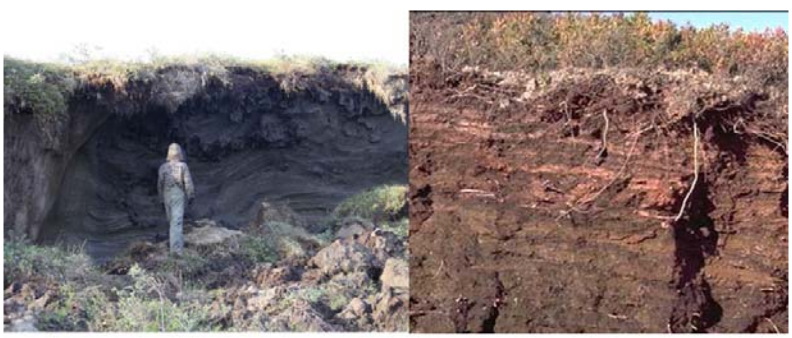


Figure 7. In Arctic and Boreal ecosystems, large reservoirs of carbon reside in frozen mineral soils in areas with permafrost (left) and in deep organic layers found in peatlands (right)

To understand how climate variability is altering the spatial and temporal heterogeneity of soil C storage, research will include field observations of soil C dynamics along with micro-meteorological measurements of C (CO_2 and CH_4) exchange and C balance (see Land-Atmosphere Feedbacks Science Theme). Continuous measurements of soil respiration will be made with autochambers that will not only be installed within flux tower footprints but will also be located independently in ecosystems that contain large soil carbon pools. Autochambers will be located along gradients of disturbance severity (thermokarst and fire) to develop data sets needed to understand how these perturbations affect soil carbon. Respiration will be partitioned between autotrophic and heterotrophic sources with isotopic methods, including in-line measurements of 13C:12C ratios, and periodic measurements of ^{14}C to determine the ages and sources of ecosystem respiration. In wetland/peatland sites, CH_4 flux can contribute up to 10% of total C in heterotrophic respiration, so studies will assess CH_4 fluxes from soil respiration as well. Intensive field measurements and experiments that manipulate key environmental controls (water depth, soil temperature, snow cover, etc.) will be complemented by less intensive, more distributed field measurements of soil respiration and laboratory measurements of soil organic matter lability that will be linked to studies of factors controlling permafrost, surface hydrology and disturbance in the other thematic areas. Finally, as abrupt losses of soil C also contribute to site and regional soil C balance, studies will also focus field measurements on recent fire or erosive thermokarst events where soil C losses can be directly estimated from biometric markers, and geochemical or geomorphological benchmarks.

Studies carried out for the disturbance theme will provide a basis for understanding the processes controlling the severity of fires in ecosystems with deep organic soils. Typically it is only the surface organic layers that are susceptible to direct combustion, and the fraction consumed is likely related to fuel moisture and fire characteristics. Direct removal of organic soil C by fire is a distinct mechanism of carbon loss that is under different controls that than those that regulate heterotrophic losses. Similarly, the formation and deposition of black carbon during fire is a distinct mechanism of carbon input to soil organic matter that is under different controls than those that regulate plant inputs. The burning of organic soils during fires and the genesis of black carbon are the subjects of considerable ongoing research, and it is expected that additional field observations will be collected during ABoVE field studies. Additional data will help refine models that determine the fraction of organic soil C susceptible to direct combustion.

2.6 Land-Atmosphere Feedbacks

This ABoVE Science Theme will investigate the role that processes occurring on the land surfaces have on regulating key characteristics of the atmosphere and climate.

The vast HNL region has particularly strong feedbacks between the Earth’s surface and its climate. Over the past half century, a strong positive feedback has resulted from decreased surface albedo from a loss of snow cover in the spring and fall. Over millennial time scales, the storage of atmospheric carbon in Arctic and Boreal soils has significantly reduced the atmosphere’s concentration of greenhouse gases; however, HNL peatlands and wetlands are one of the most likely sources of recent increases in atmospheric methane. Continued climate warming will result in further physical and biological HNL feedbacks to the Earth’s climate. Positive feedbacks would occur from additional greenhouse gas emissions from increased fires, thawing of permafrost, vegetation productivity decline and increases in heterotrophic respiration, and through further reductions in land surface albedo from snow duration decline or expansion of treeline and shrub extent in tundra. Negative feedbacks would occur from increases in net primary production and terrestrial C sink activity, increases in surface albedo through the shift from coniferous to deciduous vegetation, and an increase in clouds resulting from sea ice loss and increased evapotranspiration. Particular attention needs to be paid to clarify the roles, interactions and cumulative effects of these different feedbacks. Land-atmosphere feedback studies for ABoVE will address the following observation-driven questions:

- ***What is the spatial/temporal variability in surface albedo in HNL regions and how do changes in snow cover, surface water, and vegetation dynamics control these variations?***
- ***What is the impact of inter-annual variability in growing season length on ecosystem productivity, and net ecosystem exchange of C with the atmosphere?***
- ***What is the spatial and temporal variability in direct emissions of trace gases and particulate matter from wildland fires and what controls this variability?***
- ***What is the relative impact of changes in surface albedo versus changes in net carbon exchange on climate?***

These questions will be addressed through the use of a variety of information products derived from satellite and airborne remote sensing, with many of the products being used to address questions from other ABoVE Science Themes (Box 5). In addition to the remote sensing and field components discussed in sections 2.1 and 2.4, land surface temperature measurements will inform analyses not only of land-atmosphere feedbacks but also hydrology, permafrost, and soil carbon. Surface albedo products from existing (MODIS, MISR, and CERES) and future (NPP/NPOESS VIIRS and GCOM) remote sensing will be cross-calibrated through comparison with albedo collected from airborne platforms. These calibrated data products will provide the basis for studies of how variations in snow cover and vegetation alter albedo which in turn, affects climate. For example, albedo changes following disturbance modify the development of the land-atmosphere (planetary) boundary layer and its diurnal dynamic. Linking the observations of variations in surface albedo with ecosystem dynamics studies in ABoVE will provide a fundamental understanding of how changes in vegetation related to climate and disturbance and changes in permafrost and surface hydrology will impact climate.

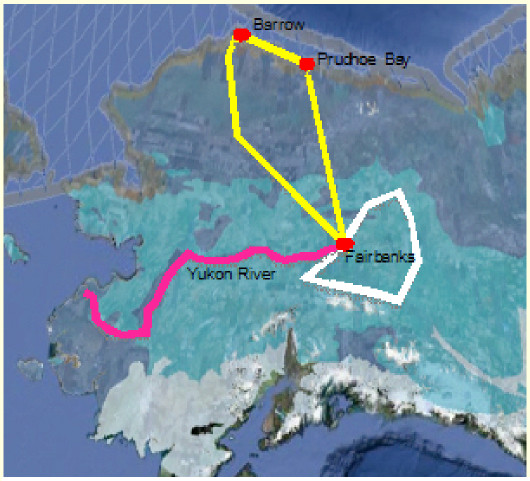
Other remotely-observed characteristics important in understanding land-atmosphere feedbacks that will be investigated during ABoVE are spatial patterns, temporal variations and underlying controls to surface temperature. Surface temperature variations and freeze/thaw cycles will be examined in relation to terrain, changes in vegetation cover, albedo, and surface water. These changes also represent important surface characteristics required to understand changes in permafrost and soil carbon.

Recent and ongoing advances in remote sensing of atmospheric trace gases will provide data sets critical to understanding spatial and temporal distribution of CO_2 and CH_4. For ABoVE, data on carbon dioxide and methane concentrations will be provided by satellite sensors (GOSAT, OCO-2, SCHIAMACHY, MOPITT, AIRS-AMSU) as well as airborne systems, in particular, data collected by the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE), an Earth Venture-1 mission recently selected for funding by NASA (Box 5).

Research from the Disturbance and Soil Carbon Science Themes will produce or provide information products for the improvement of estimates of greenhouse gas emissions from fires in Arctic and Boreal ecosystems. Satellite information products on burned area, fire severity, and seasonal patterns of burning will be used as inputs to fire emission models, and used to investigate factors that control variations in pyrogenic emissions.

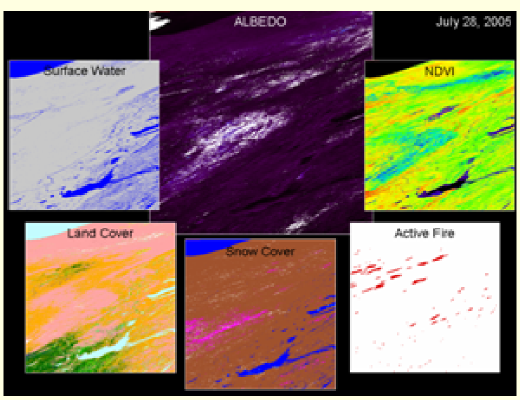
Satellite remote sensing products that estimate NPP and NEP (NPP – heterotrophic respiration) will be integrated with the results from other studies carried out for this science theme to determine the effect of net ecosystem exchange (NEE = NEP – carbon losses from fire) on radiative forcing of the earth's atmosphere. The satellite-based observations will also be

Box 5 – Land-Atmosphere Feedbacks

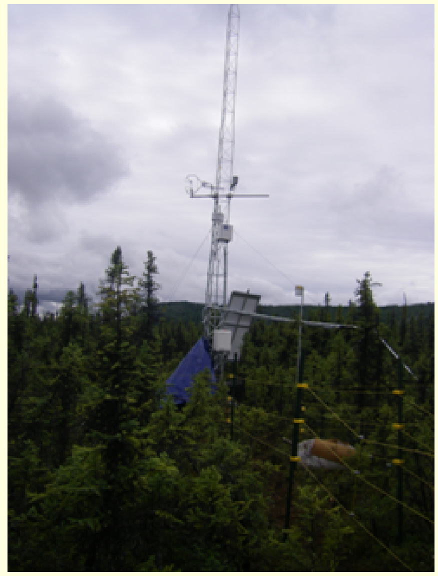


Flight lines for NASA CARVE Mission

ABoVE research will expand studies of land surface feedbacks started during BOREAS into new ecosystems, including disturbed sites. It will add to the number sites with of eddy covariance towers, and provide the opportunity to extend NASA's CARVE mission. ABoVE will make extensive use of satellite data products, and synthesize the information derived at multiple spatial and temporal scales to study the processes regulate the exchange of energy, water, and trace gases between the land surface and atmosphere.



MODIS Land Surface Characteristics



compared with outputs of process models that estimate net changes to surface albedo and terrestrial carbon cycling in HNL regions.

Addressing key knowledge gaps will also require answering process-driven questions:

- ***How do land surface processes interact to regulate the atmospheric concentration of key greenhouse gases?***
- ***Are there critical thresholds and tipping points in the processes that regulate releases of carbon to the atmosphere from large soil carbon pools?***
- ***How do interactions between land surface processes interact to regulate surface albedo and surface temperature and control the exchange of water and sensible heat between the land surface and the atmosphere?***

Much of the field-based research required to address these questions has already been outlined in the discussions of the other ABoVE Science Theme. Addressing the land-atmosphere feedback questions requires collection and integration of data collected from eddy covariance towers that measure exchanges of mass (water, carbon dioxide and methane) and energy between the land and atmosphere, as well as associated meteorological variables (albedo, radiation, soil temperature, precipitation as rain and snow, etc) (Box 5). While eddy covariance towers have been deployed in a number of different ecosystems across the HNL region, additional towers will need to be deployed during ABoVE. Additional methane and carbon dioxide flux measurements can be made using flux auto chambers. The challenge in collecting the flux data will be the development of an experimental design to collect the data needed to understand how interactions between disturbance, permafrost, and surface hydrology control exchanges of mass and energy between the land surface and atmosphere across the major ecosystem types in the HNL region. This research will coordinated with that being carried out for the Soil Carbon Science Theme.

An additional challenge will be to develop a framework that allows for the integration and linking of relatively fine scale (bottom-up) process models to other (top-down) models used to study global climate and land-atmosphere feedbacks. While the process models would be driven with *in situ* measurements and/or down-scaled climate model simulations or model reanalysis data, many, if not most of the process-based models are not developed enough to be able to address land-atmosphere feedbacks in HNL regions. Addressing these knowledge gaps will require significant model augmentation, coupling and refinement.

2.7 Human Dimensions / Impact Assessment

This ABoVE Science Theme will investigate the role that humans play in altering HNL ecosystems and landscapes and explore how climate change will impact ecosystem services and society.

While human activities play a less prominent role in disturbing landscapes and altering community composition in HNL ecosystems compared to other biomes, land management decisions do have a direct role in regulating the frequency and severity of several natural disturbances (fire and insects). In addition, in several instances, mineral exploration and resource development activities represent a significant source of disturbance at local scales. These activities include oil and gas development on Alaska’s North Slope, oil extraction from Alberta tar sands, the Mackenzie gas pipeline, and the placement of extensive oil survey lines across Alberta.

Key questions on the role of humans in HNL ecosystems include:

- ***To what extent have human ignitions and fire management policies influenced the fire regime?***
- ***Have fire and other land management policies altered the susceptibility of forests to invasions of insects and disease?***
- ***How have hydrocarbon exploration activities influenced permafrost and surface hydrology in tundra, forests, and peatlands?***

Increasingly, the knowledge being generated through basic research on the causes and effects of climate change are being used by policy makers and land managers who need to make decisions based on the assessments of the ongoing and future impacts of climate change. We envision that through collaborations with land management agencies, the new information capabilities resulting from ABoVE will allow a number of assessment-driven questions to be addressed:

- ***How will climate change influence disturbance regimes?***
- ***What options exist for mitigating the impacts of climate change on disturbance regimes?***
- ***How will climate change impact fish and wildlife habitat?***
- ***Will climate change harm or enhance production of timber and wood fiber?***
- ***How will climate change influence the ecosystem services that provide the foundation for subsistence cultures?***
- ***How will changes to surface hydrology and permafrost affect resource exploration and mineral extraction?***

Research to address these human dimensions questions will require an integrated approach using the results from studies being carried out for other science themes. Specifically, the questions on human impacts on fire and insect regimes will be coordinated with research for the disturbance science theme, with data on land management activities being integrated with other disturbance data sets to determine the role of human activities. The research on the impacts of human disturbances will be coordinated with those activities being carried out for the permafrost and surface hydrology science themes. In these cases, it will be necessary to obtain high-resolution airborne or satellite remote sensing imagery (e.g., IKONOS, QuickBird) or aerial photography to quantify the location and extent of the disturbances.

The assessment driven questions will most likely require additional research on the direct and indirect impacts of climate change on key fish and wildlife populations, specifically that linking landscape composition to wildlife population ecology. These data will require collaboration with federal, state, and provincial wildlife management agencies that are monitoring the populations of key species. In addition, research will be needed to further understand how human societies in HNL regions are likely to be impacted by the direct and indirect impacts of climate change.

ABoVE research on carbon cycling as part of the Soil Carbon and Land/Atmosphere Feedbacks Science Themes will provide the basis for improved assessments of factors regulating the carbon budgets of Arctic and Boreal ecosystems, an ecosystem service that is of increasing importance to land managers whose responsibilities include carbon management.

The inclusion of impacts assessment as part of this science theme was to a large extent based upon: (a) an increasing recognition within NASA and other U.S. and international agencies on the need to develop decision support systems to provide information and analyses to land managers, policy makers, and other decision makers; and (b) the recent development of programs within land management agencies whose mandate is to provide data required for climate treaty monitoring (e.g., the Canadian Forest Service) or to assess the impacts of climate change (e.g., the U.S. Department of Interior Landscape Conservation Cooperatives and Regional Climate Science Centers). A key component of these programs is the refinement and development of the same process-driven models that will be the focus of research in ABoVE. Because of the similarity in interests, the opportunity exists to coordinate these modeling activities and the associated research.

Figure 8. The biodiversity of the HNL region is unique and Arctic and boreal ecosystems provide habitat to many migratory species. The Indigenous Peoples that occupy the HNL region are dependent on its natural resources for subsistence.

3. RESEARCH STRATEGY / STUDY DESIGN

ABoVE will consist of activities designed to address the questions associated with each Science Theme. Integrating and synthesizing the research across Science Themes will provide the basis for addressing the three key science questions and objectives identified for ABoVE. The major components of ABoVE will consist of: (a) modeling activities that will (1) address limitations in process-based models that have been developed for the different ABoVE science themes; and (2) link the various process models used in the individual science themes to provide the capability to carry out integrated assessments on the impacts of climate change on Arctic and Boreal ecosystems; (b) an Intensive Study Period that consists of the coordinated remote sensing and field observations, process studies, experiments and modeling activities that are needed to address the Science Theme questions; (c) analysis and synthesis of data collected during the intensive study period campaign as well as from other research and monitoring activities in the pan-Arctic/Boreal region; and (d) assessment of the likely impacts of future climate change on the vulnerability of Arctic and Boreal ecosystems and landscapes at a global scale.

3.1 Overall Approach / Design

The activities conducted as part of this scoping study showed that there is a significant base of ongoing and planned research and monitoring across the Arctic and Boreal regions of North America. These ongoing research and monitoring projects, along with the development of numerous information products derived from satellite remote sensing systems by NASA and others, as well as plans for future airborne and satellite remote sensing systems, were primary considerations in developing the overall approach for ABoVE.

Because of the wide range of existing research as well as databases containing information products derived from remote sensing systems, four critical roles for NASA in sponsoring ABoVE include providing resources for:

a. collecting, compiling, distributing, and analyzing the satellite and airborne remotely-sensed data and information products required for ABoVE,

b. developing and maintaining an information system that provides access to the various data sets and databases that will be used during ABoVE

c. coordinating and synthesizing research from multiple research projects, and

d. conducting field- and model-based research to address key scientific questions not being addressed through research sponsored by other agencies and organizations.

Because of a heavy reliance on information products developed from existing and planned satellite remote sensing systems, the design for ABoVE does not call for intensive field campaigns of the type used during BOREAS (where because of the limited number of satellite remote sensing systems available in the 1990s, airborne platforms were used to collect much of the remote sensing data required to meet the study goals and objectives, and much research was focused on development of new approaches to use remotely-sensed data for modeling). The approach used for BOREAS was to coordinate the collection of airborne data during focused field campaigns. For ABoVE, airborne data will provide important, yet supplementary data to satellite remote sensing data where airborne data acquisitions will be coordinated with ground observations to provide information on key land and atmospheric characteristics and scaling attributes.

Funding provided by NASA for ABoVE will support a number of activities coordinated through a Project Office as well as individual projects that are selected through peer review. The NASA funded, investigator-led projects fall into six categories summarized in Table 2. Each project will encompass a number of different activities, including model development, refinement, validation, integration across multiple spatial and temporal scales, collection and analysis of airborne and spaceborne remotely sensed data, collection and analysis of field data, and analyses and assessments using models (Table 3). The activities for ABoVE will be carried out in three phases over a ten-year period.

During Phase I, a Science Definition Team (SDT) will be formed to: (a) identify knowledge and data gaps that need to be addressed in order to improve models of land surface processes and interactions and feedbacks between the land surface and the atmosphere; (b) review ongoing and planned research, data collection, and assessment activities that are taking place in the ABoVE Study Region that will address these knowledge gaps; and (c) develop a detailed Experiment Plan that: (1) provides for coordination of ongoing and planned activities (see Appendix A); (2) includes a data collection and analysis strategy for NASA-sponsored research that will guide the collection and compilation of the information needed to address the knowledge/data gaps; and (3) presents a framework for assessing the direct and indirect impacts of climate change on HNL ecosystems and landscapes. During Phase I, the ABoVE Project Office will also initiate the design of the ABoVE Information System.

The NASA funded, investigator-led projects will start during Phase II, which will last five and one-half years. These projects will focus on two areas of research. One set of projects will develop, implement and refine the Integrated Modeling Framework (IMF), and use the IMF to assess the impacts of climate change in HNL regions. Phase II will also include a five-year intensive study period where Multidisciplinary Science Projects (MSPs) will be conducted to address key uncertainties and to refine and validate process models. The MSPs will include collection and analysis of field data, collection of airborne remote sensing data, and development and validation of new information products from satellite and airborne remote sensing data (Table 3). The synthesis of these observations and analyses will be used to improve process models associated with the different Science Themes, as well as provide the basis for further modification and refinement of the IMF. The MSPs will be carried out in sites located across Alaska and northwestern Canada (see section 3.2).

Towards the end of Phase II, a synthesis of research being conducted in other HNL regions (outside of the ABoVE Study Region) will be initiated. This Pan Arctic/Boreal assessment will be used to develop the final version of the IMF, which will then be used for assessing the potential impacts of climate change on the ABoVE Study Region based on different scenarios during Phase III.

Table 2. Proposed activities and their timelines for ABoVE. Activities will include those funded through the Project Office, as well as those that are funded through grants from NASA and its collaborators to individual investigators.

		Phase I				**Phase II**											**Phase III**					
Study Year			**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**		**9**		**10**	
Fiscal Year	**FY11**		**FY12**		**FY13**		**FY14**		**FY15**		**FY16**		**FY17**		**FY18**		**FY19**		**FY20**		**FY21**	
A = Oct-Mar, B = Apr-Sep	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
PROJECT OFFICE ACTIVITIES																						
Develop ABoVE Experiment Plan		■	■	■																		
Instrument Installation/Maintenance						■	■	■	■	■	■	■	■	■	■	■	■					
Airborne Remote Sensing Collections								■	■	■	■	■	■	■	■	■	■					
ABoVE Information System				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Support of Working and Coordinating Groups				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
NASA FUNDED INVESTIGATOR LED PROJECTS																						
1. Integrated Modeling Framework v1 (IMFv1)						■	■	■	■	■	■											
2. Integrated Modeling Framework v2 (IMFv2)												■	■	■	■	■	■					
3. Integrated Modeling Framework v3 (IMFv3)																	■	■	■	■	■	■
4. Multidisciplinary Science Projects - 1 (MSP1)								■	■	■	■	■	■									
5. Multidisciplinary Science Projects - 2 (MSP2)												■	■	■	■	■	■					
6. Pan Arctic/Boreal Assessment (PABA)															■	■	■	■	■	■		

Table 3. Summary of different categories of research activities to be conducted by investigators funded by NASA for the different categories of research projects.

	NASA Funded Projects					
Types of Activities by NASA Funded Investigators	**IMFv1**	**IMFv2**	**IMFv3**	**MSP1**	**MSP2**	**PABA**
Model Development, Integration, Refinement	X	X	X			
Compilation/Analysis of Geospatial Data Products	X	X	X	X	X	X
Refinement and Validation of Process Models				X	X	
Collection and Analysis of Field Data				X	X	
Satellite RS Product Development and Validation				X	X	
Airborne RS Product Development and Validation				X	X	
Synthesis of Multi-Scale Observations				X	X	X
Analyses and Assessments using Models	X	X	X			

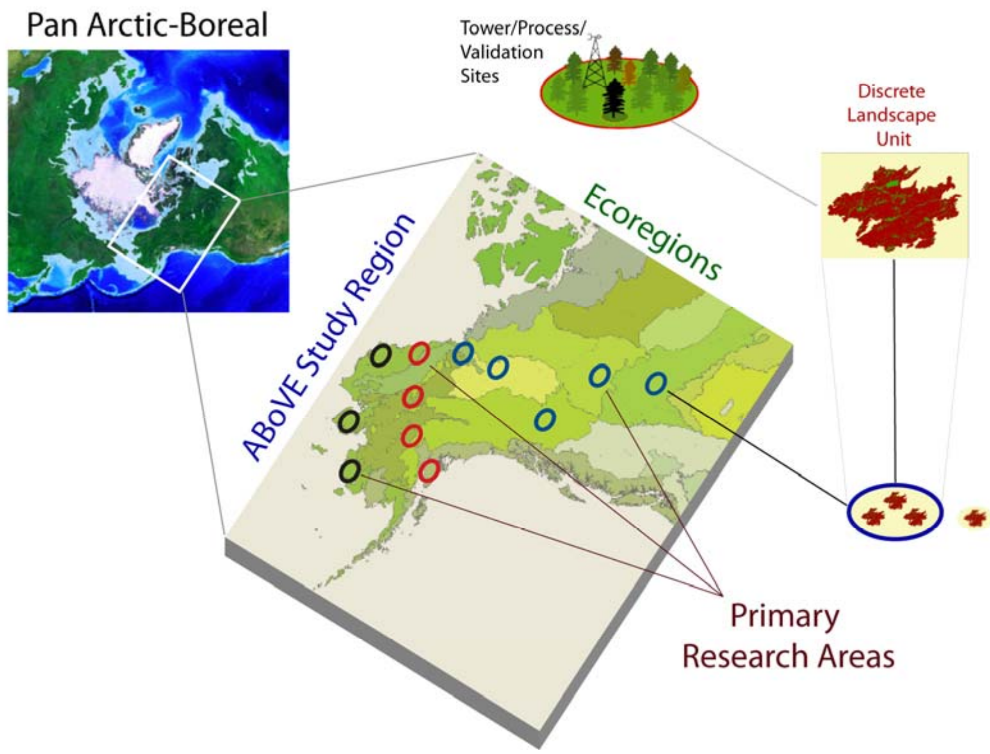
3.2 Candidate Study Sites / Regions

Research will be conducted at six discrete spatial scales during ABoVE – the largest being the pan Arctic-Boreal region and the smallest being individual sites used to conduct experiments, collect data, and make observations needed to address specific knowledge gaps and for development and validation of satellite data products (see Figure 9). The ABoVE Study Region (ASR) roughly covers the Yukon and McKenzie River Basins and the coastal plains of northern and western Alaska. The ASR includes most of mainland Alaska, and in northwestern Canada, the Yukon Territory, the western portion of the Northwest Territories, the northern portion of British Columbia and most of Alberta. It includes 8 Level II and 17 Level III ecoregions (Appendix B). The ecoregions within the ABoVE Study Region (ASR) (Figure 2) are representative of the land-cover types common to the HNL regions, including tundra, boreal forests, peatlands / wetlands, and aquatic systems (including rivers, lakes, and ponds).

More importantly, the ABoVE study region covers a broad climatic gradient in terms of temperature and precipitation, spans a region that contains all major permafrost regimes (from continuous to sporadic: Box 6), includes the major natural disturbances that are common to the HNL region, contains sufficient variation in topography and soil drainage so that significant variations in surface hydrology exist, and contains regions with large soil carbon reservoirs (Box 6). The landscapes included within the ASR provide the opportunity to conduct research on the processes regulating ecosystem dynamics, soil carbon storage, and land-atmosphere feedbacks. This research will require establishing sites that represent the range in the critical factors that control these processes, in particular, gradients in soil temperature (permafrost) and ground moisture and inundation (surface hydrology), as well as variations in the major disturbance regimes, both natural (fire and insects) and anthropogenic (oil, gas and mineral exploration and development). To capture these gradients and variations, the field component of ABoVE will take place in Primary Research Areas (PRAs) and Secondary Research Areas (SRAs) located along three North-South oriented transects (Central, Western, and Eastern). We expect that a PRA will be located in each Level II ecoregion and either a PRA or SRA in each Level III ecoregion in the ABoVE Study Region (Figure 9; Box 6).

The Western Transect is located inland of the Bering Sea, starting on the North Slope and ending on the Yukon-Kuskokwim River Delta. The PRAs along this transect will provide the opportunity to carry out research in four distinct tundra ecoregions (Level III), the transitions between several of these ecoregions, including the shrubland transition between coastal tundra and forested lowlands. The Central Transect again starts on Alaska’s North Slope and crosses interior Alaska and the foothills of the Alaska Range before ending on the Kenai Peninsula. This transect includes two tundra and six forest ecoregions (Level III), and also includes three major wetland/peatland complexes in interior Alaska (the Yukon, Minto, and Tanana Flats). The interior Alaska upland areas provide opportunities to study sub-alpine and alpine tundra in addition to coastal tundra found in the Western transects. The PRA located on the Kenai Peninsula offers a unique setting for the study of interactions between disturbances by insects followed by fire. The Eastern Transect starts in the northern Yukon Territories, contains an east-west dogleg in the southern Yukon and Northwest Territories, and ends in central Alberta. This transect includes one tundra and seven forested ecoregions (Level III) and several major peatland complexes located in the southern Northwest Territories and northern and central Alberta. It offers the opportunity to study transitions between the major biomes, in particular the latitudinal

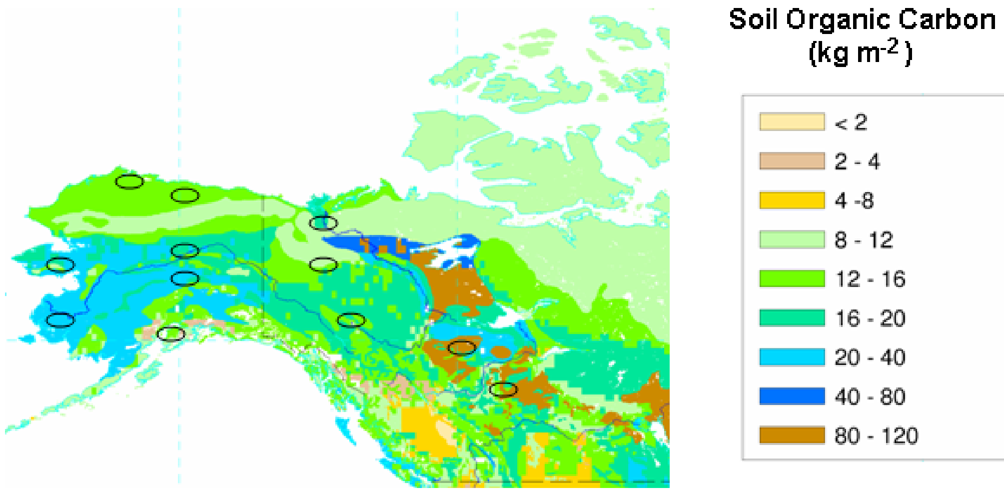
Figure 9. Schematic of relationship of the different spatial scales over which ABoVE research will take place. The Primary Research Areas (PRAs) will be located along three North-South Transects. The PRAs for the Western Transect are black, the PRAs for the Central Transect are red, and the PRAs for the Eastern Transect are blue.



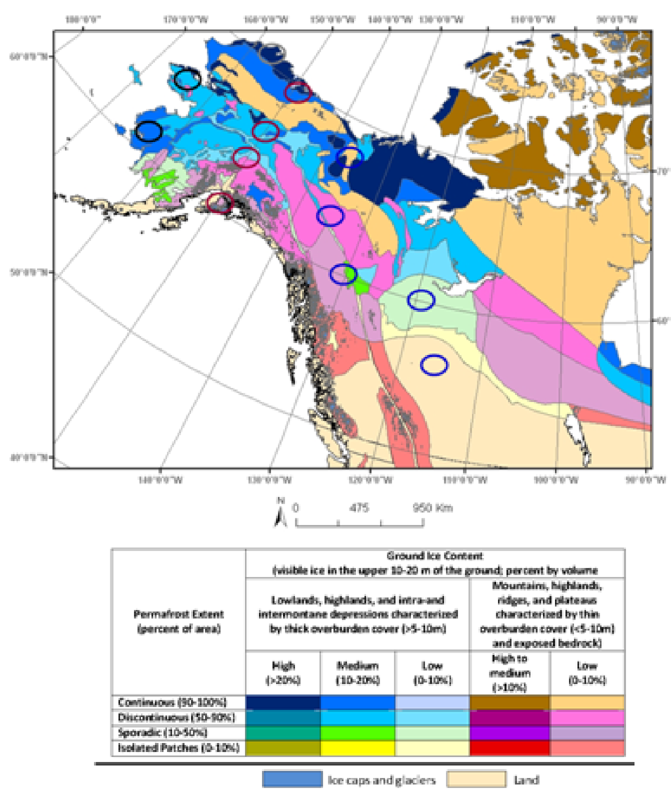
transition between tundra and forest at the northern end of the transect, and the transition associated with the northern most existence of pine forests in the central Yukon Territory.

The ABoVE PRAs (roughly twelve in number: Figure 9) will range in size from several 1,000 km^2 up to 10,000 to 40,000 km^2, depending upon a combination of factors. These include the opportunities to address specific knowledge gaps and the existence of previous or ongoing research activities and infrastructure. The experimental design for ABoVE calls for the same set of measurements, studies, and observations needed for each Science Theme to be collected or carried out in a sufficient number of PRAs and/or SRAs to account for the effects of gradients or variations in forcing processes (e.g., climate, permafrost, surface hydrology, and disturbance). We anticipate that a number of SRAs (the actual number will be determined based on development of the ABoVE Experiment Plan) will be needed to address specific science questions that are more localized (e.g., a specific insect outbreak or anthropogenic disturbance) and are not captured within a PRA). The PRAs and SRAs will provide access to regional landscapes that also include smaller-scale variations in topography and micro-topography which

Box 6 – Soil Carbon and Permafrost Gradients



The ABoVE Study Region not provides the opportunity to study processes in the terrestrial ecosystems common to the HNL region (Figure 9), but also encompasses all major permafrost regimes, which are classified based on percent of the area impacted, soil overburden, and ice content. The ABoVE study region also provides the opportunity to study processes controlling the distribution of the large soil carbon reservoirs that exist in Arctic/Boreal regions.



are important controls on microclimate and soil drainage in Arctic and Boreal ecosystems. These, in turn, provide further gradients in permafrost, surface hydrology and susceptibility to disturbance that regulate localized differences in ecosystem dynamics, soil carbon, and land-atmosphere feedbacks.

Within individual PRAs and SRAs, research will also be carried out in discrete landscape units (DLUs) that represent an individual disturbance event, watershed, or wetland/peatland complex. The DLUs will provide the opportunity to study complex interactions between disturbances and/or variations in vegetation cover, topography, and surface hydrology that occur at landscape scales.

Observations and experiments will be carried out in tower/process/validation sites that range in size from 10 by 10 m to 2 by 2 km^2. Thses sites will be used for ground observations and experiments, including flux towers (including tall towers) and autochambers. The data collected at these local scales will be used to study specific processes and land surface and atmosphere characteristics. The information derived through the analyses of these data will be used to address key knowledge gaps and also provide the basis for validation of new information products derived from remotely-sensed data.

The selection of PRAs, SRAs, DLUs and tower/process/validation sites will take advantage of previous, ongoing, and planned studies and monitoring activities that have been or are being funded by NASA and other federal agencies from Canada, Japan, and the U.S. that sponsor research in HNL regions (see Appendix A). Examples of agencies and programs that have or are sponsoring significant research in the Arctic and Boreal regions of Alaska and western Canada include: from Canada – the Canadian Forest Service and the Natural Sciences and Engineering Research Council of Canada (NSERC); from Japan – the Japanese Aerospace Exploration Agency (JAXA), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and other agencies sponsoring research through the International Arctic Research Center (IARC); and from the U.S. – NASA, NOAA, USFS, DOI, DOE, NPS, DOD, NSF and the North Slope Science Initiative. Reviewing the ongoing research and monitoring activities for the ABoVE Study Region revealed that there were a number of sites where longer-term research has been conducted, including two Long Term Ecological Research (LTER) and NEON sites sponsored by NSF, as well as sites where coordinated research has been conducted by groups of investigators (see Appendix A). These longer-term projects are important because they provide the foundation of continuous observations and research that are needed to address the ABoVE goals and objectives. In addition, a large number of state, provincial, and federal land management agencies, and Indigenous People organizations in Canada and the U.S. have conducted monitoring programs which not only provide information from field-based observations, but have developed or are developing geospatial information products or carrying out monitoring activities that could be used for ABoVE.

Finally, during ABoVE, the selection of specific discrete landscape units and the location for areas to locate process/tower/validation sites will be based upon using information derived from the analysis of remotely-sensed data, including data from aerial photographs and imagery collected by airborne and spaceborne remote sensors.

3.3 Modeling and Integrative Analyses

Modeling will provide the basis for addressing the three overarching science questions and objectives for ABoVE. A number of global-, continental-, and regional-scale models already exist for processes associated with the different Science Themes. To a large degree, however, there have been only limited attempts to link models of the specific processes (e.g., disturbance, ground-thermal dynamics, carbon cycling, ecosystem dynamics, land-surface energy exchange) that interact to regulate the responses of Arctic and Boreal ecosystems to climate change. Because of this, a mechanism to address the ABoVE science questions in an integrated fashion does not yet exist.

To address this shortcoming, one of the first activities of ABoVE will be to create a Modeling Working Group (MWG) (see Section 4.2 below). The MWG will identify areas where models do not adequately describe specific processes, and define the research need to address these deficiencies, thus defining the requirements for the research carried out during the Intensive Study Period by the Multidisciplinary Science Teams. The MWG will also identify the need for generation of specific information products (including those derived from remotely-sensed data) that are needed as model inputs or for model validation. Since the initial membership of the MWG will also be part of the SDT, these requirements and knowledge gaps will be used for the generation of the ABoVE Experiment Plan. We envision that the membership of the MWG will include researchers funded by NASA as well as other agencies, especially those involved with integrated assessment of the impacts of climate change in HNL regions.

In Study Years 3-5, the members of the MWG will develop the initial version of the Integrated Modeling Framework (IMFv1) through funds provided by NASA to link the various process models into an integrated approach that can be used for assessment (Table 2). We do not envision the creation of a single, integrated model that incorporates all the complex interactions that occur. Rather, we envision a process where in most instances, outputs from one model are used to inform or provide inputs for other models. A key component of the IMF will be to develop approaches to propagate uncertainties and provide estimates of accuracy and precision, as well as disaggregate the different sources of input and model error.

Beginning in Study Year 3, activities carried out as part of the NASA-funded Multidisciplinary Science Projects (MSPs) will focus on improving specific process based models associated with the different science themes (Table 2). The MSPs will carry out specific field studies and experiments to address gaps within models, and provide the means for developing approaches to utilize information products from new satellite remote sensing systems that will be launched during ABoVE or from data collected by airborne remote sensing systems. Finally, they will provide the opportunity to further develop and refine approaches to use remote sensing for spatial and temporal extrapolation of limited measurements. The potential exists for the MSPs to include researchers funded by NASA and other participants in ABoVE if suitable arrangements can be made between funding agencies or if collaborative activities can be established.

The synthesis of the results from the interdisciplinary research carried out during the Intensive Study Period will provide the basis for further refinement of the Integrated Modeling Framework during Phase II. The MWG will use the IMF to assess the impacts of climate change on the ABoVE Study Area. This will include refinement of models and model components using the new knowledge gained from ABoVE research during Phase II, and evaluation and validation of new modeling approaches based upon additional remote sensing data products developed during ABoVE. This process will result in IMF v2 as a result of projects funded by NASA (Table 2).

Beginning at the end of Phase II and continuing into Phase III, ABoVE will expand its geographic focus to include ongoing research from other pan-Arctic/Boreal regions. NASA funding for the Pan Arctic/Boreal Assessment (PABA) projects (Table 2) will result in a review and synthesis of research being conducted in other Arctic and Boreal regions, and determine what further modifications need to be made to the IMF. Based upon these syntheses and assessments, further modifications to the IMF will be made during Phase III in order to account for processes that may be different in other regions compared to the ABoVE Study Region. For example, among other things, it will be necessary to make adjustments to the IMF to account for different insects and diseases that are present in other regions as well as different tree and plant species that will require modification of dynamic ecosystem models. These modifications will be funded by NASA and lead to IMF v3. During Phase III, the MWG will conduct an assessment of the impacts of climate warming on the entire pan-Arctic/Boreal region using IMF v3

A final responsibility of the MWG is to insure that all the results from the ABoVE sponsored modeling and assessment activities are provided to the ABoVE Information System (AIS) in a timely-fashion.

3.4 Remote Sensing Observations

ABoVE will carry out a wide range of activities that use remotely-sensed data collected by spaceborne and airborne platforms, including data collected by U.S., Canadian, Japanese, and European platforms and systems. ABoVE research will utilize a large number of time-series, land and atmosphere information products derived from existing moderate-resolution satellite sensors (AVHRR, MODIS, SPOT Vegetation, NSCAT, ASCAT, SSM/I, MOPITT, MISR, etc) (see Table 1, Appendix C). ABoVE will also provide the opportunity to evaluate and validate time-series information products that are planned for satellite-remote sensing systems scheduled for launch over the next few years (NPP/NPOESS-VIIRS, LDCM, OCO-2, GCOM, SMAP, DESDynI, ACE, etc.), and to cross calibrate similar information products that are being developed from different satellite systems. These latter activities are likely to involve collection of airborne remote sensing data to account for sub-pixel mixing that occurs in the data collected by moderate-resolution systems or to account for diurnal variations in the surface signatures that impact the use of the satellite-data products (e.g., surface albedo, temperature).

ABoVE research will also use information products derived from high- and medium-resolution satellite systems (1 to 50 m pixels). These products are needed for studies of processes that occur at finer spatial scales than provided by moderate-resolution systems or that provide more detailed information associated with individual events (e.g., disturbance). Because of orbital considerations, these high and medium-resolution products will be generated as static maps or from selected periods of the growing season. Relatively high-resolution satellite remote sensing data (e.g., IKONOS, Quickbird) will be needed for the study of landscape deformations (such as thermokarst) that result from the warming of permafrost as well as assessing the severity of damage from insects and diseases. Use of archived, fine-resolution photography collected by airborne and spaceborne (e.g., CORONA) platforms will provide the opportunity to monitor changes of key land surface characteristics over longer time periods. The use of fine-resolution airborne and satellite products as well as aerial photographs will also be important for scaling up of field observations with the more medium and moderate resolution satellite products. Where available, ABoVE will exploit suitable land information products generated by land management agencies (e.g., the fire products being developed by the Monitoring Trends in Burn Severity Program).

A third category of satellite-based information products that will be part of ABoVE is emerging or new products. There are a number of land surface characteristics or maps that would be of great value for studies being carried out for ABoVE, but need additional research to identify appropriate methods and data for their generation and validation. Activities providing new land surface characteristics include the consistent mapping of insect and disease outbreaks, fire severity, vegetation structure and biomass, categories of peatlands and wetlands, and monitoring of hydrologic conditions (soil moisture and levels of inundation) in uplands and lowlands.

The final set of remote sensing data that will be used for ABoVE will be collected from airborne platforms. Airborne sensors will collect data that provide the opportunity to study characteristics of the land surface and atmosphere in ways not available from spaceborne systems. In many instances, the airborne remote sensing data will be collected by systems that represent test beds for future spaceborne systems, and provide the opportunity to develop and validate algorithms for new information products that will be generated from future NASA missions. For example, airborne data collected by UAVSAR, LVIS, and AVIRIS could be collected over sites containing forests that are regenerating after disturbances, in order to determine the optimal approach for classifying post-disturbance recovery and estimating biomass, areas of great importance to HyspIRI and DESDynI.

In addition, ABoVE provides an opportunity to incorporate airborne data collection from two Earth Venture-1 Missions recently selected for funding by NASA. The goals for the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) are focused on quantifying fluxes of trace gases from Arctic and Boreal ecosystems and landscapes and understanding the land-surface processes driving variations in these fluxes. The goals for CARVE are directly in line with ABoVE’s Land-Atmosphere Feedbacks Science Theme, and also begin to address several of the research questions being asked in the Permafrost, Surface Hydrology, Disturbance, Ecosystem Dynamics, and Soil Carbon Science Themes. Because the CARVE study areas and transects are all within Alaska, the data collected and analyses performed as part of CARVE would make direct contributions to ABoVE. In addition, the opportunity exists to extend the CARVE airborne remote sensing data collections during ABoVE to collect additional data. The goals for the Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) study also directly relate to the ABoVE goals and research questions, in particular those related to Surface Hydrology and Land-Atmosphere Feedbacks Science Themes. While none of the AirMOSS sites are within the ABoVE Study Region, the tower/process/validations sites used for ABoVE would provide the basis for additional AirMOSS flights during the ABoVE Intensive Study Period, especially over wetland and peatland sites. Discussions with the PIs for both CARVE and AirMOSS indicate they each have a strong interest in participating in ABoVE, especially if additional funds for aircraft operations could be provided to extend the missions time frame (CARVE) or to fly over sites that are outside of the original experiment plan (AirMOSS).

The compilation, collection, and analysis of remotely-sensed data will take place within all research projects funded by ABoVE. These activities will be coordinated by the Remote Sensing Coordinating Group (see section 4.2 below).

3.5 Field Observations, Studies, and Experiments

With respect to field observations, studies, and components, ABoVE will continue and expand upon the approaches used in previous field campaigns. Like BOREAS and LBA, ABoVE will sponsor a range of field-based observations and experiments, including the deployment of a limited number of eddy covariance towers and flux chambers. Like LBA, ABoVE will involve field-based research sponsored by a number of national and international organizations. The level of ongoing, field-based research in Arctic and Boreal regions of North America is substantially greater than was being carried out in the Amazon Region at the time the LBA Precise Science Plan was written. In North America, plans to continue and in many cases expand, field-based research in Arctic and Boreal ecosystems are well underway.

Ongoing and planned field-based research presents both an opportunity and a challenge for ABoVE. The opportunity lies in the fact that ongoing and planned research provides the basis for addressing many of the key process-based questions identified for this study. Without this ongoing and planned research, it would not be feasible to propose the large number of PRAs and SRAs that are part of ABoVE. Simply put, the ongoing and planned research in the Arctic and Boreal regions of North America provide the foundation upon which ABoVE will be built.

The challenges that existing and planned field-based research present to ABoVE include: (a) development of a mechanism that provides for meaningful collaboration and cooperation between ongoing/planned research and that sponsored by ABoVE; and (b) identifying the additional field-based research that needs to be funded through ABoVE. The Field Studies Coordinating Group (FSCG) will serve as key element of the ABoVE Research Strategy/Study Design as a means for meeting these challenges (see section 4.2 below).

ABoVE will include three categories of field observations, studies and experiments: (a) surveys of key land surface and sub-surface characteristics, (b) continuous observations and monitoring, and (c) manipulative and natural experiments. In some cases, the data collected for the first two categories will also be used for the development and validation of information products derived from satellite-remote sensing data. The data from all categories will be used to address key knowledge gaps, test hypotheses, and further develop and validate models.

Systematic surveys will be needed to provide a wide range of data, including: (a) measurements of disturbance severity across the gradients of factors that control severity; (b) observations of ecosystem recovery as a function of disturbance severity and time since disturbance (tree and plant recruitment and growth, soil carbon stocks, soil moisture and temperature, seasonal thaw depths in sites underlain by permafrost, and soil respiration); (c) measurements to document how ecosystem characteristics (soil moisture and temperature, active layer depth, water table, soil carbon, active layer depth) are controlled by key landscape features; (d) measurements of ground ice content in areas with permafrost; (e) measurement of soil carbon; and (f) collection and analysis of paleo data (tree rings and lake bottom sediments) that can be used to study disturbance history as well as understand how vegetation has changed in response to climate variability.

Some observations require collection on a continuous basis. This will require installing and maintaining different types of instruments across a number of sites that capture the key factors and gradients controlling critical land surface characteristics. Surface characteristics that require continuous monitoring include: (a) ground layer temperature as a function of soil depth in areas with permafrost; (b) ground moisture as function of soil depth in all landscape and ecosystem types; (c) water table depth in lakes, wetlands and peatlands; (d) rates of lateral exchanges of water in areas of low relief; (e) fluxes of CO_2, CH_4, other trace gases, water, and energy between the atmosphere and land surface; and (f) the presence/absence of snow, ice and water cover.

Finally, manipulative and natural experiments will be used to provide data to test specific hypotheses on the factors that control critical processes in Arctic and Boreal ecosystems. These experiments typically require the collection of continuous data or data at annual time scales, but only over a time period necessary to test a specific hypothesis. Natural experiments can be used where critical controlling factors vary as a function of a landscape feature (e.g., site drainage variations as a function of topography within a watershed). Manipulative experiments will be used to control and vary critical ecosystem characteristics (e.g., snow depth, organic layer depth, soil moisture, water table depth, soil temperature, etc.). Research involving manipulative studies is already ongoing or planned in Alaska as part of research being sponsored by NSF and DOE and in Canada by NSERC. These experiments include rainfall and snowfall exclusions, water table manipulations in peatlands, modifications to nutrient cycles, and ecosystem and permafrost warming experiments.

3.6 Technical and Logistical Feasibility / Issues

The research being proposed as part of ABoVE does not involve development or deployment of new remote sensing technologies. ABoVE research will utilize existing airborne and space remote sensing systems for the collection of data.

While most of the research for ABoVE would be conducted in locations where field-based studies have previously been carried out there is the probability that some research will be conducted in remote regions located away from road networks requiring more complex logistical arrangements. Because much ongoing research in the ABoVE Study Area does occur in remote locations, there are a number of issues that need to be considered.

There will be challenges in obtaining the amount of instrumentation (e.g., flux towers and chambers, soil temperature and moisture instrumentation) required for ABoVE, and deploying and maintaining this instrumentation in remote locations. In many cases, the deployment and operation of instrumentation in remote locations will require the use of aircraft and boat transport. The operation of this instrumentation requires development of the infrastructure and logistical support needed to provide power, maintain, retrieve data, and repair and when necessary, replace the instrumentation. In some cases, these requirements could be fulfilled through the employment of residents of Indigenous communities who would be able to provide technical support in a timely and cost effective manner. This approach would then create the opportunity to establish linkages with an important user community, as well as provide educational outreach and gain knowledge from this group of users.

If research needs to be conducted on lands owned by Native Corporations or villages, permission will have to be granted. Again, involving members of Indigenous People Communities in the planning and process of conducting the research being carried out by ABoVE would greatly facilitate working in these remote areas. However, involving people from these communities will require that the managers for ABoVE develop a strategy for involvement of Indigenous Peoples that takes their longer-term interests and needs into account (see Section 7 below).

Additional challenges will occur if several ABoVE-funded projects need to carry out field work in remote areas during the intensive study period, especially the systematic surveying of rivers, surface waters, soil carbon and soil ice content. Such research will require the provision of off-road travel support for researchers and arranging for maintaining remote field camps.

While rental vehicles from commercial vendors are available throughout the ABoVE Study Region, in most locations the use of these vehicles is not permitted on the unpaved roads that provide access to the study sites of interest. Arrangements will need to be made for procurement and maintenance of vehicles that are suitable for back-road travel for many of the researchers conducting field work funded through ABoVE.

Many regions in interior and coastal Alaska and northwestern Canada have significant populations of black and brown bears while coastal areas may also support populations of polar bears. Deploying researchers in these may require that personal safety issues be addressed, including the installation of animal exclosures around field camps and instrumentation and carrying of firearms for protection. The carrying of these firearms will require training prior to field operations.

The broad geographic range of the ABoVE Study Region will also present challenges in coordination and collection of airborne remote sensing data. Again, while this is certainly feasible, the necessary permits and authorizations may have to be obtained to allow for the collection of airborne data over military-owned land and in foreign countries (e.g., flying U.S. aircraft in Canada and Canadian aircraft in Alaska). Another logistical issue for flying aircraft in the ASR is the occurrence of large fire events during the summer. These events often result in temporary flight restrictions in airspace over and adjacent to specific fire events.

4. Organization and Management

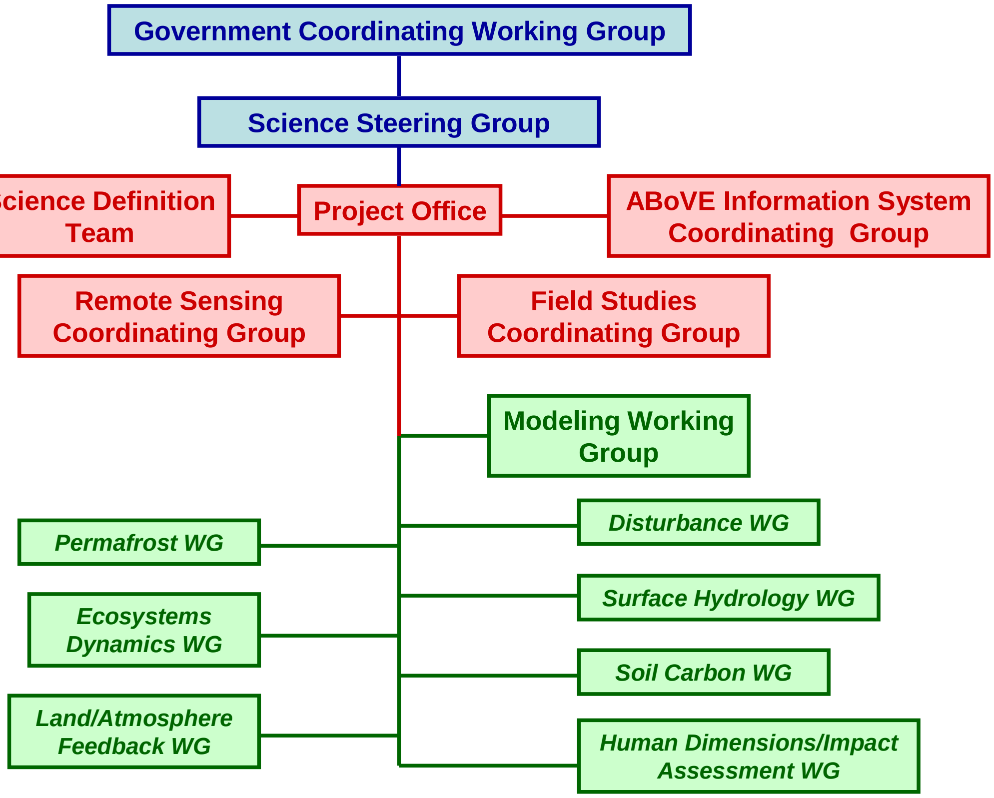
The scientific guidance, management and coordination for ABoVE will be provided through the use of a hierarchical structure that includes three basic functions: (a) program leadership and management, including oversight, planning and coordination (denoted in blue in Figure 10), (b) project coordination and logistical support (denoted in red in Figure 10), and (c) coordinating, planning, conducting, and synthesis of research (denoted in green in Figure 10). This organizational structure will provide the means to organize and manage a long-term project that will require a significant number of partnerships and collaborations, at both a national and international scale, and that also involves cross-disciplinary studies.

4.1 Scientific Leadership

ABoVE will involve several levels of scientific leadership (Figure 10). At the highest level will be a Government Coordinating Working Group (GCWG), which is needed because there is the potential for the involvement of research sponsored by agencies from at least three countries (Canada, Japan, and the U.S.) if the required agreements are negotiated. In addition, there is the potential to form collaborative relationships with a number of U.S. agencies that are conducting research, monitoring and assessment activities (Appendix A). The GCWG will be populated by program managers who are directing and managing research, monitoring, and assessment programs that involve climate change in the HNL region. It will be responsible for providing the guidance to coordinate the research funding that will be necessary to carry out ABoVE, and to provide coordination between funded activities. The GCWG would also provide coordination between ABoVE and major research programs that are coordinated at the national and international scale such as the U.S. Climate Change Research program, the North American Carbon Program, and CarboNA, or activities that are occurring at the state, provincial or territorial level. For example, the Alaska Climate Change Executive Roundtable (ACCER) was created to coordinate the activities of various federal activities that involve research and monitoring of climate change. Including a member of the ACCER on the GCWG would provide the basis for coordination of these activities with those being sponsored by ABoVE at a regional scale. Finally, the GCWG (in consultation with the Project Office and Remote Sensing Coordinating Group [see Section 4.2]) will likely need to negotiate with other international space agencies (ESA, JAXA, CSA) to secure access to satellite remote sensing data that will be used during ABoVE.

Additional oversight and guidance for ABoVE will be provided by an international Science Steering Group (SSG). This group will consist of scientists with expertise in each of the different ABoVE science themes. Based on the level of sponsorship provided to support ABoVE activities (either directly or indirectly through active collaborations), this group will be headed by two or three co-chairs, one from each country whose agencies support the research that is part of ABoVE (e.g., Canada, Japan, and the U.S., see section 5.4 below) The SSG will provide guidance to the GCWG, as well as to the Project Office for conveyance to the various coordinating and working groups that will be part of ABoVE. The SSG will provide oversight for developing the detailed ABoVE Experiment Plan based on the programmatic constraints defined by the GCWG.

Figure 10. Organization of ABoVE Steering, Coordinating, and Working Groups



4.2 Project Organization

Activities for ABoVE will be coordinated and directed by a Project Office sponsored by NASA's Terrestrial Ecology Program (Figure 10). In addition to a Project Manager and an appropriate level of staffing, the Project Office will support a Project Scientist. The Project Office will be responsible for: (a) providing oversight and management of ABoVE research activities and projects being sponsored by NASA's Terrestrial Ecology Program and other NASA program offices; (b) coordinating and providing logistical support for NASA-sponsored field research and airborne remote sensing campaigns; (c) providing logistical support to the ABoVE working and coordinating groups, including support of meetings and workshops; and (d) developing and maintaining of the ABoVE Information System.

An annual ABoVE Science Team meeting will provide the opportunity to coordinate the various activities that are part of this project and to report the results from ABoVE research across all Science Themes. Working groups will be established for each Science Theme (Figure 10). The membership of these working groups will include the principal investigators and researchers sponsored by NASA as well as scientists funded by other organizations who have agreed to participate in ABoVE. Each working group will have a chair or co-chairs and be responsible for the coordination of all research activities for a specific Science Theme. The members of each working group will also nominate participants for the Remote Sensing and Field Studies Coordinating Groups and Modeling Working Group in areas where multidisciplinary research is being planned and carried out. The science working groups will be responsible for synthesizing the results of the ABoVE research and conveying those results that address key knowledge gaps to the Modeling Working Group. Each science working group will hold meetings as needed that occur separately from the annual ABoVE Science Team meeting. Finally, the annual meetings will also provide the opportunities for the convening of breakout groups that will focus on synthesizing the results of interdisciplinary research across science themes.

As discussed previously in Section 3, the MWG will be formed during Phase I of ABoVE. This working group will provide the basis for further integration and synthesis across all science themes. It is expected that the members of this working group will also be members of other working groups; therefore, they will provide the mechanism for coordinating activities between the science working groups and the MWG. Initially the MWG will consist of the principal and co-investigators funded by NASA as part of IMFv1 in Table 2, as well as researchers and managers from collaborating groups who are carrying out integrated assessments of the impacts of climate change in HNL regions. As ABoVE progresses, new members will be added to the MWG as other research activities are funded (IMFv2 and IMFv3, as well as MSP and PABA projects) and other collaborators who are carrying out modeling activities are identified. The MWG will provide the basis for: (a) coordinating with participating land management agencies who are conducting impact assessments; (b) coordinating ABoVE modeling activities with those being carried out for other programs, such as the North American Carbon Program (NACP) and the Carbon North America (CarboNA); (c) creating an Integrated Modeling Framework (IMF) that utilizes remotely-sensed observations of key surface characteristics to allow for assessments of the impacts of climate warming on HNL biomes.

From a planning and logistics standpoint, it will be necessary to coordinate a number of the activities associated with the Intensive Study Period of Phase II and the synthesis and assessment Phase III activities. These include the collection and processing of remote sensing data, the collection, analysis and documentation of field data, and the retrieval of information needed to carry out research for ABoVE as well as archiving data products within the ABoVE Information System (AIS). Each of these activities will be carried out by a separate coordinating group, as discussed below.

The Remote Sensing Coordinating Group (RSCG) will focus on coordinating the airborne and spaceborne remote sensing data products that will either be generated or used by the different ABoVE research projects and working groups, including the MWG. The RSCG will work with the Project Office to coordinate plans for the collection of airborne remote sensing data, focusing on making sure that all user requirements are met during data collection campaigns. They will coordinate satellite remote sensing data collections and take steps to identify what new remote sensing products need to be generated to support ABoVE. The RSCG will coordinate activities with those being conducted as part of Instrument Science team research sponsored by NASA, JAXA, and CCRS. They will work with the ABoVE Information System Coordinating Group to ensure that all remote sensing data sets and information products generated as part of ABoVE are available through the AIS, and identify remote sensing data archives that contain information products that are required for ABoVE.

As part of the planning efforts during Phase I, the Science Definition Team (SDT) (see section 3.1) will identify the remote sensing information products that will be needed for the IMF v1. One of the tasks for the NASA funded IMFv1 activity will be the compilation and generation of these products. Coordination provided by the RSWG will eliminate redundancy which often occurs when different groups may require the same product or when the same or similar products are being generated by different organizations.

The Field Studies Coordinating Group (FSCG) will be responsible for reviewing field-based research activities that are part of ABoVE, and identifying opportunities for coordination and integration of this field research (see Section 4.3 below). The FSCG will identify previous, ongoing, and planned research that is being sponsored by other agencies. The FSCG can take advantage of NSF's Research Coordination Networks (RCNs). For example, two RCNs are directly related to the soil carbon science theme – the PEATNET RCN and the Vulnerability of Permafrost Carbon RCN.

The ABoVE Information System Coordinating Group (AISCG) will provide oversight on activities related to the system needed for archiving and retrieval of data and information products (see Section 4.4 below).

4.3 Field Operations

The field studies that provide the foundation for ABoVE will be quite distributed in nature, and involve research being sponsored by a number of different U.S. and international agencies. Because the criteria for selection of Primary Research Areas is the presence of significant ongoing or planned research, field research activities sponsored directly by ABoVE will be coordinated with these other activities to be able to take advantage of research support infrastructure that already exists.

The Field Studies Coordinating Group (FSCG) will be responsible for planning the integration of ABoVE-sponsored field research with other ongoing research activities. The initial members of the FSCG will be part of the ABoVE Science Steering Group, and will include researchers who have carried out research across the ABoVE study region. As part of the ABoVE SSG, the FSCG will review ongoing and planned studies, help develop the detailed ABoVE Science Plan, and based on this review, identify field research that will be sponsored by NASA. This information can then be used by the ABoVE Project Office to develop logistical support planning for ABoVE, both in terms of procuring, installing, and maintaining equipment, but also for assisting in coordination of field research.

Once ABoVE-sponsored research is initiated, the FSCG will include all researchers sponsored by NASA who are conducting field-based research, as well as researchers sponsored by other agencies who have agreed to participate in ABoVE. At this time, the FSCG will meet on an annual basis to: (a) further plan and coordinate field activities; and (b) review and synthesize the results from field activities. These synthesis activities will occur at a variety of spatial scales, including synthesis of research collected at plot, event, within and across primary/secondary study areas, and within and across ecoregions.

A final responsibility of the FSCG is to insure that all data and information products generated from field-based research and monitoring sponsored by ABoVE are provided to and thus available from the ABoVE Information System in a timely-fashion. In addition, the FSCG will also be responsible for making sure that data sets required for ABoVE that are generated and archived by other research projects have appropriate linkages within the ABoVE Information System so that these data can be obtained.

4.4 Data Management and Sharing

Following previous NASA Terrestrial Ecology field campaigns, the development of a data archive and information system will be a key component of ABoVE. However, as with the other components of this experiment plan, we envision that the ABoVE Information System (AIS) will represent an advance over previous systems.

The AIS will serve multiple roles. It will be the primary archive for all the data collected during the ISP, and provide linkages to data sets archived by others that will be used during during ABoVE. It will also be the archive for all information products, model outputs and research findings produced by researchers that are funded by NASA during ABoVE. Each NASA-funded project will be required to develop a data plan to identify the data and information products that will be collected/produced and include a schedule for providing these products. The AIS will obtain information on the planned and ongoing activities of ABoVE investigators and collaborators, including inventories of the location, timing, and types of data collected. It will also compile inventories of the location and types of data collected by other researchers that are being used by ABoVE investigators and collaborators. The AIS will include a web-based GIS that allows for review of the data within the AIS, including information on previous and ongoing investigations.

The AIS will provide a gateway to other information systems and archives containing data and information products that will be used during ABoVE. Linkages will be made with relevant satellite data product archives developed by and for NASA and other space agencies (e.g. JAXA, CSA, ESA), land-management agency archives that contain information products derived from satellite remote sensing data as well as historical archives of aerial photography, archives containing other geospatial data (e.g., large fire databases, maps of insect outbreaks, archives containing field-observations (such as those maintained by LTER projects), and archives developed by long-term research and monitoring, and assessment projects, including major research initiatives such as the NACP and CarboNA.

An increasingly important role that NASA and other state, provincial, and federal agencies have assumed is the development and implementation of decision support systems. Many of these systems are being designed to incorporate the results from research within a modeling framework in order to provide information to policy makers, land managers, and others who require information in a specific area. The AIS will not only provide the opportunity for NASA to conduct further research on the use of satellite-information products to support decision making, but also provide a critical interface for ABoVE researchers to interact at a variety of levels with scientists and managers in agencies who are responsible for assessing the impacts of climate change in HNL regions, as well as the media and the general public. The Integrated Modeling Framework will provide the basis to create unique information products based upon integrated assessments.

An ABoVE Information System Coordinating Group (AISCG) will be formed to provide the guidance needed to develop the AIS. The AISCG will include representatives from each of the other working and coordinating groups, from national space agencies where satellite information products will be used during ABoVE (including representatives from the appropriate NASA DAACs), and from agencies, projects, and groups (such as Indigenous Peoples of HNL regions) who are likely to use the results from ABoVE. During the design of the AIS, the AISCG will meet with a wide range of users to identify specific information products and methods of information delivery that are needed from the AIS, in particular users from land management agencies and from Indigenous communities. For example, in Alaska, the Alaska Climate Change Executive Roundtable would be the logical point of contact for identification of information products needed by land and wildlife managers in this region.

4.5 Timetable

Assuming a selection based on the two Scoping Studies is made in the spring of 2011, initial planning for ABoVE would commence in the summer of 2011 and continue for 2 years (Table 2). The planning phase would include: (1) a detailed review of ongoing planned research activities within the AboVE Study region and identification of partners (both domestic and foreign); (2) development of the conceptual design for the integrated modeling framework; and (3) identification of the information requirements for the integrated framework. Based on the results of these activities, a detailed experiment plan will be generated. The initial call for proposals that would be funded by NASA would be included in ROSES 2012, which allows for review and selecting the initial set of projects early in FY13, and starting these projects in the second half of FY13. The activities starting in FY13 would focus on modeling. The field studies and analyses, airborne remote sensing, and development and validation of new satellite remote sensing information products would start in FY14, and continue through the beginning of FY19. The final three years of the project would focus on conducting a Pan Arctic/Boreal assessment, ending in FY21.

5. Required Resources

5.1 Field Infrastructure

A great deal of infrastructure that would support ABoVE already exists within ongoing and planned research (see Appendix A). For ABoVE, there will be a need for the deployment and operation of additional field instrumentation based on the recommendations of the FSCG (see section 4.3). Instrumentation that could be procured, installed, and maintained by the Project Office includes: (a) meteorological stations for the collection of basic weather information across each PRA and for the tower/process/validation sites; (b) eddy covariance towers to measure fluxes of CO2, CH4, water, and energy (at least 6 permanent and 4 portable); (c) CO_2 and CH_4 flux autochambers for measurement of ground layer emissions in tundra, peatland, and wetlands for soil carbon land-atmosphere feedback studies, with the ability to collect isotope data; (d) dielectric or similar instrumentation to collect soil moisture data, along with temperature probes in permafrost, peatland/wetland sites, and all sites where ground/soil flux measurements are being collected; (e) water level in selected lake, peatland and wetland sites; and (f) digital cameras to monitor variations in snow and ice cover and water inundation.

There will be a need to deploy scientists and instruments in remote areas. As noted in Section 3, the location of the PRAs should take advantage of ongoing research because in many cases this research has already developed considerable support infrastructure, and arrangements could be made to coordinate this research with ABoVE, and for researchers sponsored by ABoVE to use or add to existing infrastructure and support mechanisms (such as the field camp funded by NSF for the Arctic LTER). In some cases, ABoVE will have to mount short (2 to 4 week long) remote field campaigns that require transportation either by riverboat or aircraft to gain access to sites needed to address critical knowledge gaps. Because of the coordination that is required, it is recommended that the cost for these field projects be paid by the Project Office and not by individual investigators.

We expect that ABoVE will have to coordinate the installation, maintenance, and repair of field instrumentation. Many of these activities would likely be coordinated with the researchers at established sites (e.g., the Arctic (Toolik Lake) and Bonanza Creek LTER sites), with researchers at local universities (e.g., the University of Alaska – Fairbanks, the University of Alberta through its Meanook Biological Research Station, and the Yukon College in Whitehorse), or with collaborators located in Indigenous communities.

5.2 Suborbital Platforms and Sensors

ABoVE will utilize a wide range of airborne platforms and remote sensing systems, many of which are summarized in Table C1 in Appendix C. ABoVE will take advantage of the CARVE Earth Venture-1 mission (2011 to 2015), and it is logical to plan for additional measurements by this mission's airborne platform to be collected beyond the 5 years planned for this study. In addition, the AirMOSS Earth Venture-1 mission airborne system would also provide valuable data on surface soil moisture in the tundra, wetland, and peatland ecosystems being studied by ABoVE; therefore, it is also a likely sensor for use in ABoVE. Other airborne instrumentation that would likely receive extensive use during ABoVE include: airborne lidars for monitoring thermokarst; airborne lidar, SAR, and hyperspectral remote sensors for monitoring the impacts of disturbance and recovery from disturbances; and airborne hyperspectral data for mapping of peatlands and wetlands.

5.3 Satellite Data Availability, Access, and/or Purchase

The wide range of satellite remote sensing systems that would provide data for use in ABoVE are summarized in Table C2 in Appendix C. While data from most of the U.S. systems and many of the foreign satellites would be available at no cost to ABoVE researchers, some data would have to be purchased or arrangements made. Purchases would have to be made of high-resolution commercial satellite data such as from IKONOS and Quickbird. Arrangements would have to be made to obtain or purchase data from remote sensing systems operated by the Canadian Space Agency and European Space Agency (e.g., ASCAT, Radarsat). Arrangements would also have to be made with JAXA to gain access to data from Japanese satellite remotes sensing systems (e.g., PALSAR, GCOM, GOSAT, etc.).

5.4 International and Other Agreements

We anticipate that research for ABoVE will be conducted by researchers from Canada, Japan, and the U.S. It will most likely be necessary and desirable for NASA to enter into some sort of arrangement with the appropriate agencies in these countries to formalize the participation in ABoVE.

The research for ABoVE will be carried out on lands managed by agencies at variety of governmental levels (state, provincial, territorial and national), where each agency has its own rules and regulations regarding the conducting of research. In addition, lands owned by Indigenous Peoples in Alaska are managed by Native Corporations. In many instances, permission will have to be granted from the appropriate managing organization to carry out specific research activities. Recently, USGS has developed cooperative arrangements with members of Indigenous People communities for the collection of scientific data that are being made available to a wide range of users. ABoVE should investigate similar arrangements to engage these communities in data collections.

5.5 Training and Education

ABoVE will provide a wide range of opportunities for education and training. The research projects supported by NASA typically fund graduate as well as undergraduate students and post-docs, and we expect this tradition to continue during ABoVE. Funding for five post-docs independent of PI-funded projects has been identified for ABoVE (see section 5.6). There will be opportunities for graduate students to develop their own independent (from their advisor's projects) research through NASA's Earth and Space Science Fellowship program. Further involvement of undergraduate students is likely to occur via collaborations with the numerous projects funded by NSF through a number of different program areas Programs. NSF funds research through their Research Experience for Undergraduates (REU) program, and we expect that this program will continue to provide support during ABoVE. For the past 6 years, the University of Alaska has developed an active outreach program to K-12 educators through the GLOBE program, and has had a variety of K-12 educational outreach projects funded by NSF. These projects provide the foundation for coordination of K-12 education during ABoVE via activities sponsored by NASA's Office of Education.

A unique opportunity for ABoVE will be interactions with the Indigenous People's communities located in both Canada and Alaska. The opportunity exists to directly involve the members of these communities in several ways. First, Indigenous peoples have significant and vast experiences based on living in Arctic and Boreal regions, and in many instances, are becoming actively involved in documenting changes that are occurring to the environment, ecosystems, and wildlife in the HNL regions. Thus, efforts will be made to engage this community in ABoVE. Second, residents of Native communities are likely candidates to aid in the collection of data in remote regions, as well as monitoring and maintaining instrumentation deployed in remote regions. There is already a significant degree of involvement of Indigenous Peoples in environmental monitoring in the ABoVE Study Region. For example, the Yukon River Inter-Tribal Watershed Council has established a program to monitor water quality and active layer thickness throughout the Yukon River Basin that involves training local technicians on the protocols for scientific data collection. Thus, ABoVE offers the opportunity for further scientific training within Native communities. Indigenous Peoples have first-hand experience and a keen interest in how climate change is impacting their environment. Outreach activities specifically designed to inform Indigenous communities of the results of ABoVE will be developed. These include employing students from Indigenous communities as undergraduate and graduate research assistants.

5.6 Cost Estimates

A budget on the order of $133 million (M) (FY 2011 dollars) is proposed to support ABoVE (Table 4). This budget would cover activities between FY2012 and FY 2021. The key elements of this budget would support the following activities:

The **Project Management** category in Table 4 includes support for experiment planning during Phase I (Table 2). In addition to the Project Scientist and Project Manager, funding provided through the project office is needed for the Science Definition Team (approximately 12 members) who would be intensively engaged in experiment planning. The Project Office would employ individuals to provide support to the Modeling Working Group, the three Coordinating Groups (Remote Sensing, Field Studies, and ABoVE Information System). Additional support would be required to maintain the ABoVE Information System, to provide administrative and grant support, and to maintain a project website. Finally, support would be provided to organize and conduct annual meetings for ABoVE as well meetings of the Government Coordination Working Group and the Science Steering Group. The funds for supporting travel to the annual meeting and to working group meetings by individual investigators would come from two sources. Individuals whose research is being directly funded through a grant from NASA would be expected to use these funds to travel to meetings. The project would provide funds to individuals who are actively participating in ABoVE, but whose funds are not adequate to travel to meetings. This latter category would include researchers and managers working for land management agencies.

The **Logistics** category in Table 4 includes costs for the Intensive Study Period that would be funded through the Project Office, but would directly support research by individual PIs or groups of PIs. The costs in this category would support purchase, installation, maintenance, and repair of equipment required to obtain key observations, deployment and operation of airborne remote sensors, direct purchase of satellite data, and to provide logistical support for research being conducted in remote sites, including providing transportation and operation of field camps.

The **Science Support** category in Table 4 includes funds that would support peer-reviewed research being conducted by individuals or small groups. The cost estimates are based on the funding of 88 different projects that would be carried out over three-year periods (Table

2). Nearly two-thirds of these would be multi-investigator, Multidisciplinary Science Projects. Support would also be provided to an average of five post doctoral researchers each year beginning in year 3, with two of the post docs beginning in year 2 to support the IMF activities. These post docs would work with the various working and coordinating groups, and focus on carrying out syntheses across multiple projects. Two of these post-docs would be assigned to the MWG to provide support in development of the suite of geospatial data products that are needed for the IMF activities.

While the total budget for ABoVE is projected at $133 M, we expect that at least one-fifth of these costs will be covered by other agencies (both national and international) who will participate in ABoVE, reducing the costs to NASA to about $107 M. While some of these shared costs will be in the Logistics category, most are in the Science Support category. We project that some of the costs associated with the Integrated Modeling Framework will be jointly-funded by agencies who are conducting integrated assessments on the impacts of climate change in HNL regions. The basis for the estimate of $25 M in shared costs for multidisciplinary science is the existence of a number of study sites and study areas located across the ABoVE Study Region where long-term research on climate change and its impacts have taken place, and where studies are being planned that will take place over the next decade, as well as the high level of funding being provided by NSF and NSERC. These sites/areas include the Bonanza Creek and Arctic (Toolik Lake) (LTER) sites, research on coastal tundra in Barrow and the Seward Peninsula, and hydrological studies at the Caribou-Poker Creek and Kuparik River watersheds.

Table 4. Estimated Costs for ABoVE (these costs cover 10 years, are in millions of dollars and assume no inflation).

	NASA	**Other Agencies**	**Total**
Project Management	**22.6**		**22.6**
Experiment planning	1.3		1.3
Project Scientist/Manager	4.5		4.5
Project Office Support Personnel	12.1		12.1
Meetings logistics	3.1		3.1
Meeting travel support (non-NASA investigators)	1.6		1.6
Logistics	**29.6**	**2.0**	**31.6**
Instrumentation purchases	5.0	1.0	6.0
Instrument installation/maintenance	1.8	0.5	2.3
Airborne Remote Sensing	20.0		20.0
Satellite data purchase	0.8		0.8
Field logisitc - remote sites	2.0	0.5	2.5
Science Support	**54.7**	**24.0**	**78.7**
Project Post Docs	5.3		5.3
Integrated Modeling Framework	12.3	4.0	16.3
Multidisciplinary Science Projects	35.3	20.0	55.3
Pan Arctic-Boreal Assessment	1.8		1.8
Total Costs	**106.9**	**26.0**	**132.9**

The Bonanza Creek LTER (BCLTER) project provides an example of the level of funding associated with long-term research that is ongoing in the ABoVE Study Region. Over the past six years, this project has been funded at ~$1 million per year, and will receive a similar level of funding during its next phase (2011 to 2016). A survey of LTER affiliated researchers was recently carried out to identify other funded research that was related to BCLTER research themes. This survey found that during the current BCLTER funding cycle (2005 to 2010), 27 BCLTER investigators were the PIs to 99 additional research projects that totaled $6.1 million in funding per year. This included funding of $4.3 M per year from NSF, $0.6 M per year from NASA, $0.5 M per year from DOI (including USGS, FWS, and NPS), $0.4 M per year from USDA (including the USFS and the Joint Fire Science Program), and $0.1 M per year from other federal agencies. The $6 M per year being provided by NSF to directly support the two LTERs plus the affiliated research discussed above is a small portion of the annual NSF budget supporting research in Alaska and western Canada. A search of its funded research project database showed that NSF funded 216 projects in this region over the past year (see Appendix A), with an average funding level of $250 K per year per project. This averages out to over $50 M per year in NSF-funded research in the ABoVE region over the past year (assuming each project has a three year length).

Based on this level of funding and the growing realization of researchers on the necessity of using remotely-sensed data to address key knowledge gaps and as the basis for monitoring and modeling key processes, we feel that there will be a strong ground-swell within the Arctic and Boreal research communities to participate in ABoVE. There are a number of research projects affiliated with both the Bonanza Creek and Arctic LTERs that involve research using satellite remote sensing data, and in many cases, parts of these projects have been funded by NASA. The PIs for both of these LTERs are actively seeking collaboration with NASA-sponsored researchers or those from other agencies who have strong remote sensing backgrounds. The PIs for both Alaskan LTERs as well as researchers involved in other NSF research have endorsed the premise behind ABoVE, e.g., the conducting of collaborative research that is funded by multiple agencies. Thus, if ABoVE provides the structure to coordinate research activities plus a modest level of funding for non-NASA investigators to attend meetings, then it is likely that activities funded by NASA could be closely coordinated with those being funded by other agencies, reducing the overall level of funding need to support the Interdisciplinary Science Projects.

6. Summary of Broad Research Community Involvement and Interests

Since the spring of 2009, discussions have taken place between the investigators of this scoping study and researchers and land managers in the ABoVE Study Region, as well as program managers from U.S. agencies that are sponsoring HNL research. These discussions focused on the proposed field campaign and research and modeling activities that would be organized and coordinated as part of ABoVE. Additional discussions took place at the August 2009 workshop on ABoVE that was held at the University of Alaska – Fairbanks, during presentations that were made at scientific meetings, and at presentations that were organized to discuss ABoVE with land management agencies. The 64 participants in the August 2009 workshop are presented in Appendix D. These discussions, along with the large number of ongoing research, monitoring and assessment programs and projects in Alaska and western Canada (see Appendix A), provide evidence that ABoVE would receive strong support from a broad segment of the scientific and land management communities in the U.S., Canada, and Japan. The draft of the ABoVE Science Plan was distributed to over 400 people and comments received from over 60 scientists, managers, and others who have interests in High Northern Latitude ecosystems and landscapes (see Appendix D), with the vast majority supporting the need for the research and monitoring activities that would be carried out as part of ABoVE.

While ABoVE will be sponsored by NASA's Terrestrial Ecology Program, the scientific questions and issues being addressed will be of interest to a number of other program areas within NASA, and provide the opportunity for collaborations with these programs. These include the Hydrological Sciences Program, the Biodiversity and Ecological Forecasting Program, the Biological Oceanography Program (in terms of linking the impacts of land processes on coastal oceans), the Land Use/Land Cover Change Program, and the Applied Sciences Program. In addition, the research being conducted as part of ABoVE provides an opportunity for collaboration with NASA researchers who are part of mission and instrument teams such as SMAP, OCO-2, and DESDynI. ABoVE will utilize satellite remote sensing data and information products not only from systems deployed by NASA and NOAA, but from systems deployed by the space agencies of Canada, Japan, and the European Union. Researchers in Canada and Japan are heavily involved in research directed towards developing information products derived from satellite data for monitoring Boreal and Arctic regions, and are therefore likely participants in ABoVE. Japan, in particular, has made significant investments in research in HNL regions via support of activities at the International Arctic Research Center (IARC) at the University of Alaska – Fairbanks. With the launching of new remote sensing systems scheduled throughout the 2000s, the Japan Aerospace Exploration Agency (JAXA) is likely to have a strong interest in cooperating with projects being sponsored by ABoVE.

Within the U.S., NSF, USFS, NOAA and DOI have sponsored long-term research projects on the North Slope and in interior Alaska, and are currently committed to sponsoring and expanding research in this region. Many of the projects funded through these agencies can be viewed as long-term observatories that can be used to assess the impacts of climate change. For example, NOAA has maintained a continuous record of atmospheric greenhouse gas concentrations from data collected at Barrow, Alaska and has interest in research that can identify the terrestrial controls these gasses. Over the longer-term, NSF's Polar Program and NOAA have sponsored PI-based research on terrestrial processes and are likely to continue to do so over the next decade. Discussions with program management in the NSF Polar Program indicated they would be very open to discussions with NASA on coordinating research with

ABoVE. DOE's Office of Biological and Environmental Research (BER) is planning to conduct a major field experiment on the impacts of climate warming on permafrost ecosystems in Alaska that will last a decade. Discussions with program and project managers in BER again indicated they are very enthusiastic about the opportunity to coordinate their research projects with those being sponsored by ABoVE. Finally, through its Carbon Cycle Science and Terrestrial Ecosystems Programs, NASA has funded an increasing number of investigators to carry out research in the ABoVE Study Area, and this research is likely to expand with the launch of SMAP, which has a strong HNL focus.

Researchers and land managers within a number of U.S. federal agencies are likely to participate or contribute significantly to ABoVE. Critical databases to be used during ABoVE would be provided from monitoring activities conducted by these agencies, in particular monitoring and mapping of fire and insect outbreaks. Scientists in land management agencies who are conducting research on the impacts of climate change on ecosystems have indicated they have a strong interest in coordinating research with projects being funded by ABoVE. For example, the USGS recently initiated a multi-year study of the impacts of climate change on surface hydrology in the Yukon River Basin. Several other federal agencies (DOI, FWS) and the State of Alaska have initiated efforts to develop the integrated modeling frameworks needed to understand the impacts of climate change on boreal and arctic ecosystems.

A number of federal and provincial agencies in Canada are sponsoring activities that would provide collaboration opportunities for ABoVE. At the federal level, a significant amount of research funded through the National Sciences and Engineering Research Council of Canada (NSERC) would provide an opportunity for collaborative research with ABoVE. The Canadian Forest Service (CFS) sponsors research in its different laboratories that is focused on the impacts of disturbance and climate change on forests, addressing the same questions that have been identified by ABoVE. At the state, provincial and territorial levels, land management agencies are responsible for compiling data on the locations and impacts of disturbance, and are responsible for developing and implementing policies addressing the impacts of disturbances and climate change. These mandates provide strong incentives for participating at some level in the ABoVE. In addition to sponsoring research on developing remote sensing information products through JAXA, other Japanese agencies are funding field-based research in Alaska through IARC, and future research would logically cooperate with that being sponsored by ABoVE.

Finally, Indigenous Peoples occupy and manage a significant portion of the HNL regions of Alaska and Canada. Indigenous Peoples communities rely to a large extent on subsistence practices where a wide range of goods and services are derived from hunting and harvesting. Indigenous Peoples have a vested interest in understanding how climate change has and will impact the natural resources upon which their lifestyles depend on. Because of their dependence on natural systems, the short and long-term observations made by Indigenous Peoples as well as their understanding of the Arctic/Boreal environment are extensive and represent a knowledge source that would be of great benefit to ABoVE. The Yukon River Inter-Tribal Watershed Council has recently initiated cooperative programs with USGS to collect data on water quality and active layer depth at sites throughout the Yukon River Basin, providing evidence of the interest of Indigenous communities in participating in monitoring and assessment activities. For all these reasons, Indigenous Peoples represent an important participant in ABoVE.

7. Issues to be Resolved

There are several issues that would have to be resolved prior to proceeding with ABoVE. First, discussions will have to be held at the inter-agency level of the federal government (U.S.) to determine how ABoVE fits within the overall framework of the U.S. Global Change Research Program, as well as the missions and programs of individual. These discussions need to determine how the research being funded by NASA through ABoVE can be coordinated with research being funded by other agencies, in particular research sponsored by NSF Polar Programs, DOE BER, and USGS. Second, discussions will have to be held with the appropriate representatives of Canadian and Japanese research agencies to develop agreements that will ultimately define the scope of ABoVE, determine the level of support that would be provided to ABoVE (both directly and indirectly through cooperative arrangements). These discussions should also focus on establishing the programmatic and scientific oversight structures for ABoVE. In particular, these discussions should also focus on how ABoVE compliments or intersects with other major initiatives (such as NACP and CarboNA), on monitoring, research, and climate impact assessment programs focused on HNL regions, and on other program areas within NASA.

Meetings should be held with representatives of the Canadian and Japanese space agencies to determine the level of interest in supporting research for the development of new products or the generation of products from satellite remote sensing data that would be used during ABoVE. These discussions should not only focus on existing satellite remote sensing systems, but those that will be launched during the 2010s. In addition, these discussions should determine the availability and planned use for airborne remote sensing systems during ABoVE.

A unique component of the Arctic and Boreal regions of North America is the presence of a large number of communities primarily populated by Indigenous Peoples. As discussed throughout this report, these communities use the natural resources for a variety of subsistence uses, and have developed a unique knowledge base on the environment in which they live. However, special attention needs to be paid to development of communication between Indigenous communities and Western cultures (including scientists sponsored by ABoVE). This will require developing a strategy to engage the leaders of Indigenous communities in identifying opportunities for providing a wide range of logistical support to ABoVE, and to create opportunities for communication between community members and ABoVE researchers who are carrying out studies in sites located near communities.

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Box 1: Photographs - Upper left: Michelle Mack; upper right: Michelle Mack; center: Michelle Mack; lower left: Eric Kasischke. lower panel: Carolyn Harf

Box 2: Images: John Lucotch; Photographs – left center and lower center: Lucas Jones; right center: E.H. Hogg.

Box 3: Image: Scott Goetz. Photographs – upper right: Michelle Mack; left center: Scott Goetz; center right: Mike Michaelson; lower right: CMMP, Colorado State University

Box 4: Soil map: U.S.D.A. Photographs: (b) Andres Baron; (c) Jill Johnstone; (d) Caitlan Hicks; (e) Edward Schuur

Box 5: CARVE Flight Lines: Charles Miller. MODIS imagery: Tatiana Loboda and Mark Carroll; Photographs – upper: Eugenie Euskirchen; center: Eric Kasischke; lower: Scott Goetz .

Box 6: Top: U.S.D.A; bottom: National Snow and Ice Data Center, map based on Brown, J., O.J. Ferrians, Jr., J.A. Heginbottom, and E.S. Melnikov, eds. 1997. Circum-Arctic map of permafrost and ground-ice conditions. Washington, DC: U.S. Geological Survey in Cooperation with the Circum-Pacific Council for Energy and Mineral Resources. Circum-Pacific Map Series CP-45, scale 1:10,000,000, 1 sheet.

Figure 1: Scott Goetz, Eric Kasischke, John Kimball and Michelle Mack

Figure 2: Andres Baron

Figure 3: Guido Grosse

Figure 4: Bill Quinton

Figure 5: Scott Goetz

Figure 6: Eric Kasischke

Figure 7: Left: Guido Gross; right: Charles Tarnocai

Figure 8: Left: Mike Loranty; right: Roberts French

Figure 9: Elizabeth Nelson

Figure 10: Eric Kasischke

List of Acronyms

Acronym	Meaning
AAFC	Agriculture and Agri-Food Canada
ABoVE	Arctic Boreal Vulnerability Experiment
ACE	Advanced Composition Explorer
ACCER	Alaska Climate Change Executive Roundtable
AirMOSS	Airborne Microwave Observatory of Subcanopy and Subsurface
AIRS	Atmospheric Infrared Sounder
AIS	ABoVE Information System
AISCG	ABoVE Information System Coordinating Group
AMSR	Advanced Microwave Scanning Radiometer
ASR	ABoVE Study Region
ASCAT	Advanced Scatterometer
ASSG	ABoVE Science Steering Group
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BCLTER	Bonanza Creek Long Term Ecological Research
BER	DOE Office of Biological and Environmental Research
BOREAS	Boreal Ecosystem-Atmosphere Study
BRDF	Bidirectional Reflectance Distribution Function
CarboNA	Carbon North America
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
CCRS	Canadian Center for Remote Sensing
CERES	Clouds and the Earth's Radiant Energy System
CFS	Canadian Forest Service
CSA	Canadian Space Agency
DAAC	Distributed Active Archive Center
DESDynI	Deformation, Ecosystem Structure and Dynamics of Ice
DLR	German Space Agency
DLU	Discrete Landscape Unit
DOC	Dissolved Organic Carbon
DOE	Department of Energy
DOI	Department of the Interior
ENVISAT	Environmental Satellite
ERS	Earth Resources Satellite
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper
FIFE	First ISLSCP Field Experiment
FSCG	Field Studies Coordinating Group
FWS	US Fish and Wildlife

GAC	Global Area Coverage
GCOM	Global Change Observation Mission
GCWG	Government Coordinating Working Group
GOSAT	Greenhouse gases Observing SATellite
HNL	High Northern Latitude
HyspIRI	Hysperspectral Infrared Imager
IARC	International Arctic Researh Center
IMF	Integrated Modeling Framework
ISLSCP	International Satellite Land Surface Climatology Project
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JAXA	Japan Aerospace Exploration Agency
LAC	Local Area Coverage
Landsat TM	Landsat Thematic Mapper
Landsat ETM	Landsat Enhanced Thematic Mapper
LBA	Large Scale Biosphere Atmosphere
LCC	Landscape Conservation Cooperative
LDCM	Landsat Data Continuity Mission
LIDAR	Light Detection and Ranging
LTER	Long Term Ecological Research
LVIS	Laser Vegetation Imaging Sensor
MISR	Multiangle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements Of Pollution In The Troposphere
MSP	Multidisciplinary Science Project
MWG	Modeling Working Group
NACP	North America Carbon Program
NEP	Net Ecosystem Productivity
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	Net Primary Productivity
NPP/NPOESS	NPOESS Preparatory Project
NPS	National Park Service
NSCAT	NASA Scatterometer
NSERC	Natural Sciences and Engineering Research Council of Canada
NSF	National Science Foundation
NSSI	North Slope Science Initiative
OCO	Orbiting Carbon Observatory
PABA	Pan Arctic/Boreal Assessment
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PRA	Primary Research Area
RCN	Research Coordinating Network
RSCG	Remote Sensing Coordinating Group
SAR	Synthetic-Aperture Radar

SCHIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SDT	Science Definition Team
SMAP	Soil Moisture Active and Passive
SPOT	Systeme Pour l'Observation de la Terre
SRA	Secondary Research Area
SSG	Science Steering Group
SSM/I	Special Sensor Microwave/Imager
TM	Thematic Mapper
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar
USDA	US Department of Agriculture
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VIIRS	Visible/Infrared Imager/Radiometer Suite

Appendix A – Planned and ongoing research and monitoring projects and programs in northwestern North America that could contribute to ABoVE

Project/Program	**Project/Program Type[1]**	**Sponsor**	**Years**
North American Carbon Program	R,L	Multiple Agencies	2003-present
CarboNA Program	R,L	Multiple Agencies	2009-present
NSF (all projects in Alaska and western Canada - 239 projects (215 in the Arctic and 24 in the Boreal)	R	NSF	Currently funded
NSF - Office of Polar Programs (180 projects)	R	NSF	Currently funded
NSF - Biological Sciences (26 projects)	R	NSF	Currently funded
NSF - Geosciences (24 projects)	R	NSF	Currently funded
NASA Earth Science Projects (average of new 10 projects funded per year)	R	NASA	2003-present
Bonanza Creek LTER	R,L	NSF/USFS	1987-2016
Arctic LTER (Toolik Lake)	R,L	NSF	1987-2016
Permafrost Warming Study	R,L	Dept. of Energy	2010-20??
Alaska Peatland Experiment	R	NSF	2005-2012
NSERC Projects	R	NSERC	
Mackenzie GEWEX Study	R	NSERC	1995-present
Hydrology, Ecology and Disturbance (HEAD) Project	R	NSERC	2000-2005
Churchill Northern Study Center Research	R	NSERC	1990-present
IP3 – Improved Processes and Parameterization for Prediction in Cold Regions	R	NSERC	2006-present
Peatland Ecology and Development Database	R	NSERC	1970-1990
Peat Task Force Study	R	NSERC	1990-2000

Key: A: assessment project or program; L - longer-term, continuing program or Project likely to continue during ABoVE; M: monitoring project or program; R: Research project or program

Impacts of Climate Change on DOD Facilities in Alaska (3 projects funded)	R	Strategic Environmental Research and Development Program (SERDP)	2010-2014
Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE)	R	NASA Earth Venture Mission	2010-2014
Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) Project	R	NASA Earth Venture Mission	2010-2014
Tree Ring Analysis Studies	R,L	Univ. of Alaska, Univ. of Regina, Univ. of Western Ontaria	2001-present
Fire and Insect Disturbances in Alaska	R	Japanese Aerospace Exploration Agency	2005-2010
Korean Arctic Multidisciplinary Program: Research on the Arctic Climate Change and Environmental Change	R	Korea Polar Research Institute	2008-201?
Delta Alaska Fire Chronosequence Study	R,L	NASA, NSF, USGS	1996-present
Kuparuk River Watershed Study (UAF Water Resources Institute)	R,L	NSF, Others	1993-present
Post-fire recovery in Alaskan black spruce forests burned in 2003 and 2004	R,L	Joint Fire Science Program, NASA, USGS	2004-present
Barrow Tundra Studies	R,L	NSF, DOE	1982-present
Human and Climate Impacts on Mackenzie River Peatlands	R	CFS, Canada IPY Program	2009-present
Carbon Source-Sink Relationships in forests and Peatlands of the Mackenzie River Valley	R	CFS, Canada IPY Program	2007-present
USGS Climate Effects Network (CEN), Yukon River Basin (YRB) Node	R	USGS	2009-2013
Scotty Creek Permafrost Degradation Studies (Southern NWT)	R,L	Univ. of Calgary, Wilfrid Laurier Univ.	1999-present
Central Alberta Peatland Studies	R,L	NSERC, NSF, NASA	1992-present
Permafrost and hydrology linkages in the Yukon Flats	R	DOD SERDP, USGS, USACE	2009-2012

Canadian Carbon Program (formerly known as the Fluxnet-Canada Research Network), includes Canada Forest Carbon Accounting Program	R,A,L	NSERC, CFS, Environment Canada	2002-present
Canada Forest Carbon Accounting Program	R,A,L	CFS	2002-present
Landscape Conservation Cooperative Program	R,A,L	Department of Interior	2010-201?
Yukon River Basin Project	R,A	USGS	2009-2014
Scenarios for Alaska Planning (SNAP)	A	University of Alaska, State of Alaska	2009-present
Alaska Climate Science Center	A	Dept of Interior	2010-201?
CircumArctic Active Layer Monitoirng Network (CALM)	M,A,L	NSF, others	1991-present
Circumpolar Biodiversity Monitoring Program	M.A	Environment Canada, DOI-FWS	2007-present
CARMA - (Circumarctic Rangifer Monitoring and Assessment) Network	M,A	Canada IPY Program, IASC	2007-present
Alaska Region Inventory and Monitoring Program	M,A,L	DOI-National Park Service	1992-present
Climate Impacts on Productivity and Health of Aspen (CIPHA)	M,A,L	CFS, Environment Canada	1999-present
North Slope Science Initiative	M,A,L	DOI	2005-present
Indigenous Observation Network (Yukon River basin hydrology)	M,A	Yukon River Inter-Tribal Watershed Council, USGS	2006-present
Permafrost Active Layer Monitoring Project	M.A	Yukon River Inter-Tribal Watershed Council, USGS	2010
NEON – 2 long-term and 5 short-term (5 year) sites in Alaska	M,L	NSF	2011 to 2016
Atmospheric Radiation Measurement (ARM) Program	M,L	DOE	2000-2020
Arctic Observatory Network (AON) - currently funds 34 projects	M,L	NSF, NOAA	2007-present
Geographic Information Network of Alaska	M,L	University of Alaska	2001-present
Alaska Statewide Digital Mapping Initiative	M,L	State of Alaska	2007-2013

Air Photo Record System	M,L	Alberta Sustainable Resource Development	1950s-present
Skyline - Yukon aerial photo archive	M,L	Yukon Energy Mines and Resources	1946-present
Rapid Assessment of U.S. Soil Carbon for Climate Change and Conservation Planning	M,L	USDA-NRCS	2009-2011
Alberta Biodiversity Monitoring Program	M,L	Government of Alberta	2007-present
Detecting and Monitoring of Forest Pests	M,L	Government of Alberta, Sustainable Resource Development	1997-present
Northwest Territory Fire Perimeter Maps	M,L	NWT Environment and Natural Resources	1984-present
British Columbia Natural Disturbance Database (Fires and Insects)	M,L	BC Ministry of Forestry	1920-present
Yukon Territory Fire History Atlas	M	Yukon Department of Community Service	1946-present
Yukon Territory Forest Insect Outbreaks	M,L	Yukon Department	2002-present
Canada Large Fire Databases	M,L	CFS	1959-presemt
Alaska Forest Health Protection Program/ Alaska Forest Insect and Disease Surveys	M,L	USFS/ Alaska Department of Natural Resources	1989-present
Alaska Large Fire Database	M,L	Alaska Fire Service/BLM	1950-present
Landsat-TM based fire perimeter data for the years 1984-2010	M,L	MTBS Program	2004-present

Appendix B – Summary of Level II and III Ecoregions within the different transects that will be used during AboVE

Transect	**West**	**Central**	**East**
Level II Ecoregions	2.2 Alaska Tundra 3.1 Alaska Boreal Interior	2.2 Alaska Tundra 2.3 Brooks Range Tundra 3.1 Alaska Boreal Interior 6.1 Boreal Cordillera 7.1 Maritime West Coast Forest	2.3 Brooks Range Tundra 3.1 Alaska Boreal Interior 3.2 Taiga Cordillera 3.3 Taiga Plain 5.4 Boreal Plain 6.1 Boreal Cordillera
Level III Ecoregions	2.2.1 Arctic Coastal Plain 2.2.2 Arctic Foothills 2.2.3 Sub-arctic Coastal Plain 2.2.4 Seward Peninsula 3.1.1 Interior Forested Lowlands and Uplands	2.2.2 Arctic Foothills 2.3.1 Brooks Range Tundra 3.1.1 Interior Forested Lowlands and Uplands 3.1.2 Interior Bottomlands 3.1.3 Yukon Flats 6.1.2 Alaska Range 7.1.3 Cook Inlet 7.1.4 Pacific Coastal Forests	2.3.1 Brooks Range Tundra 3.2.2 Mackenzie and Selwyn Mountains 3.2.3 Peel River and Nahanni Plateaus 3.3.1 Great Bear Plains 5.4.1 Mid-Boreal Uplands and the Wabasca Lowlands 5.4.2 Clear Hills and Western Alberta Upland 6.1.5 Watson Highlands 6.1.5 Yukon-Stikine Highlands/Boreal Mountains and Plateaus

Appendix C – Summary of Airborne and Spaceborne Remote Sensing Systems for ABoVE

Table C1. Airborne & Sub-orbital platforms and sensors likely to be used during ABoVE.

Sensor	Technology	Agency	Utility
EAARL	LIDAR	USGS	topography, vegetation structure, lake and pond bathymetry
UAVSAR	L-band (~1.25 GHz) phased array SAR	NASA	vegetation roughness, biomass, surface moisture & freeze-thaw status
PALS	L-/S-band radar & radiometer, 1.26 GHz & 3.15 GHz Freq.	NASA	vegetation roughness, biomass, surface moisture & freeze-thaw status
AVIRIS	Visible-IR spectrometer, 224 spectral bands	NASA	vegetation type, chemistry & condition
SAR580	X-/C-band SAR, 5.3 GHz & 9.3 GHz Freq.	CCRS	vegetation roughness, biomass, surface moisture & freeze-thaw status
AIRSAR	C-/P-/L-band SAR, 0.45GHz, 5.31GHz, 1.26GHz Freq.	NASA	vegetation roughness, biomass, surface moisture & freeze-thaw status
IFSAR	X-band SAR, 9.55 GHz Freq.	Intermap Technologies	topography
LVIS	Scanning laser altimeter	NASA	vegetation structure, surface and canopy topography
CARVE[1]	L-band radar, radiometer, atmospheric spectrometer	NASA	atmospheric total column CO_2, CH_4, CO, surface T, freeze-thaw, soil moisture
AirMOSS[1]	P-band radar	NASA	Biomass, root zone soil moisture

[1]Earth Venture-1 mission funded by NASA

Table C2. Spaceborne satellite systems likely to be used during ABoVE.

Optical-IR Wavelength Sensors				
Sensor	**Platform(s)**	**Agency**	**Time series**	**Key Sensor Characteristics**
AVHRR	NOAA, METOP	NOAA DMSP, ESA	From 1981	Optical-IR multispectral radiometer, 1-km Res., global daily coverage
GOES I-M	GOES	NOAA NESDIS	From 1976	Optical-IR multispectral radiometer; 1-4km Res., global continuous monitoring
SPOT HRV, HRVIR	SPOT	CNES	From 1986	Optical-IR multispectral radiometer, 2.5-20m Res. global 26-day repeat
ETM/TM/MSS	Landsat, LDCM	NASA, USGS	From 1972	Optical-IR multispectral radiometer, 15-120m Res., global 16 day repeat
MODIS	Terra/Aqua	NASA	From 2000 & 2002	Optical-IR multispectral radiometer, 250m-1km Res., global twice-daily repeat
ASTER	Terra	NASA	From 2000	14 channel optical-IR radiometer, 15-90m Res., global 16-day repeat
MISR	Terra	NASA	From 2000	4-band Multi-angle Imaging SpectroRadiometer, 275m-1.1km Res., global 2-9 day repeat
Hyperion	EO-1	NASA	From 2001	Hyperspectral imager, 220 bands, 30m Res., global 16-day repeat
MOPITT	Terra	NASA	From 2000	Atmospheric IR spectrometer, 22km Res., global 16-day repeat
VIIRS	NPP, NPOESS	NASA	2015 launch	Optical-IR multispectral radiometer, 400-800m Res., Global daily (optical) and twice/day (IR) repeat

Quickbird/World View	Quickbird	DigitalGlobe	From 2001	Optical-IR multispectral radiometer, 0.6-2.4m Res., global 1-3.5 day repeat
IKONOS/GeoEye	GeoEye	GeoEye	From 1999	Optical-IR multispectral radiometer, 1-4m Res., global 3-5 day repeat coverage
CORONA	CORONA	National Reconnaissance Office	1960-1972	BW photographs, 2 to 8 m resolution, selected areas
Active, Passive Microwave and Other Sensors				
AMSR	Aqua, GCOM-W	NASA, JAXA	2002-present	Microwave radiometer, 6.9-89 GHz Freq., 5-60km Res., global 1-3 day repeat coverage
ASCAT	METOP	ESA	From 2009	Radar scatterometer, 5.3 GHz Freq., 30m-1km Res. global daily coverage
AMI	ERS-1/2	ESA	From 1992	SAR and scatterometer, 25m-50km Res., 5.3 GHz Freq., global 1-35 repeat
JERS-1 SAR	JERS-1	JAXA	1992-1998	SAR, 1.3 GHz Freq., HH polarization Global coverage, 44 day repeat 18 m resolution, 75 km swath
ERS-1/2 SAR	ERS 1/2	ESA	1991-present	SAR, 5.6 GHz Freq. VV polarization Global Coverage, 35 day repeat 25 m resolution, 100 km swath
ASAR	ENVISAT	ESA	From 2003	SAR and scatterometer, 30m-150m Res., 5.3 GHz Freq., global 35-day repeat
QuikSCAT	QuikSCAT	NASA	1999-2009	Scatterometer 25 km resolution Global daily coverage
RadarSat-1,2	RadarSat	CSA	From 1996	SAR, 10m-100m Res., 5.3 GHz Freq., global 1-24 day repeat
RadarSat Constellation	RadarSat	CSA	2014 Launch	SAR, 3m-100m Res., 5.3 GHz Freq., global 1-24 day repeat

TerraSAR-X	TerraSAR-X	DLR	2007	SAR, 1-18 m, 110 GHz Freq., global, 1-24 day repeat
TanDEM-X	TanDEM-X	DLR	2010	SAR, 1-18 m, 110 GHz Freq., global, 1-24 day repeat
SSM/I	DMSP	NOAA DMSP	From 1987	Microwave radiometer, 19.3-85.5 GHz Freq., 14-56km Res., global daily repeat
SMOS	Proteus	CNES	From 2010	Microwave radiometer, 50km Res., 1.4 GHz Freq., global 23 day repeat
SMAP	TBD	NASA	2014 launch	SAR and microwave radiometer, 3-40km Res., 1.26-1.41 GHz Freq., global 1-3day repeat
PALSAR	ALOS	JAXA	From 2005	SAR, 10-100m Res., 1.2 GHz Freq., global 46-day repeat
GRACE	ESSP	NASA	From 2002	Gravimetry
SCIAMACHY	ENVISAT	ESA	From 1995	Absorption Spectrometer
OCO-2	TBD	NASA	2013 launch	NIR spectrometers, global 1.8km Res., 16-day repeat
TANSO-FTS/CAI	GOSAT	JAXA	From 2010	Vis-IR spectrometer, 0.5-1.5km Res., Up to 5600 observations globally, global 3-day repeat
TBD	DESDynI	NASA	2017 launch	LIDAR and SAR (in definition phase)
GLAS	IceSAT	NASA	2003-2009	Optical LIDAR 70 m Resolution 183 day repeat for selected ground tracks
TBD	ICEsat-2	NASA	2016 launch	Optical LIDAR (in definition phase) 10 m Resolution repeated for selected ground tracks
DPR, GMI	GPM	NASA, JAXA	2013 launch	Radar and passive microwave imager, 10-183 GHz, 5-500km Res., global 3-hourly repeat

Appendix D – List of participants in the ABoVE scoping study, including attendees at the AboVE Workshop held at the International Institute of Arctic Research, University of Alaska – Fairbanks, 10-14 August 2009 as well as reviewers of drafts of the ABoVE report.

Name	Organization	email	Workshop Attendee	Report Reviewer
Adema, Guy	National Park Service	Guy_Adema@nps.gov		X
Alexander, Heather	Univ. of Florida	hdalexander@ufl.edu	X	
Amiro, Brian	Univ. of Manitoba	Brian_Amiro@umanitoba.ca		X
Arp, Chris	USGS	carp@usgs.gov	X	
Balser, Andrew	Univ. of Alaska Fairbanks	fnawb@uaf.edu	X	
Barrett, Kirsten	USGS	kbarrett@usgs.gov	X	X
Beck, Pieter	Woods Hole Res. Center	pbeck@whrc.org	X	
Bhatti, Jag	Canadian Forest Service	Jagtar.Bhatti@NRCan-RNCan.gc.ca		X
Birdsey, Richard	USFS	rbirdsey@fs.fed.us		
Bond-Lamberty, Ben	Pacific NW Labs	bondlamberty@pnl.gov		X
Bourgeau-Chavez, Laura	Mich. Tech. Res. Inst.	laura.chavez@mtu.edu	X	X
Bowden, Breck	Univ. of Vermont	Breck.Bowden@uvm.edu	X	
Brackney, Alan	USFWS	alan_brackney@fws.gov	X	
Cable, Jessica	International Arctic Res. Ctr	jcable@iarc.uaf.edu	X	
Carroll, Mark	Univ. of Maryland	markc@umd.edu	X	X
Chapin, Terry	Univ. of Alaska Fairbanks	terry.chapin@uaf.edu	X	X
Chopping, Mark	Montclair State Univ.	chopping@pegasus.montclair.edu	X	X
D'Arrigo, Rosanne	Columbia University	rdd@ldeo.columbia.edu	X	X
Douglas, Marianne	Univ. Alberta	marriane.douglas@ualberta.edu		X
Eicken, Hajo	Univ. of Alaska Fairbanks	Hajo.Eicken@gi.alaska.edu		X
Epstein, Howard	Univ. of Virginia	hee2b@virginia.edu		X
Euskirchen, Eugenie	Univ. of Alaska Fairbanks	ffese@uaf.edu	X	X
French, Nancy	Mich. Tech. Res. Inst.	nancy.french@mtu.edu	X	X
Fukuda, Masami	International Arctic Res. Ctr	mfukuda@iarc.uaf.edu		X
Goetz, Scott	Woods Hole Res. Center	sgoetz@whrc.org	X	X
Goward, Sam	Univ. of Maryland	sgoward@umd.edu		X
Griffith, Peter	Sigma Space Corp.	peter.c.griffith@nasa.gov	X	X
Grosse, Guido	UAF	ggrosse@gi.alaska.edu		X
Grunblatt, Jesse	UAF-GINA-NSSI	jesse@gina.alaska.edu	X	X

Hall, Forest	NASA - GSFS	forrest.hall@gsfc.nasa.gov	X	X
Hanley, Thomas	USFS	thanley@fs.fed.gov		X
Harden, Jen	USGS	jharden@usgs.gov	X	X
Hayashi, Masaki	Univ. of Calgary	hayashi@ucalgary.ca		X
Hicke, Jeff	Univ. of Idaho	jhicke@uidaho.edu		X
Hinzman, Larry	International Arctic Res. Ctr.	lhinzman@iarc.uaf.edu	X	X
Hodkinson, Dan	Sigma Space Corp.	danhodkinson@verizon.net	X	
Hogg, Ted	Canadian Forest Service	Ted.Hogg@NRCan-RNCan.gc.ca		X
Hoy, Elizabeth	Univ. of Maryland	elizabeth.hoy@gmail.com	X	
Huemmrich, Fred	NASA	karl.f.huemmrich@nasa.gov	X	X
Igarashi, Tomotsu	JAXA	igarashi.tamotsu@jaxa.jp	X	X
Jin, Yufang	UC-Irvine	yufang@uci.edu	X	
Jones, Ben	USGS	bjones@usgs.gov		X
Juday, Glenn	Univ. of Alaska Fairbanks	ffgpj@uaf.edu	X	
Kane, Evan	USFS	eskane@mtu.edu		X
Kasischke, Eric	Univ. of Maryland	ekasisch@umd.edu	X	X
Kimball, John	Univ. of Montana	johnk@flbs.umt.edu	X	X
Kushida, Keiji	Hokkaido Univ	kkushida@pop.lowtem.hokudai.ac.jp	X	
Lassuy, Denny	North Slope Science Initiative	Denny_Lassuy@fws.gov	X	X
Laurence, John	USFS	jalaurence@fs.fed.gov		X
Liljedahl, Anna	Univ. of Alaska Fairbanks	akliljedahl@alaska.edu		X
Loboda, Tatiana	University of Maryland	tloboda@hermes.geog.umd.edu		X
Loranty, Michael	Woods Hole Res. Center	mloranty@whrc.org	X	
Mack, Michelle	Univ. of Florida	mcmack@botany.ufl.edu	X	X
Maracle, Bryan	Yukon River Inter-Tribal Watershed Council	bmaracle@yritwc.org	X	X
Margolis, Hank	Univ. of Laval	Hank.Margolis@sbf.ulaval.ca		X
Martin, Philip	USFWS	Philip_Martin@fws.gov	X	X
McGuire, Dave	Univ. of Alaska Fairbanks	ffadm@uaf.edu	X	X
Miller, Chip	JPL	charles.e.miller@jpl.nasa.gov		X
Mims, Shirley	UC - Irvine	smims@uci.edu	X	
Moghaddam, Mahta	Univ. of Michigan	mmoghadd@eecs.umich.edu		X
Murdoch, Peter	USGS	pmurdoch@usgs.gov	X	
Murphy, Karen	USFWS	karen_a_murphy@fws.gov	X	X
Nagano, Tsugito	JAXA	nagano.tsugito@jaxa.jp	X	
Nakau, Koji	JAXA	nakau.koji@jaxa.jp	X	

Neigh, Chris	NASA - GSFC	christopher.s.neigh@nasa.gov	X	
Oechel, Walter	San Diego State Univ.	oechel@sunstroke.sdsu.edu	X	
Payne, John	North Slope Science Initiative	John_Payne@blm.gov		X
Quintin, Bill	Wilfrid Laurier Univ.	wquinton@wlu.ca		X
Raab, Ted	Stanford	tkraab@stanford.edu		X
Randerson, Jim	UC - Irvine	jranders@uci.edu	X	
Rawlins, Mike	JPL	michael.a.rawlins@jpl.nasa.gov	X	
Romanovsky, Vlad	Univ. of Alaska Fairbanks	ffver@uaf.edu	X	X
Ruess, Roger	Univ. of Alaska Fairbanks	ffrwr@uaf.edu	X	
Rupp, Scott	Univ. of Alaska Fairbanks	scott.rupp@uaf.edu	X	
Schaefer, Kevin	NSIDC	kevin.schaefer@nsidc.org		X
Schuur, Ted	Univ. of Florida	tschuur@ufl.edu	X	X
Shasby, Mark	USGS	shasby@usgs.gov		X
Shaver, Gaius	Marine Biological Lab	gshaver@mbl.edu		X
Shea, Katie	Univ. of Guelph	kshea@uoguelph.ca	X	X
Shmelev, Denis	Moscow State Univ	denwallace@yandex.ru	X	
Shur, Yuri	Univ. of Alaska Fairbanks	ffys@uaf.edu	X	
Stinson, Graham	Canadian Forest Service	gstinson@pfc.cfs.nrcan.gc.ca	X	X
Striegl, Rob	USGS	rstriegl@usgs.gov	X	X
Tani, Hiroshi	Hokkaido Univ	tani@env.agr.hokudai.ac.jp	X	
Tape, Kevin	Univ. of Alaska Fairbanks	fnkdt@uaf.edu	X	
Tarnocai, Charles	Agriculture and Agri-Food Canada	Charles.Tarnocai@AGR.GC.CA	X	X
Turner, Woody	NASA	woody.turner@nasa.gov		X
Turetsky, Merrit	University of Guelph	mrt@uoguelph.edu		X
Verbyla, Dave	Univ. of Alaska Fairbanks	d.verbyla@uaf.edu	X	X
Waddington, Mike	McMaster Univ.	wadding@mcmaster.ca	X	X
Waldrop, Mark	USGS	mwaldrop@usgs.gov	X	X
Walker, Skip	Univ. of Alaska Fairbanks	ffdaw@uaf.edu	X	
Wang, Zhuosen	Boston Univ	wangzhs@bu.edu	X	
Wickland, Diane	NASA HQ	Diane.E.Wickland@nasa.gov	X	
Wullschleger, Stan	ORNL	wullschlegsd@ornl.gov		X
Wylie, Bruce	USGS-EDC	wylie@usgs.gov	X	
Xue, Yongkang	UCLA	yxue@geog.ucla.edu		X
Zeng, Xubin	Univ. N. Arizona	xubin@atmo.arizona.edu		X