A Notional Airborne Science Research Strategy for NASA's Arctic Boreal Vulnerability Experiment (ABoVE)

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This document expresses the opinions of the ABoVE Airborne Science Working Group and other interested parties. It does not represent the views of NASA.

Executive Summary:

This document explores possible integrated airborne science research strategies for NASA's Arctic Boreal Vulnerability Experiment (ABoVE). ABoVE airborne research will link field-based, process-level studies with geospatial data products derived from satellite remote sensing, spanning the critical intermediate space and time scales that are essential for a comprehensive understanding of scaling issues across the ABoVE Study Domain and extrapolation to the pan-Arctic. ABoVE airborne campaigns can provide remote sensing data with higher spatial and temporal resolution than available from satellite sensors as well as measurements that are not currently available from space. ABoVE airborne campaigns provide unique opportunities to validate satellite data for northern high latitude ecosystems, develop and advance fundamental remote sensing science, and explore and exploit new scientific insights from innovative sensor combinations.

ABoVE is driven by the question:

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

To address this overarching question, research during ABoVE is organized around six Science Themes that represent critical aspects of Arctic and boreal social-ecological systems: society, disturbance, permafrost, hydrology, flora and fauna, and carbon biogeochemistry. ABoVE airborne campaigns must coordinate timing, flight lines, sensor suites, etc to maximize scientific benefit and ensure delivery of critical data over ABoVE field investigations. The size and ecological complexity of the ABoVE experimental domain further complicates the development an integrated airborne remote sensing research strategy.

ABoVE envisions major airborne campaigns in 2017 and 2019 with the potential for less comprehensive bridging activities in 2018. The strategy involves Foundational Measurements made with the NASA facility instruments UAVSAR and AirMOSS on the G-III and LVIS, AVIRIS-NG, HyTES and PRISM on the ER-2 (or alternate platform configurations). These will provide domain-wide sampling and coverage of ABoVE field sites. Additional measurements can be made by other sensors with an emphasis on higher resolution coverage over specific field sites or portions of the experimental domain. The strategy will seek to leverage complementary NASA airborne activities such as ICEBridge and SnowEx, pre-launch airborne acquisitions for NISAR, HyspIRi and ASCENDS, as well as activities sponsored by partner agencies. Coordination with ongoing or planned Canadian airborne remote sensing (eg lidar-based boreal forest inventories) would be a key aspect of this strategy.

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1 Introduction & ABoVE Study Area

NASA's Arctic Boreal Vulnerability Experiment (ABoVE) is planned to be a 9- to 10-year field campaign sponsored by the Terrestrial Ecology Program focused on a large-scale study of environmental change in the Arctic and boreal region of western North America and its implications for social-ecological systems. ABoVE science is driven by the question:

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

To address this overarching question, research during ABoVE is organized around six Science Themes that represent critical aspects of Arctic and boreal social-ecological systems: society, disturbance, permafrost, hydrology, flora and fauna, and carbon biogeochemistry. A detailed explanation of ABoVE's scientific questions, objectives, and their motivation is provided in the *ABoVE Concise Experiment Plan* <http://above.nasa.gov/acep.html>. Airborne science research is an important element of ABoVE. Airborne measurements have the potential link field-based, process-level studies with geospatial data products derived from satellite remote sensing, spanning the critical intermediate space and time scales that are essential for a comprehensive understanding of scaling issues across the ABoVE Study Area and extrapolation to the pan-Arctic.

The ABoVE Study Area includes most of northwestern North America west of Hudson Bay and north and east of the coastal mountain ranges: Alaska, the Yukon and Northwest Territories (**Fig 1**). It encompasses the variability in the key land surface features that are both unique to Arctic and boreal ecosystems in North America as well as being representative of the larger Northern High Latitude region.

- The **Core Study Region** captures the regional-scale variations in surface and atmospheric conditions necessary to address ABoVE science questions and objectives. It includes landscapes and ecoregions that are rapidly changing in complex ways as well as others that are not yet changing – a combination that allows for studies on both vulnerability and resilience.

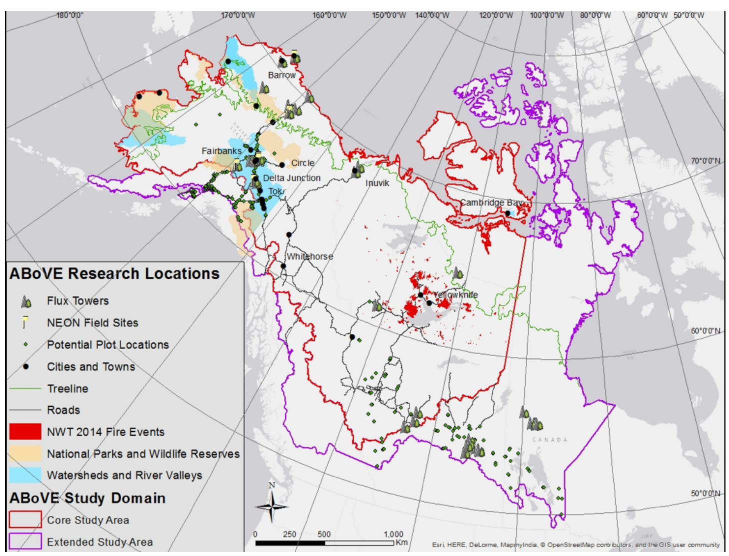

***Fig 1**. The ABoVE study domain showing the Core and Extended Study Regions as well as the location of field sites operated by the ABoVE Science Team. For more details and other maps, see http://above.nasa.gov/geospatial_map.html*

- The **Extended Study Region** borders the Core Study Region, which allows for studies focused on a subset of important changes that are not occurring in the Core Study Region (for example, insect outbreaks and forest dieback in the southern boreal forest). The Extended Study Region includes areas where research can focus on environmental conditions that might characterize those in the Core Study Region in the near future.

2 Scaling Issues & A Strategy for Sampling the ABoVE Domain

Understanding the vulnerability and resilience of the socio-ecological systems in the ABoVE domain requires knowledge of ecosystem state properties, environmental controls, processes and dynamics across multiple space and time scales. The science questions, remote sensing and monitoring tools, and integration and modeling tools used by ABoVE researchers will necessarily vary with the space and time scale(s) under consideration. Additionally, we expect the dominant processes and controls to vary across scales and for emergent properties to manifest themselves at larger space and time scales.

Microtopography controls many aspects of ecosystem, permafrost and hydrologic dynamics at site to local scales (< 1 m to ~100 m). Landscape scale (100 m to 10 km) dynamics shift to the consideration of lakebed history, habitats, disturbance patterns and small watersheds. Meso- and regional-scale (10 km to 1000 km) dynamics reflect the characteristics of ecoregions, bioclimatic zones and their gradients.

Sampling across time scales from hours to centuries is also essential for ABoVE science and provides unique challenges. Processes that occur on time scales much longer than the 10-year duration of ABoVE – such as fire recovery, shrubby encroachment, thermokarst and permafrost degradation, peatland bog-fen evolution, etc. – may be studied through sampling known chronosequences or by using space for time trades (eg using the Seward Peninsula as a proxy for a future North Slope). Hourly, daily, seasonal, annual and interannual time scale sampling will also be key to enabling ABoVE researchers to characterize fundamental processes, the differences between pulse and push forcings, and abrupt, discontinuous state changes due to disturbance events.

A key challenge for ABoVE researchers will be to develop models that accurately integrate the range of data acquired from field studies, airborne measurements, and satellite remote sensing. Approaches that enable both accurate upscaling and downscaling of ecosystem dynamics across the range of space and time scales of interest to ABoVE has to date proven elusive [Vörösmarty et al., 2010].

The ABoVE airborne science sampling strategy should therefore deliver data that span the space and time scales of data acquired at ABoVE field sites and remote sensing observations returned from satellite instruments. The strategy must also deliver data that challenge models, particularly their scaling properties, and enable their improvement. The strategy must also sample space, time, and biogeophysical gradients across the vast and diverse ABoVE Study Area.

The ABoVE Science Team developed a multi-pronged strategy to address these requirements

- **Foundational Airborne Measurements** will deliver cross-cutting remote sensing data from UAVSAR, AirMOSS, LVIS, AVIRIS-NG along Alaskan and Canadian circuits that sample critical ecosystem, vegetation, climatic regions and gradients to characterize landscape to regional scale properties and dynamics across the ABoVE domain. Supplemental Flight Lines extend the hierarchical spatial sampling of these transects to southwestern Alaska, the Canadian High Arctic, and the BERMS/BOREAS study areas.
- **Focused Airborne Measurements** will complement the Foundational Measurements by delivering high spatial and temporal resolution data for smaller spatial domains within the ABoVE Study Area. Focused Airborne Studies may be concentrated in the areas surrounding ABoVE field sites and at the intersection points of major regional scale airborne transects, provide airborne data acquisitions along the portions of the Foundational Measurement Flight Lines made with instruments that complement the Foundational Measurements, and/or provide greater space-time sampling coverage than the Foundational Measurements. Airborne in situ sampling of carbon dioxide, methane, carbon monoxide and other trace gases for the determination of local to regional scale surface-atmosphere fluxes will be essential to link remote sensing and field measurements of processes driving Arctic-boreal carbon dynamics.
- **Contributed Airborne Measurements** from NASA and ABoVE partners will integrated into the broader airborne strategy so as to optimize their benefit to ABoVE science. Contributed Airborne measurements may include data acquired in the ABoVE domain by current or planned NASA airborne campaigns (e.g. ICEBridge, SnowEx, SMAPVEX), the NEON Airborne Observatory, NOAA (e.g. Snow Surveys, Greenhouse Gas Sampling), DOE (e.g. NGEE-Arctic, Atmospheric Radiation and Monitoring Airborne Observatory), etc.

The Foundational Airborne Measurements provide a framework for investigating domain-wide science questions while the Focused Airborne Measurements allow more detailed probing of process-level questions. Contributed Airborne Measurements will be exploited to augment ABoVE-funded efforts. Together, these approaches provide a flexible, cost effective means for maximizing the science return from ABoVE airborne campaigns.

3 Flight Lines for ABoVE Foundational Airborne Measurements

Flight lines for ABoVE's foundational remote sensing measurements span the Core Study Region (**Fig. 2**). The transects feature intersection points at key infrastructure and field experiment sites, providing opportunities to link regional scale airborne

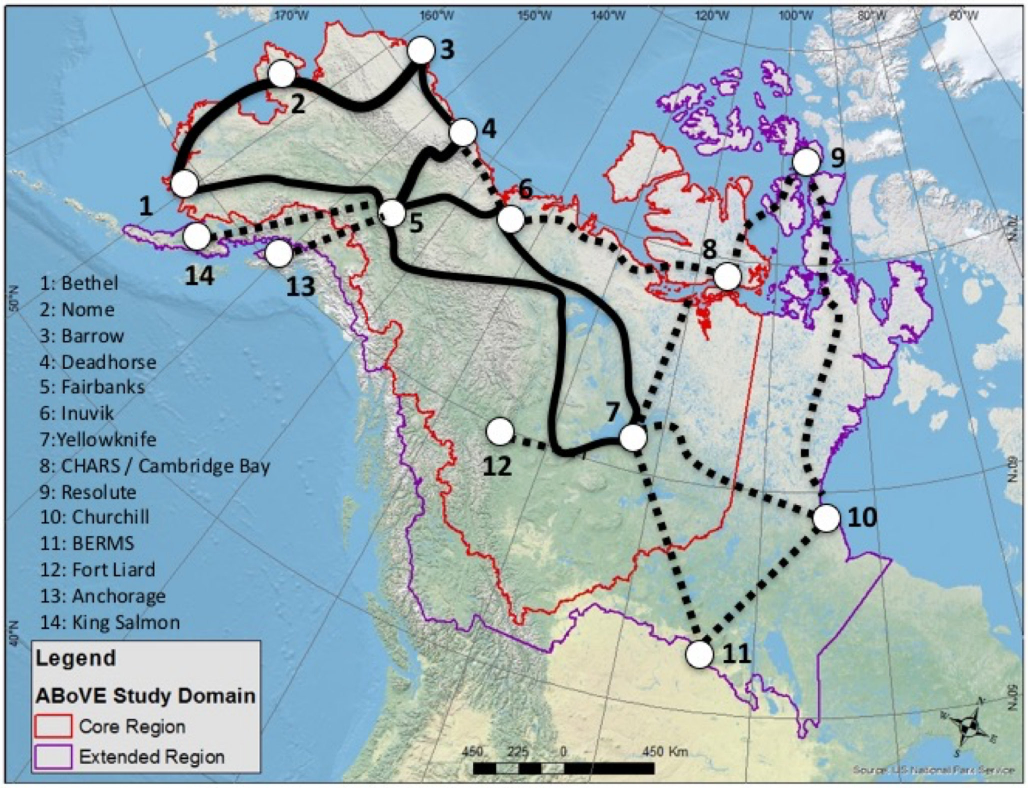

Fig 2*. Flight lines for ABoVE's foundational airborne measurements (solid lines) sample important north-south and east-west gradients within the Core Study Domain. The Alaska circuit connects nexus points 1-2-3-4-5 and the Canada circuit connects nexus points 5-6-7. Supplemental flight lines (dashed lines) expand coverage into the High Arctic and the Extended Study Region (points 8 -14)*

observations with detailed studies from airborne observations focused on higher space-time resolution (**Table 1**). Supplemental flight lines offer the potential to expand airborne remote sensing coverage into the Canadian High Arctic and the Extended Study Region.

The Foundational Measurement flight lines consist of a series of north-south and east-west transects that may be executed in 2 basic flight patterns. Both circuits can base out of Fairbanks, simplifying operations and logistics.

- The **Alaskan circuit** features two north south transects: the Western North Slope – Bering Tundra/Seward Peninsula – Bering Taiga/Yukon-Kuskokwim Delta transect (points 3-2-1) and the Dalton Highway transect (points 4-5). These are connected via east-west transects that cover the transition from the

boreal interior to the Bering taiga (points 5-1) and sampling across the North Slope Arctic coastal plain (points 4-5).
- The **Canadian circuit** features extended east-west transects cutting across the Alaskan boreal interior to the taiga plain near the Mackenzie Delta (points 5-6) then follows the northern treeline along the tundra/taiga ecotone (points 6-7) before returning across the upper Mackenzie River basin tiaga plains and across the boreal cordillera to Fairbanks (points 7-5)

Table 1. ABOVE Foundational Measurement Transect Intersection Points

Point	Name/Airport	Field Study Assets
1	Bethel, AK (PABE)	ABLE, CARVE historical data; tall tower candidate location; YK Delta field sites (Frost)
2	Nome (PAOM)	NGEE-Arctic flux towers and field sites at Teller, Kougarok, Council; fire sites (ABoVE PIs)
3	Barrow, AK (PABA)	NGEE-Arctic flux towers and field sites; Oechel flux towers; NOAA surface site; DOE/ARM North Slope Alaska site; CALM sites; BLM AIM sites
4	Deadhorse, AK (PASC)	DOE/ARM Oliktok Point site; long term vegetation measurement sites; Dalton Highway corridor
5	Fairbanks AK (PAFA)	UAF; BNZ LTER; USFS plots; etc
6	Inuvik NT (YEV)	Taiga Plains Research Network flux towers; Env Canada tower; Mackenzie Delta permafrost sites
7	Yellowknife, NT (YZK)	Fire studies (Multiple ABoVE PIs); Env Canada tower; Tundra-taiga ecotone (Eitel), etc.
8	Cambridge Bay (YCB)	CHARS and associated field sites; Env Canada tower
9	Resolute Bay (YRB)	MARS
10	Churchill (YYQ)	Env Canada tower site
11	BERMS site & East Trout Lake	BOREAS historical context & time series; Fire disturbance/recovery sites (Rogers); Environment Canada tall tower
12	Fort Liard	CFS forest inventory plots
13	Anchorage	Extension of the Dalton Highway corridor; Wrangell-St Elias Dall sheep study area (Prugh)
14	King Salmon	National Park Service SWAN transect

Supplemental flight lines (the dashed lines in **Fig. 2**) offer the potential to expand the Foundational Measurements into the Canadian High Arctic and the Extended Study Region.

The Foundational Measurement flight lines traverse important latitudinal and longitudinal gradients that control patterns of both precipitation and temperature. Additionally, data collected along these flight lines will sample across significant variations in both topography and soil characteristics that are controlled by a range of geomorphological processes, including the impacts of glaciation and variations in surface deposition (e.g., alluvial, colluvial, and eolian processes). The variations in climate, topography, and surface geomorphology control interact to control important variations in permafrost type and ice content (see, for example, Figs A8 and A9 in the ACEP). The variations in topography, geomorphology and permafrost interact to control important gradients in surface hydrology, including soil moisture and surface water inundation. This results in a complex mosaic of terrestrial and freshwater ecosystems controlled by variations in surface hydrology, in particular landscapes where upland vegetation (forests, shrublands, and tundra) are interspersed with wetlands, peatlands, small ponds, and lakes. Furthermore, the Foundational Measurement flight lines will yield airborne remote sensing data over gradients that are caused by disturbances, providing the opportunity to understand how these disturbances affect vegetation, permafrost and surface hydrology (soil moisture and inundation).

3.1 The Alaskan Circuit

The Alaskan circuit covers ~3250 km (1750 nautical miles) may be flown in a single flight day given the endurance, range and speed of the Foundational Measurement aircraft. It consists of two north-south and two east-west transects. It samples the Alaska Boreal Interior (3.1), Alaska Tundra (2.2), Brooks Range Tundra (2.3) and Boreal Cordilerra (6.1) Level II ecoregions.

A more detailed description of the Alaskan circuit and intermediate points is given in Table 2.

Table 2. Alaskan Circuit Flight Line Details

Start	End	Dist (km)	Dist (nm)
Fairbanks (PAFA)	Bethel (PABE)	850	459.0
Bethel (PABE)	Emmonak	275	148.5
Emmonak	Nome	200	108.0
Nome	Ivotuk	620	334.8
Ivotuk	Atqasuk	230	124.2
Atqasuk	Barrow	100	54.0
Barrow	Lake Teshepuk	150	81.0
Lake Teshepuk	Deadhorse	210	113.4
Deadhorse	Toolik Lake	185	99.9
Toolik Lake	Fairbanks (PAFA)	430	232.2
	TOTAL	**3250**	**1754.9**

The **Fairbanks – Bethel** segment covers areas of high interest to USFS for the Alaska boreal forest inventory and that have been densely sampled by high spatial resolution (< 1 m) lidar and hyperspectral imagery, as well as

- Eddy covariance flux towers (Ueyama) and remote sensing instrumentation at University of Alaska Fairbanks
- The Bonanza Creek LTER site (BNZ, http://www.lter.uaf.edu/) including seasonal eddy covariance flux towers (Euskirchen)
- a wide variety of fire recovery chronosequences including multiple burn areas > 1Mha from the 2015 fire season (ABoVE field sites)
- the Whitefish Lake fire burn area (near Aniak)

The **Bethel – Emmonak – Nome** segment spans the boreal Interior - Yukon-Kuskokwim Delta treeline and Bering Taiga as well as the unique Bering Tundra of the Seward Peninsula, including

- field study sites in the YK Delta near Emmonak (Frost)
- permafrost degradation sites (Schaefer)
- NGEE-Arctic Seward Peninsula sites and eddy covariance flux towers at Teller, Kougarok, and council Council

The **Nome – Ivotuk – Atqasuk - Barrow** segment links the Bering Tundra of the Seward Peninsula with a south-north transect across the western North Slope in a space for time trade: it is thought that in 50-100 years the western North Slope may resemble current conditions on the Seward Peninsula. Key field sites along this segment include

- The eddy covariance flux towers at Ivotuk, Atqasuk and Barrow delivering year round CO_2 and CH_4 fluxes (Oechel)
- NGEE-Arctic Barrow sites with extensive characterization of land surface and sub-surface properties at < 1 m resolution
- NOAA Barrow Baseline Observatory and tall tower measurements
- Circumpolar Active Layer Measurement (CALM) active layer thickness sites
- DOE/ARM North Slope Alaska site

The North Slope provides numerous opportunities for more detailed airborne studies. For example, the Bureau of Land Management AIM intensive field sites for inventory and monitoring have been established across the North Slope (**Fig. 3**). Many of these plots will be sampled by the Ivotuk – Barrow – Deadhorse legs.

The **Barrow – Lake Teshepuk – Deadhorse** segment samples the Arctic Coastal Plain and some of the highest soil organic carbon content areas in the Arctic as well as the DOE Oliktok Point tower

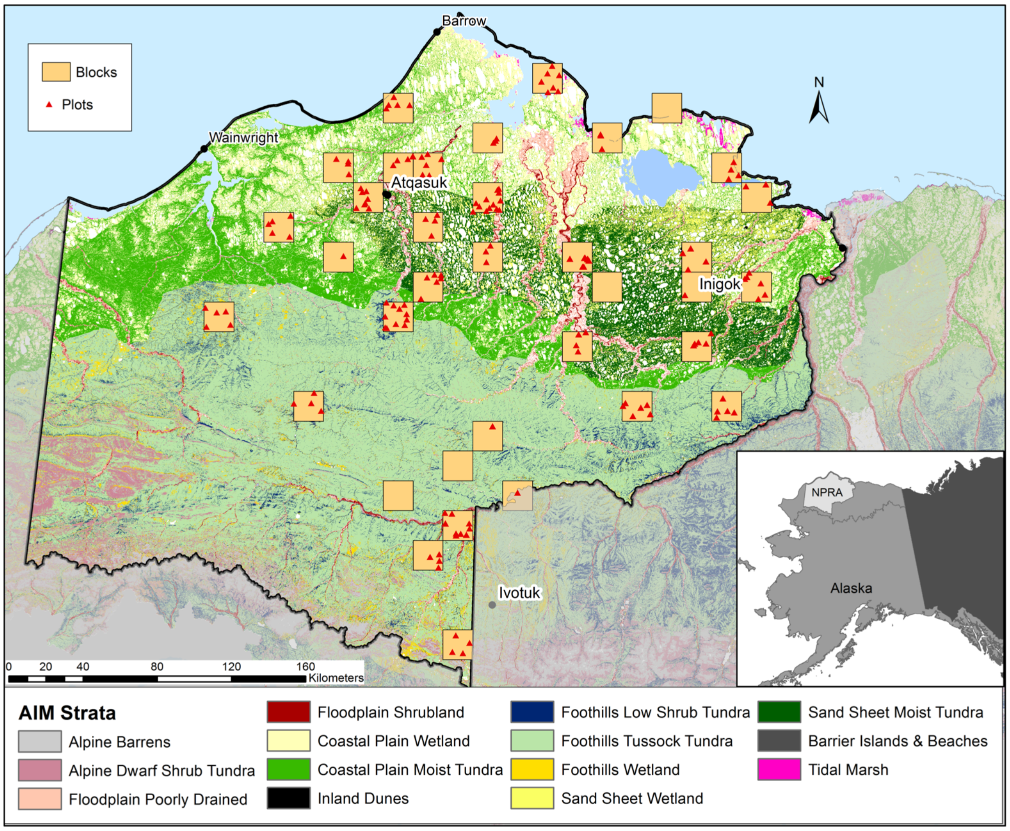

***Fig 3**. Alaska Bureau of Land Management AIM inventory and monitoring plots and blocks on the North Slope provide calibration/validation for ABoVE airborne data. Multiple sites will be sampled by the Ivotuk – Atqasuk – Barrow – Lake Teshepuk flight legs. The large number and distribution of these sites also offers an opportunity for Focused Airborne Measurements.*

The **Deadhorse – Toolik Lake - Fairbanks** segment samples along the Dalton Highway giving spatial overlap with measurements from historical field observations. Additionally, this transect provides the opportunity to overfly

- ReSALT flight lines for permafrost subsidence and past active layer thickness estimates (Schaefer)
- The Arctic Research Station and LTER at Toolik Lake
- The eddy covariance flux towers at Imnaviat Creek (near Toolik Lake) delivering year round CO_2 fluxes (Euskirchen)
- The Anaktuvak River fire scar

Note that the flight line would have to be lengthened by approximately 150 nautical miles to capture both the Dalton Highway and the Anaktuvak River fire scar in the same flight. Additionally, many ABoVE researchers would benefit from the extension of the Dalton Highway transect south from Fairbanks through the Tanana Flats to Healy, across the Alaska Range and into the Anchorage – Valdez area.

3.2 The Canadian Circuit

The Canadian circuit covers ~4200 km (2260 nautical miles) may be flown in a single flight day given the endurance, range and speed of the Foundational Measurement aircraft. It consists of two predominantly east-west transects: a southern transect from Fairbanks to Yellowknife (points 5 – 7) and a northern return transects from Yellowknife to Inuvik to Fairbanks. It samples the Alaska Boreal Interior (3.1), Boreal Cordilerra (6.1), Taiga Cordillera (3.2), Taiga Plains (3.3), Taiga Shield (3.4) and Southern Arctic (2.4) Level II ecoregions.

A more detailed description of the Canadian circuit and intermediate points is given in **Table 3**.

Table 3. Canadian Circuit Flight Line Details

Start	End	Dist (km)	Dist (nm)
Fairbanks (FAI)	Delta Junction	177	95.6
Delta Junction	Tok	165	89.1
Tok	Norman Wells (YVQ)	810	437.4
Norman Wells (YVQ)	Fort Simpson (YFS)	470	253.8
Fort Simpson (YFS)	Fort Providence (YJP)	200	108.0
Fort Providence (YJP)	Yellowknife (YZF)	220	118.8
Yellowknife (YZF)	Daring Lake	300	162.0
Daring Lake	Inuvik (YEV)	1050	567.0
Inuvik (YEV)	Old Crow	265	143.1
Old Crow	Fort Yukon	355	191.7
Fort Yukon	Fairbanks	170	91.8
	TOTAL	**4182**	**2258.2**

The **Fairbanks – Delta Junction – Tok** segment covers areas of high interest to USFS and that have been densely sampled recently by high spatial resolution (< 1 m) lidar and hyperspectral imagery

The **Norman Wells – Fort Simpson – Fort Providence – Yellowknife** segment samples the upper Mackenzie River basin and taiga plains as well as

- the CO_2 flux tower near Norman Wells
- Forestry plots along the Mackenzie River and highway corridors
- the Taiga Plains Research Network site at Scotty Creek (near Fort Simpson) <http://taigaplains.ca/research/sites/scotty-creek-nwt/>
- the Environment Canada tall tower at Behchoko (BEH, near Yellowknife)
- Numerous fire disturbance and recovery sites

The **Yellowknife – Daring Lake – Inuvik** segment samples the tundra-taiga ecotone and northern treeline separating the taiga shield and southern Arctic Level II ecoregions including the key field sites

- Caribou herds and declining vegetation near the Ekati (64°42'15.43"N, 110°36'44.72"W) and Diavik (64°29'38.41"N, 110°17'1.94"W) diamond mines
- the Tundra Ecosystem Research Station at Daring Lake NT <http://www.enr.gov.nt.ca/programs/tundra-ecosystem-research-station> including long-term flux measurements (Lafleur & Humphreys)
- the Taiga Plains Research Network sites at Havikpak <http://taigaplains.ca/research/sites/havikpak-nwt/> and Valley Trail <http://taigaplains.ca/research/sites/trail-valley-nwt/> (near Inuvik) which include seasonal CO_2 eddy covariance flux towers (Sonnentag)
- The Environment Canada tall tower at Inuvik
- Mackenzie Delta area permafrost surveys [e.g. Ramachandran et al., 2011]

The **Inuvik – Old Crow – Fort Yukon – Fairbanks** segment samples the extensive wetlands of the Mackenzie Delta, Old Crow Flats, and the Yukon Flats, including

- Old Crow Flats project
- Flight lines previously flown using airborne electromagnetic imaging (EMI) for permafrost surveys near Fort Yukon (see EMI Case Study)
- Long-term hydrology measurements in the Yukon River basin (near Fort Yukon, R. Striegl project)

Calibration/Validation Data

Site accessibility is a major constraint for sub-Arctic and Arctic fieldwork in northwestern Canada. Ideally, airborne data should be captured along flight lines that are physically accessible to collect new calibration/validation data and leverage existing ground data. Helicopter access is expensive and sometimes unavailable, and most plots are established within a few kilometres from road or river access. For example, forestry plots are typically established within 1 km of road access. The concentration of forestry plots along the Mackenzie River and highway corridors of the region are a primary driver in the design of the Canadian Circuit flight lines between Norman Wells NT and Yellowknife NT (**Fig 4**). **Fig 5** shows the clustering of sites in the Fort Providence area.

The imagery and LiDAR data collected through the Foundational Airborne Measurements will see reduced usage if acquired in areas beyond road or river access. NWTCG can provide road and river shapefiles outlining the exact boundaries of road and rivers to be used as waypoints for the airborne missions. Swath widths of 14-20 km would capture all existing field plots, providing large potential ground datasets used for calibration/validation.

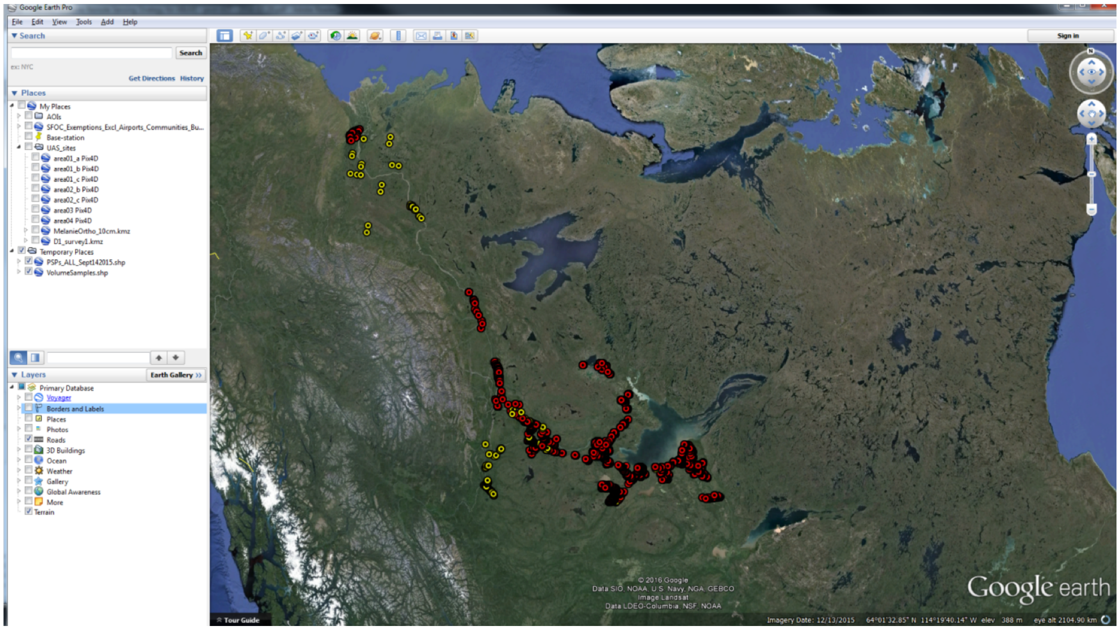

***Fig 4**. The concentration of forestry plots along the Mackenzie River and neighboring highway corridors is a primary behind the design of this portion of the Canadian Circuit flight lines between Norman Wells NT and Yellowknife NT.*

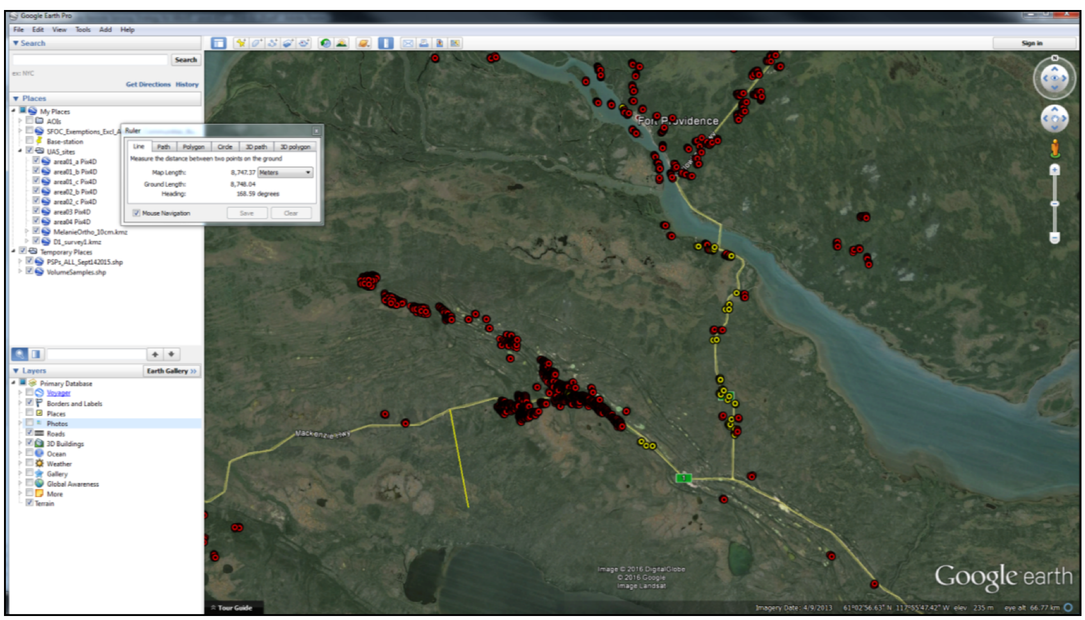

***Fig 5**. A detail of the forestry plots near Fort Providence NT showing their locations along highway corridors and the Mackenzie River. Clusters of sites like this anchor the Canadian Circuit and provide essential ground truth for ABoVE airborne data.*

3.3 The Boreal Forest and Arctic Tundra Transects

A natural outcome of the Alaskan and Canadian Circuits is the creation of two extended west-east transects

- A Boreal Forest transect stretching from the Yukon-Kuskokwim Delta on the Bering Sea coast to the heart of boreal Canada: **Bethel – Fairbanks – Tok – Norman Wells – Fort Simpson – Yellowknife** (points 1-5-7 in **Fig 2**)
- An Arctic Tundra transect reaching from the Chuchki Sea across the North Slope, Beaufort Sea coast and skirting the northern treeline of the Canadian Shield: **Barrow – Deadhorse – Inuvik – Yellowknife** (points 3-4-6-7 in **Fig 2**)

With the addition of Supplemental Flight Lines (see below), the Boreal Forest transect can be extended south and east to include the BERMS/East Trout Lake and Churchill sites (points 7-11-10 in **Fig 2**) while the Arctic Tundra transect can be extended north and east to include Cambridge Bay/CHARS and Resolute Bay/MARS (points 6-8-9 in **Fig 2**).

3.4 Supplemental Flight Lines

The Foundational Measurement Flight Lines (solid lines in **Fig 2**) balance high impact ABoVE science measurement requirements with the realities of obtaining these data with finite resources, and therefore do not sample the entire ABoVE Core Study domain or expand into the Extended Study Region. However, some researchers may develop compelling science investigations that require Foundational Measurements in areas not covered by the Foundational Measurement Flight Lines. For this reason, a number of Supplemental Flight Lines (dashed lines in **Fig 2**) have been provided as well as additional Transect Intersections (points 8 – 14 in **Table 1**). The timing and amount of Foundational Measurement data acquired along various Supplemental Flight Lines, if any, will be determined through the ABoVE Airborne Campaign selection process.

Southern Boreal – BERMS Revisit

The southern boreal – BERMS revisit circuit covers ~3200 km (1750 nautical miles) may be flown in a single flight day given the endurance, range and speed of the Foundational Measurement aircraft. It contains 3 flight legs extending from the Core Study Are into the southeastern portion of the Extended Study Region. It samples the Taiga Shield (3.4), Softwood Shield (5.1), Boreal Plain (5.4) and Hudson Plain (4.1) Level II ecoregions.

A more detailed description of the Canadian circuit and intermediate points is given in **Table 4**.

Table 4. BERMS Circuit Flight Line Details

Start	End	Dist (km)	Dist (nm)
Yellowknife	BERMS	1120	604.8
BERMS & East Trout Lake	Churchill	895	483.3
Churchill	Yellowknife	1170	631.8
	TOTAL	**3185**	**1719.8**

Airborne remote sensing over the BERMS field site was critical to the success of NASA's BOREAS field campaign [Sellers, et al. 1995; 1997; Gamon, et al. (2004)]. AVIRIS (now AVIRIS Classic or AV-C) was the main focus of remote sensing research during BOREAS. Reflights of the BOREAS flight lines for historical comparison and as a test for current remote sensing technologies is highly desired by the ABoVE Science Team. AirMOSS flew extensively over the BERMS sites in the 2011-2015 time frame. The East Tout Lake SK Environment Canada tall tower facility is ~80 km to the northeast of the BERMS site was also leveraged heavily during BOREAS, and there will be several fire disturbance sites in northern Saskatchewan being investigated by the ABoVE team. Additionally, the University of Toronto plans to install a solar-viewing Fourier transform spectrometer at East Trout Lake

BERMS is located approximately 1100 km south of Yellowknife (**Table 4**) and the major ABoVE areas of activity, making the logistics for flight lines that include this site as a supplement to the Canadian circuit challenging within ABoVE resource limitations. However, overflights of the BERMS site during transit between the ABoVE domain (nominally Fairbanks base of operations) and CONUS are feasible and could accommodate requests for Foundational Measurements in this region.

High Arctic – Canadian Shield Circuit

The High Arctic – Canadian Shield circuit samples a north-south gradient extending from Resolute Bay, the northernmost field site in the domain, through the eastern portion of the Extended Study Region to Baker Lake and Churchill. It gives a complementary north-south transect along the eastern edge of the Core Study Region from Resolute Bay through Cambridge Bay and Daring Lake to Yellowknife. It samples the Northern Arctic (2.1), Southern Arctic (2.4), Taiga Shield (3.4) and Hudson Plain (4.1) Level II ecoregions.

A more detailed description of the North Slope – Southern Arctic transect and intermediate points is given in **Table 5**.

The **Yellowknife – Daring Lake – Cambridge Bay/CHARS – Resolute Bay** segment samples the tundra-taiga ecotone across the northern treeline into the southern Arctic and northern Arctic Level II ecoregions. It includes the key field sites

- the Tundra Ecosystem Research Station at Daring Lake NT <http://www.enr.gov.nt.ca/programs/tundra-ecosystem-research-station> including long-term flux measurements (Lafleur & Humphreys)
- the Canadian High Arctic Research Station (CHARS) < http://laws-lois.justice.gc.ca/eng/acts/C-17.8/page-1.html > and neighboring research infrastructure
- The Environment Canada sampling site at Cambridge Bay
- McGill Arctic Research Station (MARS), Expedition Fjord, Heiberg Island < http://daleandersen.seti.org/Dale_Andersen/M.A.R.S..html >

Table 5. High Arctic – Canadian Shield Circuit Flight Line Details

Start	End	Dist (km)	Dist (nm)
Yellowknife (YZF)	Daring Lake	300	162.0
Daring Lake	Cambridge Bay	550	297.0
Cambridge Bay	Resolute Bay	710	383.4
Resolute Bay	Baker Lake	1165	629.1
Baker Lake	Churchill	650	351.0
Churchill	Yellowknife	1170	631.8
	TOTAL	**4545**	**2454.2**

The **Resolute Bay – Baker Lake - Churchill** segment provides a direct north-south transect from the northern Artic through the southern Arctic and Taiga Shield into the Hudson Plain. It includes

- the Baker Lake Research Station (64.31 N, 96.01 W)

When combined with the BERMS circuit, the High Arctic – Canadian Shield circuit creates a north-south transect that extends from Resolute Bay through Baker Lake and Churchill all the way to the BERMS/East Tout Lake site (points 9 -10 – 11 in **Fig 2**), effectively surveying the complete eastern portion of the Extended Study Region.

The High Arctic – Canadian Shield circuit is the longest circuit of those considered here, extending more than 4500 km (nearly 2500 nautical miles). It could be shortened by approximately 800 km by returning to Yellowknife directly from Baker Lake rather than continuing on to Churchill and then back to Yellowknife.

North Slope – High Arctic Transect

The North Slope – High Arctic transect extends across the Arctic Ocean coastline for ~2150 km (1150 nautical miles) from Barrow AK to Deadhorse AK, Inuvik NT, and on to Cambridge Bay NU (points 3-4-6-8 in Figure 2). It samples the Alaska Tundra (2.2), Brooks Range Tundra (2.3), Taiga Plains (3.3), Southern Arctic (2.4) and

Northern Arctic (2.1) Level II ecoregions as well as the caribou calving grounds on Cape Bathurst.
A more detailed description of the North Slope – High Arctic transect and intermediate points is given in **Table 6.**

Table 6. North Slope – High Arctic Flight Line Details

Start	End	Dist (km)	Dist (nm)
Barrow	Lake Teshepuk	150	81.0
Lake Teshepuk	Deadhorse	210	113.4
Deadhorse	Inuvik	625	337.5
Inuvik	Cambridge Bay	1150	621.0
	TOTAL	**2135**	**1152.8**

This transect provides continuous sampling of different North American tundra ecosystems. The Barrow – Deadhorse segment is part of the Alaska circuit. But the Deadhorse – Inuvik and Inuvik – Cambridge Bay/CHARS supplemental lines are unique to this transect. This transect could be acquired as a modification of the Canadian Circuit, replacing the Inuvik – Yellowknife segment along the northern treeline with the Inuvik – Cambridge Bay – Yellowknife segments; however, at nearly 5300 km (2850 nautical miles), that circuit becomes logistically challenging.

Liard Upland and Liard Plain

The Liard Upland and Liard Plain mid-boreal ecoregions are among the most productive in the NWT (Ecosystem Classification Group. 2007). Of significant interest is whether changes in climate resulting in observed apparent impacts to forests in Fort Providence or Fort Simpson are also occurring in more ecologically productive regions around Fort Liard.

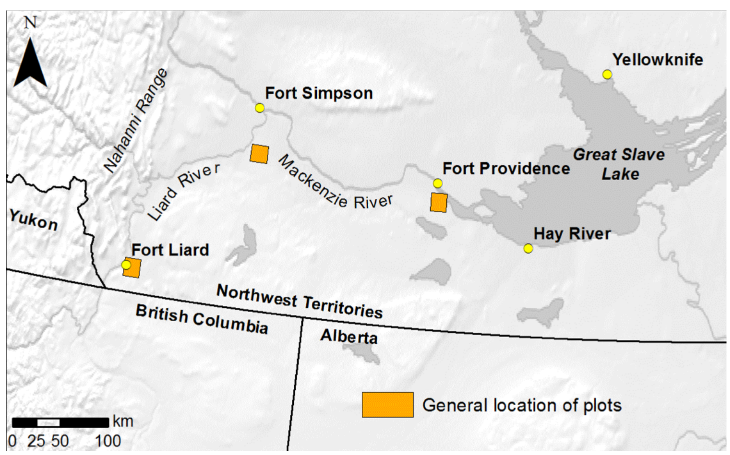

Fig 6. Overview of the CFS forest inventory study areas within the Taiga Plains Ecozone [Ron Hall, Natural Resources Canada].

Fort Liard lies ~215 km SSW of Fort Simpson on the Liard River near the border of the Northwest Territoires, the Yukon Territory, and British Columbia (**Fig 6**).

While the Canadian Forest Service established field plots in this region in 2008, there is a need to re-locate and re-measure these plots to determine what changes may be occurring particularly since warming effects in the southern Territories have been most pronounced over the past ten years. **Table 7** gives the locations of the plots in Fort Liard, Fort Simpson and Fort Providence. There are approximately 50 plots in each locale.

Table 7. CFS inventory plots in the Taiga Plains Ecozone

Ft. LIARD	Long	Lat	Ft. SIMPSON	Long	Lat	Ft. Providence	Long	Lat
LIARD_01	-123.361	60.257	SIMP_01	-121.353	61.488	PROV_01	-117.546	61.258
LIARD_02	-123.366	60.258	SIMP_02	-121.352	61.487	PROV_02	-117.561	61.257
LIARD_03	-123.366	60.256	SIMP_03	-121.352	61.485	PROV_03	-117.559	61.257
LIARD_04	-123.366	60.259	SIMP_04	-121.351	61.484	PROV_18	-117.528	61.184
LIARD_05	-123.304	60.313	SIMP_05	-121.351	61.482	PROV_19	-117.534	61.183
LIARD_06	-123.304	60.312	SIMP_06	-121.354	61.482	PROV_25	-117.507	61.139
LIARD_07	-123.303	60.311	SIMP_07	-121.356	61.483	PROV_26	-117.509	61.136
LIARD_08	-123.335	60.291	SIMP_09	-121.367	61.525	PROV_27	-117.497	61.134
LIARD_09	-123.336	60.290	SIMP_10	-121.363	61.526	PROV_48	-117.532	61.256
LIARD_10	-123.344	60.273	SIMP_11	-121.361	61.525	PROV_49	-117.537	61.254
LIARD_11	-123.342	60.272	SIMP_12	-121.361	61.524	PROV_50	-117.533	61.255
LIARD_12	-123.344	60.271	SIMP_13	-121.362	61.511	PROV_51	-117.505	61.250
LIARD_13	-123.359	60.265	SIMP_14	-121.364	61.511	PROV_52	-117.506	61.249
LIARD_14	-123.357	60.266	SIMP_15	-121.134	61.388	PROV_53	-117.496	61.221
LIARD_15	-123.449	60.240	SIMP_16	-121.133	61.390	PROV_54	-117.509	61.210
LIARD_16	-123.451	60.239	SIMP_17	-121.133	61.392	PROV_55	-117.508	61.208
LIARD_17	-123.498	60.295	SIMP_18	-121.133	61.393	PROV_56	-117.514	61.208
LIARD_18	-123.497	60.295	SIMP_19	-121.132	61.395	PROV_59	-117.508	61.211
LIARD_19	-123.498	60.296	SIMP_20	-121.130	61.395	PROV_60	-117.497	61.109
LIARD_20	-123.491	60.286	SIMP_21	-121.128	61.394	PROV_62	-117.522	61.141
LIARD_21	-123.489	60.286	SIMP_22	-121.125	61.394	PROV_63	-117.516	61.144
LIARD_22	-123.496	60.285	SIMP_23	-121.123	61.393	PROV_64	-117.523	61.141
LIARD_23	-123.419	60.245	SIMP_24	-121.125	61.391	PROV_65	-117.522	61.151
LIARD_24	-123.418	60.246	SIMP_25	-121.128	61.392	PROV_66	-117.518	61.145
LIARD_25	-123.385	60.232	SIMP_26	-121.135	61.385	PROV_67	-117.520	61.140
LIARD_26	-123.385	60.230	SIMP_27	-121.136	61.384	PROV_68	-117.522	61.152
LIARD_27	-123.387	60.232	SIMP_28	-121.136	61.382	PROV_69	-117.521	61.152
LIARD_28	-123.376	60.240	SIMP_29	-121.131	61.387	PROV_70	-117.523	61.153
LIARD_29	-123.374	60.241	SIMP_30	-121.175	61.394	PROV_71	-117.522	61.153
LIARD_30	-123.357	60.215	SIMP_31	-121.190	61.401	PROV_72	-117.517	61.144
LIARD_31	-123.356	60.214	SIMP_32	-121.199	61.405	PROV_73	-117.496	61.133
LIARD_32	-123.357	60.210	SIMP_33	-121.219	61.412	PROV_74	-117.504	61.117
LIARD_33	-123.356	60.209	SIMP_34	-121.220	61.412	PROV_75	-117.497	61.113
LIARD_34	-123.360	60.207	SIMP_35	-121.229	61.425	PROV_76	-117.506	61.117
LIARD_35	-123.359	60.206	SIMP_36	-121.227	61.425	PROV_77	-117.503	61.121
LIARD_36	-123.358	60.206	SIMP_37	-121.225	61.426	PROV_80	-117.508	61.117
LIARD_37	-123.246	60.164	SIMP_38	-121.221	61.426	PROV_81	-117.505	61.116
LIARD_38	-123.246	60.164	SIMP_39	-121.218	61.425	PROV_82	-117.507	61.118
LIARD_39	-123.293	60.170	SIMP_40	-121.221	61.424	PROV_83	-117.631	61.100
LIARD_40	-123.295	60.170	SIMP_41	-121.223	61.424	PROV_84	-117.630	61.100
LIARD_41	-123.297	60.171	SIMP_42	-121.227	61.423	PROV_85	-117.641	61.100
LIARD_42	-123.310	60.179	SIMP_43	-121.230	61.423	PROV_86	-117.649	61.103
LIARD_43	-123.308	60.179	SIMP_44	-121.335	61.426	PROV_87	-117.651	61.103
LIARD_44	-123.307	60.178	SIMP_45	-121.335	61.428	PROV_88	-117.767	61.140
LIARD_45	-123.319	60.179	SIMP_46	-121.337	61.426	PROV_89	-117.767	61.139
LIARD_46	-123.320	60.178	SIMP_47	-121.250	61.441	PROV_90	-117.766	61.137
LIARD_47	-123.317	60.177	SIMP_48	-121.255	61.440	PROV_91	-117.769	61.141
LIARD_48	-123.315	60.176	SIMP_49	-121.254	61.441	PROV_92	-117.770	61.139
LIARD_49	-123.267	60.168	SIMP_50	-121.252	61.442			
LIARD_50	-123.270	60.173						
LIARD_51	-123.268	60.165						
LIARD_52	-123.266	60.165						

Southwest Alaska Inventory and Monitoring Network (SWAN)

Fig 7. The 7 SWAN monitoring stations provide a north-south transect in Southwest Alaska that complements the Dalton Highway transect. Measurements include soil temperature profiles, snow water equivalent (SWE), precipitation and long-term vegetation study plots [Peter Kirchner, National Park Service].

Scientists from the National Park Service operate the Southwest Alaska Inventory and Monitoring Network (SWAN), 7 measurement sites in Southwest Alaska (**Fig 7**). The sites provide potential calibration/validation data for ABoVE airborne measurements including basic meteorology, soil moisture and temperature profiles, snow water equivalent (SWE), liquid precipitation, incoming shortwave radiation, and IR surface temperature. Additionally, each site is augmented by up to a dozen satellite sites with long-term vegetation study plots and 20-cm soil temperature measurements. Station data are transmitted hourly and available for assimilation. All other data are downloaded during field visits.

The seven monitoring stations are in a 300 km–long southwest to north east transect that lines up well with sites in the interior (e.g. Wonder Lake, Denali park CRN, met, soil moisture/temp) and the Dalton highway research corridor. The northernmost site lies ~200 km west of Anchorage and ~400 km east of Bethel. This transect provides an opportunity to represent latitudinal and maritime to continental gradients over the full range of permafrost conditions.

4 ABoVE Foundational Airborne Measurements

There was consensus among the ABoVE Science Team that airborne remote sensing based on multi-frequency radar, waveform lidar, and hyperspectral imagery and their combinations are the highest priority for addressing ABoVE science questions and objectives on landscape to regional scales. These **Foundational Measurements** will therefore be acquired with specified instruments along Alaskan Circuit and Canadian Circuit flight lines for the benefit of the ABoVE Science Team and the broader scientific community. Small modifications to these flight lines may be accommodated for increased science return (e.g. alternate intermediate waypoints or areas for multi-pass sampling). Additionally, certain science priorities may justify the acquisition of Foundational Measurements along one or more of the Supplemental Flight Lines.

Under this scenario, candidate payload-platform solutions would fly the synthetic aperture radar sensors UAVSAR (L-band) on the NASA Armstrong G-3 and AirMOSS (P-band) on the NASA JSC G-3 as well as the LVIS/Av-NG/HyTES/PRISM payload on the NASA ER-2. Alternate payload platform combinations that deliver comparable performance may be employed to address cost or aircraft schedule constraints.

Measurements from these payloads would be collected primarily along the Alaskan and Canadian regional circuits described above (**Fig. 2**). The speed and endurance of the G-3 and ER-2 make it possible to sample one complete circuit on each flight day. The UAVSAR/AirMOSS flights are largely independent of weather constraints since the radar penetrates to the surface through clouds and could be completed within a few calendar days. The LVIS/AVIRIS/HyTES/PRISM sensors require clear skies for maximum science return and may require 10 calendar days or more to complete baseline sampling. This includes the possibility of flying portions of each circuit rather than the entire circuit on a given flight day to take advantage of good conditions.

Flights would nominally base out of Fairbanks, AK: the G-III at Fairbanks International Airport, and the ER-2 from nearby Eilson AFB. Both aircraft have previously operated from these bases, reducing logistics cost and risk. Airports at Anchorage AK, Deadhorse AK, Inuvik NT, Yellowknife NY, and Whitehorse YT provide the required support services (secure hangars, fuel, etc.) for extended or multi-day flights of the G-III. Refueling may also be possible at additional airports in both the Alaskan (Galena, Bethel, Barrow, Nome, Kotzebue) and Canadian (Norman Wells, Fort Smith, Edmonton, Churchill, Saskatoon) sectors of the domain. ER-2 security, runway, support requirements, etc. are significantly more restrictive than those of the G-3; Elmendorf AFB (Anchorage) provides a proven backup bases of operations for the ER-2.

4.1 Multi-Frequency Radar: UAVSAR & AirMOSS

Long-wavelength radars, and in particular polarimetric synthetic aperture radars (SARs), are sensitive to geometrical and material properties of vegetation, soil surface, and subsurface profiles (van Zyl, 1989; Dobson et al., 1992; Le Toan et al., 1992; Pierce et al., 1994; Ranson and Sun, 1994; Cloude and Pottier, 1997; Haddad et al., 1996; Moghaddam and Saatchi, 1999; Saatchi and Moghaddam, 2000; Moghaddam et al., 2000; Paloscia et al., 2005; Hajnsek et al., 2003; Tabatabaeenejad et al, 2011; Tabatabaeenejad et al., 2015; many others). By "long wavelength" we are referring to the customary wavelengths of approximately 24 cm (L-band) and 70 cm (P-band). The utility of L-band for surface soil moisture retrieval has motivated the NASA SMAP mission (Entekhabi et al., 2010). Similarly, the NASA AirMOSS EVS-1 mission was motivated by the utility of P-band for retrieval of subsurface soil moisture (also called root-zone soil moisture or RZSM). For the ABoVE airborne observations of active layer properties, we consider the two NASA airborne SAR systems UAVSAR (L-band) and AirMOSS (P-band), both of which are operational systems with proven track record of high quality image data.

The polarimetric P-band SAR system AirMOSS flies on the NASA JSC G-3. It has produced estimates of root zone soil moisture (RZSM), capturing the effects of gradients of soil, topography, and vegetation heterogeneity over areas of 100 km x 25 km at nine biomes in north America during 21 annual campaigns in 2012-2015. Radar imagery from AirMOSS are available at 0.5 arcsec and 3 arcsec resolutions, and within a swath covering incidence angles of 25-55 degrees. From a typical flight altitude of 40,000 ft, this corresponds to a 14 km wide swath and 15 m spatial resolution. Calibration accuracy is approximately 0.5 dB and the system noise floor is lower than -40 dB. Proposers should recognize that there are high-power P-band radars operating at certain locations in the ABoVE Core Study Region (e.g. Fairbanks area) and that these will interfere with AirMOSS observations.

The polarimetric L-band SAR system UAVSAR flies on the NASA Armstrong G-3 aircraft. It is also capable of interferometry. From a typical flight altitude of 40,000 ft, UAVSAR delivers a 21-km wide swath and 6-m spatial resolution. The differences in swath and spatial resolution are due to higher bandwidth of UAVSAR compared to AirMOSS. UAVSAR data have been used for a number of science objectives including soil moisture retrievals, surface deformation, and vegetation height mapping.

Dual-frequency SAR observations for active layer characterization

There is a 25+-year history in the development of radar inversion algorithms to retrieve geophysical products using a wide range of frequencies, and in particular, using polarimetric L-band and P-band.
The L-band frequency has been used to estimate soil moisture in the top 0-5 centimeters in the presence of up to 5 kg/m^2 of vegetation (Dubois and van Zyl, 1995; Oh et al. 1992; others). P-band and lower frequencies have been used to (1) enhance capability to characterize vegetation effects as the amount of vegetation is increased to up to 20 kg/m2 (Dobson et al., 1992; Freeman et al., 1992; Israelsson et al., 2000; others), and (2) retrieve soil moisture in the 0 cm to 50 cm depth or more, depending on the amount of vegetation and soil moisture present (Moghaddam et al., 2007; Moghaddam et al., 2000; Tabatabaeenead et al., 2015).

Having both L- and P-band data enables the simultaneous and more accurate characterization of a larger number of unknowns than just soil moisture profiles (Moghaddam, 2009). For permafrost landscapes, for example, dual-frequency SAR enables the simultaneous retrieval of soil moisture, active layer thickness, and organic layer thickness. Depending on how the inverse problem is parameterized, it is also possible to retrieve vegetation canopy properties.

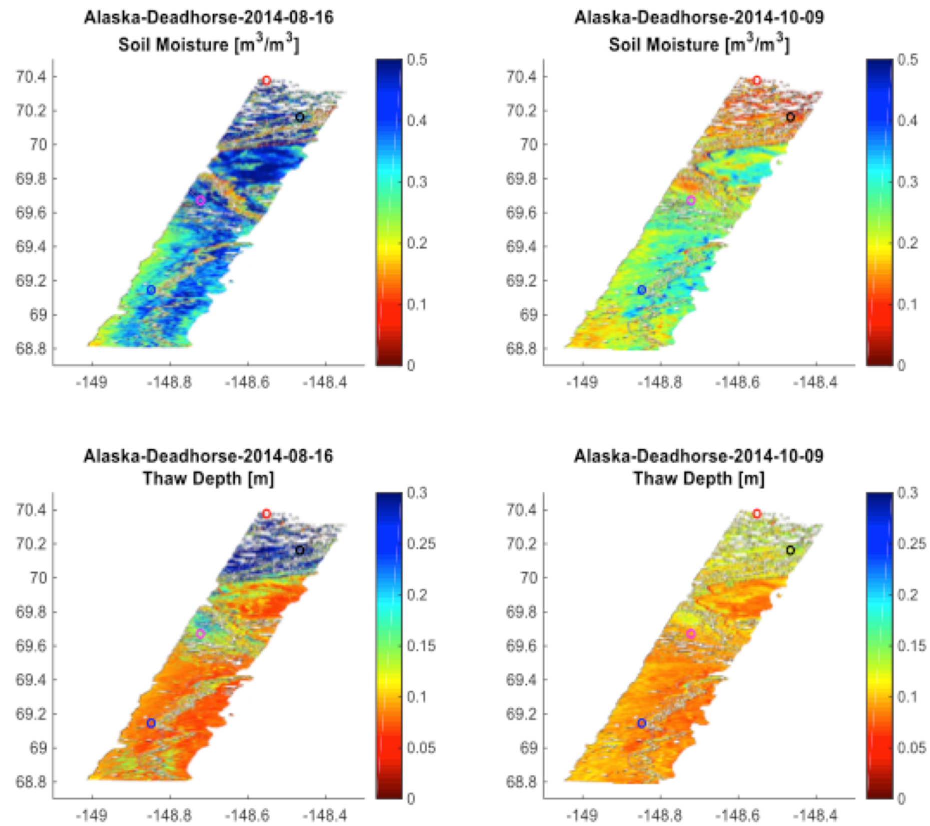

Fig 8*. Retrievals of soil moisture and active layer depth from August 2014 and October 2014, using P-band-only SAR data.*

The P-band-only retrieval approach of the AirMOSS EVS-1 mission has been applied to data collected in 2014 over a 2500-km transect in Alaska. An example of active layer depth and soil moisture retrieval is shown in **Fig 8**. Comparing the retrieval results with the few available ground observations has indicated agreement for active layer depth when the soil is not saturated. In some cases, the depth to water table has been retrieved (with good accuracy) instead of the active layer depth. Validation data are currently too few to enable a proper statistical analysis of the accuracy of retrievals, but with access to more data from the CALM network, better comparisons might be possible in the near future.

More recently, a near-simultaneous data set with both L-band and P-band was collected over the same transect. The L-band data only became available to us in December 2015 and we have not had enough time to produce active layer depth and soil moisture results from them yet. However, extensive simulation results have been generated using the combination of L-band and P-band data, which show for all cases simulated, the dual-frequency retrieval results are far superior to the P-band only results. Figure 3 shows an example, where a Monte Carlo active layer depth retrieval simulation is carried out for P-band only, L-band only, and L+P bands together, using a random calibration noise of +/- 0.5 dB (twice the magnitude of actual AirMOSS and UAVSAR calibration noise estimates).

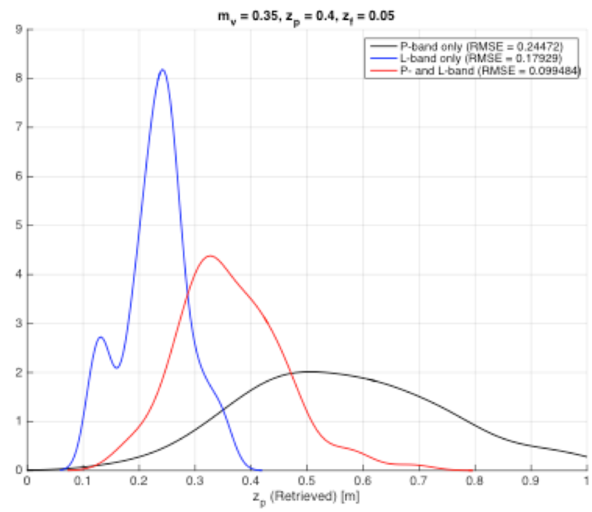

***Fig 9**. Example of how active layer estimation improves by using L-band and P-band radar data simultaneously. Figure shows the distribution of retrieved active layer depth values for a true value of 0.4 m. The joint retrieval clearly produces superior results. A ±0.5 dB noise is superimposed, which is almost twice as large as the actual calibration error of the AirMOSS and UAVSAR systems*

Based on the above and numerous other simulations, the following statements can be made about the retrievals of ALT and soil moisture (Tabatabaeenejad et al., 2014): When using P-band only, we observe that:

- Soil moisture and ALT are retrieved well if ALT is larger than about 20 cm
- Soil moisture and ALT are retrieved well for shallower ALT if soil moisture is high
- Long wavelengths re not able to “resolve” a thin and dry top layer
- If we add an organic layer on top, with only one frequency we will not have enough data to retrieve the subsurface properties and instead will have to assign prior values at least to the organic layer, which is not a desirable situation

When using a combination of P-band and L-band data, we make the following observations:

- There is twice as much independent data
- Good soil moisture retrieval is obtained for the entire range investigated
- Good ALT retrieval is obtained if ALT is less than 60 cm
- L-band provides substantial help for shallow ALT retrievals, but hinders large ALT retrieval
- There will be sufficient independent data channels to retrieve properties of both the organic and the mineral layers, as well as a density parameter associated with roots

The above observations are made from simultaneous and equal used of the L- and P-band data.

4.2 Waveform LIDAR: LVIS

ABoVE will employ the facility version of NASA's Land, Vegetation, and Ice Sensor (aka the Laser Vegetation Imaging Sensor or LVIS < http://lvis.gsfc.nasa.gov/index.html >). LVIS is an airborne, scanning laser altimeter which, when combined with aircraft position and attitude knowledge, produces topographic maps with dm accuracy and vertical height and structure measurements of vegetation [Blair 1999]. LVIS is a pulsed laser altimeter and measures range by timing a short (< 10 ns duration) pulse of laser light between the instrument and the target surface. The entire time history of the outgoing and return laser pulses is digitised using a single detector, digitiser and timing clock, and unambiguously describes the range to the surface as well as the vertical distribution of surfaces within each laser footprint.

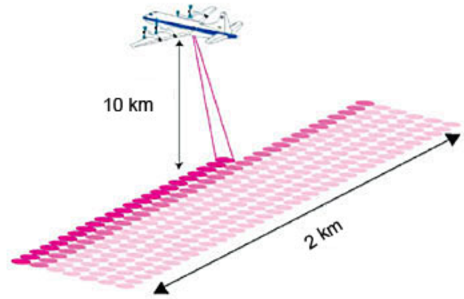

***Fig 10**. The LVIS transmit beam is scanned perpendicular to the aircraft flight path. Data on the surface below these swaths are collected, and a DEM and map can be generated from them. LVIS has a scan angle of about 12°, and can cover 2 km swaths of surface from an altitude of 10 km.*

The LVIS system operates at altitudes up to 10 km AGL and has a 12° potential field-of-view (PFOV) within which footprints can be randomly spaced across track (**Fig. 10**). Scanning is performed using galvanometer-driven scan mirrors that control the pointing of both the laser and the telescope instantaneous field-of-view (FOV). Scan mirrors are positioned in a stepped pattern, stopping to fire the laser and integrate the return signal at each beam location. This raster scan pattern efficiently covers 100% of the area within the data swath. Footprint sizes from 1 to 80 m are possible, determined by the AGL altitude of the airplane and the focal length of a diverging lens in the output path [Blair 1999].

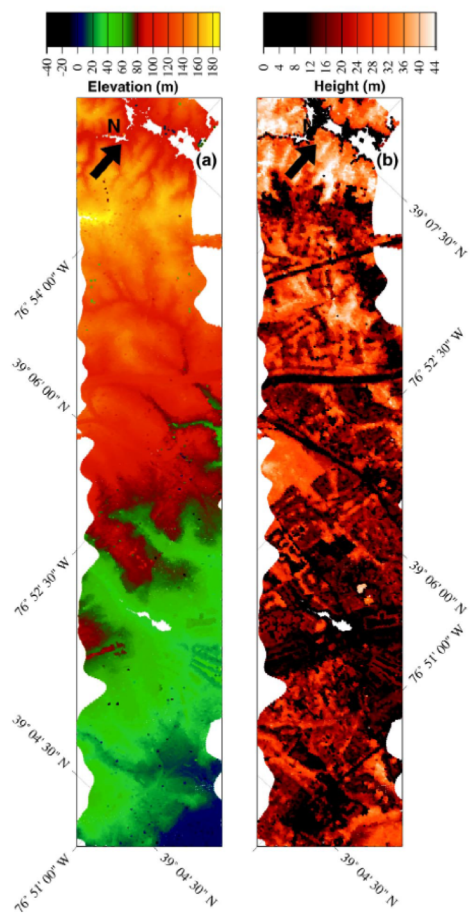

***Fig 11**. (a) Ground topography and (b) height within each footptint measured by LVIS in the Patapsco River, MD region. Laser footprints are ~20 m apart with increased density in areas of swath overlap [Blair 1999].*

An LVIS flight over the Sequoia National Forest in southeast California was flown at 6 km AGL operating at 400 Hz. A total of 35 across-track footprints were generated, 25 m in diameter, and separated by ~10 m both across and along-track. Greater than 99% of the laser shots yielded both canopy-top and sub-canopy elevation data. LVIS flights over the Bartlett Experimental Forest (BEF) in central New Hampshire (USA) were used to assess the performance of waveform lidar in a northern temperate mixed conifer and deciduous forest [Anderson 2006].

LVIS' unique capability for measuring the sub-meter topography beneath forest canopies could facilitate improved hydrologic modeling at the individual drainage basin level in areas that have traditionally escaped adequate treatment. LVIS altimertry can also be used as a key control data in optimizing pan-Arctic digital elevation maps derived from high spatial resolution stereo imagery such as ArcticDEM [Morin]

The LVIS data structure (Version 1.04) is given at http://lvis.gsfc.nasa.gov/DataStructure_LDS104.html . Data latency is (TBC) from the acquisition flight data.

LVIS is a PI-led instrument, although it is expected to transition to Facility Instrument status during FY2016. Additional querries should be directed to

J. Bryan Blair
NASA/GSFC, Code 694
Laser Remote Sensing Laboratory
301-614-6741, FAX 301-614-6744
Bryan Blair

4.3 Hyperspectral Imagery: AVIRIS, HyTES & PRISM

AVIRIS

NASA's Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) is an advanced hyperspectral imaging spectrometer that provides spectroscopic measurement in the range from 380 to 2510 nm with 5 nm sampling (427 spectral bands). Measurements in the spectral range provide access to the full set of molecular absorption and scattering properties of vegetation (**Fig 12**) and support a range of terrestrial ecology science. AVIRIS-NG is designed to meet or exceed the performance of the original AVIRIS (Green et al., 1998), now designated AVIRIS-C, that is referenced in more than 1000 journal articles.

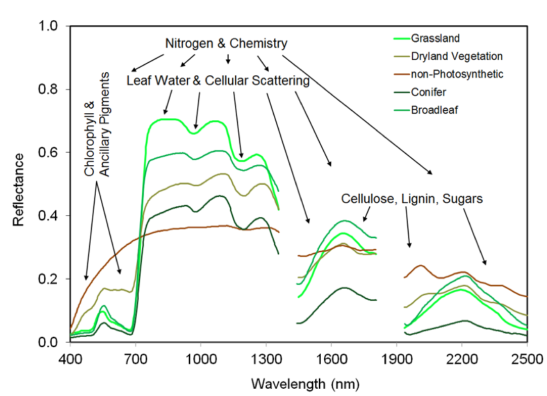

Fig 12. *Examples of vegetation spectra that can be observed within the AVIRIS-NG range for different ecosystems.*

AVIRIS-NG has a spatial swath of 600 cross-track elements and a 34° field of view with 1 milliradian sampling. With these characteristics, AVIRIS-NG delivers 4 m spatial sampling from 4 km above ground level the surface and 20 m spatial sampling from 20 km altitude. Continuous along track imaging from an airborne platform provides measurements in image cube format. AVIRIS-NG image cubes are delivered in calibrated at sensor radiance and/or atmospherically corrected surface reflectance (Thompson et al., 2015). The image cubes are orthorectified with a companion location and geometry file. The location file provides the latitude, longitude and elevation for every spectrum. The observation file provides: sensor-to-ground path length, to-sensor-azimuth, to-sensor-zenith, to-sun-azimuth, to-sun-zenith, phase angle, surface slope, surface aspect, cosine i, and UTC time for every spectrum measured.

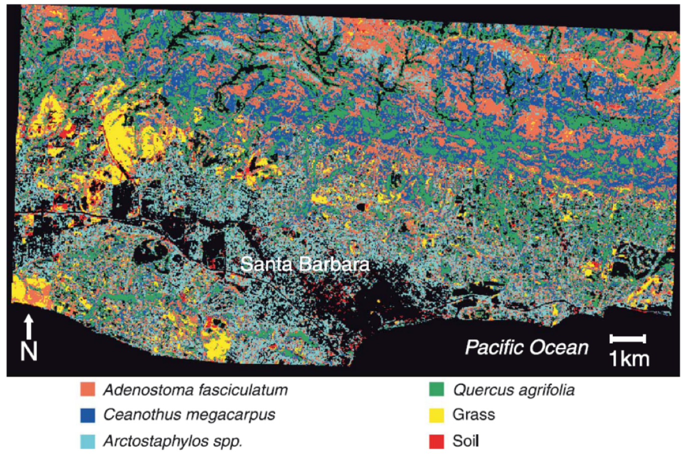

Fig 13. *Map o fplant species and landcover classification constructed from AVIRIS data using multiple end member spectracl analysis (MESMA). MESMA incorporates species and cross species spectral variability in mapping and has demonstrated 90% species type accuracy [Roberts et al., (2014)].*

Quicklook images from AVIRIS confirming the areas covered are available on the web within 48 hours of acquisition. Full image cube data products through Level 2 will be available within 14 days of acquisition.

AVIRIS-NG has been collecting spectroscopic measurements since 2012 with data successfully collected in the U.S., Greenland, and India. The AVIRIS-C instrument has flown for the NASA BOREAS campaign and in Alaska in 1995. AVIRIS-C and AVIRIS-NG spectroscopic measurements have been used to pursue terrestrial ecosystem research related to biogeochemical cycles, ecosystem functioning, biodiversity, disturbances, ecosystem services and related societal impacts. In this regard, NASA's AVIRIS-NG imaging spectrometer is well suited to support the objectives of the ABoVE experiment.

AVIRIS-NG is a facility instrument developed and operated by the Jet Propulsion Laboratory for NASA's Earth Science Division < http://aviris-ng.jpl.nasa.gov/aviris-ng.html >.

HyTES

The Hyperspectral Thermal Emission Spectrometer (HyTES) is a new airborne imaging spectrometer developed by the NASA Jet Propulsion Laboratory. HyTES has 256 contiguous spectral channels between 7.5 and 12 µm and a 50 degree total field of view. The instrument has an instantaneous field of view of 1.7066 milliradians with pixel size dependent on flight altitude. Currently the instrument operates on a Twin Otter aircraft with plans underway to modify the instrument so that it can also be flown on the NASA ER2 in early 2016. HyTES spatial resolution varies from 1.7 m for a flight altitude 1 km above surface to 34 m for a flight altitude 20 km above surface. HyTES is the first high spatial and high spectral resolution thermal infrared imaging spectrometer developed by NASA.

HyTES has had several successful deployments and used to produce HyspIRI-like datasets as well as conduct new science only possible due to its combined high spatial and spectral resolution. Currently two data products are distributed by the HyTES team: the radiance at sensor (provided as brightness temperature) and the surface temperature and emissivity. Datasets are freely available from the HyTES website (http://hytes.jpl.nasa.gov).

HyTES is a PI-led Instrument operated by the Jet Propulsion Laboratory for NASA's Earth Science Division < http://airbornescience.jpl.nasa.gov/instruments/hytes >. Additional queries should be directed to

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Jet Propulsion Laboratory
Tel: 818-354-4738
Bjorn.T.Eng@jpl.nasa.gov

PRISM

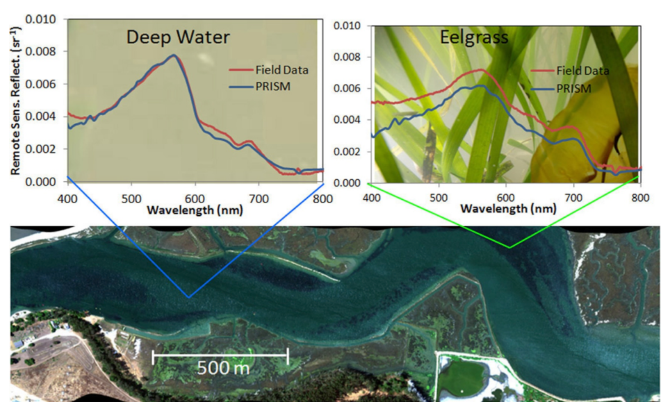

Fig 14. *PRISM remotely sensed reflectance within the Elkhorn Slough [Dierssen 2013].*

NASA's airborne Portable Remote Imaging Spectrometer (PRISM) is designed specifically for coastal and inland water applications, including higher signal-to-noise ratio (SNR) and improved spectral resolution in the critical 380–600 nm range [Mouroulis et al., 2014]. It incorporates a simple but powerful optical design that is optimized for airborne ocean color sensors. It operates in the 350-1050 nm range with a 2.83 nm sampling per pixel, and a 0.88 mrad instantaneous field of view with 608 cross-track pixels in a pushbroom configuration. The design excels in providing high throughput (F/1.8), high uniformity of response (<5% of one pixel, with tolerances considered), low polarization sensitivity (2%), while also achieving a wide field of view (31°) and diffraction-limited performance within the detector pixel size. This results in spatial resolutions of ~1 m/pixel and ~3 m/pixel from flight altitudes of ~1100 m AGL and ~ 3200 m AGL, respectively.

Since instrument completion in 2012, PRISM has flown various sites including Lake Tahoe, Monterey Bay, Southern California Bight, Sacramento Bay Delta, Florida Bay, and the Southern Ocean [*Dierssen*, 2013; *Dierssen et al.,* 2015; *Thompson et al., 2015; Fichot et al.,* 2015]. **Fig 14** emphasizes PRISM's excellent performance, showing a comparison between remote sensed reflectance from PRISM and in situ data collected in Elkhorn Slough for seagrass studies [*Dierssen,* 2013]. PRISM should, therefore, provide excellent biogeochemical and physical characterization of the extensive inland waters of the ABoVE domain.

Additionally, the Alaska Circuit and the North Slope – High Arctic transect provide numerous opportunities to acquire PRISM data over coastal waters of the Bering Sea and Arctic Ocean. Such observations would prove extremely valuable in advanced planning and analysis for the potential Arctic Colors field study by NASA's Ocean Biology and Biogeochemistry Program < http://arctic-colors.gsfc.nasa.gov/ >.

PRISM data processing benefits from AVIRIS heritage and is quite mature. PRISM standard data products are described in **Table 8**. Data products through Level 1 will be available within 90 days of acquisition; Level 2 data products will be available within 180 days of acquisition.

Table 8. PRISM Data Products

Product	Description	Latency
Level 0	Reconstructed, unprocessed PRISM digitized numbers (DN) at full resolution with GPS	≤3 Months
Level 1	Calibrated spectral radiance with geolocation information, including illumination and observation geometry	≤3 Months
Level 2	Reflectance generated following atmospheric radiative transfer inversion with geolocation, support processing information and flags	≤6 Months

PRISM is a PI-led Instrument operated by the Jet Propulsion Laboratory for NASA's Earth Science Division < http://airbornescience.jpl.nasa.gov/instruments/prism >. Additional queries should be directed to

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4.4 Exploiting Multi-Sensor Observations

Waveform Lidar + Multi-frequency Radar. Research activities combining lidar and radar remote sensing have increased in recent years. The main focus in combining lidar-radar forest remote sensing has been on the retrieval of the aboveground biomass (AGB), which is a primary variable related to carbon cycle in land ecosystems, and has therefore been identified as an essential climate variable. The most promising prospects for combining lidar and radar data are in the use of lidar-derived ground elevations for improving large-area biomass estimates from radar, and in upscaling of lidar-based AGB data across large areas covered by spaceborne radar missions [Kaasalainen 2015]

Waveform Lidar + Hyperspectral Imaging. Numerous studies have demonstrated that joint acquisition of hyperspectral imagery and waveform lidar provide improved forest metrics over use of either data set alone, providing a promising adjunct to traditional forest inventory efforts and ecosystem characterization [eg Asner 2007]. Anderson et al. [2008] analyzed AVIRIS and LVIS data from the Bartlett Experimental Forest (BEF) in central New Hampshire and found that the integrated sensor data explained 8–9% more of the variation in basal area (BA), above-ground biomass (AGBM) and quadratic mean stem diameter (QMSD) than AVIRIS or LVIS metrics alone. Additionally, estimated error for these variables was 5–8% lower for the joint analyses. Notably, in an analysis using integrated data limited to unmanaged forest tracts, AGBM coefficients of determination improved by 25% or more, while corresponding error levels decreased by over 25%. This result is significant since nearly 50% of Canada's boreal forest and until recently all of Alaska's boreal forest are unmanaged.

4.5 Foundational Measurement Campaign Timing

The Foundational Measurement campaigns will be timed for two major science objectives:

Active Layer Thickness/Permafrost State Characterization
UAVSAR and AirMOSS will be deployed in mid-May/early-June to capture freeze/thaw dynamics and late-August/early-September to acquire maximum active layer thickness data.

Vegetation Structure and Function
LVIS/AVIRIS-NG/HyTES/PRISM will acquire data in late-June/mid-July to characterize vegetation structure and function during the peak of the growing season.

5 Focused Airborne Measurements

Focused studies with higher space-time resolution for local to mesoscale studies Target ABoVE field studies and the transect intersection points where multiple gradients can be placed in context. Coverage (or partial coverage) of the Foundational Measurement flight lines with complementary measurements that enable significant insights into ABoVE science questions & objectives not provided by the Foundational Measurements alone are strongly encouraged.

The use of NASA Facility Instruments and other instrument packages are encouraged. Proposals for the Focused and Complementary Measurements will be judged on the scientific merit of proposed measurements as well as their cost effectiveness and cost realism.

Numerous Case Studies are provided in the Appendices as examples of focused studies. These are not a comprehensive list and alternative concepts that meet high priority ABoVE science objectives are strongly encouraged.

6 Integrating ABoVE Partners Into the Airborne Science Strategy

ABoVE's broad array of partners provide many opportunities for collaboration in the Airborne Science activities. These range from contributing key field sites and/or data for airborne remote sensing validation to complementary airborne science data acquisition and analysis. Here we identify some of the Partner contributions and how they may be integrated into the ABoVE Airborne Science strategy.

6.1 NASA Airborne Campaigns & Opportunities

Numerous NASA airborne campaigns will acquire data in and around the ABoVE domain in the 2017 – 2019 time frame, eg SnowEx and ICEBridge. Additionally, ABoVE may leverage other planned activities, such as those from the Biodiversity or Ocean Biology and Biogeochemistry Programs.

SnowEx

SnowEx is a multi-year airborne snow campaign beginning in winter 2016-2017. Its goal is to collect multi-sensor observations plus calibration/validation data to enable trade studies for snow satellite mission designs (http://snow.nasa.gov).

SnowEx aims to evaluate remote sensing technologies and algorithms for mapping key snow properties such as snow water equivalent, snow depth, snow covered area, snow albedo, snow melt status, and snow temperature. Building on the Cold

Land Processes Experiment (CLPX) campaigns of 2002-2003 SnowEx will focus more on the challenges of mapping snow in forested environments. In recent years, forest structure characterization with lidar combined with snow mapping with hyperspectral, lidar, and radar have opened up new possibilities.

SnowEx Year 1 field and airborne activities will focus on a mountain site within the CONUS (still TBD) that has dry snow in both open and forested environments. Fieldwork will take place from late 2016 through early 2017. A small subset of sensors – such as lidar – that require snow-off background measurements may require limited observations prior to the snow season.. The full suite of sensors will nominally fly in February 2017 to collect multi-sensor observations in non-melting snow conditions. SnowEx Year 2 will focus on data analysis from Year 1 and planning for Years 3-4 field and airborne activities. For Years 3-4 (2018/2019), there is interest in acquiring snow data in one or more locations within the ABoVE domain, particularly in the Alaskan boreal forest ecoregion.

Operation IceBridge

NASA's Operation IceBridge images Earth's polar ice in unprecedented detail to better understand processes that connect the polar regions with the global climate system (http://www.nasa.gov/mission_pages/icebridge/index.html). IceBridge utilizes a highly specialized fleet of research aircraft and the most sophisticated suite of innovative science instruments ever assembled to characterize annual changes in thickness of sea ice, glaciers, and ice sheets. In addition, IceBridge collects critical data used to predict the response of earth's polar ice to climate change and resulting sea-level rise. IceBridge also helps bridge the gap in polar observations between the end of the ICESat-1 mission and the launch of ICESat-2.

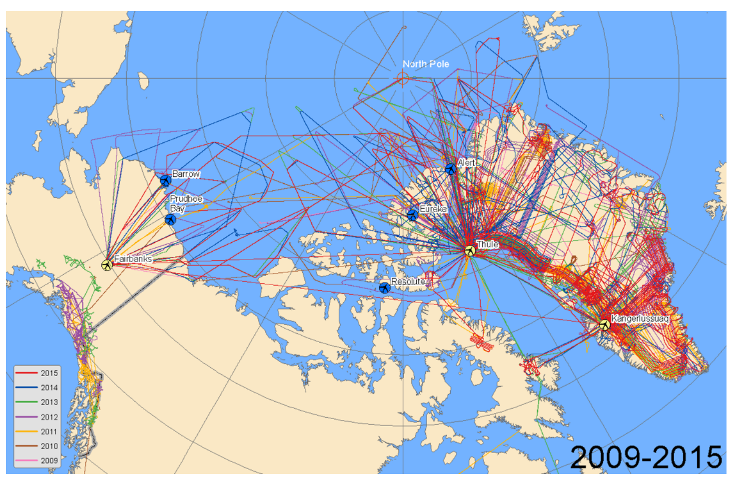

Fig 15*. Map of IceBridge flight lines from 2009-2015. There are significant opportunities to leverage IceBridge flights out of Fairbanks, flights over the Canadian High Arctic, and along the Gulf of Alaska coastline.*

IceBridge will continue annual campaigns to measure ice thickness and extent in Greenland and the Arctic Ocean through 2019, and then through ICESat-2 launch and early operations for validation purposes. ICEBridge includes radar and altimeter instruments that might benefit ABoVE researchers studying for example permafrost, hydrology interactions and freeze-thaw state if flight lines could be augmented to acquire transects over the ABoVE domain. Spring Arctic Ocean ice extent flights have based out of Fairbanks in the past, and could offer excellent opportunities for collaborative science. Additionally, ICEBridge has typically flown the P-3, the DC-8 or C-130 and there may be opportunities to augment their payloads with ABoVE-specific instrumentation.

NASA Biodiversity Program

There is natural synergy between the science questions and objectives of ABoVE and NASA's Biodiversity program. These should be explored in greater detail and aligned as much as possible at both the programmatic and science levels.

Additionally, the NASA Biodiversity call A.7 in ROSES 2015 (NNH15ZDA001N-BIODIV) calls for planning for major biodiversity airborne campaigns based around the NASA ER-2 with LVIS lidar and 2 or more of the HyTES, AV-NG, PRISM hyperspectral imagers. These sensors and sensor combinations were identified as high priority for ABoVE airborne science at the first ABoVE Science Team Meeting in Minneapolis (9/29 – 10/2/15). ER-2/sensor engineering and integration tests are already underway. This significant investment greatly reduces cost and risk to ABoVE science campaigns.

Arctic-COLORS

NASA's Ocean Biology and Biogeochemistry program commissioned a scoping study for Arctic-COLORS (Arctic-COastal Land Ocean inteRactions, http://arctic-colors.gsfc.nasa.gov), that, through a proposed field campaign, aims to improve understanding and prediction of land-ocean interactions in a rapidly changing Arctic coastal zone, and assess vulnerability, response, feedbacks and resilience of coastal ecosystems, communities and natural resources to current and future pressures. The overarching objective of Arctic-COLORS is to determine present and future impacts of terrigenous, atmospheric, and oceanic fluxes on the biogeochemistry, ecology and ecosystem services of the Arctic coastal zone in the context of environmental (short-term) and climate (long-term) change. This focus on land-ocean interactions in the nearshore coastal zone is

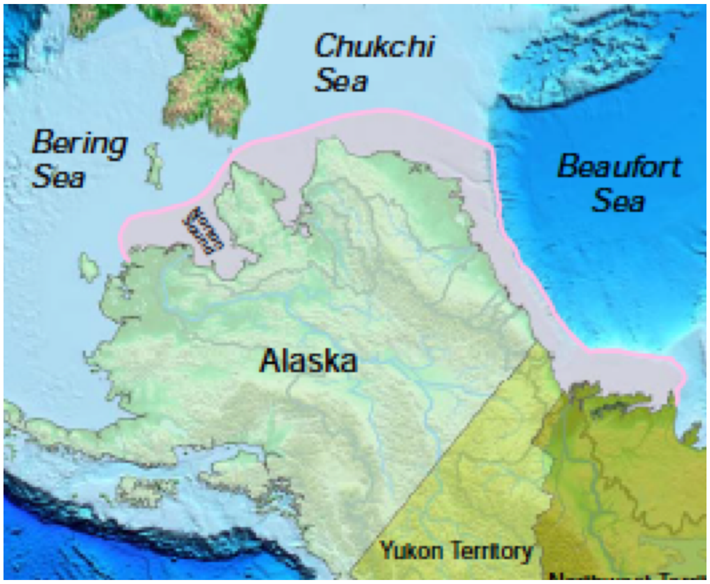

***Fig 16**. Map of Arctic-COLORS planned experimental domain (pink shaded area). The Arctic-COLORS nearshore emphasis complements and extends ABoVE's terrestrial emphasis.*

a unique contribution of Arctic-COLORS compared to other NASA field campaigns in polar regions. Arctic-COLORS offers a natural hydrologic cycle/coastal ocean complement to ABoVE, particularly flights of the PRISM sensor over coastal oceans of the ABoVE domain. Arctic-COLORS field activities are notionally scheduled for 2019-2025 and might overlap with the second year of intensive ABoVE airborne activites.

6.2 US Partner Airborne Campaigns & Opportunities

Numerous opportunities exist for ABoVE to leverage Contributed Airborne Measurements from partner organizations. A few examples of such collaborations are given below. This list is not exhaustive and the ABoVE Science Leadership continue to explore collaborations that will benefit ABoVE Science and the ABoVE Science Team.

DOE/NGEE-Arctic

The ARM Aerial Facility (AAF) flew 35 flights from May through September 2015 as part of the Airborne Carbon Measurements (ARM-ACME) campaign to construct regional carbon budgets and estimate CO_2 across Alaska's North Slope. Similar flights in 2016 – 2019 would significantly enhance ABoVE science and complement planned ABoVE airborne data acquisitions. https://www.arm.gov/sites/aaf

Additionally, ABoVE has a formal partnership with the DOE NGEE-Arctic program (http://ngee-arctic.ornl.gov/). NGEE-Arctic will provide extensive field data acquisitions from its Barrow (Phase I) and Seward Peninsula (Phase II) field sites. We also note the recent initiation of surface in situ CO_2 and CH_4 concentration measurements to augment the ARM mobile facility at the Oliktok Point, AK North Slope Alaska site (https://www.arm.gov/sites/amf/oli/).

NOAA

NOAA's greenhouse gas aircraft program has collected bi-monthly vertical profiles to 8000 m altitude of CO_2 and CH_4 concentrations from Poker Flat, AK since 2000. Since 2009 this program began new, ongoing greenhouse gas measurements in Alaska through collaboration with the U.S. Coast Guard. Bi-weekly Arctic Domain Awareness flights on C-130 aircraft generally begin in Kodiak, continue to Barrow, and return back to Kodiak after altitude profiles over Kivalina and Galena. On-board measurements include continuous CO_2, CH_4, CO, and ozone, as well as 24 flask samples analyzed at NOAA for CO_2, CH_4, CO, and 50 additional gases. In addition to spanning a large geographic region, the measurements also span the entire growing season, from late March to late November each year [Karion et al., 2011]
These observations will be complemented in August-September 2016 by a 4-6-week deployment of the NOAA Twin Otter out of Deadhorse to collect atmospheric CO_2 and CH_4 data over the North Slope. http://www.esrl.noaa.gov/gmd/ccgg/aircraft/

Additional opportunities exist to leverage other NOAA airborne deployments in Alaska such as the annual spring snow surveys.
http://www.nohrsc.noaa.gov/snowsurvey/

NSF/NEON
The NEON airborne observation platform (AOP) collects annual remote sensing data over NEON field sites using sensors mounted on an airplane. The AOP consists of a hyperspectral imaging spectrometer, a full waveform and discrete return LiDAR, and a high-resolution Red, Blue Green (RGB) camera. Data from the AOP show landscape-scale changes in numerous physical, biological and biochemical metrics, such as vegetation cover and density, canopy chemistry, and topography, including elevation, slope and aspect. For additional details, see http://www.neonscience.org/science-design/collection-methods/airborne-remote-sensing.

The ABoVE science leadership are actively working with NEON to coordinate flights of the NEON AOP with ABoVE airborne data acquisitions in the 2017 – 2019 period.

USDA Forest Service (USFS)
NASA and the USDA Forest Service scientists are collaborating on an ambitious project to inventory forest resources in the Tanana Valley of interior Alaska. The pilot project combines forest inventory plots and airborne remote sensing data from NASA Goddard's Lidar, Hyperspectral, and Thermal Airborne Imager (G-LiHT). Until recently, the remote forests of interior Alaska had never been included in national inventories of U.S. forest resources based on the costs and complexity of acquiring field data in remote and difficult terrain. The partnership between NASA and the Forest Service leverages unique capabilities for airborne remote sensing and ground surveys of forest structure and composition.

Other US Agencies
ABoVE is negotiating partnerships with US Geological Survey (USGS Alaska Science Center, http://alaska.usgs.gov/), the National Park Service (NPS Alaska Regional Office, https://www.nps.gov/akso/index.cfm), and other US agencies. In particular, ABoVE scientists will benefit from

- USGS LIDAR acquisitions in the Yukon Delta National Wildlife Refuge in 2016
- NPS Lake Clark National Park/Cook Inlet coastal mapping LIDAR data acquisitions planned for 2017

6.3 Canadian Airborne Campaigns & Opportunities

Polar Knowledge Canada (POLAR)
Polar Knowledge Canada (POLAR, https://www.canada.ca/en/polar-knowledge.html) has been ABoVE's primary Canadian partner during development and early field deployments. POLAR has also coordinated planning for ABoVE-related activities with other Canadian agencies and partners within the Canadian portion of the experimental domain. POLAR field research is coordinated through the Canadian High Arctic Research Station (CHARS) in Cambridge Bay, Nunavat. CHARS is a world-class research station that supports field logistics and maintenance and accommodations for visiting researchers. POLAR is exploring options with ABoVE to extend flight lines above the boreal forest treeline and into the high Arctic.

Canadian Forest Service (CFS)
The Canadian Forest Service (CFS, http://www.nrcan.gc.ca/forests) are responsible for research below the treeline and throughout the boreal forest portion of the ABoVE domain. CFS have extensive forest inventory and monitoring plots established along rivier and road corridors that are central to ABoVE airborne and field activities (Figs 4-6, Table 7). CFS are actively engaged in helping ensure that ABoVE flight lines capture as many of these sites as possible. Upon remeasurement of these CFS plots, these data could serve as a basis for Cal/Val of airborne remote sensing data.

CFS have acquired significant airborne data over the Canadian portion of the ABoVE domain in the past (see **Fig 18** below, for example). The ABoVE Science Leadership are working with CFS to identify all relevant CFS legacy airborne data and to maximize the ABoVE science benefit of any future CFS airborne data acquisitions within the ABoVE domain.

Potential Canadian Partners
Many Canadian agencies have expressed interest in collaborating with ABoVE, although these interactions are not as mature as those with POLAR or CFS. Evolving discussions with the Canadian Space Agency (CSA, http://www.asc-csa.gc.ca/), Natural Resources Canada (NRCan, http://www.nrcan.gc.ca/home), Canadian Centre for Mapping Earth Observations (CCMEO, formerly the Canadian Centre for Remote Sensing CCRS http://www.nrcan.gc.ca/earth-sciences/geomatics/10776), and the National Science and Engineering Research Council (NSERC, http://www.nserc-crsng.gc.ca/) may lead to formal and/or formal partnerships with these agencies. Additionally, ABoVE Leadership are engaged in discussions with the governments of the Northwest and Yukon Territories as well as multiple indigenous peoples about partnerships that would benefit ABoVE airborne activities.

6.4 Other Partnering Opportunities

AIRMETH (AWI)

AIRMETH (Airborne measurements of methane fluxes) delivers airborne eddy covariance measurements to estimate surface-atmosphere CH_4 fluxes in the circumpolar Arctic [Kohnert 2014]. Measurements are done with the research aircraft Polar 5 owned by Alfred Wegener Institute (AWI), Helmholtz Center for Polar- and Marine Research. AIRMETH deployments occurred out of Barrow AK in July of 2012 and 2013 and sampled across the North Slope coastal plain (**Fig 17**). Additional flights in July 2012 sampled the Mackenzie Delta. The AIRMETH payload includes turbulence measurements as well as a fast CH_4 analyzer (Los Gatos RMT-200). Wavelet decomposition combined with sensitivity footprints enables spatial discretization of the turbulence statistics and CH_4 fluxes at the ~100 meter scale [Metzger 2013]. The CH_4 flux detection limit is ~5 mgCH$_4$ m^{-2} d^{-1} (0.2 mgCH$_4$ m^{-2} h^{-1}) at the 95% confidence interval [Sachs 2014]. Comparisons of AIRMETH overflights with CH_4 flux towers in Barrow, Atqasuk and Inuvik are in progress. Preliminary analyses yield average CH_4 emissions of 17 mgCH$_4$ m^{-2} d^{-1} from the North Slope in July 2012, consistent with the Chang [2014] estimate of 11 mgCH$_4$ m^{-2} d^{-1} and considerably lower than the 30-50 mgCH$_4$ m^{-2} d^{-1} typically observed from EC towers and flux chambers [Olefeldt 2013].

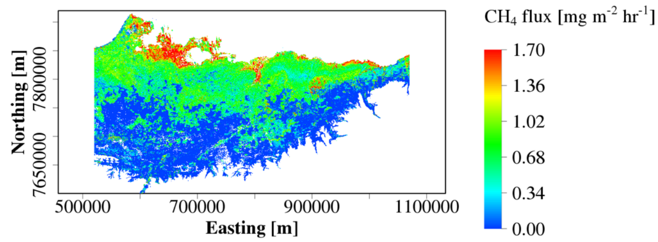

***Fig 17**. AIRMETH estimate of CH_4 fluxes on Alaska's North Slope for July 2012 (monthly mean = 17 mgCH$_4$ m^{-2} d^{-1}). Fluxes were estimated at a resolution of ~100 m using a wavelet transformation [Metzger 2013] of airborne eddy covariance data recorded during multiple flights from Barrow*

AIRMETH plans flights over North Slope Alaska and the Mackenzie Delta again in summer 2016. Principal Investigator Torsten Sachs is very keen to collaborate with ABoVE researchers during the 2017-2019 airborne intensives.

HALO Research Aircraft (DLR)

Researchers at the German Space Agency's (Deutsches Zentrum für Luft- und Raumfahrt e.V. DLR) Institut für Physik der Atmosphäre have developed CO_2 and CH_4 remote sensing and in-situ instruments for the HALO research aircraft (http://www.halo.dlr.de/). In particular, they are focused on pre-flight and on-orbit validation for the CH_4 measurements to be returned by MERLIN (LRD ~2020, https://directory.eoportal.org/web/eoportal/satellite-missions/m/merlin) and the

TropOMI instrument aboard ESA's Sentinel 5P (LRD late-2016, https://earth.esa.int/web/guest/missions/esa-future-missions/sentinel-5P).

In 2017, HALO will fly the Carbon Dioxide and Methane (CoMet) campaign over Central Europe, and are in exploratory talks to extend the campaign to the North American Arctic-Boreal region in conjunction with ASCENDS pre-Phase A flights of CO_2 and CH_4 lidar instruments aboard NASA's DC-8. The CoMet science consortium includes DLR; the Institut für Umweltphysik, Universität Bremen; Max-Planck-Institut für Biogeochemie, Jena; and the Institut für Umweltphysik, Universität Heidelberg. Additionally, the CoMet team are interested in exploring options for airborne campaign coordination with ABoVE in the 2019-2022 time frame.

CANMAM (UK NSERC)

The Methane and other greenhouse gases in the Arctic: Measurements, process studies and Modelling field campaign (MAMM) recorded airborne and ground-based measurements of methane (CH4), carbon dioxide (CO2) and boundary layer thermodynamics over the Fennoscandian landscape in 2012 [O'Shea 2014]. Airborne CO_2 and CH_4 fluxes were found to be relatively consistent with seasonally averaged surface chamber and eddy covariance measurements.

Principal Investigator Euan Nisbet has developed plans for a Canada-based follow on to MAMM: the *CANadian emissions of natural Methane, Anthropogenic Methane, and other non-CO_2 greenhouse gases (CANMAM).* CANMAM flight lines would be cover the Canadian portion of the ABoVE domain from the BERMS sites to the Mackenzie Delta. Although CANMAM was declined by the UK Natural Environmental Research Council (NERC) in 2015, there remains great interest in in the CANMAM team to deploy to North America in conjunction with the ABoVE airborne intensives.

CANMAM would include both summer (July/August) and winter (January/February) FAAM aircraft campaigns, with around 150 hours total. This enables 8-12 five-hour flights in each measurement period and allow for weather. Careful flight planning will allow CANMAM to sample at altitudes down to 200 ft above ground in remote wetland areas to ensure good mixed boundary layer measurement. CANMAM would also fly at altitudes up to 30000 ft to characterise regional and long-range transport and tropospheric mixing and entrainment into boundary layer air masses. The contrast between summer and winter emission and source profile (i.e. a wetland-biogenic "on-off switch") allows CANMAM to contrast anthropogenic versus biogenic sources. Forest fire emissions and impacts will be studied as the opportunity arises (likely in the summer campaign). Longer range transport and the background upon which local emissions are added, will be assessed by isotopic methane, ethane, and other trace gas measurements.

The FAAM BAe146 aircraft is capable of flying from below 100m across wetlands, to the upper troposphere and Arctic stratosphere. It will measure methane and a train of other gas species (CO_2, CO, N_2O, O_3, H_2O, etc.). The aircraft is also equipped for sampling air in steel flasks ('Whole Air Sample (WAS) bottles) and in grab samples taken in Tedlar bags. The aircraft is also equipped for remote sensing and the onboard ARIES spectrometer compares with satellite retrievals to investigate CH_4 'hot spots' and regional enhancement.

7 Satellite Sensor Synergies

NASA, the Canadian Space Agency, and other space agencies support numerous Earth remote sensing satellites that record essential observations for ABoVE research. ABoVE airborne remote sensing data can also provide essential cal/val data for satellite sensors. Additionally, there are several satellite remote sensing instruments under development that will benefit tremendously from ABoVE airborne data for pre-launch algorithm development and/or validation.

Table 9 highlights several satellite sensors that provide key data sets for ABoVE researchers and that will directly benefit from ABoVE airborne observations. This list is not comprehensive and researchers are encouraged to use satellite remote sensing data from all available sources in conjunction with ABoVE airborne data to develop new insights into the vulnerability and resiliency of Arctic-boreal ecosystems.

Table 9. Recent or Planned Satellite Sensors Relevant to ABoVE airborne science

Satellite	Launch Date	Res.	Measurements & Data Products
OCO-2	July 2014	2 km	NIR spectral radiances; Column CO_2; Solar induced chlorophyll fluorescence (SIF)
SMAP	Jan 2015	30 km	L-band radiometer; surface and root zone soil moisture; freeze-thaw state; carbon balance estimates
Radarsat-2 (CSA)	2007	3m	C-band polarametric radar; wetland mapping and discrimination; soil moisture; snow pack monitoring and analysis; sea- and river-ice
Trop-OMI (ESA)	Late-2016	7 km	NIR spectral radiances; Column CH_4 & CO; Solar induced chlorophyll fluorescence (SIF)
ICESat-2	2019		Photo-counting LIDAR; above ground biomass; digital elevation maps
NISAR	2022	TBD	L-band synthetic aperture radar; above ground biomass
MERLIN (CNES/DLR)	2018	100 m (TBC)	NIR spectrally resolved LIDAR; Column CH_4
HyspIRi	TBD	30 m	UV-VIS-SWIR-TIR hyperspectral radiances; vegetation chemistry and species; biodiversity
ASCENDS	TBD	100 m (TBC)	NIR spectrally resolved LIDAR; column CO2

8 Case Studies

We present a series of case studies that address how airborne remote sensing may be used to resolve key gaps in ABoVE science.

8.1 Wildlife & Ecosystem Services

The Wildlife and Ecosystems Services working group have identified major gaps in remote sensing product maturity and/or suitability that threaten successful completion of ABoVE science objectives. The case studies below use science questions related to snow and ice properties and fine-scale vegetation structure to illustrate how these gaps may be overcome.

8.1.1 Snow & Ice Properties

Although datasets used to derive snow cover dynamics products are available and suitable to the majority of ABoVE studies, datasets suitable for assessing dynamics in other snow properties that are important to understanding wildlife behavior/health and availability/accessibility of ecosystem services, are inadequate in their spatial and/or temporal resolutions, and/or are challenging to retrieve from satellite sensors. The two most critical missing datasets are for icing events and snow depth.

How does snow depth affect wildlife mobility and subsistence community access to natural resources?

Snow depth affects wildlife movement and can severely hinder the ability of residents to access subsistence resources, because people rely on the ability to travel via boat, snowmachine, and dog team through the vast roadless expanses of the ABoVE domain. Snow depth reconstructed from historical data sets (eg Arctic LCC snow data - more info here) do not cover the entire ABoVE Study Domain, and are particularly lacking in mountainous regions. Snow depth modeling approaches require high spatial resolution imagery and altimetry data during snow on (early spring) and off conditions in a few key locations throughout the ABoVE Study Domain.

ABoVE Target Areas: Wrangell St. Elias
Airborne data: High-resolution imagery and lidar (≤1m)
Sampling Strategy: Data acquisition surveys over ~50 km x 50 km (TBC) regions during late spring pre-thaw (snow on) and post-thaw (snow-off) conditions
Targets of opportunity: Coordinate with winter/spring travel corridor mapping for subsistence communities

How do icing events affect wildlife mobility, access to forage and mortality?

Icing events reduce mobility and access to forage and have caused recent catastrophic die-offs in northern ungulate populations (Putkonen et al. 2009, Rennert et al. 2009, Stien et al. 2010, Hansen et al. 2011, Hansen et al. 2014). Although the AMSR passive microwave sensor provides daily based surface freeze thaw retrievals (Podest, McDonald and Kimball, 2014) that could be combined with optically based dataset of snowcover extent (ie. MODIS snow product) to isolate snow cover status (J. Kimball, personal communication), the 6 km spatial resolution of AMSR is too coarse to study animal habitat selection and movement patterns, especially in complex mountain landscapes. Conversely, while finer scale freeze-thaw data is potentially available from spaceborne synthetic aperture radars (SARs) including ALOS PALSAR (L-band, ~100m) and Sentinal-1 (C-band, ~90m) the 2-4 week revisit time of these sensors is too sparse to study animal habitat selection and movement patterns. ABoVE research requires is daily sampling at less than 1km spatial resolution to detect the occurrence of icing events.

8.1.2 Fine-scale Vegetation Structure

How does 3D vegetation structure affect wildlife behavior in Arctic and boreal ecosystems?

The spatial and vertical resolutions of global- and regional-scale vegetation structure remote sensing products are too coarse to yield a comprehensive understanding of how 3D vegetation structure affects wildlife behavior at multiple scales within the ABoVE Study Domain. ABoVE wildlife and ecosystem services research requires a vegetation structural dataset (for near-present day) that covers the entire ABoVE domain with ≤30 m spatial resolution and ≤10 cm (TBC) vertical resolution. The fusion of high-resolution satellite (Worldview 3, Landsat) and airborne imagery, altimetry and vegetation vertical structure products will be required to create the wall-to-wall vegetation structural dataset. Airborne data acquisitions should emphasize the short-structure ecosystems that are underrepresented in currently available datasets which focus primarily on forested regions: shrublands and upland tundra, the tundra-taiga ecotones in the Yukon-Kuskokwim Delta and across the Canadian NWT, and recently burned areas for both shrublands and forests.

ABoVE Target Areas: Shrublnds near Toolik Lake/Alaska North Slope and northwestern Canada; tundra-taiga ecotones in the Yukon-Kuskokwim Delta, the Mackenzie Delta, and along the Canadian Shield; ABoVE fire recovery project sites
Airborne data: High-resolution imagery and lidar (≤1m)
Sampling Strategy: Data acquisition during peak of the summer growing season (~June – July)
Targets of opportunity: Burn recovery areas from the 2014 and 2015 fires in the NWT and Interior Alaska, respectively. Eitel tundra-taiga ecotone field sites

How does fine-scale vegetation structure determine wildlife travel corridors?

Subsistence communities rely on travel corridors across the landscape to access essential resources. However, travel corridors, modes of travel, resource needs, and accessibility each have distinct seasonal characteristics. Additionally, disturbances such as thermokarst features, ice conditions, wildfire severity, etc. may significantly alter subsistence resource availability and accessibility. Seasonal, high spatial resolution (~1 m) vegetation structure maps are needed within and around travel corridors of representative subsistence communities in the ABoVE domain. Ideally, airborne data would be collected for each study location in the winter, spring, summer and fall during at least one study year.

Airborne data: High-resolution imagery and lidar (≤1m)
Sampling Strategy: Mapping of ~25 km x 25 km (TBC) areas around rural subsistence communities during deep winter, spring thaw, mid-summer, early cold season refreeze
Targets of opportunity: Subsistence communities in the Yukon-Tanana Valleys near G-LiHT surveys for the US Forest Service; communities near regions targeted for snow depth and icing surveys

8.2 Arctic-Boreal Vegetation Structure and Disturbance

Vegetation structure and disturbance issues cut across multiple ABoVE Tier 2 science questions, as well as ecosystem dynamics and ecosystem services objectives.

8.2.1 Fire & Topographic Change in Boreal Forests

How does organic matter consumption during fires in boreal forests alter surface topography and subsidence from subsequent melting of permafrost?

Numerous ABoVE studies target the impacts of fire in boreal forests, including both short and long-term changes in carbon stocks, ecosystem structure, and forest composition. Seasonal airborne data acquisition would can differentiate post-fire changes due to organic matter consumption (C losses) from surface elevation changes due to permafrost melting or subsidence. Appreciable melting can occur during the same season in which the fire occurred, especially for May-June fires in Interior Alaska. Airborne remote sensing data acquisitions flown over a chronosequence of recent fires in the early-, mid-, and late-growing season is required to understand these competing processes.

Changes in ground surface elevation following fire provide a direct measure of the impact of organic matter consumption on surface topography and subsidence. Airborne surveys of the number of standing live and dead trees address the questions 'What is the relationship between fire severity and tree survival?'; 'How much aboveground biomass is directly consumed by fire?'; and 'How does fire intensity affect seed and seedling survival, and post-fire vegetation types and forest regrowth rates?

ABoVE Target Areas: Yellowknife NT, Interior AK (Tanana or Yukon watersheds), Yukon-Kuskokwim Delta

Airborne Data: Surface elevation; Individual live tree, burned stem, and understory vegetation heights with a horizontal resolution of ≤1 m and vertical resolution of ≤1 cm. Fine-resolution (< 1 m TBC) passive optical imagery for for context (air photos, hyperspectral, thermal or other multi-spectral data in the VNIR/SWIR region). The sensor choices depend on the specific questions of interest for characterizing fire effects (e.g., ground cover composition, forest composition, or characteristics of burn severity).

Campaign mode: Seasonal data collection, with repeated flights over a selected chronosequence of recent fires.

Targets of opportunity: Possibility to collect pre-post fire data for burns in 2017, if flight conditions permit data acquisition in the likely path of actively burning fir

8.2.2 Boreal Ecosystem Dynamics & Carbon Balance

The boreal zone and its ecosystems provide numerous provisioning, regulating, cultural, and supporting services. For about the past 7000 years, climate, fire, insects, diseases, and their interactions have been the most important natural drivers of boreal ecosystem dynamics, including rejuvenation, biogeochemical cycling, maintenance of productivity, and landscape variability. Layered upon natural drivers are changes increasingly caused by people and development and those related to human-caused climate change. Effects of these agents vary spatially and temporally, and, as global population increases, the demands and impacts on ecosystems will likely increase. Understanding how humans directly affect terrestrial and aquatic ecosystems in the boreal zone and how these effects and actions interact with natural disturbance agents is a prerequisite for informed and adaptive decisions about management of natural resources, while maintaining the economy and environment upon which humans depend [Price 2013].

The North American boreal forest covers ~3.7 million km^2 and provides ecosystem services at local, regional, and global scales, including the storage of large amounts of carbon in living biomass and soils [**Fig 18**; Margolis et al., 2015; Kurz et al. 2013]. However, this carbon is vulnerable to climate change, and the amounts sequestered vary in response to changes in fire frequency, severity and distribution (Amiro et al. 2009) as well as insect epidemics (Kurz et al. 2008). Climate change has the potential to create positive feedbacks through which decreases in forest carbon sequestration lead to increased atmospheric CO2 concentrations, further exacerbating climate warming [Koven 2015; Soja et al. 2007]. More frequent and larger wildfires, increased insect infestations, and changing vegetation structure due to melting permafrost are likely consequences of increased temperatures in the boreal forest region (Price et al. 2013).

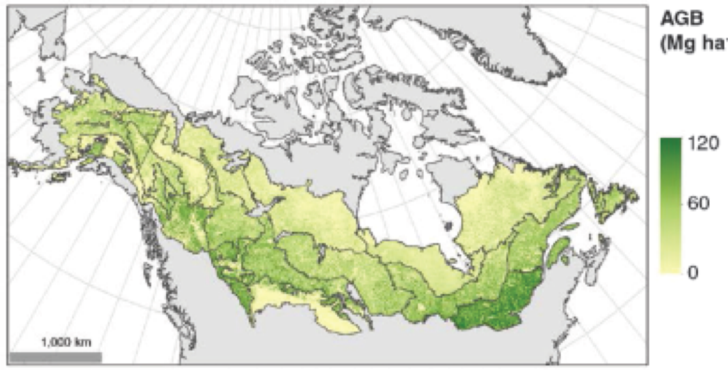

***Fig 18**. Distribution of above ground biomass (AGB) in the boreal forest of North America [Margolis, 2015]*

- What is the carbon balance of the boreal ecosystems within the ABoVE domain now, what has it been in recent decades, and what is its future trajectory?
- Could higher net primary productivity (NPP) offset anticipated C losses resulting from increased disturbances?
- Do the processes that drive carbon balance differ for managed vs unmanaged boreal ecosystems?

To understand how boreal forest carbon (C) dynamics might respond to anticipated climatic changes, one must consider two important processes. Climatic changes are expected to increase the frequency of fire and other natural disturbances that would change the forest age-class structure and reduce forest C stocks at the landscape level. Second, global change may result in increased greening and net primary productivity [Kurz 2008].

8.2.3 Fire Disturbance & Post-fire Recovery in Boreal Forests

Fire is the primary disturbance agent in the boreal forest with future climate change likely to increase fire frequency. In fact, Bond-Lamberty et al. [2007] found that fire was the dominant driver of carbon balance over the 1000 km x 1000 km BOREAS study region. More frequent and larger fires in the late twentieth century resulted in deciduous trees and mosses increasing production at the expense of coniferous trees [Bond-Lamberty 2007].

In the absence of active fire suppression, the northern boreal of Canada is dominated by large, stand-replacing crown fires, typically started by lightning strikes (De Groot et al., 2013; Stocks et al., 2002;Wooster, 2004). As the majority of these northern forests are unmanaged and not subjected to routine forest inventory (Gillis, Omule, & Brierley, 2005), a strong characterization of the impacts of these fires on forest structure is lacking. Additionally, due to the large extent of the northern boreal and the limited access to these forests (Andrew,Wulder, & Coops, 2012), quantifying the structural response to a range of fire events is difficult through field measurement alone.

Bolton et al. [2015] found that structural development following fire is highly variable across boreal landscapes, as site conditions, species composition, and fire severity can vary both within and between fires (Bonan & Shugart, 1989; Greene et al., 2004; Johnstone et al., 2004). A spatially explicit understanding of this variability in structural development, both within and between disturbance events, is required to improve characterizations of carbon loss and uptake across forested landscapes. This is of particular importance in high latitude forests, where local variation in received solar radiation and permafrost contributes to a high diversity of site conditions (Bonan & Shugart, 1989). Our results suggest that pre-disturbance conditions are a strong indicator of stand development following fire, as patches classified as dense forest prior to burning displayed faster growth and recovery than patches classified as open forest. Knowledge of pre-disturbance conditions and expected growth can therefore lead to more spatially explicit predictions of stand development and carbon uptake following disturbance.

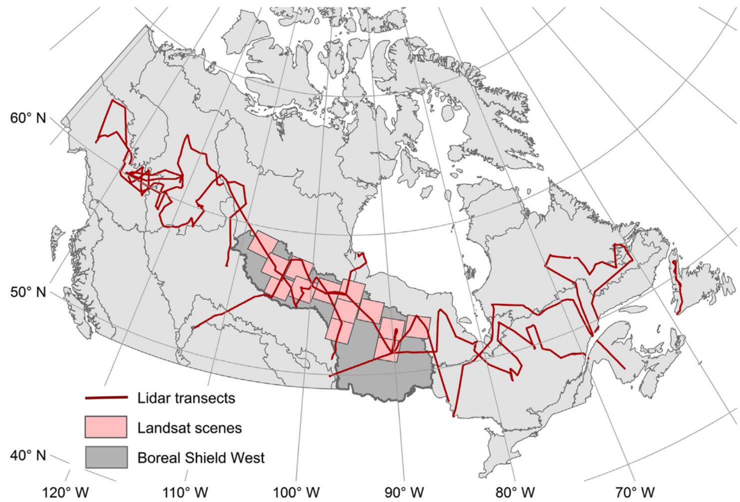

***Fig 19**. The airborne lidar transects and selected Landsat scenes overlaid on the terrestrial ecozones of Canada [Bolton 2015]. The overlapping Landsat-lidar analyses cover portions the primary and extended ABoVE domains. Much of the 25,000 km of lidar sampling occurs in other portions of the ABoVE domain.*

8.2.4 Challenges for Understanding and Managing the Canadian Boreal Forest

What is the carbon balance of unmanaged boreal forest within the Canadian portion of the ABoVE Core Study Region and how does its recent evolution, current state and future trajectory differ from that of the managed boreal forest?

A detailed synthesis of the unique challenges for understanding and managing Canada's vast boreal forests have been presented in a series of review papers [Brandt 2013; Kurz 2013; Price 2013; Lempriere 2013], following on the comprehensive characterization of the North American boreal zone by Brandt [2009]. Canadian forest research priorities and policy needs have been described in *A Blueprint for Forest Carbon Science in Canada 2012-2020* [Bernier 2012].

Canada's boreal woodlands and forests cover ~ 270 Mha (3.1 million km2) [Kurz 2013]. Canada's managed boreal forest, ~145 Mha or 54% of the nation's total boreal forest area, stores 28 Pg carbon (C) in biomass, dead organic matter, and soil pools. From 1990 to 2008, Canada's managed boreal forest acted as C sink of 28 Tg C year−1, removing CO2 from the atmosphere to replace the 17 Tg of C annually harvested and store an additional 11 Tg of C year−1 in ecosystem C pools. The C balance of the unmanaged boreal forest, ~125 Mha or 46% of Canada's total boreal forest area, is currently unknown. *Reducing the uncertainties of the current and future C balance of Canada's boreal forest requires addressing gaps in monitoring, observation, and quantification of forest C dynamics, with particular attention to the 125 Mha of unmanaged boreal forest with extensive areas of deep organic soils, peatlands, and permafrost containing large quantities of C that are vulnerable to global warming* [Kurz 2013].

Approximately 40% of the forested area is underlain by permafrost, some of which is already degrading irreversibly, triggering a process of forest decline and re-establishment lasting several decades. Quantifying the multiple effects of climate change will be challenging, particularly because there are great uncertainties attached to possible interactions among them, as well as with other land-use pressures. Key knowledge gaps exist in understanding boreal mitigation strategies that are robust to climate change and how mitigation could be integrated with adaptation to climate change [Lempriere 2013]. Considerable ingenuity will be needed from forest managers and scientists to address the formidable challenges posed by climate change to boreal ecosystems and develop effective strategies to adapt sustainable forest management practices to the impending changes [Price 2013].

ABoVE Target Areas: Managed and unmanaged boreal forest tracts within the Canadian sector of the ABoVE Core Study Region

Airborne data: High-resolution imagery and lidar (≤1m) for above-ground biomass, structure, function, composition and chemistry; airborne atmospheric CO_2, CH_4 and CO measurements

Sampling Strategy:
High resolution imagery & lidar: Data acquisition surveys over both managed and unmanaged boreal forest transects during late June/Early July
Atmospheric CO_2, CH_4 and CO: Flights every month from April – November across the Canadian boreal forest sector with vertical profiles from ground level to ~5000 masl every 200-300 km and in the vicinity of any eddy covariance flux towers or tall towers;

Targets of opportunity: Coordinate with fire and disturbance field studies; past or planned airborne lidar transects by CFS

8.3 Topographic Control of Hydrology-Permafrost Interactions

Hydrology-permafrost interactions are inseparably linked to topography across the ABoVE domain on scales from centimeters to >100 km. A common thread for these studies is a need for the most accurate possible digital elevation maps. Airborne remote sensing provides extensive sampling over regions that are not easily accessible from the ground but that are experiencing disturbance and rapid change.

8.3.1 Thermokarst & Permafrost Degradation

Thermokarst is defined as the thawing of ice-rich permafrost or melting of massive ice, and the subsequent surface subsidence and formation of characteristic landforms (van Everdingen 1998). In fact, thermo-erosive and thermo-abrasive processes are also controlled by thermokarst (French 1996). For example, Hinkel et al. [2003] found 72% of a 1572 km^2 large study area on the Barrow Peninsula in Alaska, including drained thermokarst basins and lakes, represented thermokarst-affected terrain

Once permafrost starts to thaw, all components of the affected ecosystems change, and there are strong positive and negative feedbacks that control how degradation progresses. Thermokarst features occur across a wide range of terrain and ground-ice conditions, develop into a wide range of sizes (m^2 to km^2), and have numerous degradation and stabilization stages that can span a wide range of ages. Grappling with this heterogeneity of terrain, dynamism, size and ages requires a multi-component and multi-scale approach.

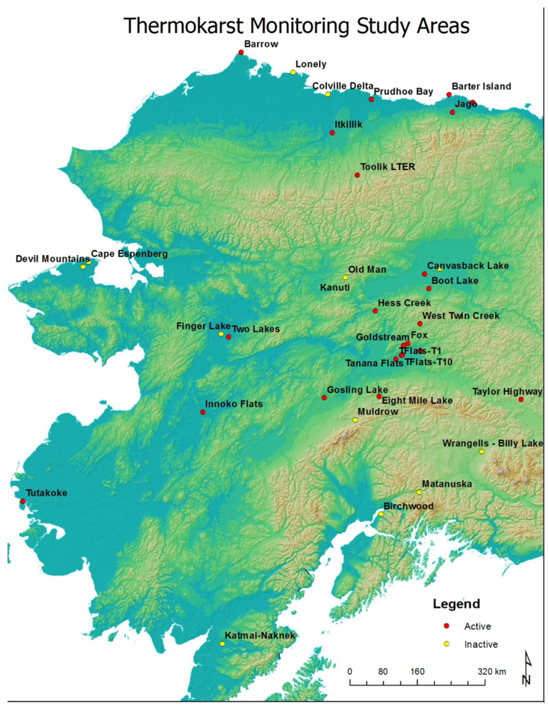

Fig 20. Sites for the Alaska Thermokarst Monitoring Network are concentrated along the Dalton Highway corridor between Prudhoe Bay (Deadhorse) and Anchorage (Alaskan Circuit). Other sites are sampled by the Fairbanks – Tok and the Fort Yukon – Fairbanks portions of the Canadian Cicuit. [Image courtesy T. Jorgenson]

Jorgenson and coworkers have been developing a monitoring network for Alaska that integrates regional, landscape and local scale monitoring strategies. For regional assessment of the nature, extent, and trends of thermokarst features, we acquired high-resolution stereo airphotos at 10-km spacing along longitudinal transects across Alaska and determined the absence or presence of thermokarst and its type in the center of air photos. Determinations at the systematically distributed points were done through photo-interpretation based on changes in vegetation, topography, and pattern recognition based on experience gained from field surveys. For landscape-level monitoring of change, 27 study areas widely distributed across Alaska with active thermokarst where they have been mapping thermokarst features within 20–50 km^2 areas at 1:2,000 scale using airphotos and satellite imagery from ~1950, ~1980, and ~2010 to document intermediate-term changes (**Fig 20**).

For local-scale monitoring and evaluation of thermokarst processes, a comprehensive set of ecological components have been sampled along 200–500 m transects at the 27 study areas, representing different landscapes, including topography (surveying, ground-based LiDAR, or airborne LiDAR), hydrology (water-table surveys, water-level recorders, time-lapse photography), soils and ground ice (coring and sampling for ground-ice and soil organic carbon content), paleoecology (peat and stratigraphic interpretation, radiocarbon dating), thaw depths and permafrost table (probing and geophysical surveys), soil and water thermal regimes (dataloggers), and vegetation (occular estimates and point sampling by species). At the most intensive study areas, sampling for the entire suite of components has been stratified into 4–6 degradation/stabilization stages with each stage replicated at three sites (plots). The field surveys and remote sensing are designed to be repeated every 5 and 10 years, respectively.

8.3.2 Inundation, Surface & Sub-surface Hydrology

Seasonally inundated areas and water-saturated soils are common features of lowland Arctic and boreal permafrost environments. With the onset of snow melt, and water percolation down through the snowpack, a principal factor controlling stream channel flow, aside from active layer depth, is topography. Both sophisticated modeling techniques and high spatial resolution digital elevation models (DEMs) are needed to define stream channel networks accurately and hence establish a comprehensive link between the drainage network and seasonally inundated areas.

Surface water flow in permafrost landscapes leads to thermo-erosion and the development of gully systems (McNamara et al. 1999). Thermokarst (ground subsidence after ground-ice ablation) leads to ponding and lake formation since thaw waters accumulate in thermokarst depressions (Grosse et al. 2013). Liljedahl et al. (2012) examined the sensitivity of a hydrological model to topography in DEMs representing unique tundra landscape features (low and high-centred polygons, as well as drained thaw lake basins). They found that the water balance in a polygonal permafrost landscape has significant effects on the partitioning between infiltration and runoff and that indeed permafrost micro-topography may have larger implications on the water balance that are not considered at regional scales.

Subsurface flow within the thawed active layer needs also be considered. Wang et al. (2009) found that active layer thawing processes have a considerable impact on the spring runoff regime. Increases in active layer depth allow water infiltration and subsurface flow rather than surface runoff. Diffuse subsurface flow within organic rich active layers is also a common phenomenon, with the extent of organic terrain significantly influencing the runoff regime (Quinton 2003).

The ABoVE domain has very few hydrologic measurements making it difficult to predict flood events and make progress on research questions that require information on the water balance. Measurements of surface water elevation using air-borne radar interferometry over river courses, flood planes and repeat cross sections would provide estimations of discharge volumes and patterns in un-gauged systems [eg Pendinotti et al., 2014], thus supporting critical science needs in the region.

8.3.3 Active Layer Thickness & Permafrost Physical State

The Remotely Sensed Active Layer Thickness (ReSALT) product uses the Interferometric Synthetic Aperture Radar (InSAR) technique to 1) measure long-term subsidence trends resulting from the melting and subsequent drainage of excess ground ice in permafrost, and 2) measure seasonal subsidence resulting from the expansion of soil water into ice as the active layer freezes and thaws, and 3) estimate Active layer thickness (ALT) from the seasonal subsidence assuming a vertical profile of water within the soil column. In addition, ReSALT can identify individual thermokarst features as spatial anomalies in the subsidence trends. ReSALT was funded as a pre-above project in 2013.

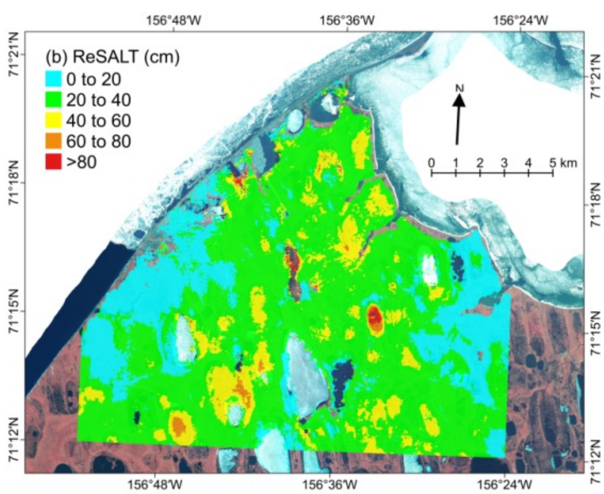

Figure 1: ALT from the ReSALT Product at Barrow, Alaska. The basic product consists of subsidence trends, seasonal subsidence, ALT, and associated uncertainties

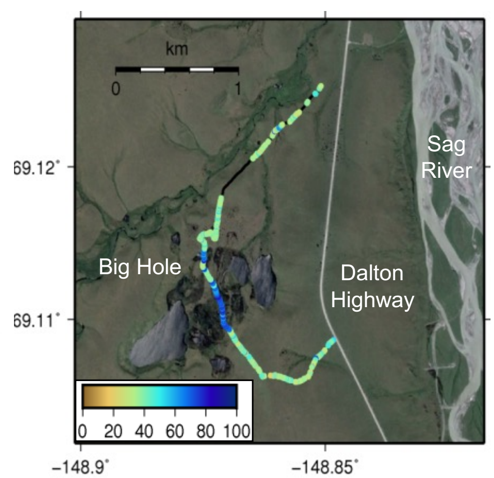

Figure 2: A sample GPR survey of ALT (cm) for the Big Hole wetland near Happy Valley airport on the North Slope of Alaska. Black indicates missing data.

The ReSALT project has produced seven products on the North Slope of Alaska at Barrow, Deadhorse, Happy Valley, the Anaktuvik fire zone, and Toolik Lake. In addition, we have two products of validation data at Barrow and Toolik Lake each consisting of ~15 km of ALT surveys collected using Ground Penetrating Radar (GPR) and probing. Figure 1 shows ALT from the ReSALT product at Barrow Alaska and Figure 2 shows a sample ALT survey at the Big Hole wetland near the Happy Valley airport on the North Slope of Alaska

8.3.4 Active Layer Thickness & Permafrost Physical State

Permafrost systems such as those in Alaska are believed to be among the most vulnerable to the effects of global warming, and may be at risk of reduction or loss. Quantifying their properties, such as the active layer thickness (ALT), is of great importance in understanding their effects from, and on, climate change. Permafrost and its associated ALT have also been shown to impact the type and dynamics of overlying landcover in the boreal and arctic regions, including those with both mineral and organic soils, and emergent, scrub/shrub, and forested vegetation types.
Time-series measurements of permafrost soil temperatures in Alaska have shown pervasive warming trends within these systems. Loss or reduction of permafrost can have detrimental impacts on infrastructure in northern communities due to diminished terra firma. Permafrost dynamics and excessive thawing can also have a significant positive feedback on climate change.
Even though many researchers have investigated and collected data on the spatial distribution and depth of permafrost in Alaska, these measurements have been of very limited spatial extent; no consistent information is available on the depth of the active layer at a larger and continuous regional scale and for different seasons. Currently, no consistent time-series information is available on the active layer thickness at a larger and continuous regional scale. Measurements of soil moisture within the active layer are even more scarce. Direct manual measurement of the depth of the active layer is infeasible due to the large spatial extent, heterogeneity, and the inaccessible nature of the areas of interest. No remote sensing technique has been used heretofore for *direct* observations of the depth of permafrost interface and the active layer properties. Use of low-frequency SAR observations may offer the only feasible method for such direct observations. Furthermore, use of two or more frequencies is expected to increase accuracy of retrieved active layer and permafrost products, as explained earlier in this document.

ABoVE Target Areas: Entirety of Alaskan and Canadian circuits, with the supplemental measurements highly desired to capture a larger range of vegetation, topography, soil, and temperature gradients for mapping of active layer properties; the larger the coverage domain, the better data set we will have for upscaling to the entire domain.

Airborne data: UAVSAR (L-band) and AirMOSS (P-band) radar, acquired "simultaneously" (within a few hours)

Sampling Strategy:
Spatial sampling: should be designed to cover north-south and east-west transects in Alaska and Canada to the extent resources allow. The Foundational Measurements provide the most critical areas, and supplemental measurements will allow better representation, especially for any upscaling analyses.
Temporal sampling: at a minimum should capture the end of the freeze-thaw transition season (~May) and the fully thawed season (late August). Capturing the shoulder seasons (April-May and October) are highly desirable for permafrost dynamics. For coincident studies of vegetation state and productivity, a mid-summer acquisition is highly desirable.

Targets of opportunity: The supplemental flight paths shown in Figure 2, and especially the BERMS sites are highly desirable. BERMS sites have been the subject of much data acquisition and analysis since BOREAS started in 1993. There is quite a bit of airborne radar (L and P band), hyperspectral, and optical satellite data collected at these sites, as well as a long history of flux tower data and in-situ soil moisture data. Most recently, BERMS has been one of the main study sites for the AirMOSS EVS-1 mission, with 3 years and more than 25 flights over the sites.

8.3.5 ArcticDEM Reference Elevation Dataset Requirements

Accurate high-resolution elevation data are essential to hydrology-permafrost interactions research, Such data may be analyzed to yield slope and curvature parameters from which surface and subsurface flow networks may be deduced. Morin and the ArcticDEM team are using commercially available satellite data to produce elevation models -- with a resolution of between 2 and 8 meters -- for all Arctic landmasses north of the 60N. **Fig 21** shows a detail of Point Hope, Alaska.

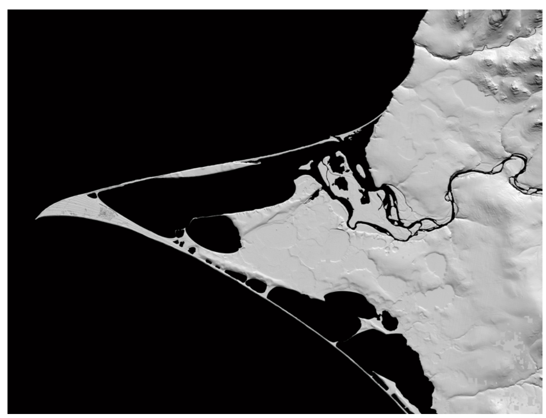

***Fig 21**. High-resolution digital elevation model of Point Hope, Alaska from the ArcticDEM*

Digital topography produced by the ArcticDEM team may have noise and biases inherited from uncertainties in the satellite orbits and slight miscalibration in the optical sensors. The Digital Elevation Models (DEMs) that we produce are referenced to the GRS80/WGS84 Ellipsoid. Initially, we do not indent to translate the DEMs to orthometric heights, although we have not ruled out the possibility of orthometric DEMs for some of our final products.

Reference elevation data are required to minimize artificial vertical shifts in the DEMs (see **Fig 22**). The most effective types of ground control (level-0 and level-1) are acquired from airborne LiDAR and InSAR sensors, respectively. Level-4 satellite data lack accuracy, but provide critical spatial coverage. We appreciate the help of our international partners populating the ground control database. The more data sources we can call upon, the better the final product will be. For all sources, we require certain core attributes: longitude, latitude, height, reference datum, date of survey, and estimate of uncertainties.

Level-0 LiDAR, Photogrammetry and Structure from Motion data

Well-positioned, quality controlled, dense (more than 1 return per square meter) point clouds are the best form of ground control for ArcticDEM. We require associated metadata including platform and instrument type, positioning type, operator (and contact information of the operator). We can also utilize point clouds generated from ground-based LiDAR and InSAR surveys. LAS file are preferred, but we can also ingest other formats and DEMs.

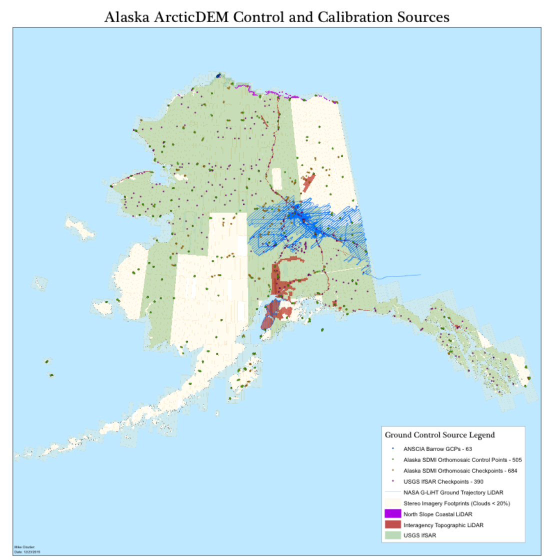

Fig 22*. Map showing the distribution of Alaska ArcticDEM control & calibration sources. Much of the state has been surveyed by USGS IfSAR (leve-1, green shading), but vast sections in the northeast and southwest remain unsampled (white). High accuracy LiDAR validation (level-0) is available only in the eastern Interior (NASA G-LiHT, blue lines), near Anchorage and in a narrow swath along the Dalton Highway (Interagency LiDAR, brown), and along sections of the North Slope coast (purple).*

Level-1 InSAR surveys

Well-positioned airborne InSAR has the potential to provide good ground control, presuming that the airborne data itself is well controlled.

Level-2 Kinematic GNSS ground surveys

Dense ground surveys along identifiable features or grids of GNSS points collected at a high rate have the data density required. Full details of the survey must be known, including operator, equipment, base station location, antenna type, and antenna height. ASCII or translatable binary files are most useful.

Level-3 Cadastral points and GNSS locations.

Single GNSS points from continuous or campaign GNSS stations are useful, but we require full knowledge of the both the antenna offset and, critically, the relationship between the antenna mark and the ground around the station. We prefer a network of stations if possible. We need information about the antenna, antenna offset, monument and, monument location if possible. Several photos showing the antenna, its relationship to the ground, and the area around the antenna will allow us to extract the height of the ground using structure from motion algorithms. It will often be the case that we will have to manually identify GNSS points in imagery.

Level-4 ICESat and Cryosat-2 altimetry.
Large footprint LiDAR and RADAR elevations from satellite missions provide the least information, but the most spatial coverage. We rely on having as many possible returns of non-changing surfaces within a DEM swath. This is difficult for some areas of the world with tree coverage and or extensive ice, but no bedrock.

The data required for ArcticDEM validation may be acquired as part of other ABoVE airborne lidar and SAR remote sensing activities and do not seem to drive airborne remote sensing priorities. Coverage in critical ABoVE regions such as the North Slope, the Yukon-Kuskokwim Delta, the Seward Peninsula, the Mackenzie River Delta, and the Yellowknife area would be extremely valuable. Note that current validation efforts focus only on Alaska and extensive validation data will be needed for the Canadian part of the ABoVE domain.

8.3.6 Airborne Electromagnetic (AEM) Surveys

Remote sensing technologies provide valuable information about Earth's surface and near-surface environment extending to within the upper 1 meter or so belowground. However, many details about cryospheric, hydrogeologic, and geomorphic properties at greater depths are largely unknown, yet are critical to the response of permafrost-affected landscapes to climate change (Gogenini et al. 2014) and, thus, are of significant importance to ABoVE science priorities. For example:

- The pattern of discontinuous permafrost controls hydrologic flowpaths and potential connections between surface water and deeper groundwater systems;
- Deep permafrost thaw after fire or from other sources of disturbance are difficult to characterize over large areas;
- Extents of deep permafrost degradation are largely unknown, and belowground thaw may indicate precursors to future thermokarst degradation before there are ground-surface expressions.

Airborne electromagnetic (AEM) surveys are uniquely capable of mapping subsurface properties from depths of a few meters to 100 meters or more belowground, over regional study areas of hundreds-to-thousands of square kilometers. Recent AEM applications in Arctic and Antarctic environments have illustrated the value of these data for mapping deep permafrost and geologic characteristics in relation to complex hydrologic systems (Minsley et al., 2012; Mikucki et al., 2015).

There are natural synergies between AEM and other more traditional or emerging remote sensing techniques that, together, can provide a holistic understanding that spans Earth's near-surface and deep subsurface environments. Combined analysis of AEM and Landsat-derived products has shown value in improving interpretations of active layer thickness and permafrost distribution in the Yukon Flats ecoregion (Pastick et al., 2013), for example. Data fusion approaches that utilize other remote sensing modalities (e.g. radar, hyperspectral, lidar) along with AEM have received little attention, but have significant potential for ABoVE studies.

AEM surveys could be used in the ABoVE mission to map subsurface permafrost distribution for select intensive research sites, or as part of airborne remote sensing missions that integrate topography, thermokarst, soil moisture, active layer thickness, and vegetation properties along regional transects. AEM surveys could provide foundational baseline data for monitoring permafrost degradation, or existing AEM surveys in the Yukon Flats or Alaska Highway corridor could be resurveyed to assess short-term permafrost and active layer changes. The extensive areas subjected to severe burn intensity during 2014 in the Northwest Territories and 2015 in Alaska offer unique survey opportunities as well.

Specialized companies are typically contracted to provide AEM data. Given the tight schedule for ABoVE airborne campaigns, and the investment in specialized instrumentation would be required by NASA to develop comparable airborne sensors, contracting for AEM data seems the most cost effective approach.

8.4 Linking ABR Carbon Cycling and Vegetation Dynamics

Accurate understanding of ecosystem carbon balance (net ecosystem carbon balance, NECB) encapsulates the full range of space-time sampling challenges ABoVE faces.

- Diurnal to centennial timescales
- Flux rates change by orders of magnitude over distances of a few meters – how to integrate site level understanding to accurate landscape, regional, pan-Arctic C budgets
- Fire distorts near steady-state conditions and may shift sign of annual C balance for a landscape/region/pan-Arctic depending on the severity of the fire season
- Case is better/worse for understanding of CH4
- Long lifetime of ABR SOC has previously been governed by cold, wet conditions – will that persist under expected climate warming?
- When, where, how much, what form will mobilized PF C release take?

8.4.1 Arctic-Boreal Carbon Cycle Dynamics

What is the impact of large-scale greening and browning on the seasonal and annual carbon budgets?

The Carbon in the Arctic Reservoirs Vulnerability Experiment (CARVE) flew hundreds of hours over boreal and arctic Alaska in 2012-2015, spanning

March/April to September/early November (see Chang et al 2014). Using a model-data framework we have determined regional CO2 and CH4 emissions from CARVE observations. Fig. 1 shows the aircraft optimized CO2 fluxes for Alaska 2012-2014. In panel 1a, the observationally constrained growing season (red) begins almost 4 weeks later than the growing season estimated from a satellite driven CO2 flux model (black, described in detail in Luus and Lin, 2015). The 4 week premature uptake appears to be an artifact of the MODIS EVI (Enhanced Vegetation Index) product used to represent the light use efficiency when calculating gross primary productivity (GPP) in the model. In panel 1b, the same model with solar-induced chlorophyll fluorescence (SIF) from the OCO-2 satellite representing light use efficiency coincides well with the timing of the observationally constrained growing season. A 2-4 week change in the start of the short arctic growing results in the previous estimates of a small carbon sink (from the EVI-driven model) into a large carbon source in 2013 and 2014. Resulting questions are: What is the relationship between the timing of SIF increase and the annual carbon budget? What is the impact of large-scale greening and browning on the seasonal and annual carbon budget?

Similar results are observed by regional scale tall tower and eddy covariance flux towers: Both the CRV tower near Fairbanks (NOAA, Karion et al 2015) and eddy flux sites near Fairbanks (Euskirchen, Ueyama) see a difference in the beginning of the EVI driven simulation and the observed growing season of only a week or two in the boreal region. A detailed analysis of the Barrow CO2 data shows that there is insufficient land-sector data in June to robustly capture the beginning for any given year so the overall length of the growing season cannot be calculated. However, eddy flux data from towers sampling the tundra on the North Slope show the EVI-driven model to be 3-4 weeks premature (Euskirchen, Oechel), highlighting how the growing season dynamics of the boreal forests are distinctly different from tundra ecosystems, which are well represented across the CARVE aircraft domain. Our results highlight dependency of growing season and spring phenology on ecosystem type. How is the apparent agreement of the beginning of carbon uptake and SIF related on the leaf-level for each ecosystem type? What are the functional underpinnings of SIF and non-photochemical quenching (NPQ) on the site level? By combining regional observations to detailed site level observations, important processes within the ecosystem can be scaled up.

Although not well suited to characterize spring-time CO2 fluxes from the North Slope, Barrow CO2 does reveal a systematic premature growing season across northern high latitudes in intercomparison studies of dynamic global vegetation models (J Randerson, personal communication), which, unlike satellite driven diagnostic models, are designed to mechanistically represent the structure and functioning of land ecosystems. This bias can also be traced to errors in the calculation of gross primary productivity. Can the spring awakening of carbon uptake, which is not captured, be correctly represented by process models of tundra or boreal ecosystems? In particular, year-round observationally constrained regional scale fluxes of CO2 over tundra ecosystems are urgently needed in order to test CO2 flux models and their drivers. Can the functional relationships identified above improve the models and reduce uncertainty?

ABoVE Target Areas: North Slope, Alaska
Airborne data: Airborne atmospheric CO_2, CH_4 and CO measurements
Sampling Strategy: Flights every ~2 weeks from April – November across the North Slope with vertical profiles from ground level to ~5000 masl over Toolik Lake, Ivotuk, Atqasuk, Barrow, Umiat, and Deadhorse where long-term eddy covariance flux towers or continuous atmospheric concentration measurements are made
Targets of opportunity: Field sites examining tundra greening and its associated biogeochemistry

8.4.2 Characterizing Biogeochemical Drivers of ABR Carbon Cycle Dynamics

What is the functional relationship between solar induced fluorescence (SIF) and surface-atmosphere carbon exchange at the landscape, ecosystem, and regional scales within the ABoVE domain?

Recent results from the CARVE project have highlighted how airborne measurements of CO_2 and CH_4 concentrations can be used to successfully calculate regional carbon fluxes. A coordinated series of new aircraft measurements and careful coordination with site-level measurements are required to understand the biogeochemical drivers that drive the observed seasonal pattern on the process-level, and to properly represent these in carbon cycle models.

The onset of photosynthetic CO_2 uptake in the spring appears to be a particularly important period for the carbon balance and a lever for climate sensitivity. From CARVE, we learned that satellite measurements of solar-induced chlorophyll fluorescence (SIF) represented the timing of the Alaskan regional carbon spring and fall (and therefore the growing season length) much more accurately than widely used MODIS EVI (Enhanced Vegetative Index). The observed onset of photosynthesis was 2-3 weeks later than the greening shown by EVI, a lag sufficient to reverse the sign of the overall carbon balance. The spatial and temporal coverage of satellites such as GOME-2 and OCO-2 makes it difficult to determine the functional relationships between SIF and carbon exchange at the landscape and ecosystem scales. For this reason, high-resolution airborne studies are needed, closely linked to smaller scales (ecosystem) and large (satellites).

To elucidate the processes controlling the SIF and carbon exchange relationship, airborne measurements of SIF (high resolution CFIS spectrometer) should be combined with a thermal infrared imager and hyper-spectral reflectance measurements (e.g. AVIRIS-ng) to determine both SIF and vegetation traits, including seasonal shifts in the pigment pool, chlorophyll and carotenoid pigment pools and effective leaf area (related to leaf area index and clumping). These observations can then be related to the representative carbon flux each smapled ecosystem type derived from concurrent airborne in-situ sampling of CO_2 and CH_4.

This complementary approach would enable us to disentangle effects of changes in absorbed radiation from those in photosynthesis and fluorescence efficiencies in the SIF signal and determine their temperature sensitivities, and to relate remotely sensed attributes directly the carbon balance at ecosystem and regional scales. This mechanistic understanding of the SIF signal is necessary to understand the drivers of the seasonality of regional carbon fluxes. Thus, we encourage focus on the shoulder seasons, with particular attention to to correctly determine the timing of carbon uptake in spring and the onset of emissions in fall, the key to determining the annual carbon budget for major ecosystems.

Carbon cycle dynamics during the shoulder seasons are influenced by freeze/thaw thresholds, and are particularly sensitive to climate change. Of these two periods, the spring season would be the highest priority, both because of the more favorable illumination conditions, and because of the likely influence of this spring transition on annual photosynthetic uptake. Coordinating the aircraft measurements with ground-based sites will combine the spatial coverage provided by the aircraft with the temporal cover- age provided by long-term ground based measurements and could provide further mechanistic in- sights. Ideally, pre-defined transects crossing different biomes as well as ground-based observations should be repeated several times during the shoulder seasons, especially at the onset of the growing season. The same strategy can be applied to regions with observed greening or browning trends (see below), helping to unravel the causes for those trends.

The ABoVE domain has recently evidenced greening and browning trends as determined by the maximum MODIS NDVI (Normalized Difference Vegetation Index). Tier 2 Science Objective Ecosystem Dynamics 5 states: *Determine the causes of greening and browning trends and their impacts on ecosystem form and function*. With different ecosystems showing greening (e.g. north slope of Alaska) and browning (e.g. south-west Alaskan tundra) [Bieniek et al., 2015], the impact of these NDVI trends on the ecosystem function and how this propagates through to the annual carbon budget should be examined for each ecosystem in detail. However, as stated above, EVI (and, in initial tests, NDVI) estimates that vegetation in the tundra is active nearly a month earlier than the carbon uptake begins so care should be taken to relate NDVI to ecosystem function in detail for each ecosystem. Separately, Walther et al (2015) also show differences between the spring timing of SIF and EVI onset in boreal evergreen forests.

Flights (combining hyper- spectral imaging with carbon fluxes) over areas that show both browning and greening, will provide a means to tie the NDVI trends to ecosystem behavior. Airborne flights also need to assess snow cover and surface hydrology, both of which confound the interpretation of NDVI, and this is another reason for including imaging spectrometry. Airborne measurement should explicitly consider different vegetation types with contrasting functional behavior (e.g.

evergreen vs. deciduous forests, as well as mixed forests) for their contrasting impacts on the optical signals (e.g. Gamon et al. 2015)

ABoVE Target Areas: North Slope, Alaska
Airborne data: Airborne atmospheric CO_2, CH_4 and CO measurements
Sampling Strategy: Flights every ~2 weeks from April – November across the North Slope with vertical profiles from ground level to ~5000 masl over Toolik Lake, Ivotuk, Atqasuk, Barrow, Umiat, and Deadhorse with long-term eddy covariance flux towers or continuous atmospheric concentration measurements
Targets of opportunity: Field sites examining tundra greening and its associated biogeochemistry

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