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SYNTHESIS AND REVIEW

An overview of NASA's Arctic Boreal Vulnerability Experiment (ABoVE): Development, implementation, advances and knowledge gaps

Scott J. Goetz[1], Charles Miller[2], Peter Griffith[3], Abhishek Chatterjee[3,4], Natalie Boelman[5], Laura Bourgeau-Chavez[6], David Butman[7], Howard Epstein[8], Joshua Fisher[9], Nancy French[6], Elizabeth Hoy[10] John S. Kimball[11], Elisabeth Larson[2], Tatiana Loboda[12], Michelle Mack[13], Mahta Moghaddam[14], Paul Montesano[2], Laura Prugh[7], Michael Rawlins[15], Adrian V. Rocha[16], Brendan M. Rogers[17], Kevin Schaefer[18]

[1] School of Informatics and Computing, Northern Arizona University, Flagstaff AZ, USA
[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, USA
[3] NASA Goddard Space Flight Center / SSAI, Greenbelt MD, USA
[4] Universities Space Research Association, Columbia, MD, USA.
[5] Lamont-Doherty Earth Observatory and Department of Earth and Environmental Sciences, Columbia University, Palisades NY, USA
[6] Michigan Technological University Research Institute, Ann Arbor MI, USA
[7] School of Environmental and Forest Sciences, University of Washington, Seattle WA, USA
[8] Department of Environmental Sciences, University of Virginia, Charlottesville VA, USA
[9] Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles CA, USA
[10] NASA Goddard Space Flight Center / GST, Greenbelt MD, USA
[11] Numerical Terradynamics Simulation Group, University of Montana, Missoula MT, USA
[12] Department of Geographical Sciences, University of Maryland, College Park MD, USA
[13] Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff AZ, USA
[14] School of Engineering, University of Southern California, Los Angeles CA, USA
[15] Department of Geosciences, University of Massachusetts, Amherst MA, USA
[16] Department of Biological Sciences, University of Notre Dame, South Bend IN, USA
[17] Woodwell Climate Research Center, Falmouth MA, USA
[18] National Snow and Ice Data Center, University of Colorado, Boulder CO, USA

E-mail: scott.goetz@nau.edu

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Abstract

NASA's Arctic Boreal Vulnerability Experiment (ABoVE) is a large coordinated multi-disciplinary research effort addressing ecosystem changes taking place in biomes of the Arctic and boreal region. Although the geographic focus of the field campaigns centers on northwestern North America, ABoVE research is ultimately designed to address scaling from field measurements to multi-sensor airborne data acquisitions to satellite remote sensing and ultimately to terrestrial biosphere models. As such, ABoVE has pan-Artic and pan-boreal implications and applications. Here we provide an overview of ABoVE development, implementation, research progress, and findings at the midpoint of its planned ten-year effort. We do not restrict this synthesis and review to the papers in the ABoVE focus collection of ERL alone, given they represent only part of the publications that have arisen from ABoVE thus far. Rather, we briefly highlight a selection of some key publications and then focus on articulating knowledge and associated data gaps that still need to be addressed. These gaps are critical research areas for further advancing our understanding of the interactions and feedbacks between the climate system and changes in the spatial and temporal environmental drivers of dynamics in carbon, hydrology, snow, permafrost, disturbance and vegetation composition, structure and function. Addressing these gaps will also advance our ability to capture these dynamics in prognostic models.

Keywords: carbon, climate, composition, dynamics, feedbacks, forest, function, hydrology, interdisciplinary, modeling, permafrost, phenology, ecosystem services, structure, socioecological, tundra, vegetation

1. Introduction

Climate change is underway across the high northern latitudes and is impacting ecosystems and people in myriad ways that we are only just beginning to fully appreciate, document, and represent in models (Box et al. 2019, Fisher et al. 2018, Meredith et al. 2019). NASA's ten-year Arctic Boreal Vulnerability Experiment (ABoVE) is a coordinated multi-disciplinary research effort designed to address the overarching science question: How vulnerable or resilient are ecosystems and society to environmental change in the Arctic and boreal region (ABR) of western North America? ABoVE examines this question from a vulnerability-resilience framework that incorporates drivers of change, the impacts of those changes on ecosystems and people, the consequences of those impacts in terms of ecosystem services (e.g., provisioning, climate regulation), and the responses to those changes by people operating within the overall social-ecological system (Figure 1). Within this framework, ABoVE poses a number of specific science questions that are focused along thematic or disciplinary lines (Table 1), and each of these questions have related research objectives focused on both terrestrial ecosystem dynamics and_ecosystem services (Table 2). Here we use the term ecosystem dynamics in a broad sense to include environmental drivers, related disturbance regimes (e.g., fire, insects), permafrost distribution and properties, hydrologic system characteristics, vegetation and animal dynamics, and associated carbon stocks and fluxes (Figure 2). ABoVE has working groups focused on each of these thematic areas, as described below.

The scope of ABoVE has been ambitious from the outset, not only in terms of the timeline (approximately a decade long) but also via its focus on a coordinated multi-disciplinary research program, including intensive field campaigns that are documenting changes taking place in terrestrial carbon, vegetation, hydrologic and disturbance regimes across a nearly 4 million km^2 domain in northwestern North America (Figure 3). ABoVE also seeks to capture those dynamics in models to inform and improve them and to forecast future change accurately across the study domain as well as advance our understanding of these changes across the broader pan-ABR terrestrial and freshwater ecosystems. Moreover, from the outset, ABoVE research activities have sought to include the social-ecological aspects of environmental changes already underway, their implications for people and wildlife, including the ability to inform land resource management, and the potential to address climate change mitigation and adaptation efforts. To encompass such an ambitious scope, ABoVE has implemented a strategy that spans spatial scales from "leaf to orbit" (*sensu* Piers Sellers), making observations at plot, tower, airborne, and orbital scales and feeding these data into various integrated modeling frameworks (Figure 2). A coordinated research effort of this breadth, magnitude and duration is not common in many agency funding programs but was ultimately advanced, after a decade of scoping and planning (Kasischke et al. 2010, Goetz et al. 2011).

2. Timeline and Development

ABoVE was conceived in 2008 in response to a NASA call for proposals to advance coordinated field campaigns focused on terrestrial ecosystems that were important from an ecological, biogeochemical and physical climate system perspective. After the scoping study proposal was selected (see Kasischke et al. 2010, Goetz et al. 2011), a series of community workshops was held to begin the process of developing a program that addressed the critical aspects of terrestrial ecosystem processes in the region, while also scoping a campaign that was realistic from a logistical and budgetary perspective. This led to the competitive formation of a science definition team (SDT) which, over a two-year period, drafted the ABoVE concise experiment plan (ACEP 2014). The ACEP details the design and execution of field campaigns (see Miller et al. 2019) to include, among other components, multiple aircraft carrying a suite of sensors to acquire data coincident with *in situ* measurements on the ground, and leveraging wherever possible longer-term measurement efforts already underway.

The conceptual timeline for ABoVE research activities presented in the ACEP generally follows three objective-driven phases over the duration of the effort. The research focus evolves across each phase as guided by the vulnerability-resilience framework, where studies of ecosystem dynamics provide the foundation for further research on the consequences to, and the responses of, society to changing ecosystem services. The first two phases predominately focused on objectives oriented around ecosystem dynamics. The third phase will focus on the analysis and synthesis of ABoVE research following the completion of the main portion of field and airborne data collection activities. Researchers funded under ABoVE participate as members of the Science Team, which helps ensure that projects can leverage opportunities for collaboration, facilitates thematic syntheses, and allows for economic coordination and logistics support for ABoVE field and modeling activities. Additionally, ABoVE implemented a process by which researchers funded under other programs or by international science organizations might apply to become ABoVE Affiliated Projects with full Science Team benefits.

All present and past projects, and associated participants, are listed on the ABoVE website. The first round of pre-ABoVE research project support took place in 2013 with the selection of 11 proposals (each 3-4 years in duration) ($4.8M) focused on collecting, compiling and/or developing fundamental data sets intended to inform and advance the first of the three phases of ABoVE research. In mid-2015, 22 Phase I investigations were selected ($18.1M) covering a diverse range of disciplinary and interdisciplinary research addressing the themes laid out in the ACEP. These were focused primarily on ecosystem dynamics, including development and analysis of remote sensing and *in situ* field data, as well as modeling and early synthesis investigations. This selection of projects was augmented in 2016 with nine projects ($8.25M) dedicated to participation in the airborne remote sensing component of the initial 2017 field campaign (Miller et al. 2019). Phase II of ABoVE kicked off in 2019 with the selection of 19 proposals ($15.7M) concentrating on using data collected during the initial campaign to better understand ecosystem dynamics across scales, to address the societal impacts of change across the study domain, to advance modeling of ecosystem dynamics and services, and to assess emerging remote sensing technologies, particularly the use of solar induced florescence (SIF) to estimate vegetation productivity.

The Phase II selections included many principal investigators from Phase I, but more than half of the Phase II projects were led by investigators new to ABoVE. The selections balanced the continuity of the Phase I focus on Ecosystem Dynamics with the Phase II transition to include Ecosystem Services research. These new project teams joined the Science Team that already had nine core thematic working groups (WGs), some of which were reoriented and reorganized to integrate the new teams. The core working groups are organized thematically and currently include (i) Vegetation Dynamics and Distribution, (ii) Vegetation Structure and Function, (iii) Fire and Insect Disturbance, (iv) Snow Dynamics and Impacts (aka Snowscapes), (v) Hydrology and Permafrost, (vi) Carbon Dynamics, (vi) Ecosystem Modeling. These WGs are complemented by other more focused or recently formed groups addressing Ecosystem Services & Knowledge Co-production, Synthetic Aperture Radar (SAR) applications, Spectral Imaging (spectroscopy), and Wetlands, among others (a full list with members can be found on the ABoVE website).

At this point in its expected 10-year timeline, there are 67 projects supported by the ABoVE component of NASA's Terrestrial Ecology (TE) program. These are augmented with another 27 projects supported by other components of the NASA Carbon Cycle and Ecosystems Focus Area that address some aspect of research aligned with ABoVE science questions and objectives (Tables 1, 2). Another 27 affiliated projects are supported by other non-NASA research programs, including Canadian and European agencies. ABoVE also has two key partners with official agreements to coordinate and collaborate: the Department of Energy's Next Generation Ecosystem Experiment in the Arctic (NGEE-Arctic, Wullschleger et al. 2011) and the Canadian Polar Knowledge (POLAR) program, which supports a suite of related research projects led by Canadian investigators (Houben et al. 2019). Additional informal partnerships have been established between ABoVE and a range of other US (e.g. NEON) and Canadian (e.g. Forest Service) agencies, programs and entities. Many of these partners have representatives who are collaborators on NASA supported ABoVE projects.

Field campaign activities began in 2016 and are nominally expected to end in 2025. Undoubtedly additional research will continue beyond 2025 given there will be extensive data products to be mined, some 200 of which are already published and archived for that purpose on the ORNL DAAC (Oak Ridge National Labs – Distributed Active Archive Center) via their Earthdata Portal. Because of a rich set of field measurements that were already ongoing in Alaska and western Canada at the initiation of ABoVE, it was ultimately possible to design an airborne campaign that acquired data over thousands of field sites (Hoy et al. 2018), covering more than 450,000 km^2 of terrestrial and freshwater systems (including some repeated acquisitions), providing the context for linking *in situ* measurements with data from NASA and other earth observing satellites. The 2017 campaign included eight airborne platforms carrying a suite of instruments measuring multi-spectral and hyperspectral surface reflectance properties (AVIRIS-NG), backscatter from multi-frequency multi-polarized synthetic aperture radars (SAR), surface topography and 3-dimensional canopy structure from light detection and ranging (Lidar) via the Laser Vegetation and Ice Sensor (LVIS), atmospheric trace gas concentrations acquired from multiple sensors and airborne platforms, and other data sets as summarized in Miller et al. (2019). Repeat airborne data collection campaigns took place in 2018 (L-band SAR, AVIRIS-NG) and 2019 (L-band SAR, AVIRIS-NG, LVIS full waveform lidar). Further coordinated field and airborne campaigns in 2020 and 2021 were delayed by the COVID-19 pandemic but are expected to resume once safe to do so and all necessary permissions are granted, both in Alaska and Canada, including in particularly vulnerable remote and Indigenous communities.

3. Outcomes to Date

ABoVE research has been and continues to be a priority within NASA, both scientifically and programmatically, as well as within U.S. federal government programs (e.g. in the US Global Change Research Program, the Interagency Arctic Research Policy Committee, the North American Carbon Program) and with Canadian and other international programs (e.g. the European Climate Change Initiative Permafrost CCI (Obu 2019), the NASA-ESA Arctic Methane and Permafrost Challenge, and the European Research Commission supported Synergy Project Q-Arctic, among others).

In addition to the data sets archived at the ORNL-DAAC, noted earlier, the only feasible way to summarize here the scope of the research output of ABoVE is by providing some information on the breadth and diversity of peer-reviewed publications that have come out thus far. Even that summary will quickly become dated as many more publications are currently in review and yet others in preparation.

3.1 Publications and synthesis activities

ABoVE has produced numerous high impact publications: papers that are already well cited and/or have provided novel research insights. Examples include documenting the increasing role of lightning as a major driver of fire disturbance (Veraverbeke et al. 2017); quantifying the amount of mercury stored in permafrost across the Arctic (Schuster et al. 2018); assessing the impact of increasingly severe fire disturbance on release of legacy carbon that escaped historical burning (Walker et al. 2019); characterizing soil respiration outside the growing season and the extent to which it offsets annual gross primary production (Commane et al. 2017; Natali et al. 2019); capturing and modeling the ebullition of methane from abruptly thawing lakes (Walter-Anthony et al. 2018); providing a novel map of the circumpolar taiga-tundra ecotone based on vegetation structure (Montesano et al. 2020); documenting the trends and drivers of vegetation productivity patterns across the pan-Arctic and Oro Arctic domains (Berner et al. 2020, Myers-Smith et al. 2020); tracking the changing migration and movement patterns of animals across the ABR over the past three decades (Joly et al. 2019, Davidson et al. 2020); assessing the drivers and amplitudes of changing seasonal atmospheric CO2 concentrations (Lin et al. 2020); documenting shifts in boreal forest composition arising from more severe wildfires (Mack et al. 2021) and associated impacts of fire disturbance on aboveground biomass changes (Wang et al. 2021). These papers are just a sample of the many impactful publications arising from ABoVE research. There are of course many others that deserve recognition but can't be included in this brief summary. In simple terms of numbers of publications, as of this writing (mid 2021), there are over 400 papers in the ABoVE database, of which some 300 are associated with NASA-funded projects and have already been cited, in aggregate, at least 12,000 times. Some two dozen of these have been cited more than 100 times each.

Beyond the publications by individual project teams, there are currently nearly two dozen ongoing synthesis activities that not only integrate within these thematic areas but also across them. Some examples of ongoing synthesis efforts include those focused on Arctic-boreal wildfire combustion (Walker et al. 2020a, 2020b), boreal post-fire regeneration (Baltzer et al. 2021), temporal and spatial variations of active layer properties in permafrost regions, carbon budget of the ABoVE domain, methane budgets and change dynamics, projecting carbon – climate feedbacks, and a multi-disturbance synthesis including fire impacts on permafrost degradation fire and insect effects on vegetation composition and function, as well as other disturbance types. Many of the publications noted here emphasize these cross-disciplinary and synthesis aspects of ABoVE research, and some of them are discussed further in a following section on knowledge and data gaps.

3.2 Presentations and outreach

The impact of ABoVE research is also captured in terms of presentations at professional meetings. These are more difficult to document, given the diversity of projects, participants and meetings at which the research may be presented. One indicator of impact, in terms of the number of presentation and audience in attendance, is the annual Fall meeting of the American Geophysical Union (AGU), one of the largest science meetings in the world with over 25,000 attendees across all disciplines of earth and space science, and with hundreds of oral presentation sessions. Beginning in 2016, members of the ABoVE Science Team have organized sessions entitled "The Resilience and Vulnerability of Arctic and Boreal Ecosystems to Climate Change" at AGU which have included some 200 oral presentations and 500 posters. These are among the largest of any of AGU's organized sessions, both inside and outside of AGU's Biogeosciences section, and have been attended by at least 1700 participants. This is a simple indicator of ABoVE's reach but is also important in terms of facilitating interaction among science team members and the broader scientific community. Additional examples of outreach activities are summarized in the following section.

3.3 ABoVE Management and Support by the Carbon Cycle and Ecosystems Office

A unique component of ABoVE is the field campaign support provided by staff in the Carbon Cycle and Ecosystems Office (CCE Office) at NASA Goddard Space Flight Center. CCE Office staff work with the ABoVE science leadership to coordinate, facilitate, and enhance the work of both individual projects and the Science Team. The range of support includes coordination and support for field operations and logistics (assisting with permitting, and safety and risk management for field activities); access to cyberinfrastructure for data analysis and planning; management of airborne science campaigns; communications and public engagement via NASA and other platforms; providing educational opportunities via internships; interactions with local and regional stakeholders and organizing the annual ABoVE Science Team Meetings.

Communications and public engagement during ABoVE have been conducted through both formal and informal efforts. The primary formal public engagement efforts were executed through ABoVE's collaboration with NASA's Earth to Sky Partnership (ETS) to design and produce professional development for interpreters and environmental educators, and to build, sustain and expand a community of practice in science education and communication. ABoVE and ETS have conducted a series of professional development events highlighting research in the ABoVE domain. Events have included workshops in Alaska and Canada, presentations at regional and national education and science conferences, and distance-learning opportunities such as webinars and self-study modules. Earth to Sky also supported ABoVE scientists by facilitating connections with land managers in the research domain. Through these endeavors, ETS has assisted the ABoVE team in connecting with local and regional stakeholders and their communities. Informal public engagement has been conducted through a number of channels including NASA's Office of Communications and interviews with journalists associated with high-profile print, broadcast and online media outlets.

Educational activities and internships are also supported by the CCE Office. Since 2015, ten undergraduate and graduate students have participated as summer student interns, with projects designed to introduce students to Arctic research and experience the collaborative nature of ABoVE projects. Additionally, many ABoVE investigators sponsor student internships at their own institutions, helping to engage the next generation of students in scientific research. More details and links to these various efforts can be found on the ABoVE web site.

As ABoVE matures and more research products are available from the projects and science team, the CCE Office works with stakeholders to share these results, learn about other activities in the region, foster collaborations, and accelerate the flow of information from research to operations (and back again). A record of these past meetings (and planned future events) can be found under "Meetings and Events" on the ABoVE website. During the COVID pandemic, the CCE Office has collaborated with the Government of Yukon, the Government of Northwest Territories, and the Alaska Center for Climate Assessment & Policy (ACCAP) to hold webinars focused on research in each of these regions and across the ABoVE study domain. They have effectively expanded the outreach of ABoVE, allowing for broader participation and reducing the time, cost, and carbon emissions associated with travel to remote regions. While face-to-face interactions are vital for building and maintaining collaborative relationships, the possibility of increased frequency of engagement via virtual events means that these webinars and related activities are likely to continue well after the pandemic has passed.

3.4 Development of Standard Protocols, Map Projections and Science Cloud Computing Capabilities

In an effort to provide a collaborative compute and data sharing space for ABoVE researchers, the CCE Office partnered with the NASA Center for Climate Simulation (NCCS) to create and provide access to a high-performance science cloud computing capability. Known as the ABoVE Science Cloud, this capability combines high performance computing with emerging technologies and data management with tools for analyzing and processing geographic information, large-scale modeling, analysis of remote sensing data, and copious disk storage for "big data" with integrated data management. The ABoVE Science Cloud is accelerating the pace of new Arctic science for researchers participating in the field campaign. In addition, all published ABoVE data products are added to the science cloud for easy access and use by ABoVE investigators.

The ABoVE campaign produces data across various spatial extents and resolutions, thus early in the campaign a standard reference grid and projection was developed (Loboda et al. 2019). Data producers are encouraged to archive datasets using these standards. The compatibility of these datasets across the individual projects facilitates interoperability in scientific analysis. This standard reference grid is particularly useful for the modeling teams within ABoVE as individual researchers can easily pull data for the grid cells relevant to their analyses. Additionally, it eases archiving and distribution of datasets, both for near-term use throughout the duration of the field and airborne campaigns, as well as longer-term archiving of data at the ORNL DAAC Earthdata Portal. Standardized protocols have been developed to help ABoVE researchers ensure their data are properly formatted and documented for long-term archiving, and that data publications are generated with digital object identifier (DOI) numbers for other researchers to cite.

4. Research to Address Key Knowledge and Data Gaps

As part of the advances made by the ABoVE Science Team and CCE Office support summarized earlier, both knowledge and data gaps have been identified that require additional concerted effort and coordinated focus to resolve. Following is a synopsis of some of these gaps and the ways in which we expect research will evolve to address them over the duration of ABoVE and, in many cases, beyond.

4.1 Vegetation Composition, Distribution and Productivity Dynamics

The circumpolar dynamics of boreal forest and arctic tundra vegetation, which encompasses vegetation composition and function, including demographic processes such as mortality and recruitment, have been assessed using satellite-based remotely sensed data since the 1990s, with datasets extending back to the early 1980s (Myneni et al. 1997, Jia et al. 2003, Bunn et al. 2005, Goetz et al. 2005, Bhatt et al. 2010, Ju and Masek 2016, Berner et al. 2020). Findings from these studies led to the "greening" versus "browning" paradigm, which has been a persistent framework for understanding both interannual anomalies and long-term trends in ABR vegetation productivity dynamics (e.g. Myers-Smith et al., 2020).

Warming air temperatures and shrub expansion appear to play a dominant role in increases in tundra vegetation biomass and productivity (Martin et al. 2017, Mekonnen et al. 2021) while water limitation is a potential cause of decreases in boreal forest productivity and increases in mortality (e.g., Bunn & Goetz 2006, Peng et al. 2011). CO_2 fertilization has likely facilitated greening in both biomes (Thomas et al. 2016, Tagesson et al. 2020); however, many of these vegetation dynamics studies have focused on specific regions and/or compared differences among regions, identifying a high degree of within-biome spatial heterogeneity in vegetation trends (e.g., Epstein et al. 2012, Bhatt et al. 2017, Martin et al. 2017, Reichle et al. 2018). Past studies have also noted temporal trends were not always consistent and changed over time, for example identifying a dampening or reverse of the tundra greening signal since the early 2000s (e.g., Bhatt et al. 2013).

From the context of these historical and more recent studies as part of ABoVE, several key knowledge gaps were identified along with ways advance our understanding vegetation dynamics in boreal and tundra ecosystems, focusing on drivers of interannual changes and long-term trends in productivity and issues related to spatial scaling.

4.1.1 Knowledge Gaps. Despite considerable progress, the drivers of changing annual boreal and tundra ecosystem primary productivity remain only partially resolved; in other words, what determines a “good” versus “bad” year for vegetation and how does it differ spatially both within and between ecosystems? Inter-annual variability in productivity for boreal forests and arctic tundra is challenging because temperature, snowpack, timing of snowmelt and soil thawing, summer precipitation, solar radiation, soil nutrients, permafrost / active layer, and herbivory, including time lags up to or greater than one year, all drive interannual productivity and other vegetation demographics such as mortality and regeneration. Yet the dominant drivers and how they interact varies considerably at spatial scales ranging from regional to site-level (e.g., Buermann et al. 2018, Berner et al. 2020).

Addressing this knowledge gap requires both “bottom-up” and “top-down” approaches, and in particular, the combination of relatively high temporal frequency field, remote sensing, and environmental driver data. Field observations of meteorological, eco-physiological, and ecosystem function variables covering at least the entire growing season, preferably the spring and fall “shoulder” seasons, and optimally over the entire year can be combined with coincident remotely sensed indicators of primary production and potential controls at various spatial scales. However, robust datasets of key response and controlling variables are still needed (e.g., photosynthesis and gross primary productivity, above- versus below-ground allocation of net primary productivity, soil properties and nutrients, snow depth and properties, active layer dynamics, soil moisture, disturbances). For example, improved characterization of above- versus below-ground allocation at intensively studied sites could help determine the degree to which satellite-observed greening is related to decreased allocation below-ground in response to warmer temperatures and greater nutrient availability.

Longer-term trends in ABR vegetation productivity are extremely important for understanding the responses of these ecosystems to climate change (e.g. changes temperature, precipitation and evaporative demand). Boreal forest and arctic tundra greening and browning trends have been identified from landscape to circumpolar scales, yet the environmental controls that drive these trends, particularly at different spatial scales, have yet to be fully understood. Although these environmental controls are related to those that govern interannual variability, more slowly evolving processes such as changes in vegetation composition, structure, and demographics are key. For example, shrub expansion has been documented as one of the primary drivers of tundra greening (e.g. Mekonnen et al. 2021), and fire history / stand age combined with successional processes and site-level water balance helps explain the often-complex patterns of boreal greening and browning (Girardin et al. 2016, Hember et al. 2017, Sulla-Menashe et al. 2018). Nevertheless, there is still much we do not understand with regard to the mechanisms and implications of the greening / browning phenomenon that hampers our ability to project these dynamics with confidence into the future.

4.1.2 Addressing Gaps. To address these knowledge gaps, multi-decadal and spatially-extensive field monitoring of vegetation composition, structure, and function will help improve our understanding of environmental controls on long-term greening and browning patterns. Continued development, refinement and utilization of spatial maps and time-series products of key environmental variables are needed (Fisher et al. 2018). Combining these fundamental data with time series of vegetation composition, productivity and allocation (i.e., above- and belowground), biomass, and structure can greatly improve our understanding of trend attribution across ABR landscapes.

Given the vast areal expanses of ABR ecosystems and the fine scales at which vegetation dynamics operate, it is also critical to improve the spatial and temporal scaling (up and down) of vegetation properties and dynamics. These are identified and constrained at spatial and temporal scales that relate to current and common field methodologies (e.g., plot sampling, flux towers) and remote sensing instruments / platforms (e.g., the Landsat and Sentinel series, MODIS, VIIRS). A key question is when data are not available at fine spatial or temporal scales, can coarser data (e.g., satellite remote sensing) allow us to understand system features at those finer scales? Conversely, what can Landsat, Sentinel or other higher resolution imagery data tell us about spatial variability within moderate resolution imagery (e.g., from MODIS and VIIRS sensors)? How can these image data sets also be used together to better characterize temporal variability, both seasonally and across years? What insights will the new generation of hyperspectral and high-spatial resolution thermal infrared satellite sensors reveal about changing vegetation structure, function, and composition? How can other currently operational missions (e.g. ICESAT-2) and new missions in development (e.g. NISAR) augment optical imagery for assessing vegetation properties and dynamics across scales?

Ultimately, continued improvement of merging multi-source and multi-scale remote sensing data will be critical for improving our understanding of vegetation dynamics scaling. Particularly promising is the potential to merge traditional NASA and ESA satellite imagery such as MODIS, VIIRS, Landsat, or Sentinel-2 with newer high-resolution imagery such as available from Maxar, Planet Labs, or other providers. Simulation modeling can also help to fill in both spatial and temporal scale gaps, from both upscaling and downscaling perspectives, and functional relationships in field data will assist in model enhancement and parameterizations. Finally, the identification of "super sites" where comprehensive field, drone, airborne, and satellite data overlap will be crucial for identifying key linkages across scales.

4.2 Vegetation Structure and Function

Ongoing transformations in vegetation structure (e.g. stand age, height, biomass) and function (e.g. productivity, succession, allocation) in the ABR are linked to shifts in the patterns of seasonal freeze/thaw cycles, snow cover, local- and landscape-scale disturbances, broad-scale patterns of temperature and precipitation, and changes in permafrost state and condition. Gaps in our knowledge of and data on these vegetation transformations are the foci of some current efforts, while others will need to be addressed in future ABoVE research.

4.2.1 Knowledge Gaps. The biomass, extent, demography, and overall spatial patterns of boreal woody vegetation remain key subjects of interest due in part to some of the knowledge gaps (expressed as questions below) in our understanding of vegetation structure and function, and the boreal forest's influence on high-latitude carbon cycling, surface albedo and associated feedbacks to climate (Randerson et al. 2006, Bonan 2008, Rogers et al. 2015, Wulder et al. 2020; Liu et al., 2020).

4.2.1.1 How have patterns of boreal forest structure changed over recent decades? Vegetation patterns may shift in a number of ways within the current geographic extent of woody structure. Shifts in vegetation structure and its spatial patterns across landscapes are linked with biogeochemical and biogeophysical processes that may result in a redistribution of vegetation biomass, changes to forest age-structure, rearrangements of successional pathways, and changes in growth rates. Such geographic and demographic shifts in structure, which are tightly coupled with disturbance dynamics, may alter the strength of aboveground carbon sinks, and also influence, as well as respond to, changes in permafrost stability. As such, updating information on forest structure will help to refine models that use forest age to model rates of growth, carbon fluxes, and the seasonality of surface albedo.

4.2.1.2 How will the boreal biome change at the northern extent of its current range? Vegetation, field and airborne studies indicate shifts in treelines are localized, and not consistent across broad domains (Rees et al., 2020, Timoney and Mamet, 2020). High resolution spaceborne imagery can capture fine-scale vegetation patterns, but consistent observations of vegetation structure in the high northern latitudes remains challenging. As research increasingly considers the spatial biomass patterns and dynamics of short stature and sparse woody vegetation, methods for resolving these features across broad extents need to be enhanced to provide a reliable stream of appropriately scaled data (Montesano et al. 2020). Although climate drives many aspects of northward treeline expansion, there are a variety of local-scale factors that also influence the fate of northward range expansion and associated vegetation structure. For example, demographic bottlenecks are associated with seed availability, germination and survival of recruits, as well as other physical constraints (e.g., topography, soil organic layer depth) that need to be considered in models of tree dispersal and migration.

4.2.1.3 How do patterns of forest structure link to belowground processes? There has been some work assessing vegetation structure indicators of belowground processes, which suggests potential for linking them to remote sensing observations (Baltzer et al., 2014, Carpino et al., 2018). However, vegetation structure can have contrasting effects on surface energy and insulation, particularly when snow cover is considered. There is need to assess the observable changes in vegetation structure that indicate changes, for example, in permafrost thaw on the margins of its extent. Observations of the depth, extent and timing of snow cover along with vegetation patterns may help reveal critical permafrost vulnerabilities to thaw. Similarly, remotely sensed aspects of vegetation structure may be able to inform research into belowground plant processes associated with primary productivity and carbon allocation, as well as heterotrophic respiration processes associated with decomposition.

4.2.2 Addressing Gaps. A first data gap associated with the observations of vegetation structure is information on the uncertainty of its measurement, and factors that drive uncertainty across multiple scales of observation. In heterogeneous boreal/tundra environments, current spaceborne structure estimates often have high relative errors. ICESat-2 lidar data have potential derive forest structure information across the boreal forest biome, but photon counting lidar from space is new technology and errors in estimates of structure (e.g. height and biomass) are substantial, particularly in boreal conifer environments (Montesano et al. 2015, Neuenschwander and Pitts 2018). These uncertainties may obscure subtle yet relevant changes. Calibrating ICESat-2 data with airborne lidar data and field measurements of structure may help reduce uncertainty in estimates of forest structure metrics and thus extend their applicability to boreal ecosystems. Similarly, the NISAR mission currently scheduled for launch in early 2023 will provide contiguous maps of ABR vegetation structure every 12 days (or less at higher latitudes) based on repeat-pass interferometric L-band SAR (Kellogg et al., 2020). These all-weather, high-frequency maps will provide unprecedented data for assessing vegetation structure dynamics. Maximizing the information derived from NISAR measurements will advance understanding of how best to integrate contiguous SAR maps with the more detailed but spatially and temporally sparse vegetation structure data from space-based lidar systems.

Second, to advance forest change analyses using spaceborne remote sensing data, a standardized global reference network for vegetation structure is needed. Ground validation that is free, open, dynamically updated, quality checked and follows global protocols (databases of plots, trees, geolocation accuracies, plot geometries, etc.) would remove the burden of data collection from individual projects and potentially improve the efficiency in their use for calibration and validation of spaceborne and airborne observations.

Finally, there is a persistent data gap in the consistent, image-based, fine-scaled observation of surface topography and vegetation. Currently, fine resolution data are available from the commercial sector (e.g., the Maxar series of Worldview and GeoEye satellites), including along-track stereo image pairs. However, these are not designed primarily for measuring vegetation structure, and differences in acquisition timing and geometry create inconsistencies in how vegetation structure contrasts with the background ground surface in open canopies. Research addressing data product development from a spaceborne platform with a primary mission to estimate surface topography and vegetation structure, such as the future Surface Topography and Vegetation mission (http://science.nasa.gov/earth-science/decadal-stv) recommended by the Decadal Survey on Earth Science and Applications from Space (NAS 2018), could enhance our ability to study subtle and fine-scaled vegetation structure changes in arctic and boreal regions.

4.3 Disturbance

Climate change has led to an intensification of wildfire in the ABR biomes resulting in changes in the vulnerability and resiliency of ecotypes and individual tree species (Whitman et al. 2018, Walker et al. 2020a, Bourgeau-Chavez et al. 2020, Baltzer et al. 2021) as well as changes in permafrost thaw (Schadel et al. 2018, Holloway et al. 2020) and carbon cycling (Rogers et al. 2020, Walker et al. 2020b). How these effects are manifesting is highly variable, for example, in the tundra vs boreal-taiga, uplands vs. lowlands and across other geographic, geomorphic, and permafrost gradients. As noted earlier, monitoring from remote sensing shows areas that have different vegetation productivity trends (greening/browning) and areas of shrub encroachment, but airborne and satellite remote sensing has also advanced characterization of burn severity and combustion of organic soil layers (Walker et al. 2020b, French et al. 2020), wetland and upland extent mapping, plant functional type classification, and patterns and rates of change arising from multiple causes. Field data provide the fine scale measurements needed to quantify and understand fire effects and how to scale to broader regions using remote sensing.

4.3.1 Addressing Knowledge and Data Gaps. Work is underway as part of ABoVE to include wildfire effects into terrestrial ecosystem models, which is essential for predicting future changes. Field data collected during the ABoVE campaigns and associated remote sensing products fill many of the needs for modeling, but several knowledge and data gaps remain. Moreover, current ABoVE projects are focused on some aspects of the interactions between or among climate, wildfire and/or hydrology and permafrost (e.g. changes in active layer thickness, subsidence, soil moisture), but there is need for further studies of the interactions and feedbacks among these, as well as incorporating multiple other types of disturbances (insect pests and pathogens, logging, infrastructure development, etc). Here we identify and outline three primary questions to address both knowledge and data gaps.

4.3.1.1 What are the broadscale effects and resiliency of tundra to wildfire and the long-term feedback effects on climate? A synthesis of wildfire effects was conducted for both carbon consumption and post fire trajectories across boreal North America (Walker et al. 2020b, Baltzer et al. 2021), and a similar synthesis for the tundra domain has recently been initiated. Most of the North America tundra research for ABoVE has been conducted in Alaska. Limited wildfire activity has been documented in Arctic Canada, but recent increases in Eurasia warrant a broader assessment of wildfire in the tundra biome. Capability to detect smaller fires with more consistent monitoring methods will help to better quantify tundra fire, since most fires in the region are small (French et al. 2015) and the evidence of their occurrence is short-lived (Loboda et al. 2013). Similar to what was done for the boreal biome (see 4.3.1.3 below), there is a need to develop a resiliency framework for arctic ecosystems under a variety of burn severity conditions.

Figure 4 shows post-fire successional trajectories developed from a literature review in arctic tundra and the interactions with burn severity impacts on the soil microenvironment and successional trajectories (Rocha 2021). There is need for more explicit understanding of fire impact on subsurface hydrology that influences vegetation conversion and ecosystem change. Understanding the interactions and feedbacks between warming at high latitudes and altered vegetation patterns and fire regimes (e.g. post-fire recovery) is essential for predicting longer-term climate impacts in ecosystem models.

Future climate warming and increased human activities are expected as the Arctic becomes more accessible with sea-ice loss and longer warm seasons. These variables are anticipated to increase the occurrence of fire in the tundra biome (Dewilde and Chapin 2006, Hu et al. 2015, Young et al. 2017). A more active tundra fire regime could impart an important, but poorly understood, positive climate feedback through increased loss of carbon and species composition shifts (e.g. shrubification). Moreover, post-fire emissions of other important greenhouse gases that are likely to be altered by the wetter post-fire soils, such as methane, are poorly understood and require greater attention. Improved quantification of the long-term carbon balance of tundra fires is needed, especially for the stability and recovery of carbon in severely burned areas and in retrogressive thaw slumps, which ecosystem biogeochemical models indicate take very long to recover to pre-disturbance conditions, especially under a warming climate (Jiang et al., 2017, O'Donnell et al., 2011, Pearce et al., 2015).

Finally, there is also a need to assess the climate forcing and feedbacks of tundra fires associated with large changes in species composition, carbon balance, and surface energy exchange. Such an assessment will require coordinated measurement and modeling activities that can better constrain tundra fire impacts under a non-stationary warming climate.

4.3.1.2 How do site-level drainage patterns, as affected by topography and permafrost presence, influence combustion and post-fire vegetation successional trajectories? Broad scale data on site-level soil drainage conditions is needed for understanding and modeling wildfire behavior, combustion, and post-fire vegetation trajectories. Whether a site is poorly drained or well drained will determine moisture conditions and what vegetation grows there. In turn, the soil drainage will determine soil C loss/accumulation, wildfire susceptibility, depth of burn, and how the site recovers post-fire.

Despite recent advances in advancing the resolution of digital elevation models (DEMs), most of the boreal region (as opposed to the Arctic region) has DEMs that are either low resolution, outdated, or are digital surface models rather than bare-earth elevation. Furthermore, soil drainage is affected not only by topography but also permafrost and, as such, is dynamic. It is thus not surprising that implementing DEM-derived topographic wetness metrics across large areas often does not correlate well with actual conditions. Higher resolution (5-20 m) data are needed for site-level and landscape scale analyses. Methods are needed to map site-level soil drainage conditions, e.g. using time series of SAR backscatter before and after rain events to indicate poor or well drained conditions, with the expectation that sites with well drained conditions will increase in backscatter and then quickly decrease, whereas poorly drained sites will maintain smaller backscatter changes due to rain events. Some progress on this has been advanced as part of ABoVE projects, including use of the airborne SAR data (see SAR section below), but methods and models need to be improved and additional SAR data sources (including the upcoming NISAR mission) could be used to advance this work.

4.3.1.3 What are the drivers of post-fire tree recruitment failure in boreal North America? Two ABoVE wildfire synthesis activities have focused on boreal wildfire effects on carbon combustion (Walker et al. 2020a, b) and fire severity and landscape variability on evergreen conifer tree recruitment, particularly the vulnerability and resiliency of the predominant species, black spruce (Baltzer et al. 2021). While there have been several studies of the effects of wildfire on regeneration and resiliency in the boreal region, better understanding of temporal changes in post-fire successional trajectories is needed. From the synthesis of data across Alaska and boreal North America (Baltzer et al. 2021), a substantial proportion (~10%) of sites experienced tree recruitment failure.

This raises questions about the drivers of recruitment failure and demonstrates the need for a meta-analysis of the processes controlling post-fire germination and seedling establishment in both tundra and boreal systems. The ability to monitor both post-fire soil moisture and nutrient dynamics at the field-scale is needed since they may both be controls on post-fire trajectories after successful seedling establishment. This soil moisture information must be locally relevant since it is highly variable in space and time. Understanding how these controls change with fire severity is critical information to mapping and modeling post-fire succession.

Related, future boreal wildfire is expected to lead to a doubling of the relative dominance of deciduous broadleaf trees, with commensurate declines in contributions from evergreen conifer trees and herbaceous plants (Mekonnen et al. 2019, Foster et al. 2019, Mack et al. 2021). Post-fire deciduous broadleaf tree growth under future climate is sustained from enhanced microbial nitrogen mineralization caused by warmer soils and deeper active layers, resulting in taller trees that compete more effectively for light. Understanding how these shifts are affecting and will affect wildfire regimes (e.g. flammability, fire self-limitation) and climatic feedbacks (e.g. albedo forcing) is needed.

4.4 Hydrology, Snow and Permafrost

Long term monitoring and assessment via field, remote sensing and modeling across regions is needed to more completely understand the amplification of climate warming, wildfire disturbance and the interaction with post-fire hydrology and permafrost thaw (Turetsky et al. 2019). For example, while research conducted during ABoVE thus far has shown cold-season soil respiration is a key component of the tundra carbon budget, contributing substantially to the transformation of tundra ecosystems from land carbon sinks to sources (e.g. Commane et al. 2017, Natali et al. 2019), there is still need for research on how fire disturbance, different snow properties, such as depth and density, and the presence of ice layers, affect the insulative properties of snow, and how they impact multiple processes in ABR ecosystems.

4.4.1 Key Knowledge and Data Gaps Here we summarize key knowledge and data gaps in the context of the ABoVE science objectives related to hydrology, snow and permafrost, as well as related linkages to carbon cycle processes and modeling, and ecosystem services.

4.4.1.1 What is the nature of water cycle intensification and regional impacts? Polar amplification of global warming may be promoting greater intensification of the water cycle in the ABR (Rawlins et al. 2010, Serreze and Barry 2011; Vonk et al., 2019). However, the nature and regional impacts of this intensification are unclear due to sparse observations and associated large uncertainty in nearly all components of the terrestrial water budget (e.g., precipitation, evapotranspiration, surface-snow-soil-groundwater storages, runoff and river discharge). A warmer and longer ice-free season over the Arctic Ocean is contributing to greater and more variable precipitation (Bintanja et al. 2020). At the same time a warmer atmosphere and longer ice-free season may be enhancing evapotranspiration (ET) over land (Zhang et al. 2011), although the magnitudes and spatial and seasonal distributions of regional trends in both precipitation and ET are uncertain. Permafrost degradation and active layer deepening may offset potential ET increases through redistribution of surface water to the subsurface (Walvoord and Kurylyk, 2016, Rawlins et al. 2019; Tank et al., 2020). Regional warming and water cycle intensification may manifest in complex changes in the available water supply supporting ABR ecosystems through asynchronous behavior in precipitation and ET, and non-linear changes in terrestrial water storage and linkages.

Warmer temperatures are also driving a regional decline in the duration of snow cover, although the maximum winter snowpack is projected to increase in continuous permafrost areas and decline in discontinuous permafrost areas (Callaghan et al. 2011, Brown et al. 2021), with uncertain impacts on underlying permafrost and potentially significant feedbacks to the water, energy and carbon cycles (Yi et al. 2015). Snow cover changes are projected to be larger in the shoulder seasons (Thackeray et al. 2019), which should have the greatest impact on ecosystems, surface-atmosphere energy exchange, and hydrological processes (e.g., streamflow). However, sparse observations from Arctic rivers, particularly during the early and late 'shoulders' of the thaw season, represent a major data gap that hinders a fuller understanding of how Arctic ecosystems may respond to warming (Shogren et al. 2020).

River discharge over the pan-Arctic is generally increasing and river seasonality is shifting, with larger winter flows and lower summer flows (Rennermalm et al. 2010), but with large regional variation in the trends (Brabets and Walvoord 2009, Déry et al. 2016). The underlying processes contributing to the discharge increase are uncertain, although contributing factors likely include increasing precipitation, enhanced moisture flux from lower latitudes, degradation of ice-rich permafrost, increasing fire disturbance, and glacial melt (McClelland et al. 2004, Neal et al. 2010, Zhang et al. 2013, Bintanja et al. 2020). Water cycle intensification implies more rapid movement of water through terrestrial storages and transport pathways; however, we know very little regarding the current status of surface, soil and groundwater storages, water residence times, or how water connectivity and associated transport pathways are changing in relation to climate and permafrost changes within the ABoVE domain and across the pan-Arctic (Walvoord and Kurylyk 2016, Jafarov et al. 2018).

4.4.1.2 Is the Arctic-boreal region becoming wetter or drier in a warmer climate? The ABR is warming at roughly twice the global rate and this trend is projected to continue (Meredith et al. 2019). Precipitation is generally increasing with atmospheric warming and an associated decline in Arctic sea-ice (Bintanja and Selten 2014), albeit with uncertain seasonal and regional distributions. Compensating water losses from ET are also expected to increase in a warmer atmosphere, although the rate and distribution of the ET trend is uncertain (Rawlins et al. 2010), while the regional impacts of changing vegetation, permafrost and terrestrial water storages on water availability are also unclear (Walvoord and Kurylyk 2016). Thus, a major uncertainty is whether regional warming and an associated increase in precipitation is leading to wetter or more arid land surface conditions. While hydrological and land surface model simulations suggest that drying of near surface soils may occur (Rawlins et al. 2013, Andresen et al. 2020), the strengthening of environmental restrictions to surface evaporation may help to maintain the presence of regional wetlands in a warmer climate (Liljedahl et al. 2011).

Whether the system is becoming warmer and wetter or warmer and drier has major consequences for the regional hydrology and associated linkages to ecosystems and ecosystem services. The uncertainty is exacerbated by the complexity of degrading permafrost and changing vegetation patterns on the surface hydrology. Regional warming is promoting widespread permafrost degradation, including surface subsidence, deeper active layers and talik expansion (Jones and Arp 2015, Box et al. 2019). The associated increase in soil water storage volume and surface-groundwater interactions may cause a shift from surface to groundwater dominated hydrologic flows (Frey and McClelland 2009), which could alter surface water inundation patterns, including lakes and wetlands, and surface-atmosphere water-energy exchanges (Walvoord and Kurylyk 2016). Landscape variations in surface water trends are spatially complex, but may follow gradients in regional disturbance, with general inundation increases during the initial stages of permafrost thaw, and surface drying in discontinuous and sporadic permafrost areas (Watts et al. 2012, Nitze et al. 2017, Haynes et al. 2018). The pattern, rates and net effect of these changes on the surface water budget are highly uncertain. The degree to which these changes impact water-carbon-energy cycles and linkages, nutrient flows, ecosystem productivity, animal habitats and human systems is also uncertain.

4.4.1.3 What is the impact of degrading permafrost on the hydrologic redistribution and fate of soil organic matter? Arctic warming and the degradation of near-surface permafrost has been relatively well documented (e.g. Serreze and Barry 2011, Biskaborn et al. 2019). These trends are promoting the mobilization and potentially enhanced decomposition of extensive soil organic carbon (SOC) stocks (Schuur and Mack 2018). However, much less is known regarding how permafrost degradation, changing seasonal hydrology and surface-groundwater interactions are influencing the lateral movements and redistribution, transformation and ultimate fate of SOC in these systems. Soil destabilization and mass wasting events from thawing permafrost are becoming more widespread, which can rapidly mobilize and transport large amounts of SOC to adjacent waterways and wetlands (Turetsky et al. 2020). Leaching rates of dissolved organic carbon from lowlands tend to be higher in very young collapse-scar bogs, which also have the highest methane production potential (Treat et al., 2014). Deepening active layers and increasing talik formation is enhancing surface and groundwater interactions, and groundwater entrainment and transport of SOC. The extent of transport, storage and potential release of carbon in these systems is largely unknown, but the ultimate fate of this carbon has significant potential to offset (through long-term storage) or exacerbate (through GHG Emissions) the permafrost carbon feedback (Schuur and Mack 2018). The extent of SOC entrainment and transport also has potentially significant impacts to aquatic ecosystems and water quality upon which human systems depend (Toohey et al. 2016, Mu et al. 2019, Connolly et al. 2020, Schaefer et al. 2020, Vucic et al. 2020).

4.4.1.4 What are the impacts of recent and projected hydrologic changes on human systems? Regional warming is promoting a general increase in annual discharge for rivers across the pan-Arctic (Rawlins et al. 2010). The seasonality of river flows is also changing, including a general increase in winter and advance in the spring freshet, along with lower summer base flows (Walvoord and Striegl, 2007, Duan et al. 2017). Changes in river seasonality have potentially significant impacts on the human systems which depend upon these resources through associated impacts on water supplies and water quality, navigation and hydroelectric generation, and wildlife (e.g., salmon, beaver). Warmer temperatures are reducing the duration and stability of lake and river ice cover, potentially increasing travel risk and isolating regional communities (Brown et al. 2018, Cold et al. 2020). Widespread permafrost degradation and the formation and expansion of talik in many areas is changing lake and wetland distributions, with uncertain impacts to wildlife (Box et al. 2019). Permafrost thaw and associated groundwater discharge have the potential to mobilize increasing amounts of soil organic matter and deliver these carbon and other nutrients to coastal waters (Connolly et al. 2020). The mobilization of sediment and contaminants from degrading permafrost into rivers and lakes may impose risks to human health by contaminating food and water supplies. Regional decreases in the stable frozen and snow-covered seasons are potentially reducing the duration and safety for winter travel, which may increase the isolation and costs of sustaining regional communities and infrastructure (Cold et al 2020). Regional warming is also promoting a general increase in the frequency and severity of climate extremes, including anomalous snowmelt, rain-on-snow (ROS) and icing events (Kim et al. 2015, Pan et al. 2018), with implications for wildlife (especially caribou) as well as spring flooding and summer drought (Buermann et al. 2013, Nilsson et al. 2015).

The individual and aggregate effects of these environmental trends and hydrologic extremes on ecosystem services and sustainable human systems are uncertain, but affect nearly all aspects of human welfare, including water quality and food supply, recreation, transportation, safety and cost of living.

4.4.1.5 How are snow dynamics impacting wildlife and associated ecosystem services?

While global circulation models provide relatively robust future temperature projections given alternative warming scenarios, projected changes in precipitation (including snow and ice) are far less certain (Wrzesien et al. 2018). New data assimilation and modeling approaches that integrate in-situ, remotely sensed (optical and passive microwave), and meteorological data are needed to improve the accuracy of current observations, generate broader suites of available snow products, and increase the predictive accuracy of climate projection models. In addition to these research gaps regarding the snowpack itself, feedbacks between snow properties and wildfires remain a key gap in understanding disturbance regimes of the ABR. Wildfires remove vegetation and organic soils and, in doing so, modify albedo, which can strongly influence snow accumulation patterns and melt rates (Micheletty et al. 2014, Moeser et al. 2020, Uecker et al. 2020). In turn, these changes impact moisture available during the growing season, which may strongly influence post-fire recovery. While these feedbacks have been investigated to some degree in the western US, they have not yet been well examined in boreal forests, which characterized by drier, shallower snowpacks.

ABoVE research has led to several new insights regarding effects of snow conditions on vegetation changes, year-to-year CO2 flux variability, as well as wildlife communities. With respect to the latter, changes in spring snow phenology strongly affect the timing of avian migrations (Oliver et al. 2018, 2020) and survival of young ungulates (van de Kerk et al. 2018), but carnivores may be less sensitive to these changes (van de Kerk et al. 2018, Mahoney et al. 2020, Oliver et al. 2020). These apparent disparities in their sensitivities likely impact interactions among them, with consequences not only for their respective reproductive successes but also for ecosystem functioning (Schmitz et al. 2018). For this reason, understanding how shifts in snow phenology affect both predators and prey in the ABR, especially during the fall season, remains a key knowledge gap.

The role of wildlife in mediating feedbacks between wildfire regimes and boreal vegetation (e.g. patterns of post-fire movements of caribou) is critical to understanding spatiotemporal dynamics in future landscape flammability as the ABR continues to warm. Observational and modeling approaches that integrate animal tracking, remotely sensed landscape status, and meteorological data will provide quantitative understanding of how fire-induced habitat loss and landscape homogenization result in displacement of wildlife and/or reduced biodiversity. Conversely, migration of animals into new domains, e.g. beaver on the North Slope of Alaska, extensively modify hydrology (Jones et al. 2020). These alterations in animal community composition can in turn alter herbivory, carbon and nutrient cycling, thereby shaping the trajectory of vegetation succession which ultimately feeds back to influence landscape flammability.

As noted in the previous question, addressing the cascading implications of shifting snow properties and seasonality on socioecological systems within the ABR ecosystems is needed, as snow and ice conditions greatly impact the ability of residents to travel, hunt, and work (e.g., via ice roads in winter). Observational and modeling approaches that integrate fine spatial and temporal resolution remotely sensed landscape information and meteorological data will enable quantitative understanding of how factors such as the timing of fall leaf-off and snow-on dates are changing and affect wildlife viewing and successful hunting for subsistence communities, and how seasonality in stream and river water levels affects lake connectivity that is critical to fisheries.

4.5 SAR Remote Sensing for Monitoring Permafrost Landscape Change

Synthetic Aperture Radar provides a powerful tool to measure surface characteristics that help address the science questions or fill the gaps identified by several other ABoVE working groups, including but not limited to Disturbance, Hydrology and Permafrost, and Carbon Dynamics. Its ability to return observations under all weather conditions is a major advantage in the ABR, where persistent cloud cover is challenging for optical remote sensing. In terms of missing or underdeveloped parameter estimation using SAR, the gaps tend to fall in three general categories: infrastructure, coverage, and algorithms. Infrastructure refers to limits in instrumentation, organizational support, and data processing techniques. Coverage refers to limits in data extent in space and time required to meet science objectives. Algorithms refer to areas where we need to develop or adapt the SAR retrievals required to answer open science questions, test hypotheses, or develop practical applications.

4.5.1 Cold Season Snow Properties

Winter snow conditions influence permafrost, ecosystem, carbon cycle, and hydrology dynamics all year round, but ABoVE projects have largely focused on summer growing season conditions. Only a handful of projects study winter snow conditions, yet most of the ABoVE working groups identify snow as a critical, but missing factor (see previous section). To address this gap, ABoVE leadership has been working towards collaborations with SnowEx (Snow EXperiment) campaigns supported by the NASA Terrestrial Hydrology program. This coordination effort has been delayed by ongoing SnowEx campaigns in the conterminous US and also set back by the global COVID-19 pandemic, but has recently advanced with plans for coordinated ABoVE – SnowEx campaigns in 2022-23.

Coordinated SAR data acquisitions can play a key role in characterizing winter snow conditions using both backscatter and interferometric SAR (InSAR). Basic SAR capabilities and infrastructure in Ku-band, X-band, L-band and P-band already exist. While Ku-band has been the most exploited for measuring snow conditions, the capabilities of other SAR frequencies may provide valuable contributions to retrievals of snow properties, such as snow water equivalent (SWE). Snow algorithms for various SAR bands have been developed but validation and algorithms appropriate to Arctic conditions remain limited and little explored. SAR data thus have the potential to help fill major gaps in our knowledge of winter snow conditions, and coordination with SnowEx will help move this research forward.

4.5.2 Deriving Data Products of Permafrost Properties from Past and Future Satellite Missions

To answer primary ABoVE science questions and objectives (Tables 1-2), NASA and the broader research community need data that extend across decades. A long-term SAR record can be used to address basic questions about permafrost, hydrology and ecosystem dynamics identified by the various ABoVE working groups. The airborne campaign data cover several years already, with additional acquisitions planned, but only for areas where flight lines have been or will be acquired. NASA and the broader earth observation community (e.g., the international Committee on Earth Observations Satellites, CEOS) do not have capabilities for systematically mapping the subsurface properties of permafrost landscape prior to launch and commissioning of the upcoming NISAR mission. Past satellite coverage in permafrost regions is sporadic in both space and time. Efforts to combine and calibrate records from different satellites and across SAR wavelengths are needed to measure long-term changes in permafrost properties and changes through time.

The NISAR L-band satellite mission has monitoring permafrost landscapes as one of its core objectives but has no defined permafrost data products to be generated. Algorithm development is a priority in order to have permafrost data products ready in time for use by the ABoVE science team and other members of the research community over the next decade, a period which is expect to experience extensive changes in high latitudes permafrost environments. The NISAR instrument, coverage and repeat cycle are well aligned with requirements for monitoring permafrost landscapes. Existing algorithms can measure subsidence and, to some extent, active layer thickness for small, scattered patches across the landscape, but efforts are needed to scale these existing algorithms and to advance other approaches to ensure meaningful derivation of permafrost properties from the landscape to pan-Arctic extents.

4.5.3 Decoupled Aboveground Biomass and Soil Moisture Estimation

One of the biggest gaps in SAR research lies in the development of algorithms to tease apart backscatter signals from aboveground biomass versus attenuation relative to volumetric soil moisture. Soil moisture is a key variable required for improving our collective understanding changes in permafrost, ecosystem, fire and vegetation dynamics. Aboveground biomass remains a key variable in ecosystem and carbon cycle dynamics (see section 4.2). The biomass signal represents noise to some, but signal to others, and vice versa for soil moisture. As a result, soil moisture and biomass algorithms are often developed independently, whereas they need to be developed together via simultaneous solutions in retrieval algorithms. This is particularly challenging in that the low stature of trees, shrubs and tussocks, coupled with cold, wet soils make algorithms designed for temperate and tropical zones ineffective in the ABR. Moreover, current algorithms typically assume mineral soils, rather than the organic soils typically found in permafrost regions. Algorithms focused that account for both vegetation and soil conditions to simultaneously estimate biomass and soil moisture are critically needed to advance utilization of SAR data in the parts of the ABR with permafrost.

4.5.4 Monitoring the Built Environment

Robust techniques are needed to monitor the vulnerability of the built environment to changes in permafrost, particularly in areas subject to subsidence as a result of permafrost thaw. When ice melts and the ground subsides, crucial infrastructure such as pipelines, highways and buildings are vulnerable to damage and supply chain disruptions. SAR data can be used to monitor subsidence and to detect infrastructure movement, advancing the potential for preventative measures rather than expensive repair and replacement costs. Efforts are needed to calibrate and advance existing algorithms to monitor potential disruption to key elements of the built environment in the ABR.

4.6 Carbon Dynamics

The carbon cycle system of the ABR is in transition (Box et al. 2019, Meredith et al. 2019). In order to evaluate the future direction of the ABR carbon cycle and associated carbon-climate feedbacks, we require comprehensive knowledge of its current state, its response to environmental change and process-level understanding of the relative contributions of various drivers of change and their interactions. For example, it is evident that the ABR terrestrial environment, particularly within the ABoVE study domain, has come under increasing pressure due to higher temperatures and altered precipitation patterns (see section

4.4), which has in turn led to altered plant growth, increased permafrost thaw, and enhanced lateral flows of carbon through freshwater systems and coastal erosion.

How the ABR carbon cycle will continue to respond to such environmental changes, what the fate of the northern high latitude soil carbon pool and the ecosystems will be, and the extent to which it will impact the trajectory of the ABR carbon balance (net sink, net source, or approximately neutral) remain uncertain. In addition, both wildfire and pest-pathogen outbreaks (section 4.3) can have significant effects on both the short- and long-term carbon cycling processes and shift ecosystems from net sinks to near neutral, or even net sources (e.g. Commane et al., 2017).

4.6.1 What is our current understanding of carbon cycle dynamics over the ABoVE domain As part of ABoVE research, carbon cycle studies are motivated by one of the fundamental science questions identified in the Concise Experiment Plan (2015): *How are the magnitudes, fates, and land- atmosphere exchanges of carbon pools responding to environmental change, and what are the biogeochemical mechanisms driving these changes*? This focus has led to a diverse array of studies focused on science-driven data collection within the first phases of ABoVE research. Analyses thus far have focused on a full spectrum of spatial scales, from plot-scale measurements of CO2 and CH4 fluxes to obtain process-level understanding of relevant drivers (Helbig et al. 2020, Natali et al. 2019) to broader scale regional measurements of atmospheric CO2 and CH4 concentrations derived from airborne campaigns and tall towers that focus on identifying processes unique to the northern high latitudes, which are highly uncertain or misrepresented in our current suite of regional and global models (Zona et al. 2016, Commane et al. 2017, Jeong et al. 2018, Sweeney et al. 2020). In addition, measurement of variables from CO2 isotopologues to total dissolved nitrogen and phosphorus are being made at a variety of in situ locations. These measurements are now providing knowledge about ecosystem processes and their interactions that control the production, transformation and carbon residence time in various pools across the ABoVE domain (Bogard et al. 2019, Wickland et al. 2018).

Knowledge gained from these studies have provided fundamental process-based insights into: (a) how changes in climate and disturbance are driving changes in vegetation, soil temperature, and the hydrological cycle, which in turn are affecting aboveground biomass, net primary productivity, heterotrophic respiration, and soil organic carbon production (Yi et al. 2020, Montesano et al. 2020, Mekonnen et al. 2019), (b) the role of increased drought stress and fire disturbance on ecosystem productivity, response and post-fire recovery (Wang et al. 2019, Dieleman et al. 2020), (c) quantifying changes in phenological cycle, both magnitude and amplitude, especially due to summer carbon uptake becoming increasingly offset by release of carbon from soils during the fall and early cold seasons (Commane et al. 2017, Parazoo et al. 2018, Natali et al. 2019, Liu et al. 2020, Lin et al. 2020), and (d) underestimation of methane fluxes at the ecosystem to regional scale, in part due to the low solubility of methane in water leading to ebullition (bubbling) flux to the atmosphere that is heterogeneous in time and space (Sweeney et al. 2016, Miller et al. 2016, Peltola et al. 2019, Elder et al. 2020, 2019). Lessons learnt from these and ongoing studies are helping to understand how climate change and disturbance events interact with above- and belowground communities and processes to alter carbon biogeochemistry, including the transfer and release of carbon from one carbon pool to another (e.g., terrestrial ecosystems to surface waters or to the atmosphere). These studies are also providing novel insights into how source-sink dynamics of the northern high-latitude ecosystems, especially within the ABoVE domain, are undergoing profound and predictable shifts as both climate and atmospheric composition evolves.

4.6.2 What are the current carbon dynamics knowledge and data gaps? As we prepare to enter the third phase of ABoVE, focused on analysis and synthesis of datasets that have been and are being collected, and integration of those datasets with our modeling frameworks, four key knowledge gaps centered on carbon dynamics come to the fore.

4.6.2.1 Addressing uncertainty in carbon budget estimates. The carbon budget of the ABoVE domain remains highly uncertain. While it is clear the region acted as a net carbon sink as carbon accumulated in terrestrial ecosystems over the Holocene, there is little agreement (outside of specific site locations) on whether changing climate in the modern period has shifted these ecosystems into net carbon sources. Resolving the current budget and fully quantifying the current state is needed to project changes that may occur in the future. This is a focus of one of the ongoing Carbon Dynamics working group synthesis activities but will require further resolution in the final phase of ABoVE.

4.6.2.2 Addressing processes in the shoulder seasons. Our ability to understand the processes dominating the carbon cycle (both carbon dioxide and methane gases) at the start and end of the growing seasons is inadequate – a concerted effort is needed to identify when these changes are happening (as the growing season is itself evolving), observe these changes via in situ and remote sensing assets (or a combination thereof) and then conduct targeted assimilation experiments to inform and improve our models.

4.6.2.3 Incorporating disturbance. Disturbance regimes in the ABoVE domain are changing and intensifying. Which of these disturbances are changing the fastest or are the most climate sensitive and which of these have the largest influence on carbon fluxes? Fire combustion of organic soils, in particular, emits vast quantities of CO2 to the atmosphere that can offset a large proportion of the annual uptake from net primary production (Walker et al. 2019). Continued long-term monitoring at existing sites and continuing observational data streams will be needed to provide a long-term stable context to interpret the changes that are occurring and facilitating the attribution of the resultant fluxes to specific disturbance events.

4.6.2.4 Improving carbon cycle model representation. Our current generation of ecosystem and Earth system models are still limited in representing ABR carbon cycle processes (Fisher et al. 2018, Huntzinger et al. 2020, Wright and Rocha 2018). Carbon cycle models must be able to simulate varied ecosystem responses to environmental changes at multiple spatial and temporal scales, and the corresponding effects on ecosystem productivity and net carbon uptake to estimate realistic and credible carbon-climate feedbacks (Grosse et al. 2016, Schuur & Mack 2018, Holloway et al. 2020). These models rely on bottom-up parameterizations based on inventories and other ground-level data, but continued availability of site-level, airborne and remote sensing data provide an opportunity to inform and improve these model estimates. This is addressed in more detail in the following section.

Ultimately observational networks, both *in situ* and space-based, will be needed to detect potential carbon cycle changes and emissions, and to provide early warning of phenomena we do not yet understand (Duncan et al. 2020). Addressing these critical uncertainties will require a coordinated observation effort over the land, atmosphere, coastal and anthropogenic domains, together with coupled carbon-climate models and advanced data assimilation systems.

4.7 Ecosystem Modeling

As noted at the outset and reiterated in the previous section, the ABR is the source of large uncertainties in global climate projections (Fisher et al. 2018a, Meredith et al. 2019). As such, improving the representation and accuracy of processes, sensitivities, and dynamics in terrestrial biosphere models (TBMs) (Fisher et al. 2014) for this region motivates the key objectives of ABoVE research. There are three primary reasons why TBM uncertainties are large for the ABR (Fisher et al. 2018a): (1) Processes: the extreme environments in ABR ecosystems do not function like those in most of the world; (2) Data: field data in the ABR have been sparse, thus challenging in terms of understanding and parameterizing processes; (3) Scale: the land mass of the ABR is the largest of any biome on Earth, thus small errors in assumptions or process representation operating at fine scales compound to create large uncertainties. Despite these challenges, ABoVE research has advanced our capabilities for modeling ecosystem processes but substantial gaps remain. We outline some of the advances and the primary gaps here.

4.7.1 Process Level Understanding There has been a sustained effort in improving vegetation phenology and sensitivity to environmental drivers across TBMs. Phenology is sensitive to the intertwined trifecta of air temperature, soil temperature, and soil moisture, which in turn alter photosynthesis, respiration, carbon allocation, and hydrology (Parazoo et al. 2018a, Parazoo et al. 2018b, Arndt et al. 2019, Birch et al. 2020, Shi et al. 2020a, Wang et al. 2020, Zhang et al. 2020a). Similarly, permafrost dynamics and talik formation are strongly tied to snow cover, necessitating careful treatment of vertically-resolved soil porosity and thermal conductivity to determine the vulnerability and loss of the massive soil carbon stores and exposure of pollutants (Huntzinger et al. 2020, Jafarov et al. 2020, Jan et al. 2020, Schaefer et al. 2020, Yi et al. 2020). Still, there persist known links of permafrost dynamics to soil moisture and temperature that have yet to be fully integrated into TBMs. Moreover, process representation of disturbances such as fire dynamics (i.e., intensity, mortality, combustion) and thermokarst—and associated land cover change—are underdeveloped in most TBMs. Likewise, methane emissions and underlying wetland dynamics also present a known weakness in TBMs (Saunois et al. 2016, Zona et al. 2016). Finally, linking TBM ecosystem dynamics to social outcomes in integrated assessment models remains a final frontier for reducing the large uncertainties of future land and energy use aligned with climate mitigation targets.

4.7.2 Data Needs for Model Parameterization and Performance We are currently in a golden age of terrestrial and atmospheric remote sensing, and intensive airborne and field campaigns in the ABR have considerably expanded data availability over the last decade (Miller et al. 2016, Fisher et al. 2018a). While modeling has motivated data collection, the data collected now motivate intensive modeling investigations (Fisher et al. 2018a). These data are critical for improving and benchmarking TBMs (Stofferahn et al. 2019, Duncan et al. 2020). Data encompass vegetation structure (e.g., biomass), composition (e.g., canopy chemistry/traits), and function (e.g., photosynthesis, evapotranspiration), as well as soil carbon age, active layer thickness, wetland distributions, and the environmental drivers that affect them (Michaelides et al. 2019, Rogers et al. 2019, Salmon et al. 2019, Shi et al. 2020b, Zhang et al. 2020b). Nonetheless, ABR data integration into TBMs has only just begun, and assimilation frameworks are underway to integrate a larger array of these valuable data.

4.7.3 Advancing Process Integration Across Scales The last frontier of integrating process with data is by scale across both space and time. There has been progress in scaling tree-level interactions among soil, permafrost, wildfire, and climate—and connecting these to climate-coupled models with demography, hydrological response unit tiling, and vector-based tracking—though vegetation migration remains a challenge (Fisher et al. 2018b, Foster et al. 2019, McDowell et al. 2020). Scaling polygonal tundra, once a major barrier in TBMs, is now possible using intermediate scale models for hydrology (Clark et al. 2015, Jan et al. 2018). For measurements, a hierarchy of towers, drones, aircraft, and spacecraft enable upscaling structural and functional traits through high-resolution optical, thermal, lidar and SAR observations (Serbin et al. 2019, Yang et al. 2020). Still, further work is needed to more strongly connect remotely sensed data to biophysical properties, and high spatial resolution meteorological data are required for higher resolution model runs (Morrison et al. 2019). Top-down flux inversions of atmospheric CO2 measurements with improved-resolution transport models provide large-scale constraints on net CO2 fluxes at increasingly higher spatial resolutions (Hu et al. 2019, Byrne et al. 2020, Sweeney et al. 2020). Incorporation of carbonyl sulfide (OCS/COS) will enable a step-change in our ability to disentangle gross from net CO2 fluxes (Whelan et al. 2020). However, there are elusive aspects of the landscape that remain difficult to scale and model. These include topographically fine-scale processes such as thermokarst and insect disturbance (and associated impacts on hydrology and carbon cycling), as well as harder-to assess dynamics such as thaw depth and lateral hydrological movement (Michaelides et al. 2019).

We have learned much about processes in a modeling context within the past decade. We can quantify the impact on carbon cycling from phenological and permafrost sensitivity to environmental drivers, and uncertainty reductions through incorporation of remotely sensed structure, composition, and function. We have charted paths on how to scale fine-grain vegetation and surface properties both in models and measurements. Yet, we also have roadmaps not yet traveled from *process* (e.g., permafrost dynamics, disturbance, methane), *data* (e.g., contiguous high spatial resolution data, spectral interpretation, assimilation frameworks), and *scale* (e.g. lateral movement, vertical dynamics). It is important we follow these roadmaps to guide the path of future research.

5. Summary and Way Forward

ABoVE research has advanced our understanding of the multi-dimensional processes shaping terrestrial (including aquatic) ecosystem changes underway in the Arctic-boreal region, particularly but not exclusively in North America. The scope of ABoVE, in terms of the breadth and depth of the science team, has allowed us to not only conduct unprecedented coordinated airborne and *in situ* field measurement campaigns (with more planned), but also to substantially advance multidisciplinary research across a diverse range of working groups focused not just on individual projects but also larger integrated efforts and synthesis activities. Some of those advances were highlighted herein, with many more "in the pipeline", but there are clearly still significant challenges ahead in terms of addressing knowledge and data gaps. We have focused on those here to guide future research, not just for ABoVE's final synthesis phase but also for other large scale interdisciplinary research efforts ongoing elsewhere (including via our partners) as well as those likely to follow in the years ahead, after ABoVE comes to completion. Addressing these gaps will help advance process level understanding and associated prognostic modeling. We hope it will also raise awareness of the rapid changes already underway across the circum-Arctic and boreal domain, and inform policies designed to avert changes that adversely impact ecosystems and the communities which live in them.

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Figure Captions

Figure 1. Schematic of vulnerability – resiliency framework showing ABoVE research in the context of addressing the causes of change (drivers), the subsequent changes to ecosystems (impacts), the influence on ecosystem services (implications), and the social systems (responses) that cycle back to addressing the drivers. Also show is the ABoVE scaling approach that hierarchically links measurements

varying in resolution from the leaf level to plots, towers, aircraft and satellites which, in turn, inform models. Each level of resolution increases the extent of area encompassed.

Figure 2. Thematic areas of ABoVE research, which generally correspond with the working groups described in sections 2-4. Airborne platforms and the sensors they deployed are indicated. The extent of data acquisitions is shown in Figure 3. Details of the various instruments flown are provided in Miller et al. 2019.

Figure 3. ABoVE study domain with airborne instrument flightlines showing where data were collected in the snow-free months of 2017 through 2019. Many of the sites where field data were collected are indicated as dots and, by design, generally align with airborne data acquisitions.

Figure 4. Post-fire successional trajectories in arctic tundra and their interactions with burn severity impacts on the soil microenvironment and climate change. Trajectories in severely burned tundra increase soil subsidence and the likelihood of retrogressive thaw slumps due to warmer, deeper and wetter post-fire soils. Severe burns tend to shift vegetation communities from graminoid to shrubs 10-30 years post-fire, due to changes in hydrology and nutrient availability. The soil thermal environment is less impacted in low/moderate severity burns, resulting in successional trajectories that return to their pre-fire community composition and C balance. Climate change will result in more severe fires that interact with climate to catalyze biome shifts from tundra to tall deciduous shrub and tree communities.

Author ORCIDs

Goetz	0000-0002-6326-4308
Miller	0000-0002-9380-4838
Griffith	0000-0002-4267-7429
Chatterjee	0000-0002-3680-0160
Laura Borgeau-Chavez	0000-0001-7127-279X
David Butman	0000-0003-3520-7426
Joshua Fisher	0000-0003-4734-9085
Nancy French	0000-0002-2389-3003
Hoy	0000-0002-0104-5118
John Kimball	0000-0002-5493-5878
Tatiana Loboda	0000-0002-2537-2447
Michelle Mack	0000-0003-1279-4242
Mahta Moghaddam	0000-0001-5304-2616
Michael Rawlins	0000-0002-3323-8256
Brendan Rogers	0000-0001-6711-8466
Kevin Schaefer	0000-0002-5444-9917

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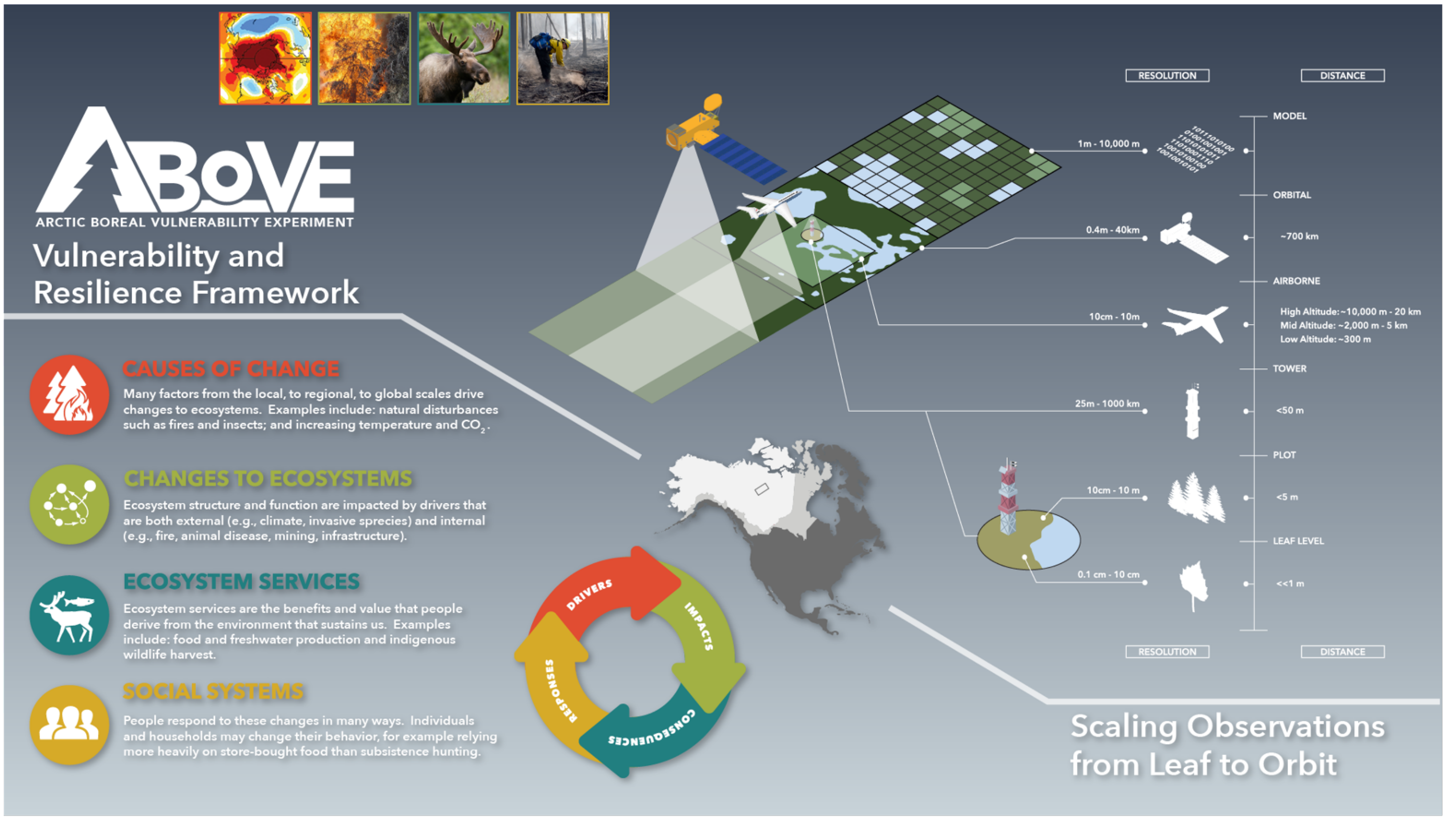


ABoVE

ARCTIC BOREAL VULNERABILITY EXPERIMENT

Vulnerability and Resilience Framework

CAUSES OF CHANGE

Many factors from the local, to regional, to global scales drive changes to ecosystems. Examples include: natural disturbances such as fires and insects; and increasing temperature and CO_2.

CHANGES TO ECOSYSTEMS

Ecosystem structure and function are impacted by drivers that are both external (e.g., climate, invasive sprecies) and internal (e.g., fire, animal disease, mining, infrastructure).

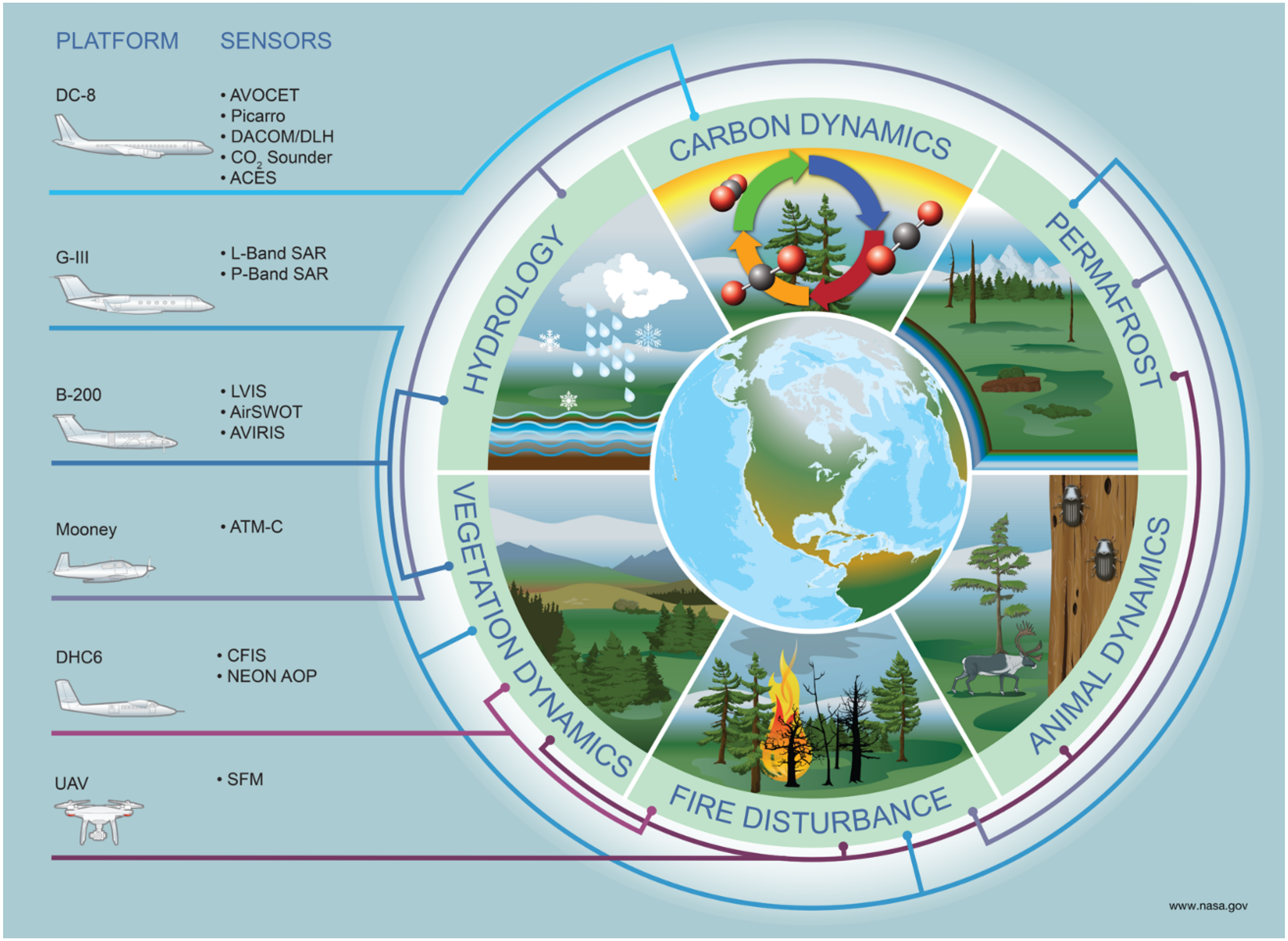
ECOSYSTEM SERVICES

Ecosystem services are the benefits and value that people derive from the environment that sustains us. Examples include: food and freshwater production and indigenous wildlife harvest.

SOCIAL SYSTEMS

People respond to these changes in many ways. Individuals and households may change their behavior, for example relying more heavily on store-bought food than subsistence hunting.

Scaling Observations from Leaf to Orbit



PLATFORM	SENSORS
DC-8	• AVOCET • Picarro • DACOM/DLH • CO_2 Sounder • ACES
G-III	• L-Band SAR • P-Band SAR
B-200	• LVIS • AirSWOT • AVIRIS
Mooney	• ATM-C
DHC6	• CFIS • NEON AOP
UAV	• SFM

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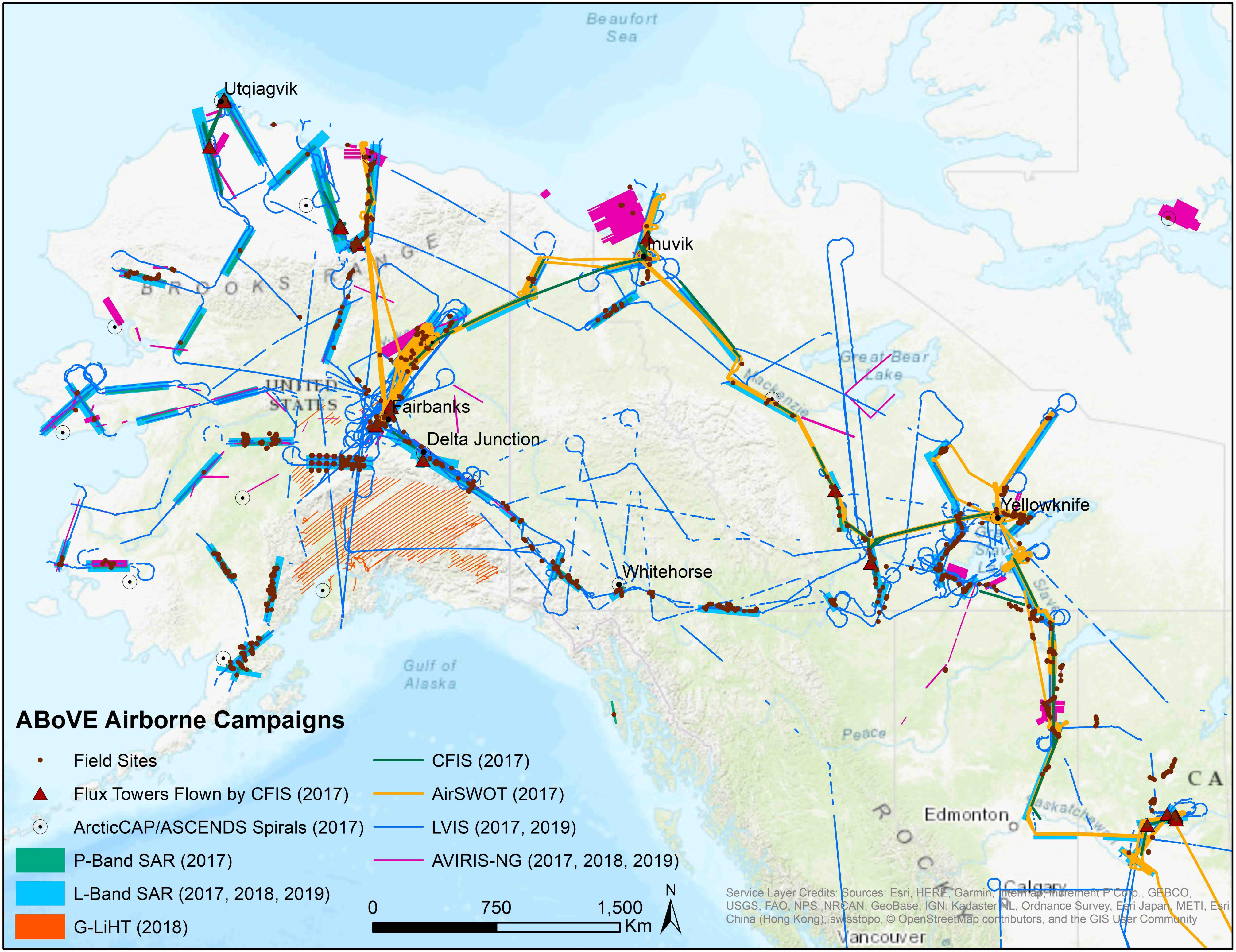

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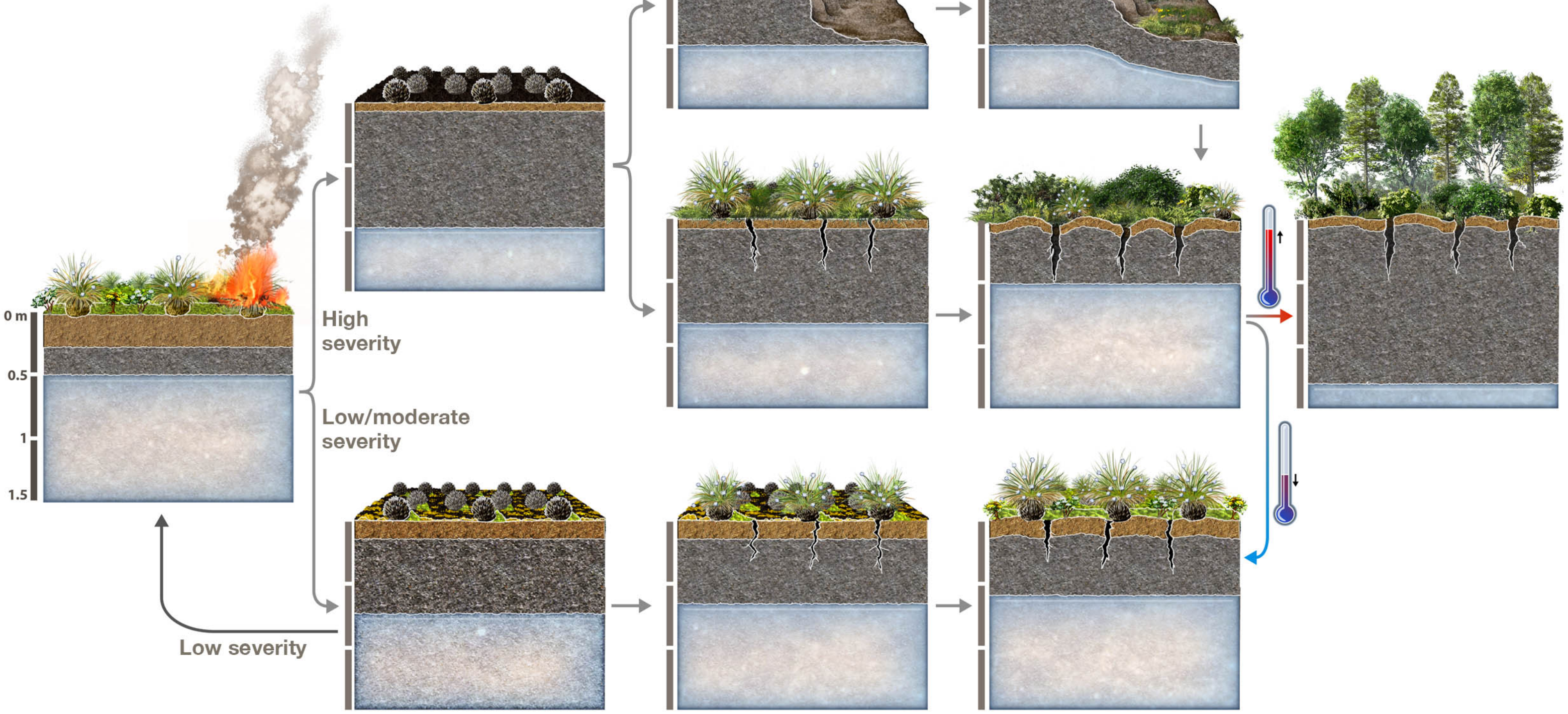
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High severity
Low/moderate severity
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Table 1. ABoVE thematic Science Questions

A) Ecosystem Dynamics:

1. *Disturbance Regimes*: What processes are contributing to changes in disturbance regimes and what are the impacts of these changes?
2. *Permafrost*: What processes are controlling changes in the distribution and properties of permafrost and what are the impacts of these changes?
3. *Hydrologic System*: What are the causes and consequences of changes in the hydrologic system, specifically the amount, temporal distribution, and discharge of surface and subsurface water?
4. *Flora and Fauna*: How are flora and fauna responding to changes in biotic and abiotic conditions, and what are the impacts on ecosystem structure and function?
5. *Carbon Pools and Fluxes*: How are the magnitudes, fates, and land-atmosphere exchanges of carbon pools responding to environmental change, and what are the biogeochemical mechanisms driving these changes?

B) Ecosystem Services:

1. How are environmental changes affecting critical ecosystem services - natural and cultural resources, human health, infrastructure, and climate regulation.
2. How are human societies responding?

Table 2a. ABoVE Science Objectives: Ecosystem Dynamics

1. *Permafrost Vulnerability Resilience*: Determine how interactions among vegetation, soil characteristics, hydrology, and disturbances influence surface energy exchange and mediate permafrost vulnerability and resilience to climate change.
2. *Microbes, Plants, Animal Interactions*: Determine how and where interactions among microbes, plants, and animals exert control over ecosystem responses to climate change and disturbances.
3. *Vegetation, hydrology, disturbance interactions*: Understand how vegetation attributes and hydrologic conditions interact, and respond and feedback to disturbance.
4. *Snow Impacts*: Quantify how changes in the spatial and temporal distribution of snow impacts ecosystem structure and function.
5. *Vegetation Productivity Changes (Greening and Browning)*: Determine the causes of greening and browning trends and their impacts on ecosystem form and function.
6. *Controls on Carbon Biogeochemistry*: Elucidate how climate change and disturbances interact with above- and belowground communities and processes to alter carbon biogeochemistry, including release to surface waters and the atmosphere.
7. *Changes to Fish and Wildlife Habitat*: Determine how the spatial and temporal dynamics in both faunal abundance and characteristics of fish and wildlife habitat co-vary across gradients of climate and disturbance.

Table 2b. ABoVE Science Objectives: Ecosystem Services

1. *Transportation & Infrastructure*: Assess how future climate warming is likely to affect infrastructure and transportation networks.
2. *Human Health*: Determine how changes to disturbance regimes, flora and fauna, permafrost conditions, and/or hydrology influence human health outcomes in the ABR.
3. *Subsistence*: Evaluate how changes to ecosystems will influence subsistence opportunities.
4. *Land Management*: Analyze how changes to natural and cultural resources will impact local communities as well as influence land management policies and practices.
5. *Climate Regulation*: Determine the sources of variations in climate feedbacks from Arctic and boreal ecosystems and assess the potential for future changes to climate regulating services at regional to global scales.
6. *Ecosystem Services Interactions*: Determine the degree to which changing environment and altered human activities result in synergistic or antagonistic changes in ecosystem services.

Table 3. Knowledge gaps needed to address science objectives for (a) ecosystem dynamics, (b) ecosystem services. Numbers in column 2 refer to sections of the paper. Section 4.7 (Ecosystem modeling) is cross cutting. The science objectives are briefly described in Table 2.

(a) Science Objectives – Ecosystem Dynamics	**Knowledge Gaps**
Permafrost Vulnerability Resilience	4.3, 4.4, 4.5, 4.6
Microbes, Plants, Animal Interactions	4.3, 4.4
Vegetation, hydrology, disturbance interactions	4.1, 4.2, 4.3, 4.4
Snow Impacts	4.1, 4.2, 4.4, 4.6
Vegetation Productivity and Structure Changes	4.1, 4.2
Controls on Carbon Biogeochemistry	4.2, 4.3, 4.6
Changes to Fish and Wildlife Habitat	4.1, 4.2, 4.4

(b) Science Objectives – Ecosystem Services	**Knowledge Gaps**
Transportation & Infrastructure	4.3, 4.4, 4.5
Human Health	4.3
Subsistence	4.1, 4.4, 4.5
Land Management	4.3, 4.4
Climate Regulation	4.1 – 4.6
Ecosystem Services Interactions	4.3, 4.4,