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Navigating the New Arctic (NNA) is one of

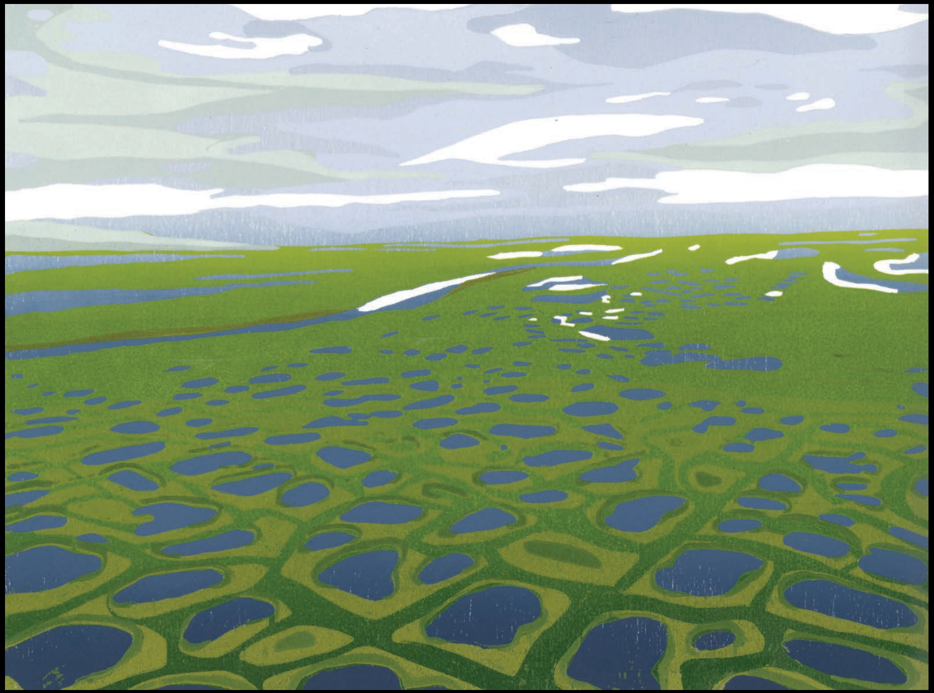
NSF'S 10 BIG IDEAS

NSF is investing $30 million in each Big Idea to identify and support emerging opportunities for U.S. leadership in Big Ideas that serve the Nation's future.

Landscape evolution and adapting to change in ice-rich permafrost systems (NNA-IRPS)

D. A. “Skip” Walker,

Institute of Arctic Biology and Department of Biology and Wildlife,
University of Alaska Fairbanks (UAF)



Evolution of low-centered polygons into high-centered polygons under the influence of a warming climate. **Wood cuts by Ina Timling.**

Co-investigators and collaborators

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Geophysical Institute

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Robbin Garber-Slaght

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Native Village of Point Lay

Kali School

Taġiuġmiullu Nunamiullu Housing Authority (TNHA)

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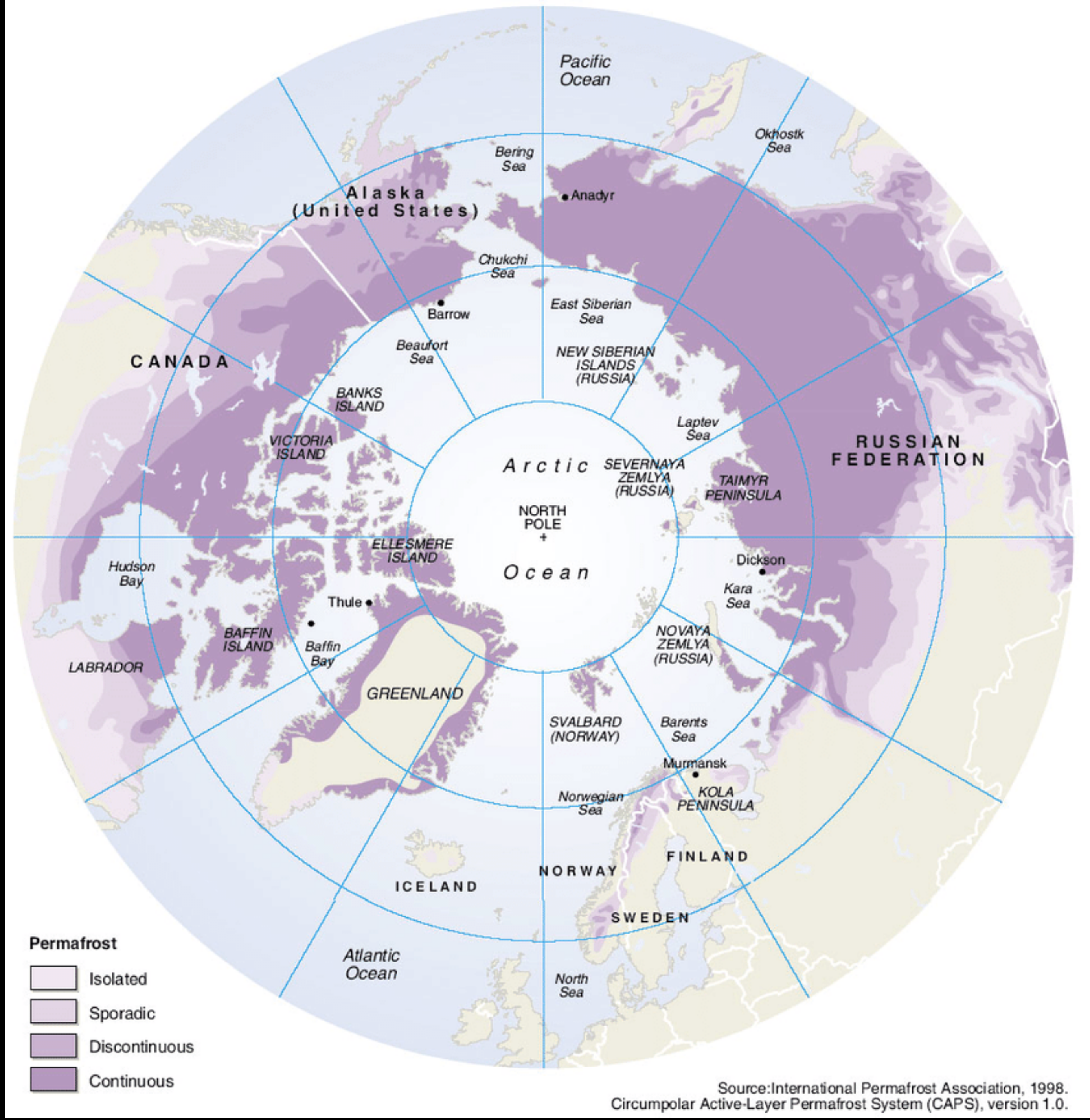
T-MOSAiC Project



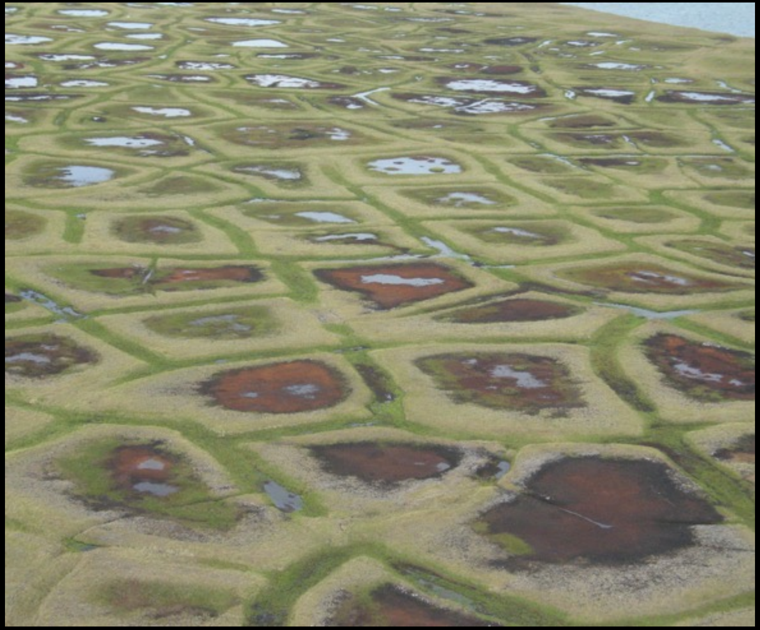
Permafrost

- Ground that remains below 0 ˚C for two or more years.
- Occurs beneath approximately 20% of the Earth's surface.
- Estimated to contain twice as much water as all lakes and rivers on Earth (0.022% vs. 0.011%).
- Most areas with continuous and discontinuous permafrost (darker purple areas in this figure) are extraordinarily sensitive to climate change.

Ice-Rich Permafrost

Ice wedge, Misha Kanevskiy

Coastal erosion of Ice wedges, USGS



Low-centered and high-centered ice-wedge polygon, Misha Kanevskiy

- **The most susceptible element of Arctic systems to climate change. If the ice in IRP melts. the soil becomes liquid and collapses!**

- IRP is permafrost with *excess ice* (ice that exceeds the volume of the pore spaces in the soil).
- Includes ice-wedges, tabular ice, lens ice, pingo ice.
- Nearly 50% of the Arctic is underlain by ice-rich permafrost.
- Many arctic landforms, such as ice-wedge polygons, pingos are the result of various forms of massive ground ice.

What happens if the ice in IRP melts…

Thermokarst ponds: Matt Nolan

Thaw lakes: Ann Blasubramaniam:

Thermal erosion gully: Polar Field Services.

Themocirque and gully: https://www.21stcentech.com

Thermokarst

- The process caused by melting ground ice that results in subsidence of the ground surface and characteristic landforms such as thaw ponds, irregular surfaces, and thaw lakes.
- Common forms include thermokarst ponds, and thaw lakes.

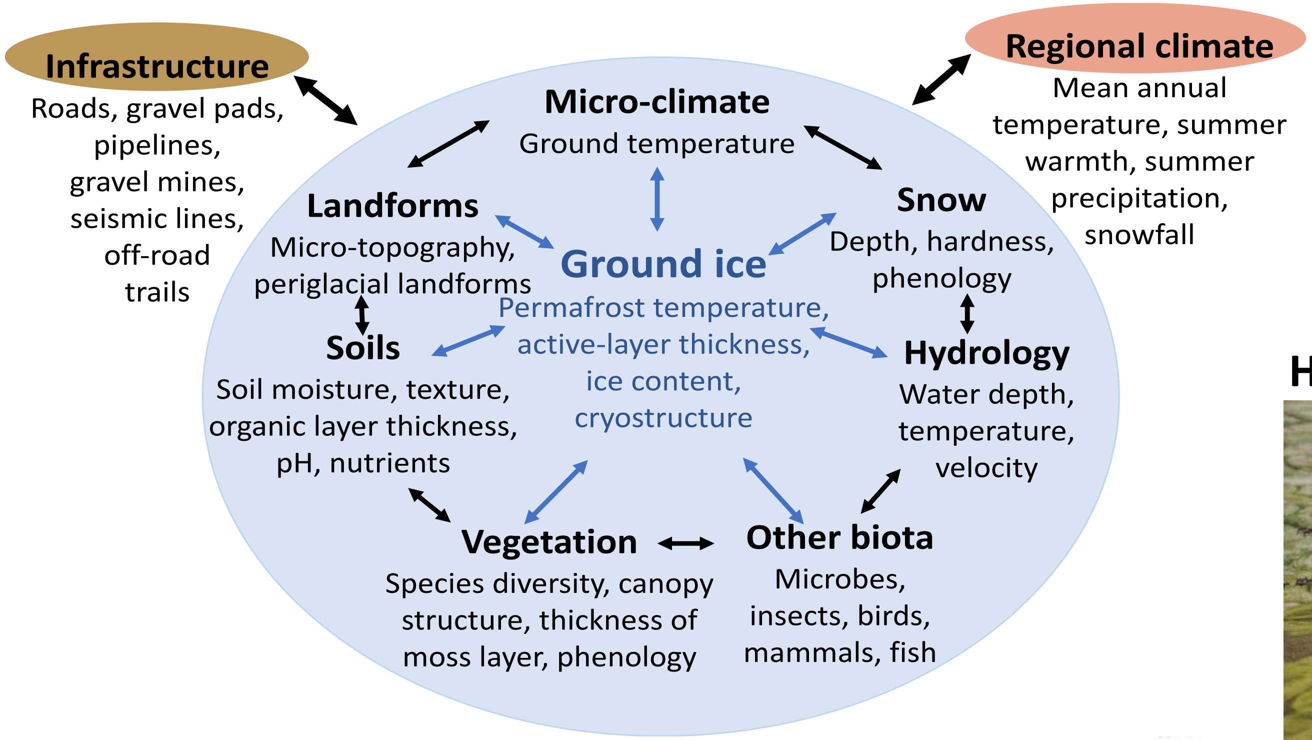
Thermal Erosion

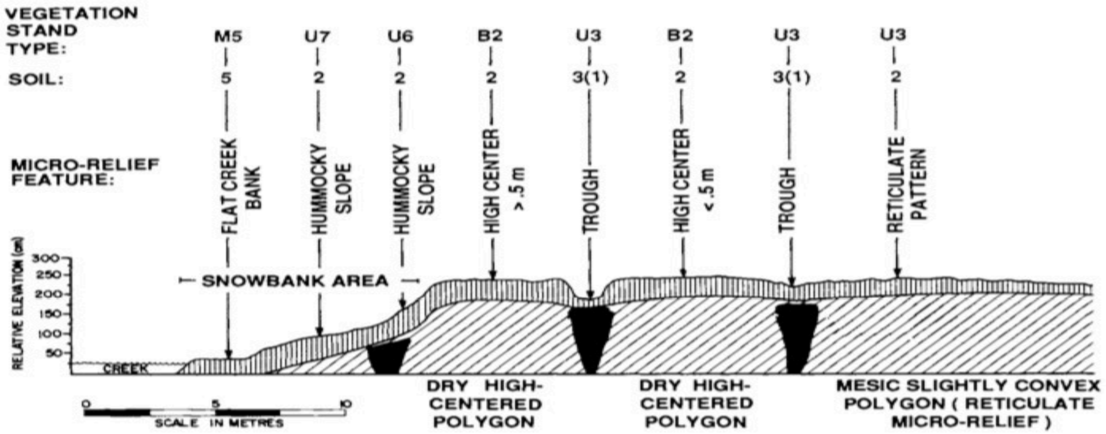
- Refers to the erosion of the land surface by thermal and mechanical processes.
- Common forms include thermal erosion gullys

Ice-rich-permafrost systems (IRPS)

Cryostratigraphy

Patterned ground





Walker & Everett. 1991. *Ecological Monographs*.

Hydrological connections

Fish and Wildlife connections

Thermokarst economic and social impacts

Recent abrupt changes in thermokarst

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L02503, doi:10.1029/2005GL024960, 2006

Abrupt increase in permafrost degradation in Arctic Alaska

M. Torre Jorgenson,[1] Yuri L. Shur,[2] and Erik R. Pullman[1]

Received 14 October 2005; revised 28 November 2005; accepted 5 December 2005; published 24 January 2006.

[1] Even though the arctic zone of continuous permafrost has relatively cold mean annual air temperatures, we found an abrupt, large increase in the extent of permafrost degradation in northern Alaska since 1982, associated with record warm temperatures during 1989–1998. Our field studies revealed that the recent degradation has mainly occurred to massive wedges of ice that previously had been stable for 1000s of years. Analysis of airphotos from 1945, 1982, and 2001 revealed large increases in the area (0.5%, 0.6%, and 4.4% of area, respectively) and density (88, 128, and 1336 pits/km^2) of degrading ice wedges in two study areas on the arctic coastal plain. Spectral analysis across a broader landscape found that newly degraded, water-filled pits covered 3.8% of the land area. These results indicate that thermokarst potentially can affect 10–30% of arctic lowland landscapes and severely alter tundra ecosystems even under scenarios of modest climate warming. **Citation:** Jorgenson, M. T., Y. L. Shur, and E. R. Pullman (2006), Abrupt increase in permafrost degradation in Arctic Alaska, *Geophys. Res. Lett.*, *33*, L02503, doi:10.1029/2005GL024960.

1. Introduction

[2] Although thawing and settling of ice-rich terrain (thermokarst) is widespread in the subarctic zone where permanently frozen ground (permafrost) is discontinuous [*Jorgenson et al.*, 2001; *Halsey et al.*, 1995], the ground in the arctic zone of continuous permafrost has been considered stable because of much lower mean annual air temper-

vides only limited protection, and thermokarst due to human disturbance frequently has been observed in the Arctic, even at cold temperatures. Here we report an abrupt increase in natural degradation of ice-wedges during a period of an unprecedented 2–5°C increase in mean annual ground temperatures (MAGT) in northern Alaska since the 1980s [*Osterkamp*, 2003; *Clow*, 2003].

2. Methods

[3] We evaluated the degradation of ice wedges in northern Alaska at three spatial scales that included: (1) field surveys within two small, intensive sites (0.6-km^2); (2) photo-interpretation of a time-series of aerial photography within the two intensive sites; and (3) image processing of the spectral characteristics of aerial photography for two larger areas (14.5-km^2). During field surveys in Aug. 2003 and 2004, we sampled 43 plots in the two intensive areas (C1 and C2) 10–40 km west of the Colville River and 20 km south of the coast to assess changes in vegetation, microtopography, and soils associated with ice-wedge degradation evident on the ground. For vegetation, the cover of dominant live and dead species was visually estimated to evaluate patterns of plant mortality and recovery. For microtopography, relative elevations of the ground and water surfaces were surveyed with an auto-level. The stratigraphy of soil plugs from the active layer and shallow 1-m cores from the underlying permafrost was described using standard soil methods with special emphasis in differentiating fibrous peat comprised of varying plant

Jorgenson et al., 2006:
Abrupt ice-wedge degradation
in northern Alaska

Global Change Biology

celebrating 20 years

Global Change Biology (2014), doi: 10.1111/gcb.12500

Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska

MARTHA K. RAYNOLDS[1], DONALD A. WALKER[1], KENNETH J. AMBROSIUS[2], JERRY BROWN[3], KAYE R. EVERETT[4]†, MIKHAIL KANEVSKIY[5], GARY P. KOFINAS[6], VLADIMIR E. ROMANOVSKY[7,8], YURI SHUR[5] and PATRICK J. WEBBER[9]

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Abstract

Many areas of the Arctic are simultaneously affected by rapid climate change and rapid industrial development. These areas are likely to increase in number and size as sea ice melts and abundant Arctic natural resources become more accessible. Documenting the changes that have already occurred is essential to inform management approaches to minimize the impacts of future activities. Here, we determine the cumulative geoecological effects of 62 years (1949–2011) of infrastructure- and climate-related changes in the Prudhoe Bay Oilfield, the oldest and most extensive industrial complex in the Arctic, and an area with extensive ice-rich permafrost that is extraordinarily sensitive to climate change. We demonstrate that thermokarst has recently affected broad areas of the entire region, and that a sudden increase in the area affected began shortly after 1990 corresponding to a rapid rise in regional summer air temperatures and related permafrost temperatures. We also present a conceptual model that describes how infrastructure-related factors, including road dust and roadside flooding are contributing to more extensive thermokarst in areas adjacent to roads and gravel pads. We mapped the historical infrastructure changes for the Alaska North Slope oilfields for 10 dates from the initial oil discovery in 1968–2011. By 2010, over 34% of the intensively mapped area was affected by oil development. In addition, between 1990 and 2001, coincident with strong atmospheric warm-

Raynolds et al. 2014:
Abrupt ice-wedge degradation due to infrastructure
and climate change at Prudhoe Bay

Ice-wedge degradation is occurring widely across the whole Arctic: Liljedahl et al. 2016

nature geoscience

ARTICLES

PUBLISHED ONLINE: 14 MARCH 2016 | DOI: 10.1038/NGEO2674

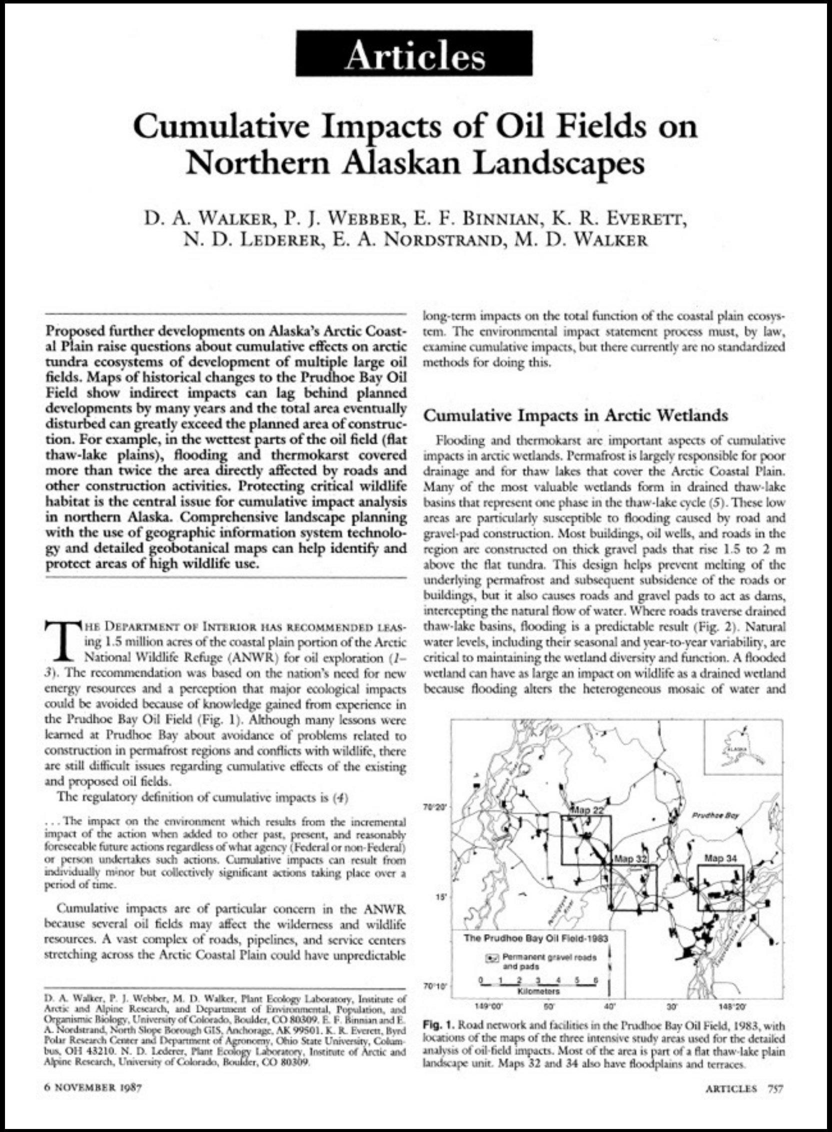
Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology

Anna K. Liljedahl[1*], Julia Boike[2], Ronald P. Daanen[3], Alexander N. Fedorov[4], Gerald V. Frost[5], Guido Grosse[6], Larry D. Hinzman[7], Yoshihiro Iijma[8], Janet C. Jorgenson[9], Nadya Matveyeva[10], Marius Necsoiu[11], Martha K. Raynolds[12], Vladimir E. Romanovsky[13,14], Jörg Schulla[15], Ken D. Tape[1], Donald A. Walker[12], Cathy J. Wilson[16], Hironori Yabuki[17] and Donatella Zona[18,19]

Ice wedges are common features of the subsurface in permafrost regions. They develop by repeated frost cracking and ice vein growth over hundreds to thousands of years. Ice-wedge formation causes the archetypal polygonal patterns seen in tundra across the Arctic landscape. Here we use field and remote sensing observations to document polygon succession due to ice-wedge degradation and trough development in ten Arctic localities over sub-decadal timescales. Initial thaw drains polygon centres and forms disconnected troughs that hold isolated ponds. Continued ice-wedge melting leads to increased trough connectivity and an overall draining of the landscape. We find that melting at the tops of ice wedges over recent decades and subsequent decimetre-scale ground subsidence is a widespread Arctic phenomenon. Although permafrost temperatures have been increasing gradually, we find that ice-wedge degradation is occurring on sub-decadal timescales. Our hydrological model simulations show that advanced ice-wedge degradation can significantly alter the water balance of lowland tundra by reducing inundation and increasing runoff, in particular due to changes in snow distribution as troughs form. We predict that ice-wedge degradation and the hydrological changes associated with the resulting differential ground subsidence will expand and amplify in rapidly warming permafrost regions.

Cumulative impact analyses of oil and gas activities

1987: Prudhoe Bay: Walker et al., Science



Articles

Cumulative Impacts of Oil Fields on Northern Alaskan Landscapes

D. A. Walker, P. J. Webber, E. F. Binnian, K. R. Everett, N. D. Lederer, E. A. Nordstrand, M. D. Walker

Proposed further developments on Alaska's Arctic Coastal Plain raise questions about cumulative effects on arctic tundra ecosystems of development of multiple large oil fields. Maps of historical changes to the Prudhoe Bay Oil Field show indirect impacts can lag behind planned developments by many years and the total area eventually disturbed can greatly exceed the planned area of construction. For example, in the wettest parts of the oil field (flat thaw-lake plains), flooding and thermokarst covered more than twice the area directly affected by roads and other construction activities. Protecting critical wildlife habitat is the central issue for cumulative impact analysis in northern Alaska. Comprehensive landscape planning with the use of geographic information system technology and detailed geobotanical maps can help identify and protect areas of high wildlife use.

The Department of Interior has recommended leasing 1.5 million acres of the coastal plain portion of the Arctic National Wildlife Refuge (ANWR) for oil exploration (*1–3*). The recommendation was based on the nation's need for new energy resources and a perception that major ecological impacts could be avoided because of knowledge gained from experience in the Prudhoe Bay Oil Field (Fig. 1). Although many lessons were learned at Prudhoe Bay about avoidance of problems related to construction in permafrost regions and conflicts with wildlife, there are still difficult issues regarding cumulative effects of the existing and proposed oil fields.

The regulatory definition of cumulative impacts is (*4*)

> . . . The impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time.

Cumulative impacts are of particular concern in the ANWR because several oil fields may affect the wilderness and wildlife resources. A vast complex of roads, pipelines, and service centers stretching across the Arctic Coastal Plain could have unpredictable long-term impacts on the total function of the coastal plain ecosystem. The environmental impact statement process must, by law, examine cumulative impacts, but there currently are no standardized methods for doing this.

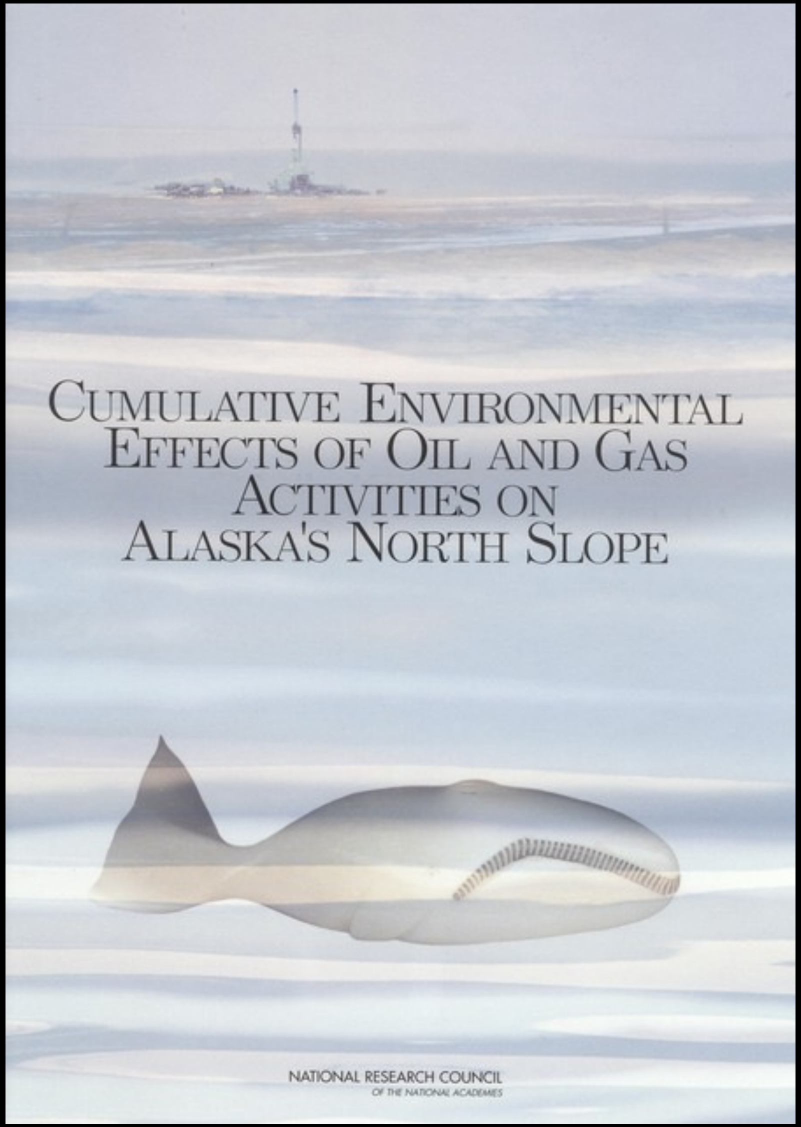
Cumulative Impacts in Arctic Wetlands

Flooding and thermokarst are important aspects of cumulative impacts in arctic wetlands. Permafrost is largely responsible for poor drainage and for thaw lakes that cover the Arctic Coastal Plain. Many of the most valuable wetlands form in drained thaw-lake basins that represent one phase in the thaw-lake cycle (*5*). These low areas are particularly susceptible to flooding caused by road and gravel-pad construction. Most buildings, oil wells, and roads in the region are constructed on thick gravel pads that rise 1.5 to 2 m above the flat tundra. This design helps prevent melting of the underlying permafrost and subsequent subsidence of the roads or buildings, but it also causes roads and gravel pads to act as dams, intercepting the natural flow of water. Where roads traverse drained thaw-lake basins, flooding is a predictable result (Fig. 2). Natural water levels, including their seasonal and year-to-year variability, are critical to maintaining the wetland diversity and function. A flooded wetland can have as large an impact on wildlife as a drained wetland because flooding alters the heterogeneous mosaic of water and

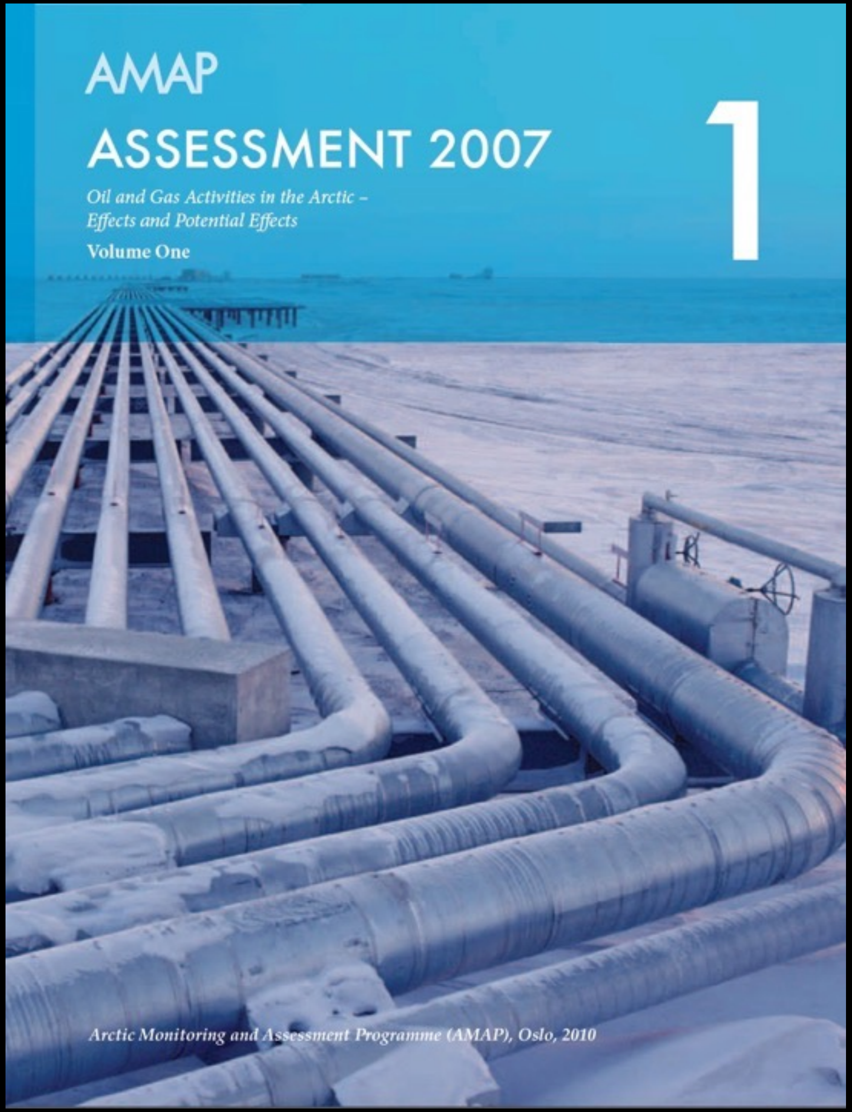
Fig. 1. Road network and facilities in the Prudhoe Bay Oil Field, 1983, with locations of the maps of the three intensive study areas used for the detailed analysis of oil-field impacts. Most of the area is part of a flat thaw-lake plain landscape unit. Maps 32 and 34 also have floodplains and terraces.

D. A. Walker, P. J. Webber, M. D. Walker, Plant Ecology Laboratory, Institute of Arctic and Alpine Research, and Department of Environmental, Population, and Organismic Biology, University of Colorado, Boulder, CO 80309. E. F. Binnian and E. A. Nordstrand, North Slope Borough GIS, Anchorage, AK 99501. K. R. Everett, Byrd Polar Research Center and Department of Agronomy, Ohio State University, Columbus, OH 43210. N. D. Lederer, Plant Ecology Laboratory, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309.

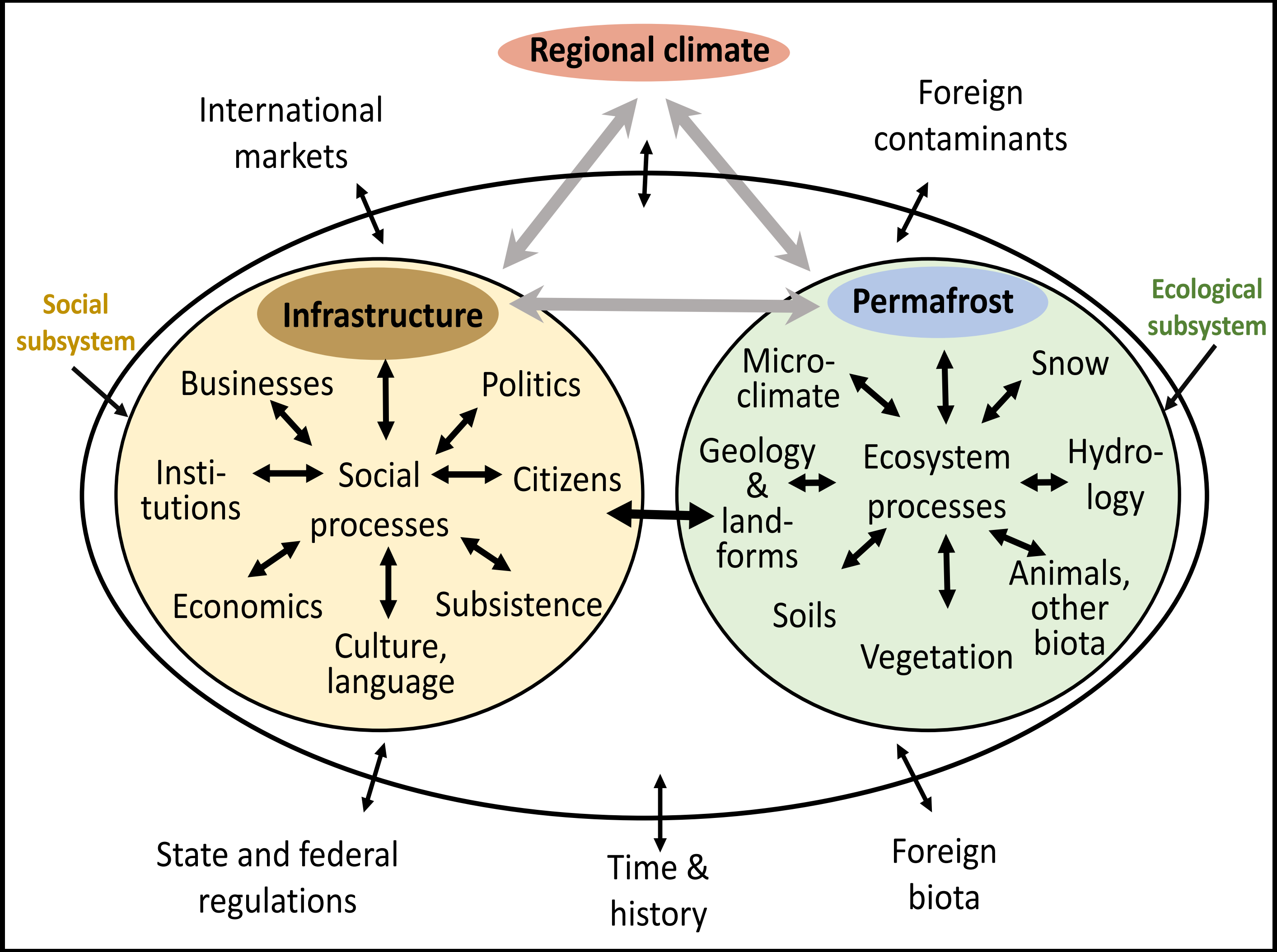
2003: North Slope, 2003 NRC report



2008: Arctic wide, AMAP report



Our NNA project is considering impacts to both the ecological and social components of arctic systems

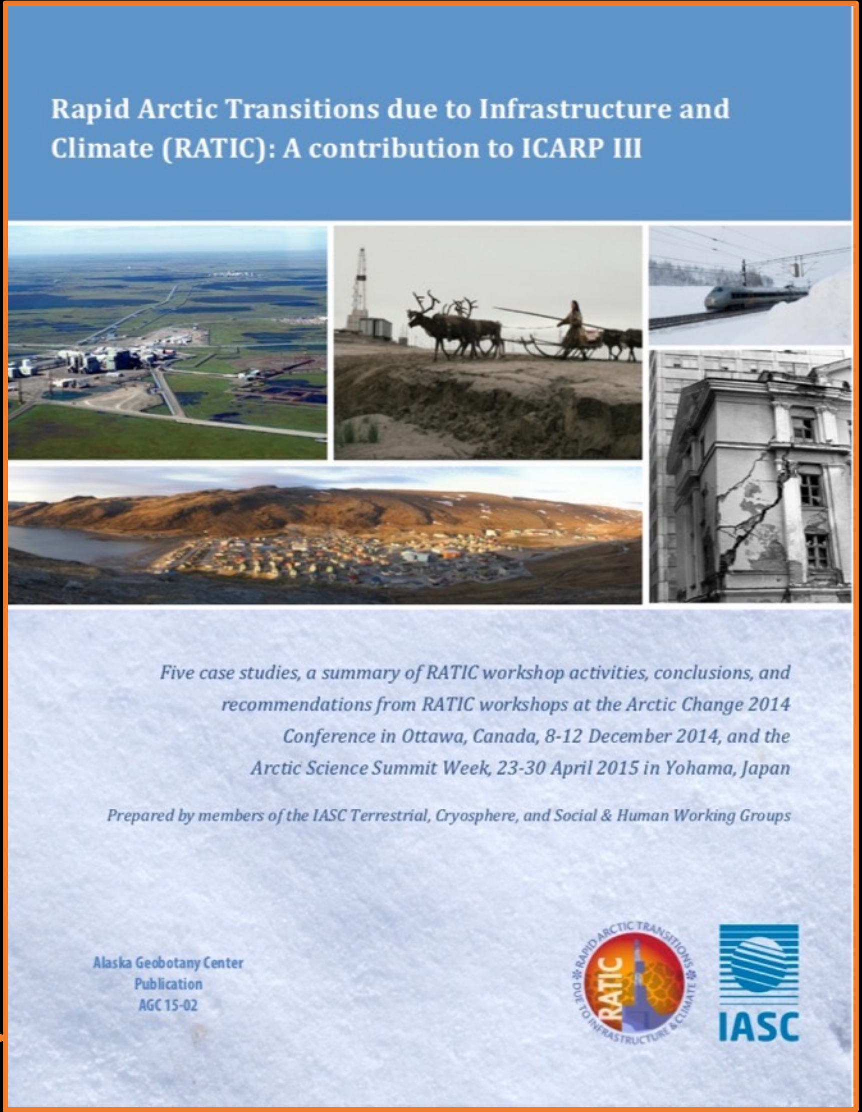


Based on Whiteman et al. 2004, *Ambio* 33: 371_376

RATIC

Rapid Arctic Transitions due to Infrastructure and Climate

- IASC cross-cutting activity mainly involving the IASC Terrestrial, Social & Human, and Cryosphere working groups
- Forum for developing and sharing new ideas and methods regarding sustainable development in the face of rapid arctic change
- Workshops:
  - Arctic Change 2014, Ottawa, Canada
  - ICARP III, 2015 , Yohama, Japan
  - ASSW 2017, Prague
  - ASSW 2019, Arkhangelsk
- White paper



https://www.geobotany.uaf.edu/library/pubs/WalkerDAed2015RATICWhitePaper-ICARPIII.pdf

RATIC white paper:

Five case studies of infrastructure impacts to social systems

Road & pad impacts
Prudhoe Bay oil field, AK

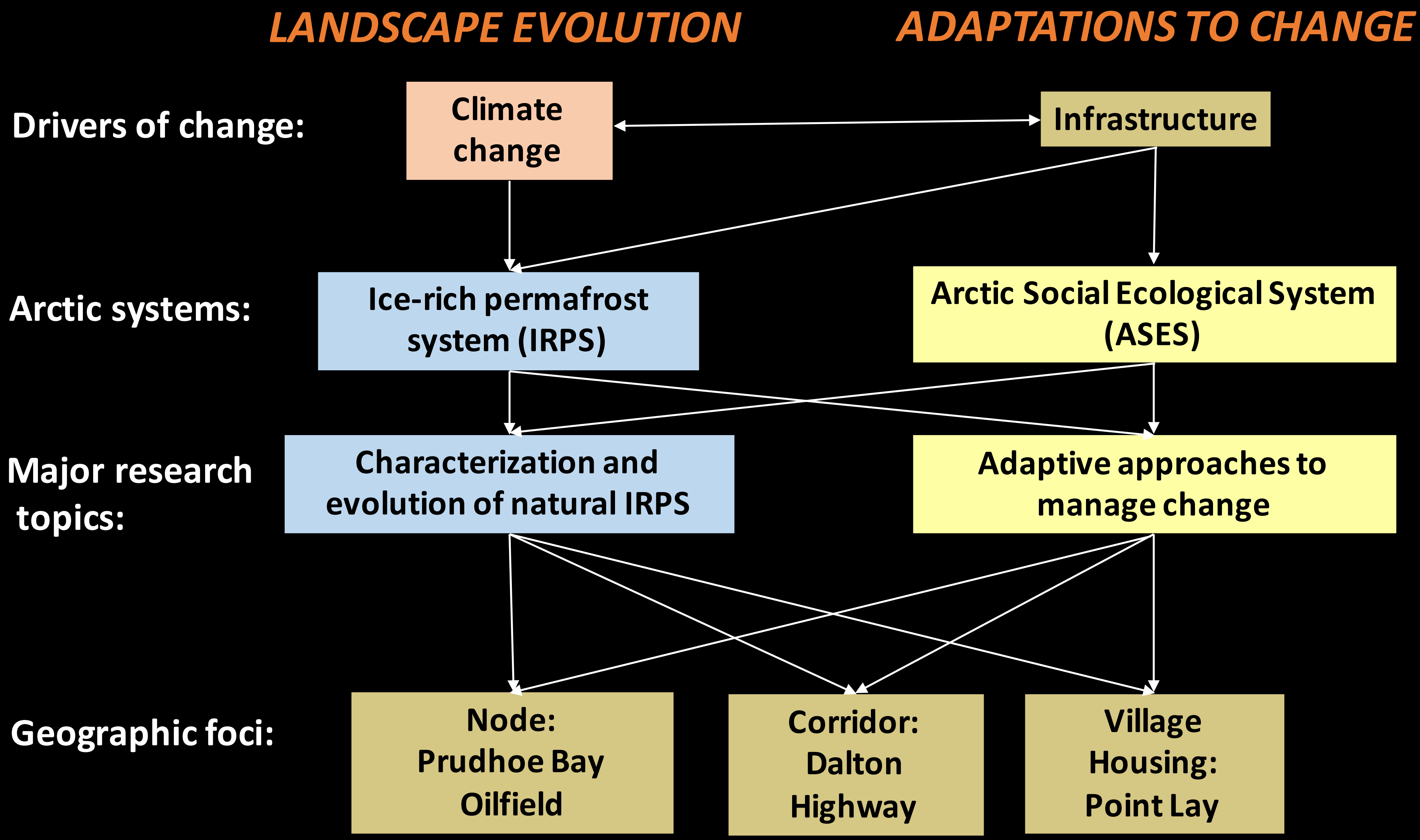
Nenets subsistance
Bovanenkovo gas field , RU

Roads & airstrip stability,
arctic villages, CA

Rail corridors, NO

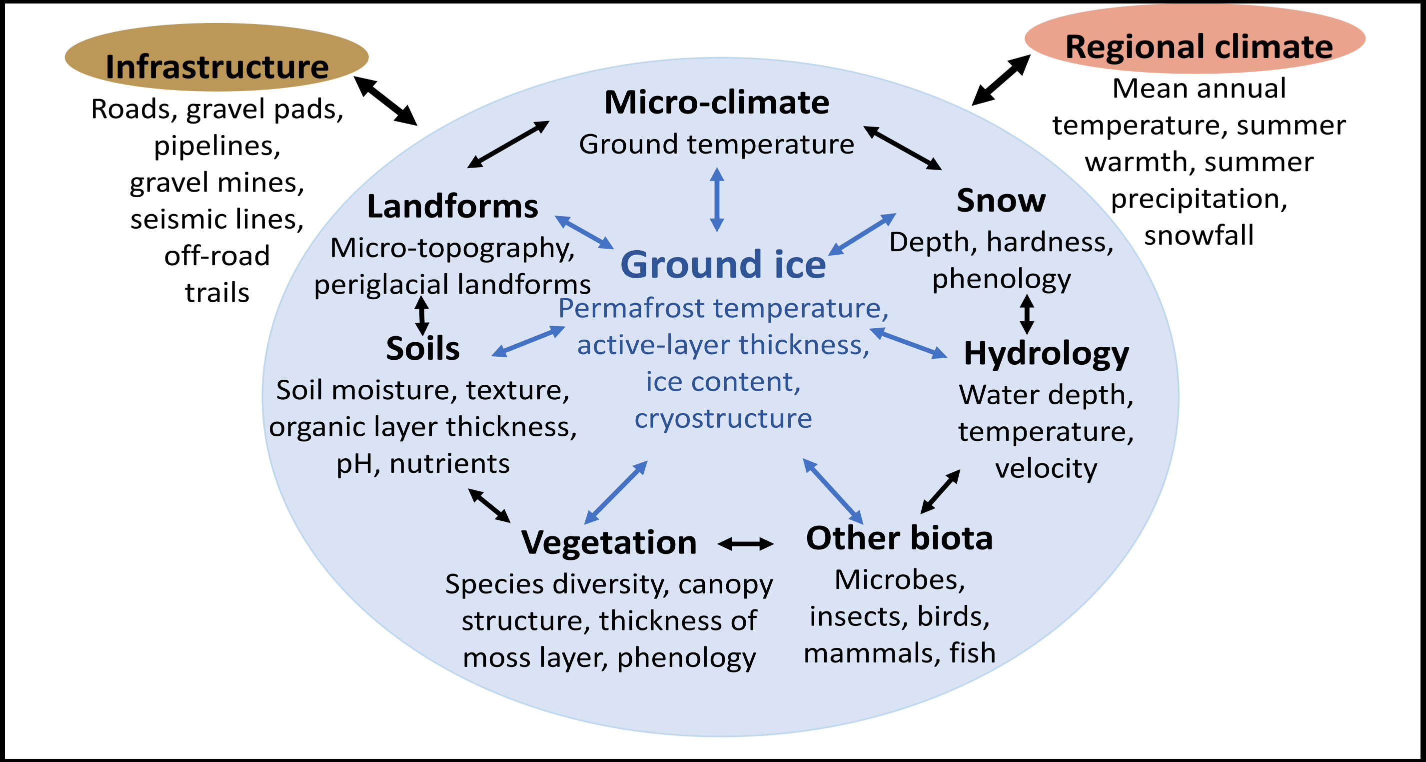
Urban
infrastructure,
RU

Our NNA-IRPS proposal
Major themes and linkages



Key questions and transformative element

- Where, why, and how is ground ice accumulated?
- How have IRPS evolved and how are they currently changing?
  - How do differences in vegetation, water, and time influence the accumulation and degradation of ground ice in IRP landscapes?
  - How the loss of ground ice can radically change these systems and their components?
- How can people and their infrastructure adapt to the changes?

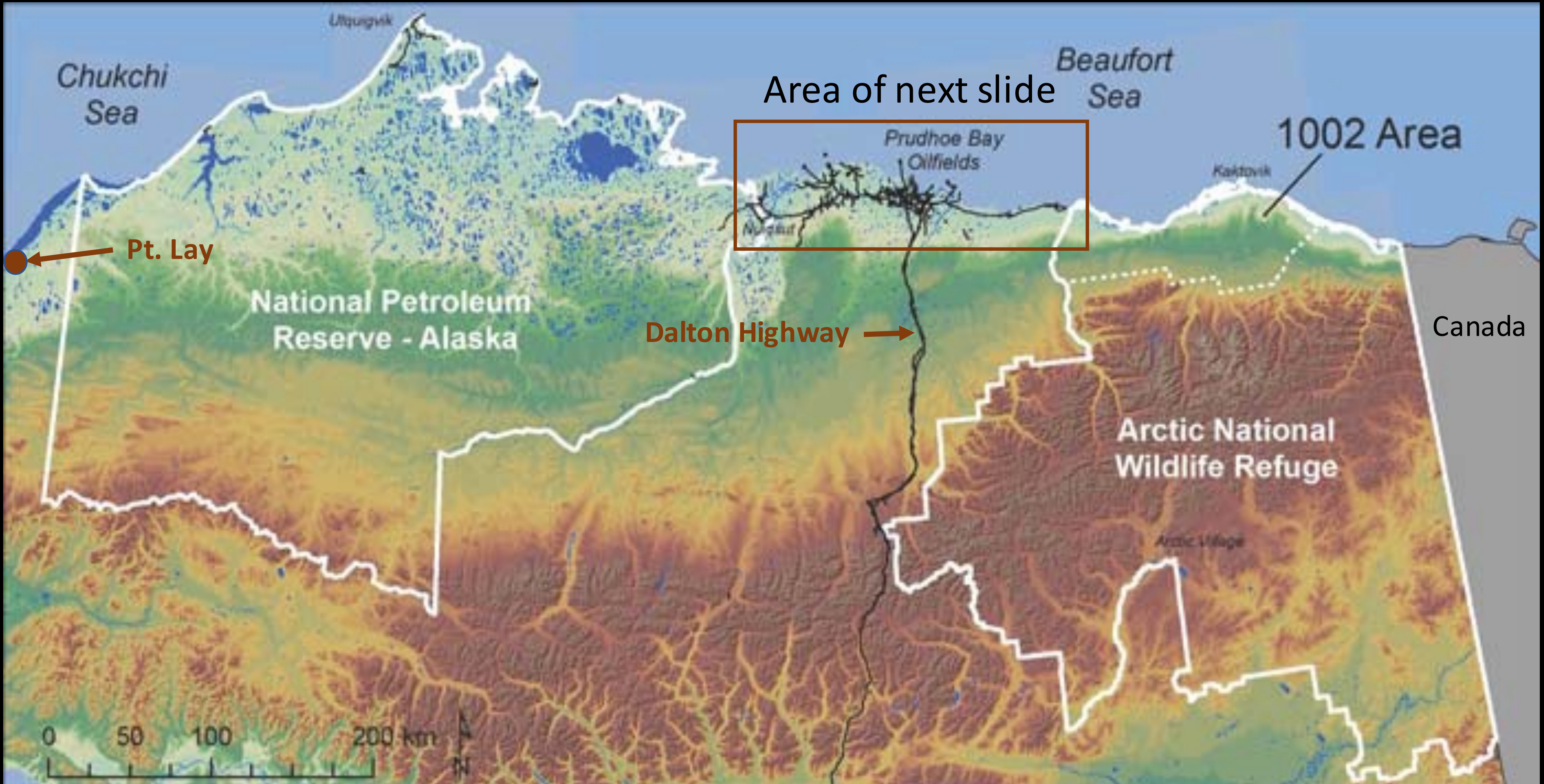


Transformative element:

A new conceptual model of permafrost evolution that places ice-rich permafrost at the center of a web of changing Arctic system components. We will show that IRP has a role similar to a keystone biological species and if removed or drastically reduced, totally transforms the system.

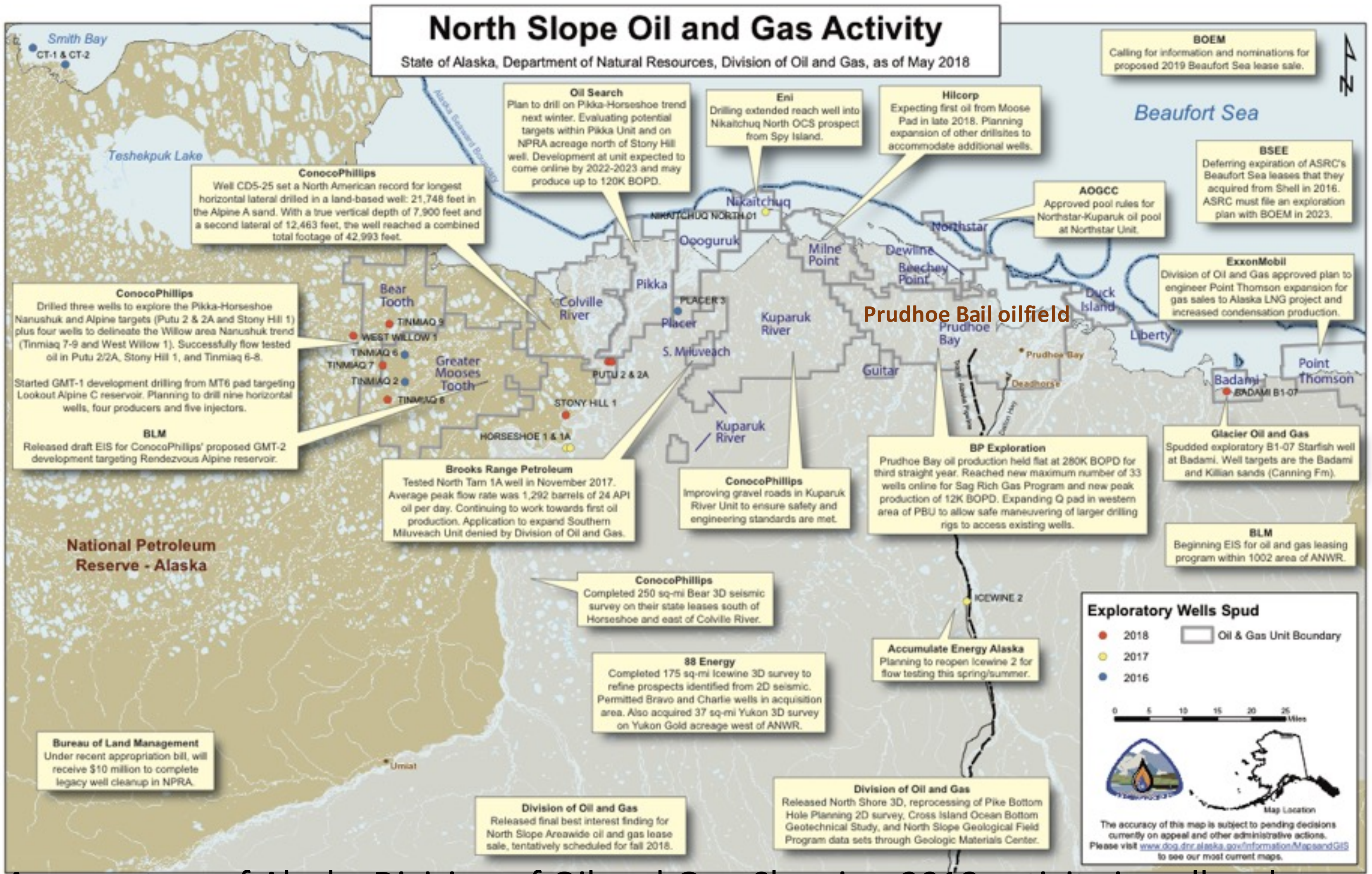
Area of research: northern Alaska

Northern Alaska oilfields, Dalton Highway & Point Lay



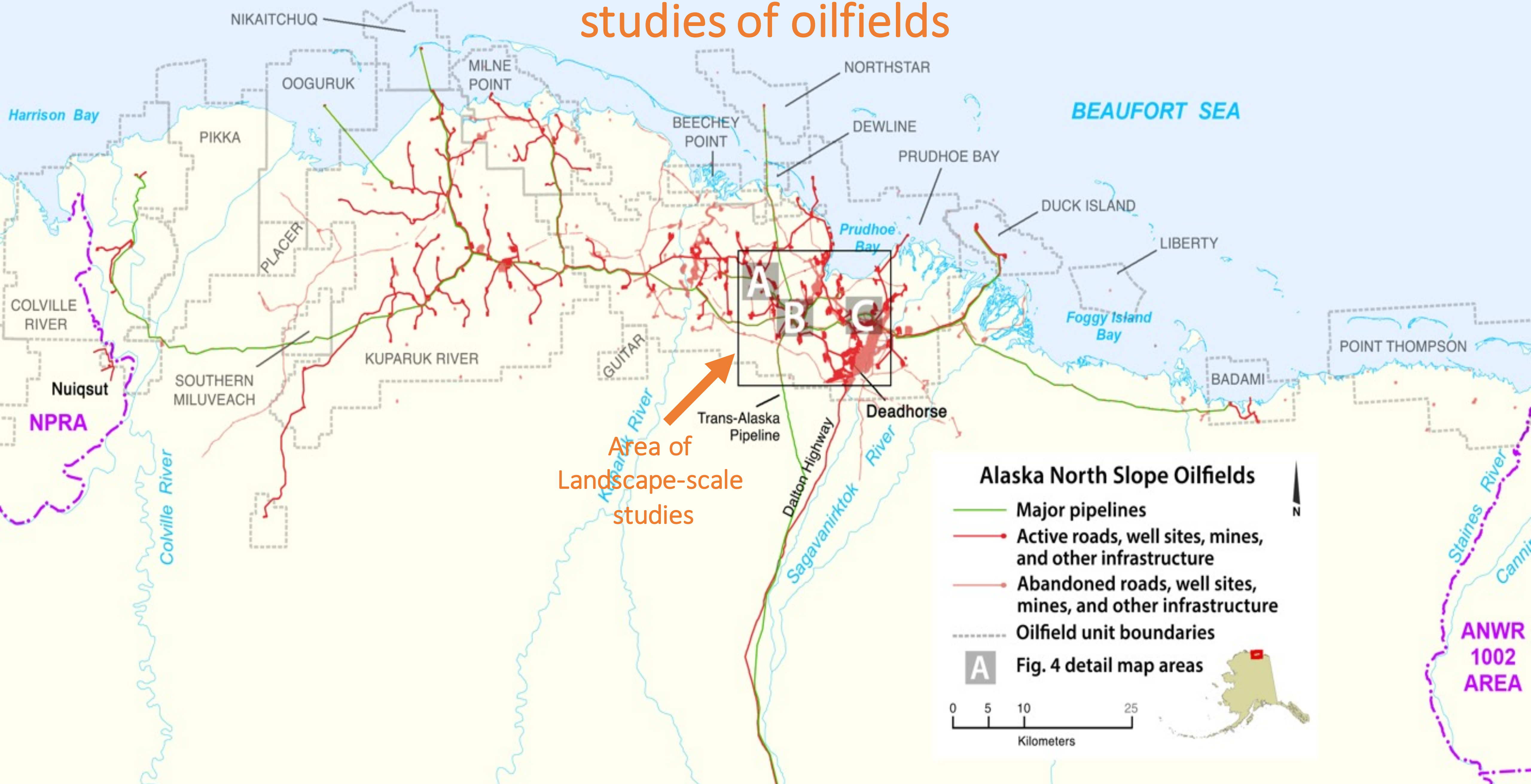
Adapting to change:

Rapid expansion of oil development in northern Alaska 1968–present



Map courtesy of Alaska Division of Oil and Gas, Showing 2018 activity in yellow boxes.

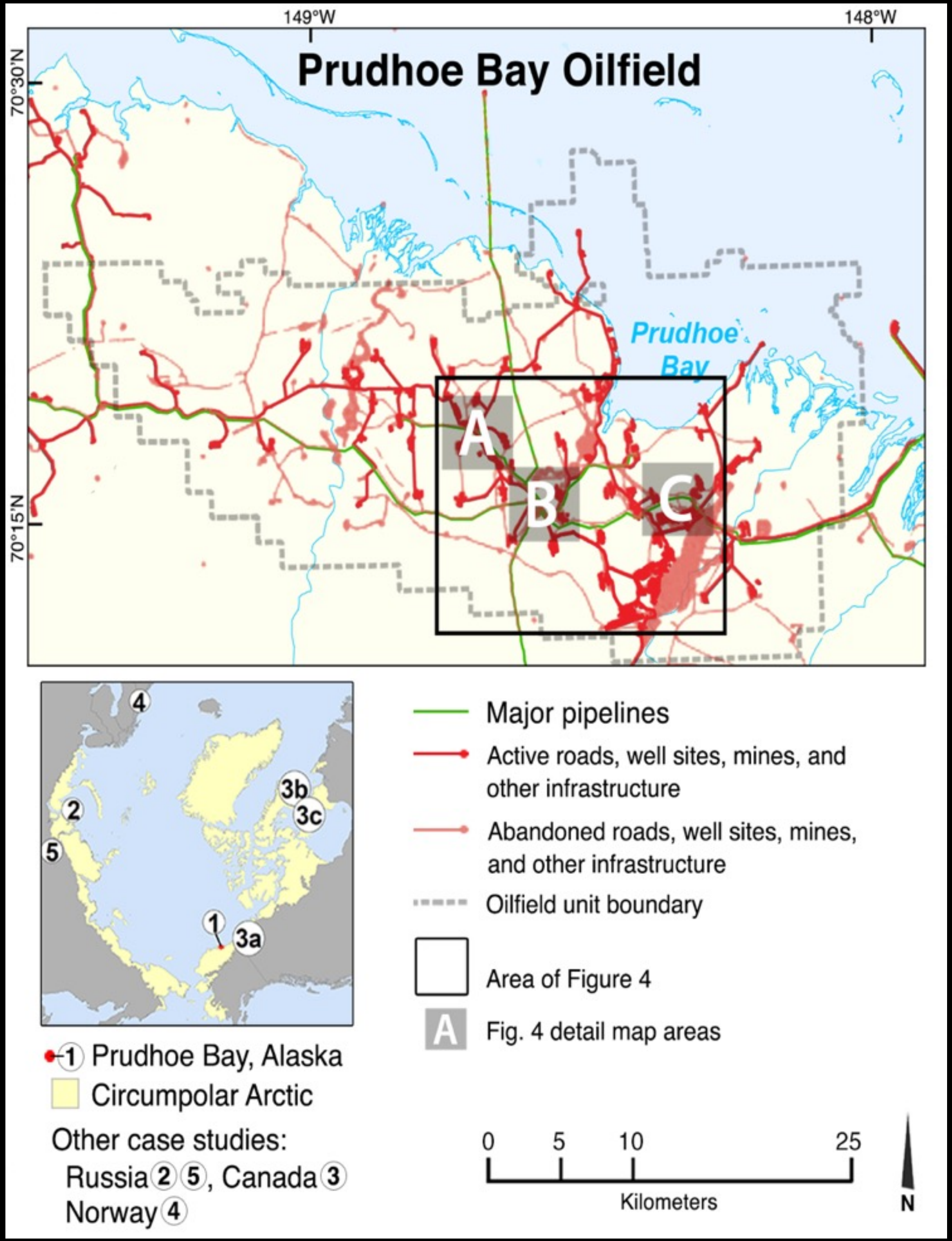
Area of regional- and landscape-scale studies of oilfields

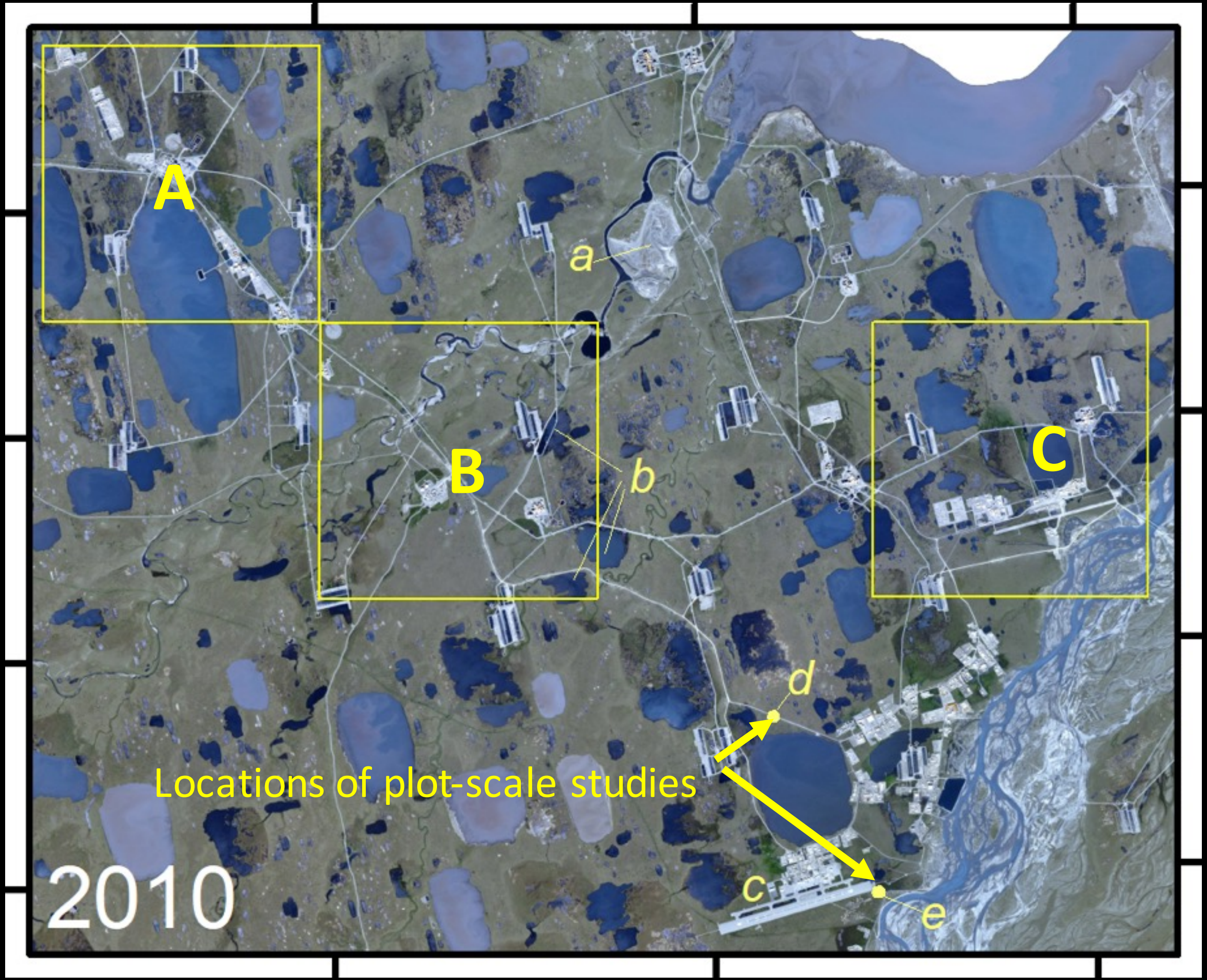


Area of Landscape-scale studies

Areas of landscape-scale studies:

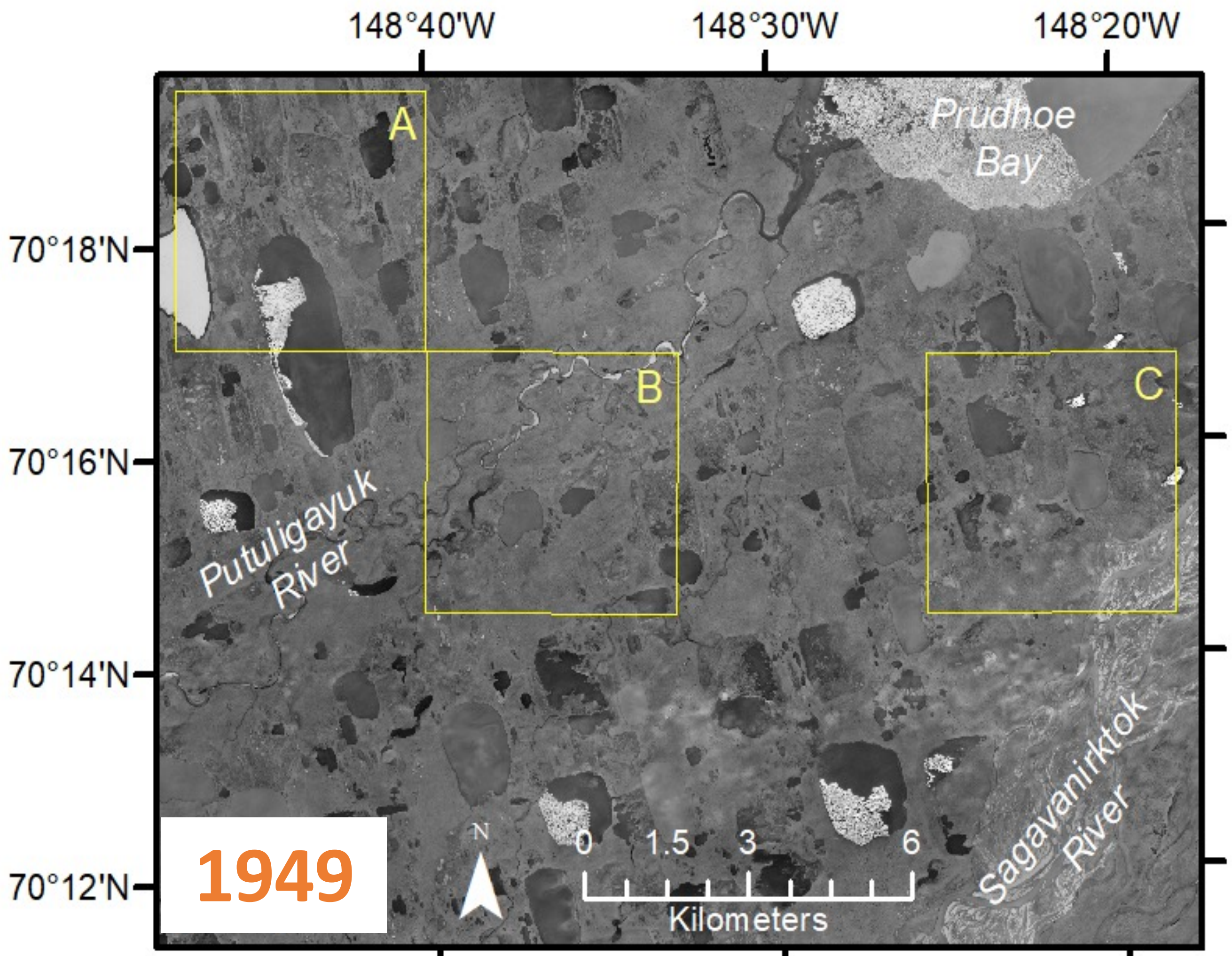
3 long-term study areas in the oldest parts of the Prudhoe Bay Oilfield, A, B, C



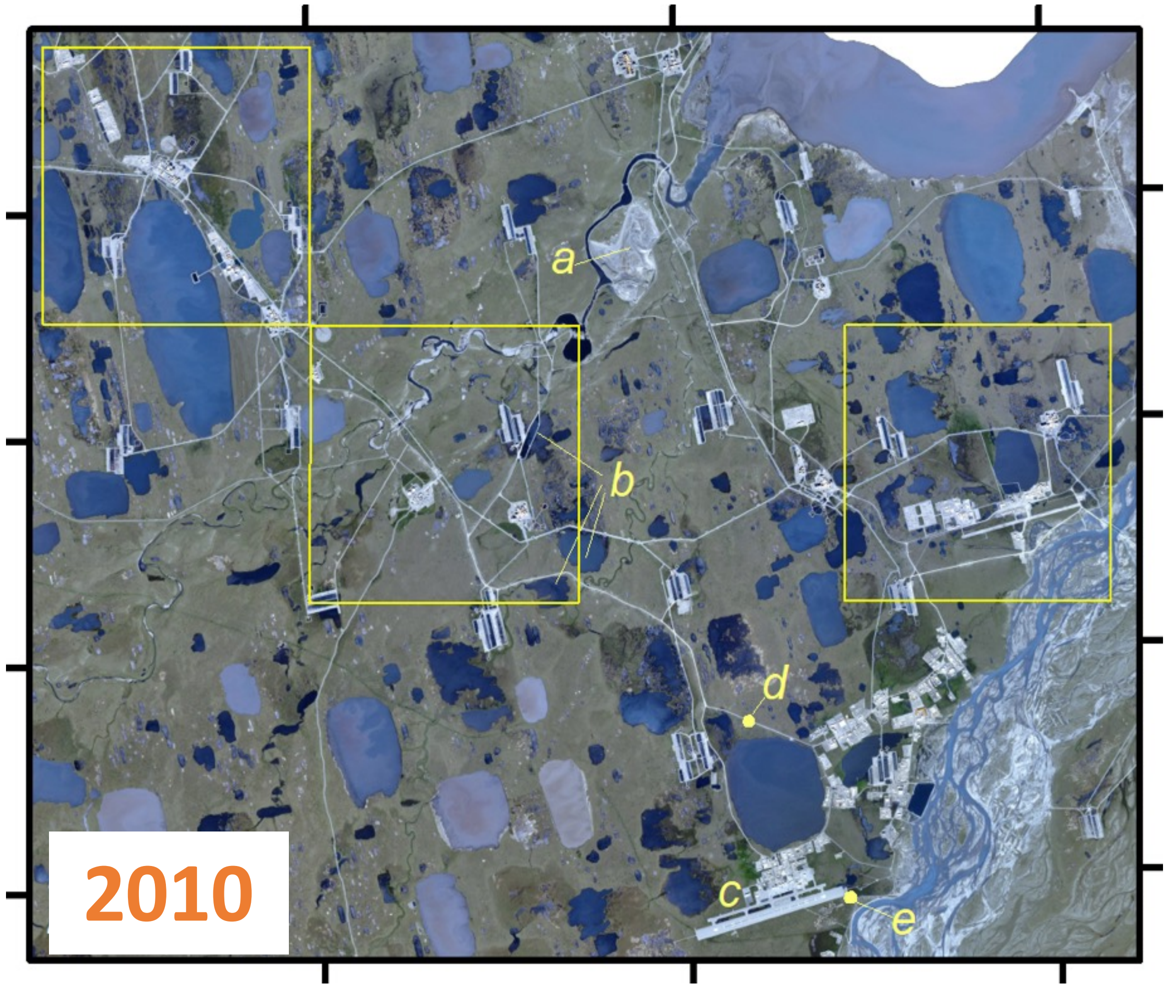


61 years of IRPS landscape evolution

Studies of natural and developed landscapes prior to and after development

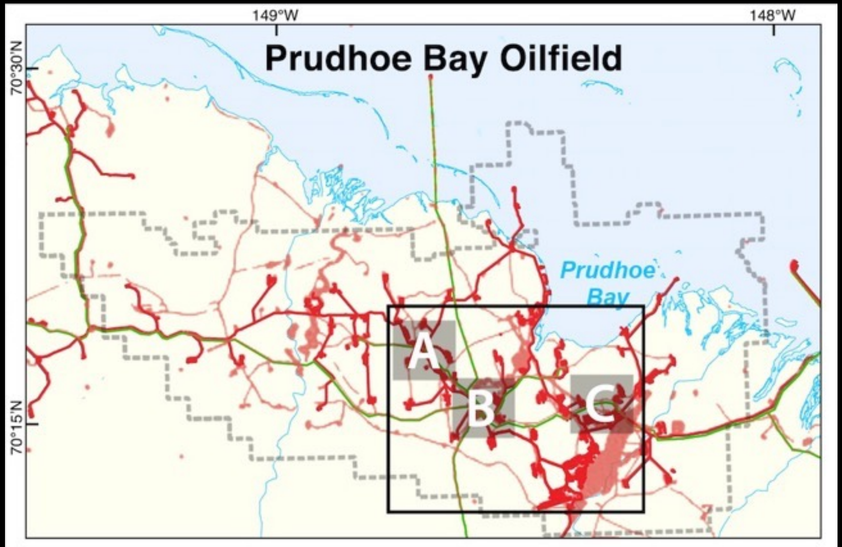


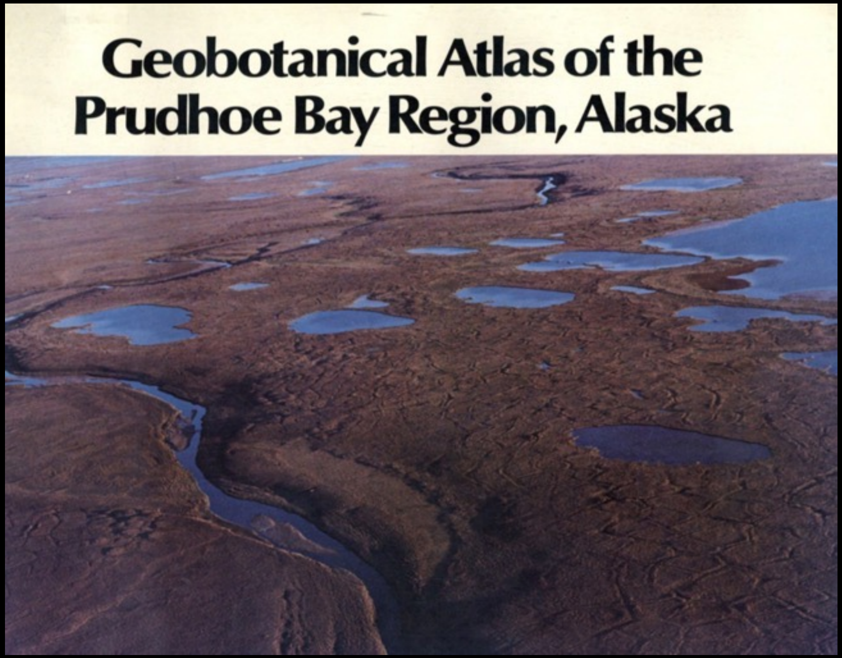
U.S. Navy BAR photograph mosaic, 1:50,000 scale.

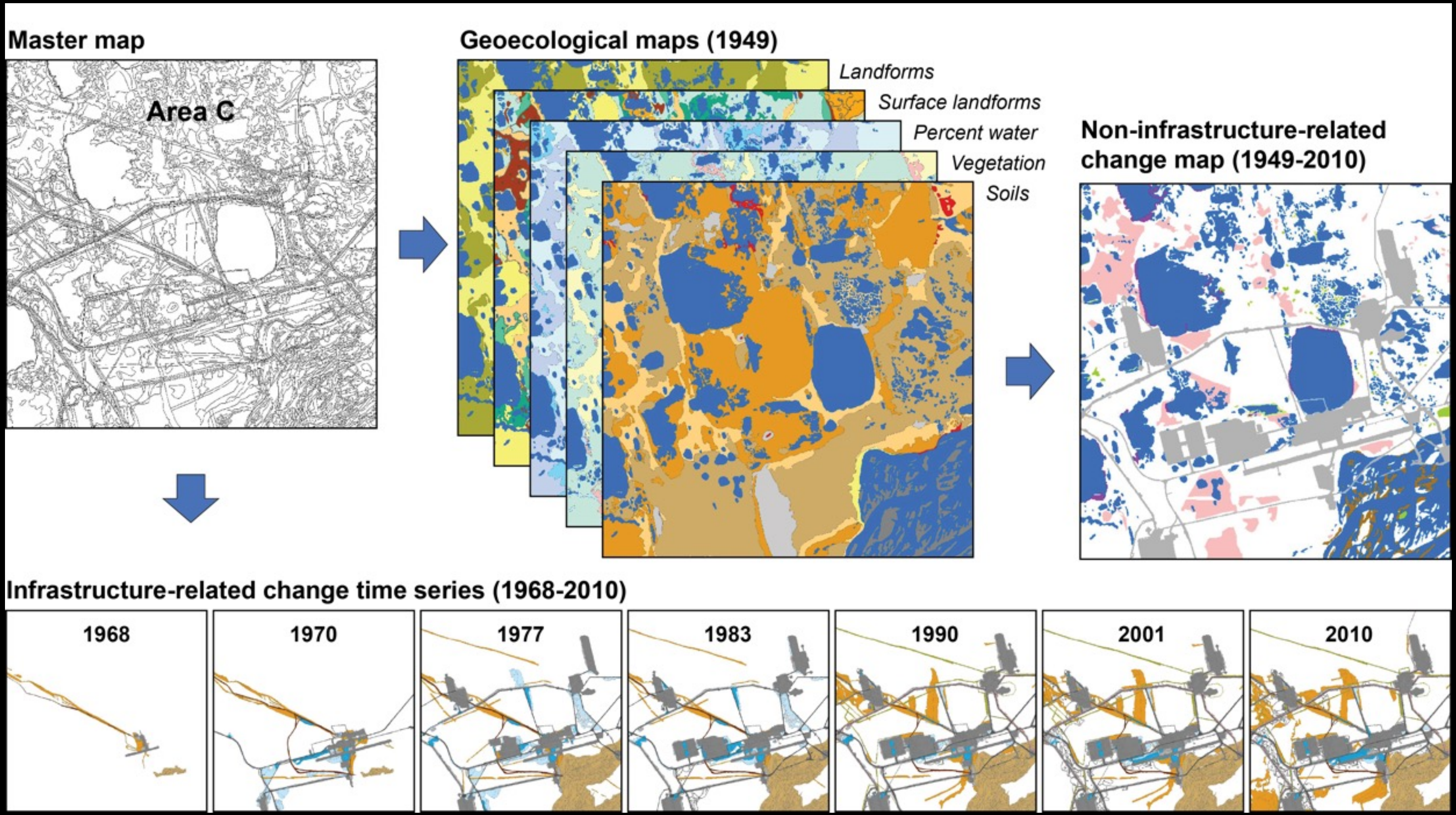


SPOT satellite image, 1.5-m pixel resolution.

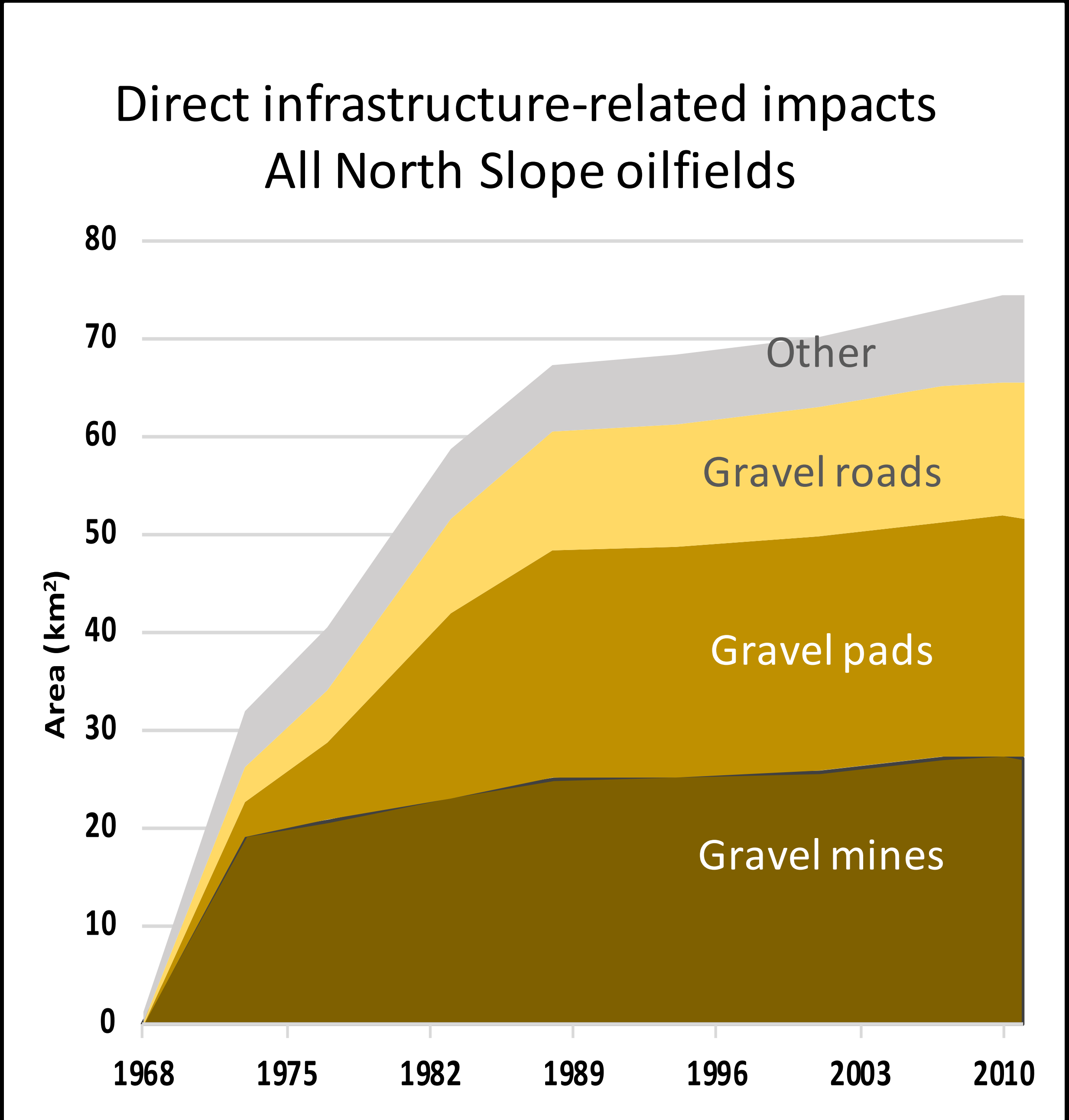
Integrated geoecological and historical-change mapping







- **Baseline**: 1949 Navy BAR aerial photographs and Walker, D. A., Everett, K. R., Webber, P. J., & Brown, J. (1980). *Geobotanical atlas of the Prudhoe Bay region, Alaska*. *CRREL Report 80-14*.
- **2010 Historical change analysis**: Raynolds et al. (2014) *Global Change Biology,* 20: 1211–1224



Trends at regional-scale direct impacts (footprint)

Area impacted

- 27.4 km^2 gravel mines
- 23.5 km^2 gravel drill sites & construction pads
- 12.6 km^2 gravel roads
- 10.8 km^2 other (airstrips, off-shore drilling islands, peat roads, etc.)

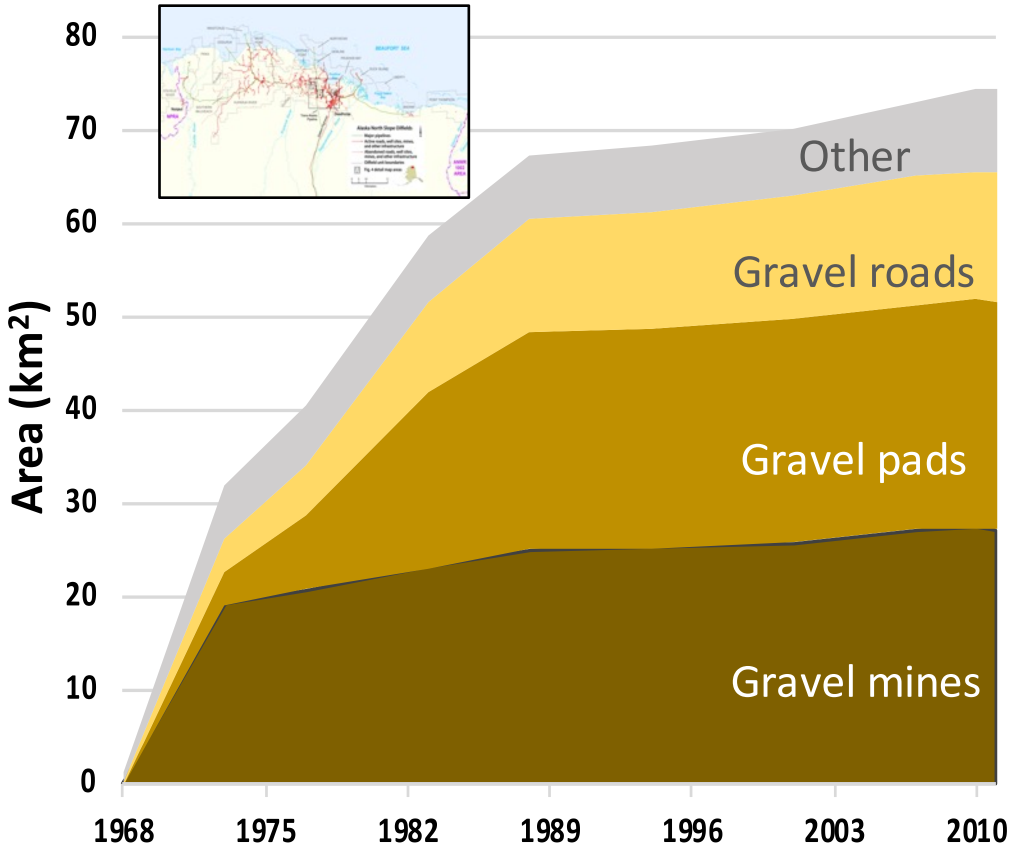
74.3 km^2 total footprint

Rate of increase

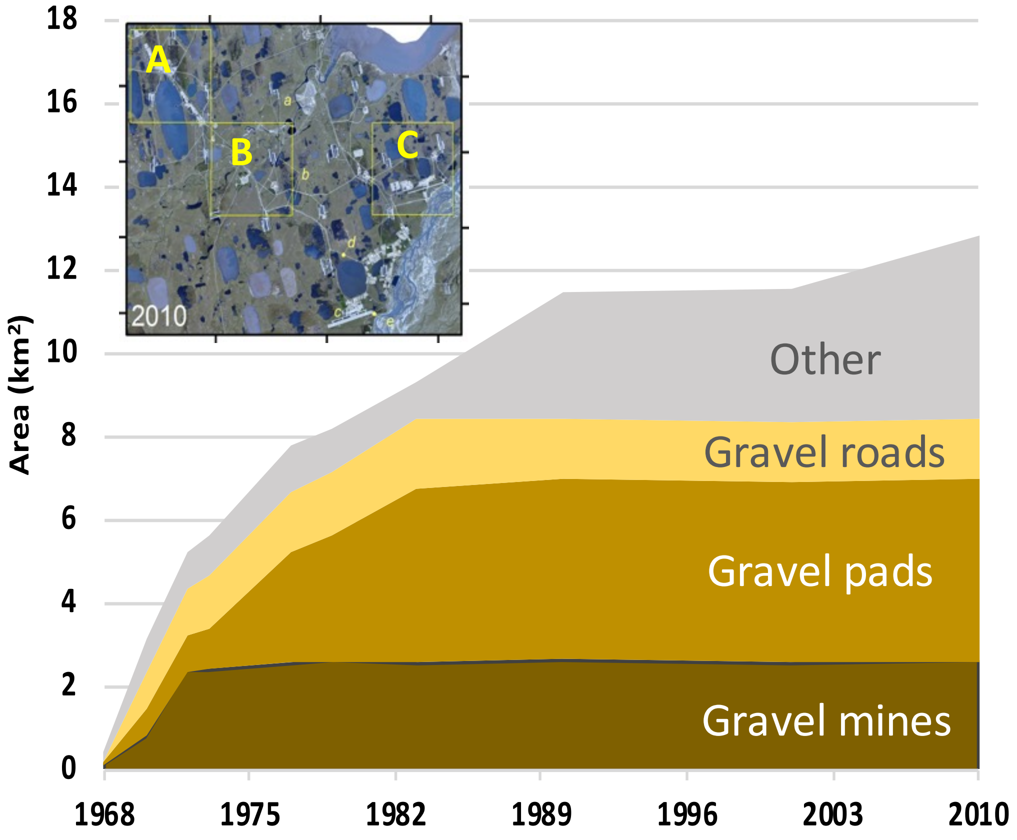
- Very rapid during main development phase 1968–1989.
- Reduced rate during production phase to 2010.

Comparison of regional- and landscape-scale direct infrastructure-related impacts

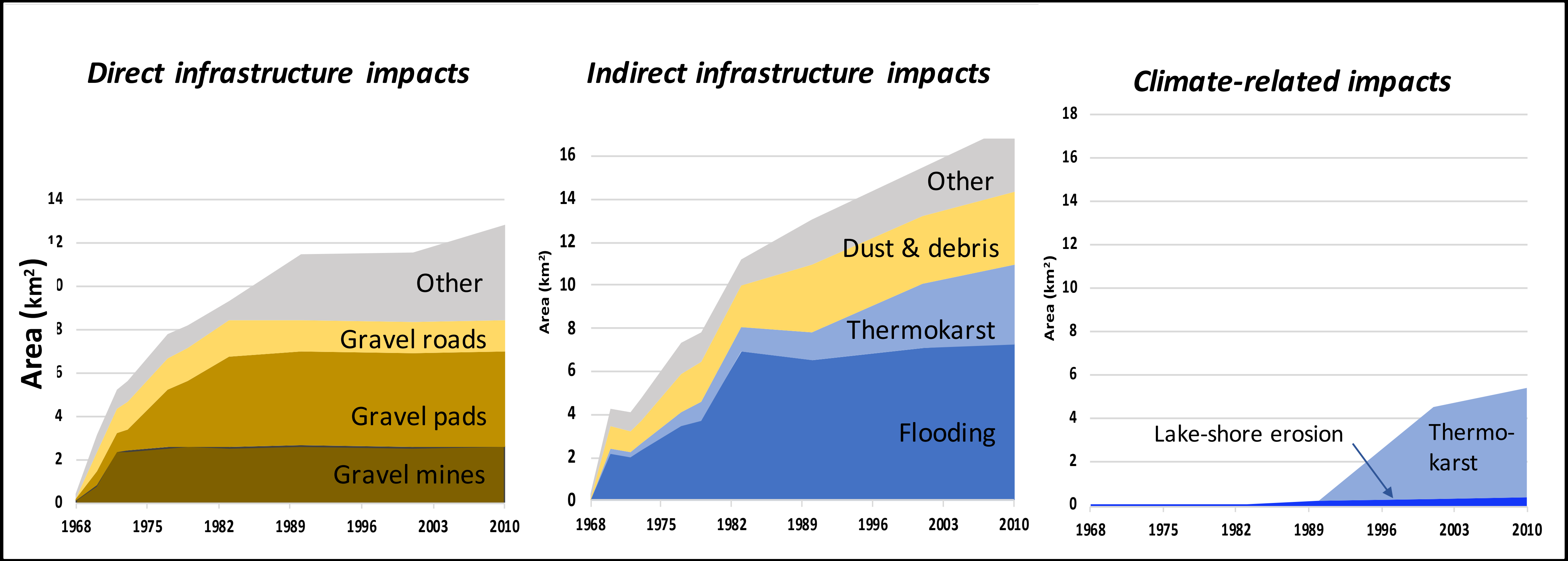
Regional-scale analysis
All North Slope oilfields



Landscape-scale analyses,
Areas A, B, C



Comparison of direct, indirect infrastructure- and climate-related impacts in Areas A, B, C



- Anthropogenic direct impacts slowed rate of increase after about 1983.
- Indirect impacts slowed in 1983but continued to increase.
- Area of indirect impacts exceeded area of direct impacts after 1982.
- Climate-related thermokarst started to occur in 1983 and increased dramatically after 1990.

Plot-level monitoring

IRPS observatories

Node:
Prudhoe Bay Oilfield

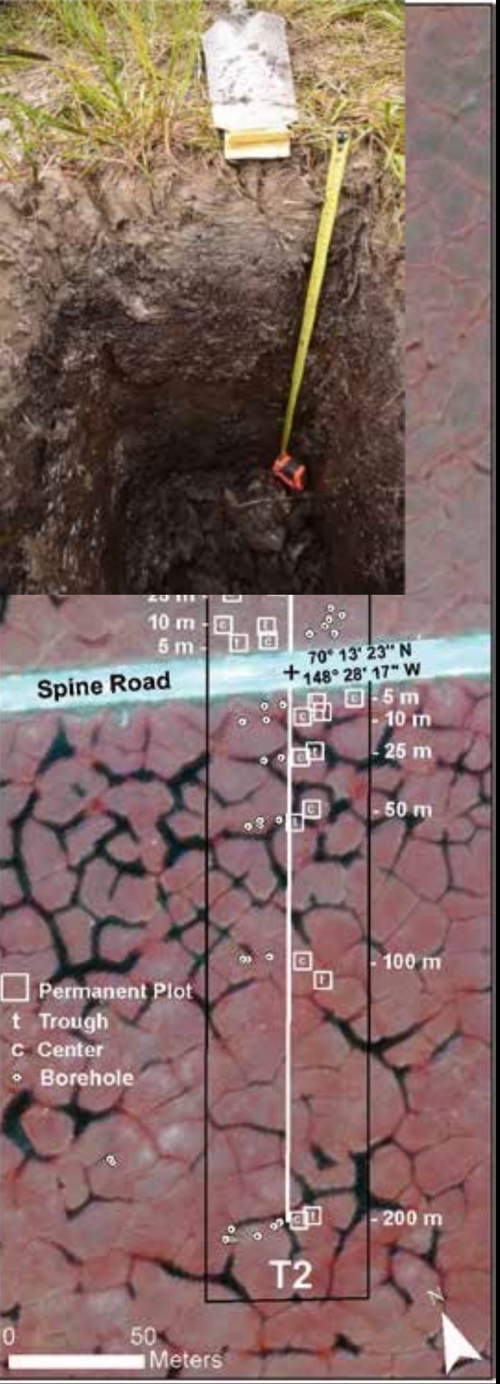
Corridor:
Dalton Highway

Village Housing:
Point Lay

subhankarbanerjee.org

motorcycle-usa.com

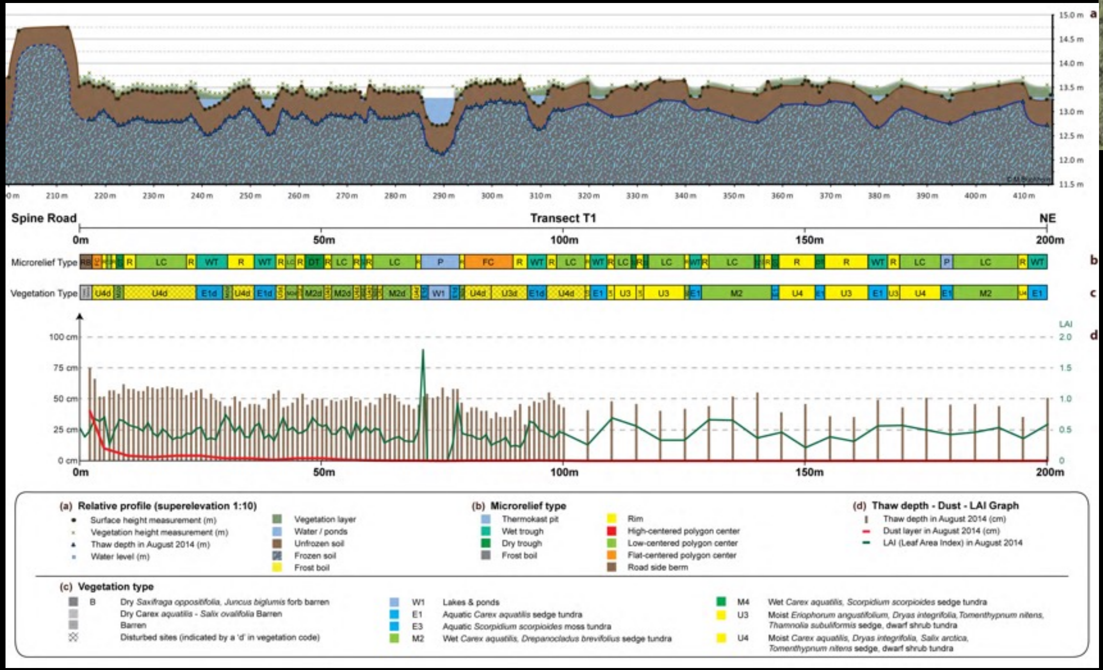
AlaskaTeenMedia

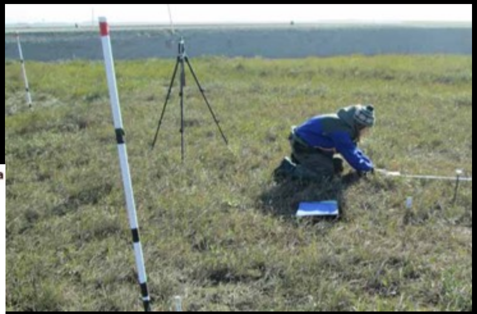


Plot-level monitoring:
IRPS roadside observatory, Prudhoe Bay

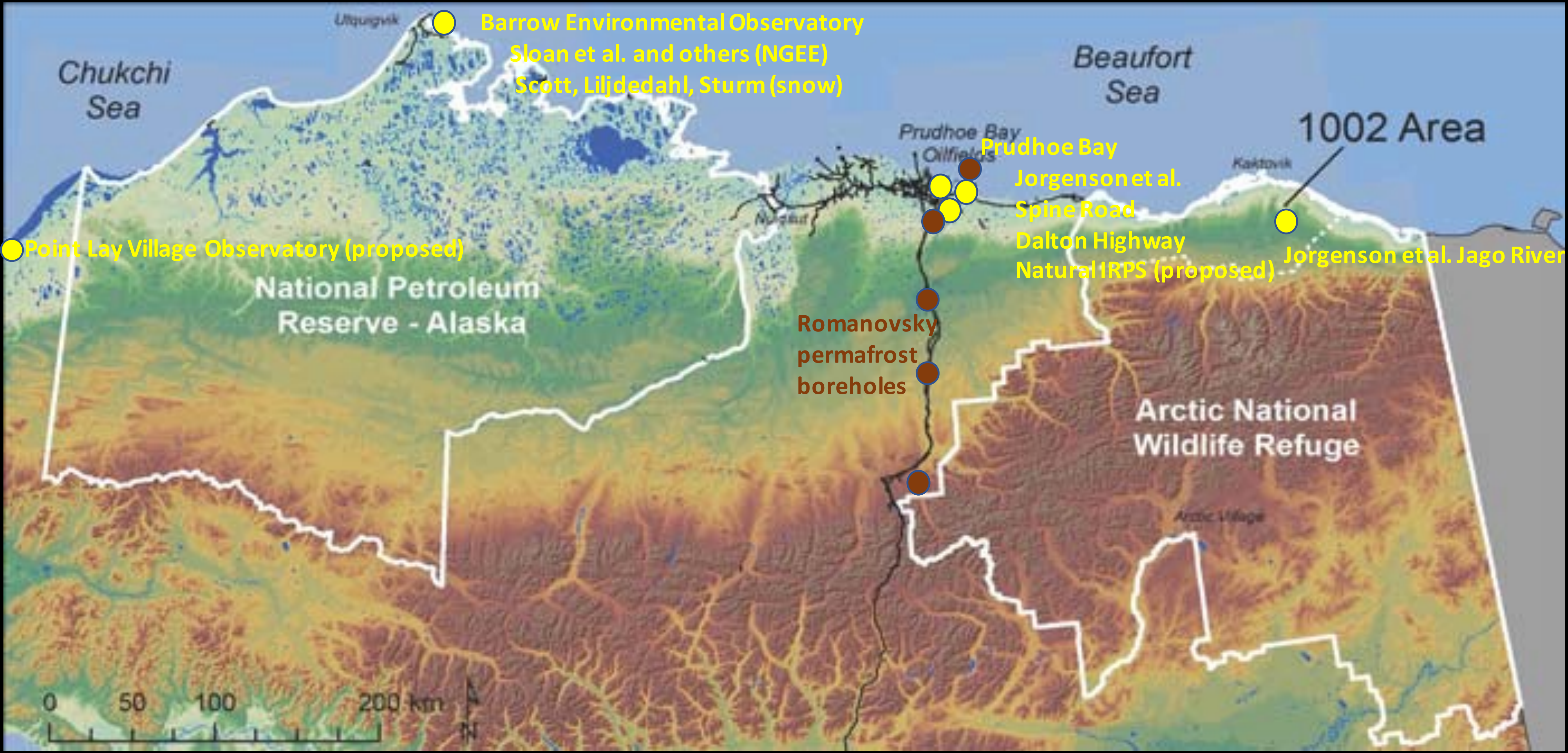
- Aerial photo time series
- Transect surveys
  - Micro-topography
  - Permafrost cores
  - Active layer

- Vegetation
- Soil
- Snow
- Dust
- Flooding





Network of NNA-IRPS observatories



Adapting to change at Point Lay:

Major impacts to housing due to coastal erosion and ground subsidence

Point Lay infrastructure amidst rapidly changing ice-wedge polygons and eroding coastal bluffs, and changing drainage systems. Courtesy of North Slope Borough.

Subsiding ice-wedges: Base of steps was at ground level and there was no thermokarst when house was built in late 1980s.

CCHRC housing adaptations to change at Point Lay

Photos courtesy of the Cold Climate Housing Research Center

Work with village stakeholders, the school and research team to develop:

- Solutions to address infrastructure issues pertaining to changing subsurface conditions.
- Drill and place subsurface monitoring instrumentation.
- Work with the Point Lay School to develop material for the education of students and local residents.
- Develop permafrost outreach materials for homeowners and contractors, including video on permafrost foundations.
- Best practices guidelines to build new and retrofit existing foundations.

Point Lay's other climate change story

Walrus hauling out on barrier island since 2007 due to no sea ice.

International Collaboration
T-MOSAiC
Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections

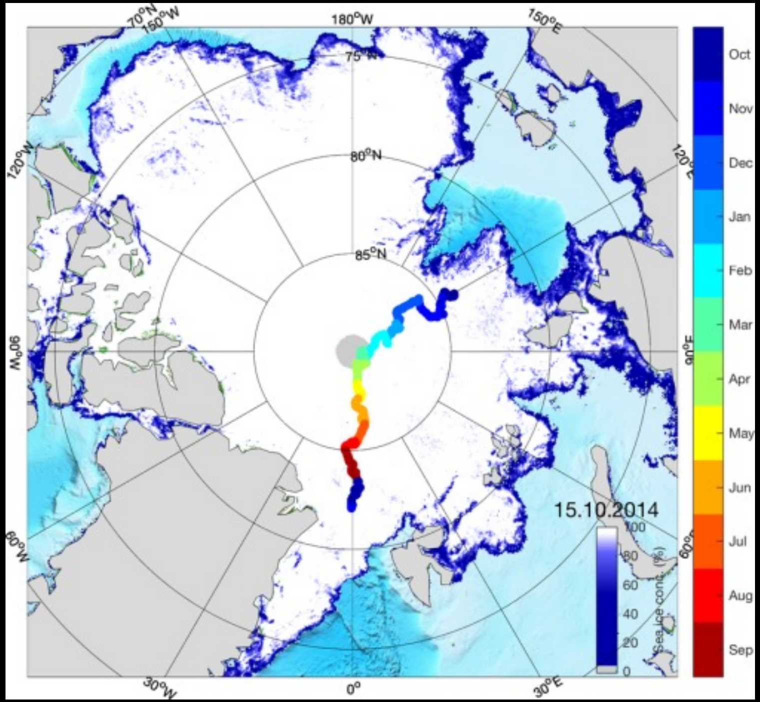
Canadian, pan-Arctic, land-based program that would extend the marine activities of MOSAiC to lands surrounding the Arctic Ocean.

Objective: Coordinate complementary activities that aid and benefit from MOSAiC by extending the work to the lands surrounding the Arctic Ocean and to the northern communities who live on those lands.

MOSAiC

International Arctic Drift Expedition

International Collaboration



Route

Polarstern

2019-2020 Modern repeat of Nansen's Fram Expedition

Science observations

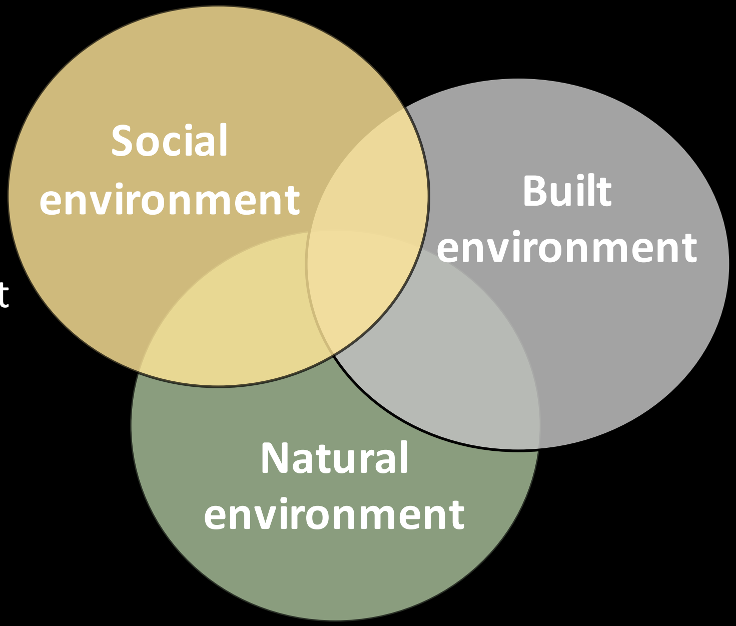
T-MOSAiC
Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections

The Infrastructure
Action Group
of T-MOSAiC

Scientific questions for the social, natural, and built environments in the NNA-IRPS & T-MOSAiC-RATIC collaboration

Social environment

- What are the historical indigenous housing adaptations to climate change and can these aid in finding modern solutions?
- How do the adaptive responses of ice-rich permafrost vary in different ASES?
- What are the social, economic, political & technological drivers of IRPS change in different ASES?
- How can scientists, industry, and local communities collaborate to develop adaptive approaches to sustainable development?



Built environment

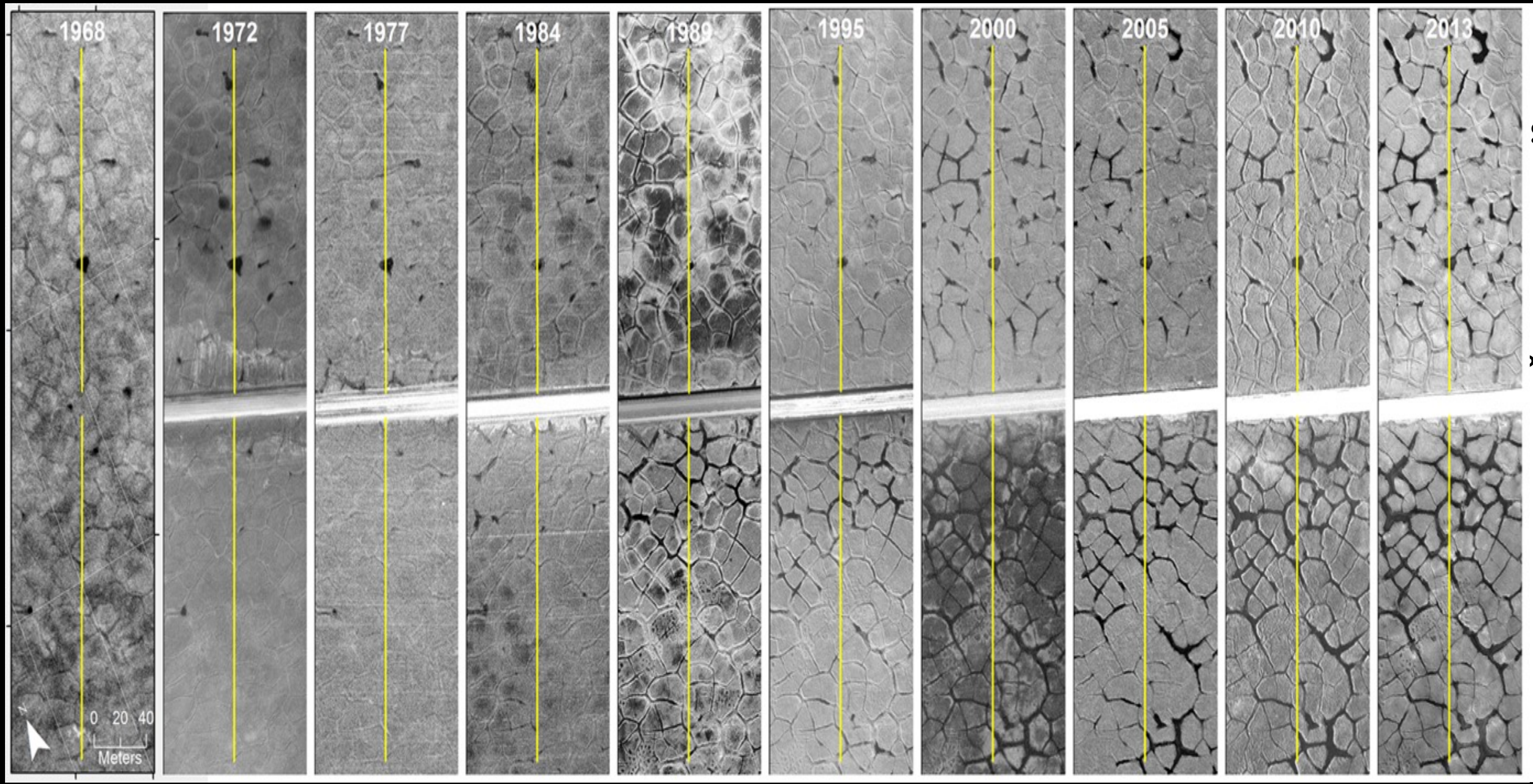
- Can we improve engineering solutions for IRPS problems related to urban nodes, remote villages, and transportation corridors?
- How are roads in IRPS affecting intensity of flooding events? And jhow can we reduce the intensity?
- Can we develop adaptive engineering solutions that include consideration of local culture, and indigenous knowledge?
- Can we develop circumpolar remote-sensing tools to document infrastructure expansion and its consequences at multiple scales?

Natural environment

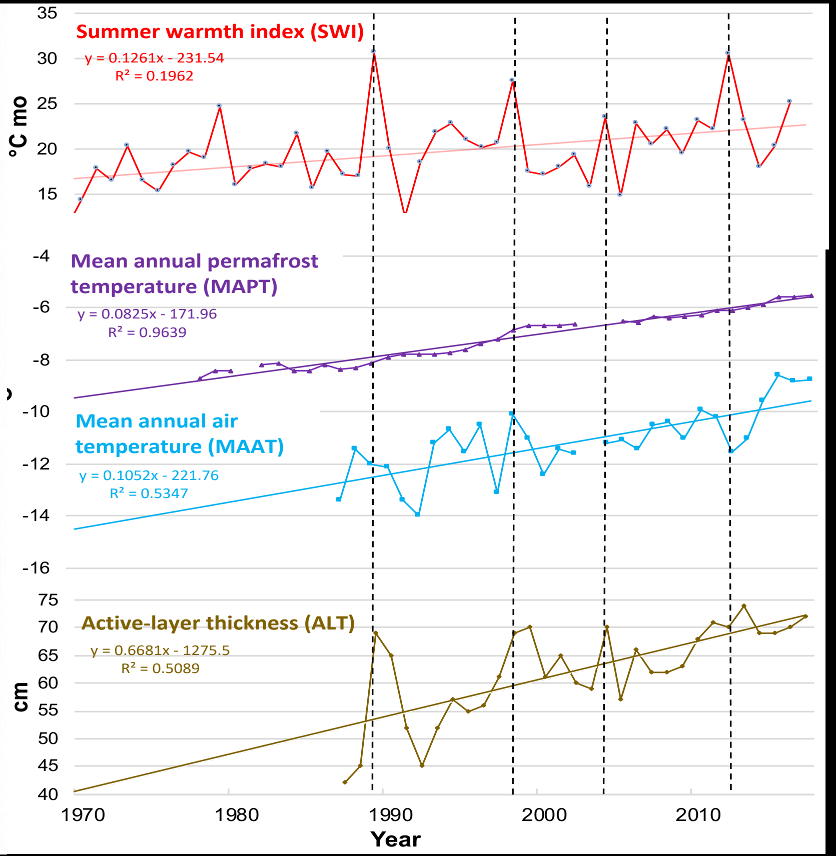
- How do natural IRPS responses to climate and infrastructure changes vary along N-S bioclimate gradients?
- How are these changes linked to observed changes in sea-ice and the marine environment?
- Can we develop standardized monitoring protocols for terrestrial ecosystem responses? at multiple scales using remote sensing and ground observations?
- What are the circumpolar impacts to IRPS of historical changes in air temperatures and flooding?
- What are the total ecosystem consequences pf the documented abrupt thermokarst changes?
- What are the ecosystem consequences of widespread 3D-seismic exploration?

Lake Colleen observatory: abrupt thermokarst expansion

Time-series of thermokarst along main Spine Road

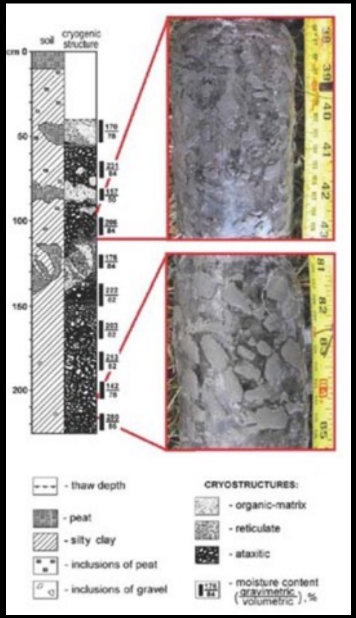


Time-series of temperature and thaw

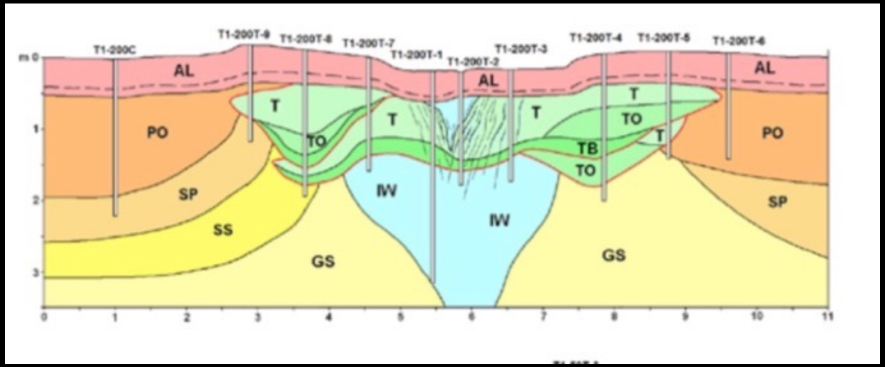


Ground-ice characterization and evolution

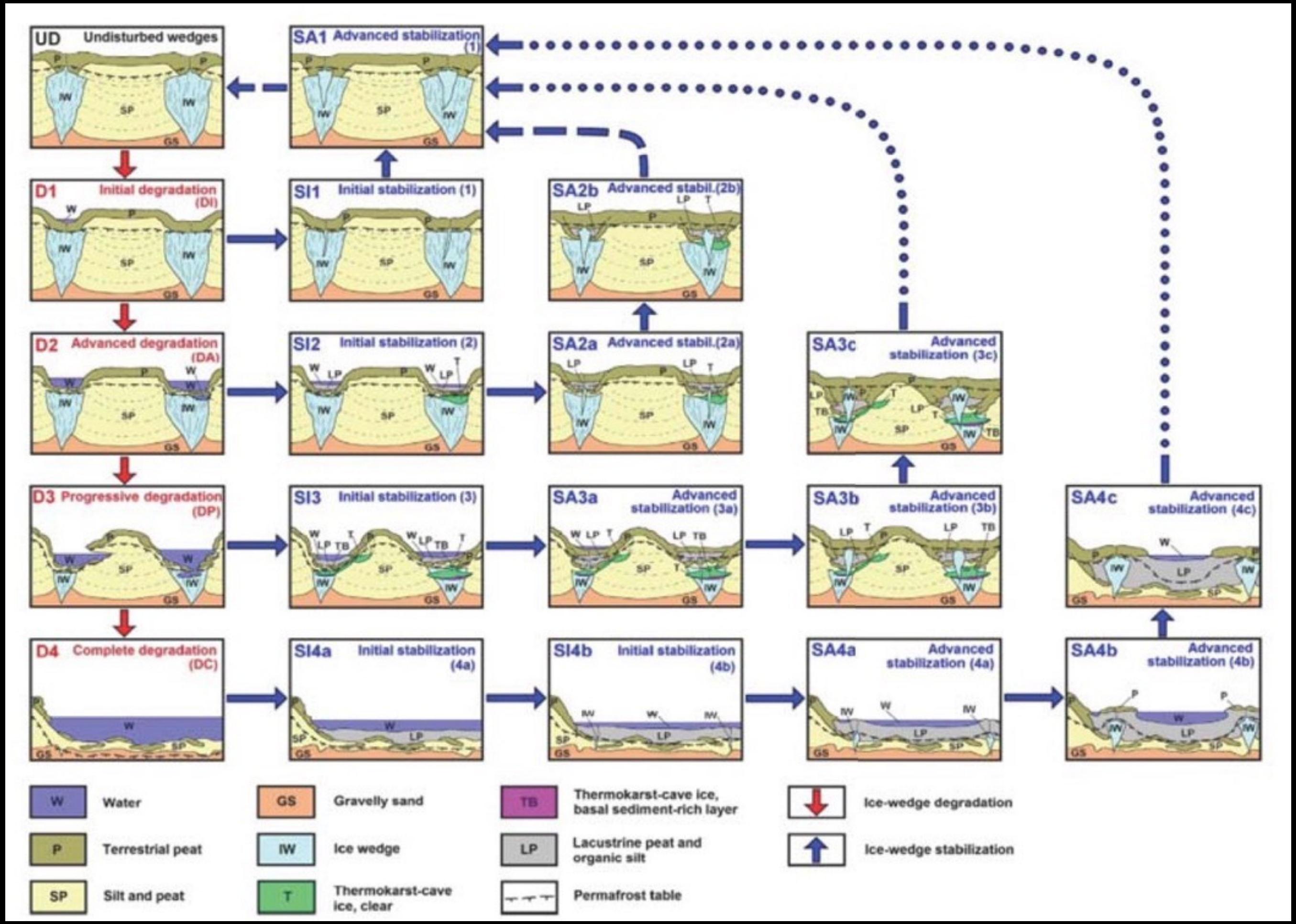
Boreholes



Profiles



Scenarios of IRP change




2015 Sagavanirktok River Icing and Flood

First trucks after April 1-13 closure. April 13, 2015

Flooding is becoming a major issue for oilfield operation

- 2015 aufeis and flooding disrupted road traffic and communication for over 3 weeks in April and May.
- Alaska Governor declared a disaster twice.
- Major economic impacts.
- National security issue.
- Serious flooding also occurred in 2016 and 2018.


Repeat of aufeis and flooding in 2016

Photo: AK DOT&PF, Feb 26, 2016

Jun 3, 2018, Photo: Courtesy of BP Alaska Exploration

Thermokarst collapse due to flooding Dalton Highway

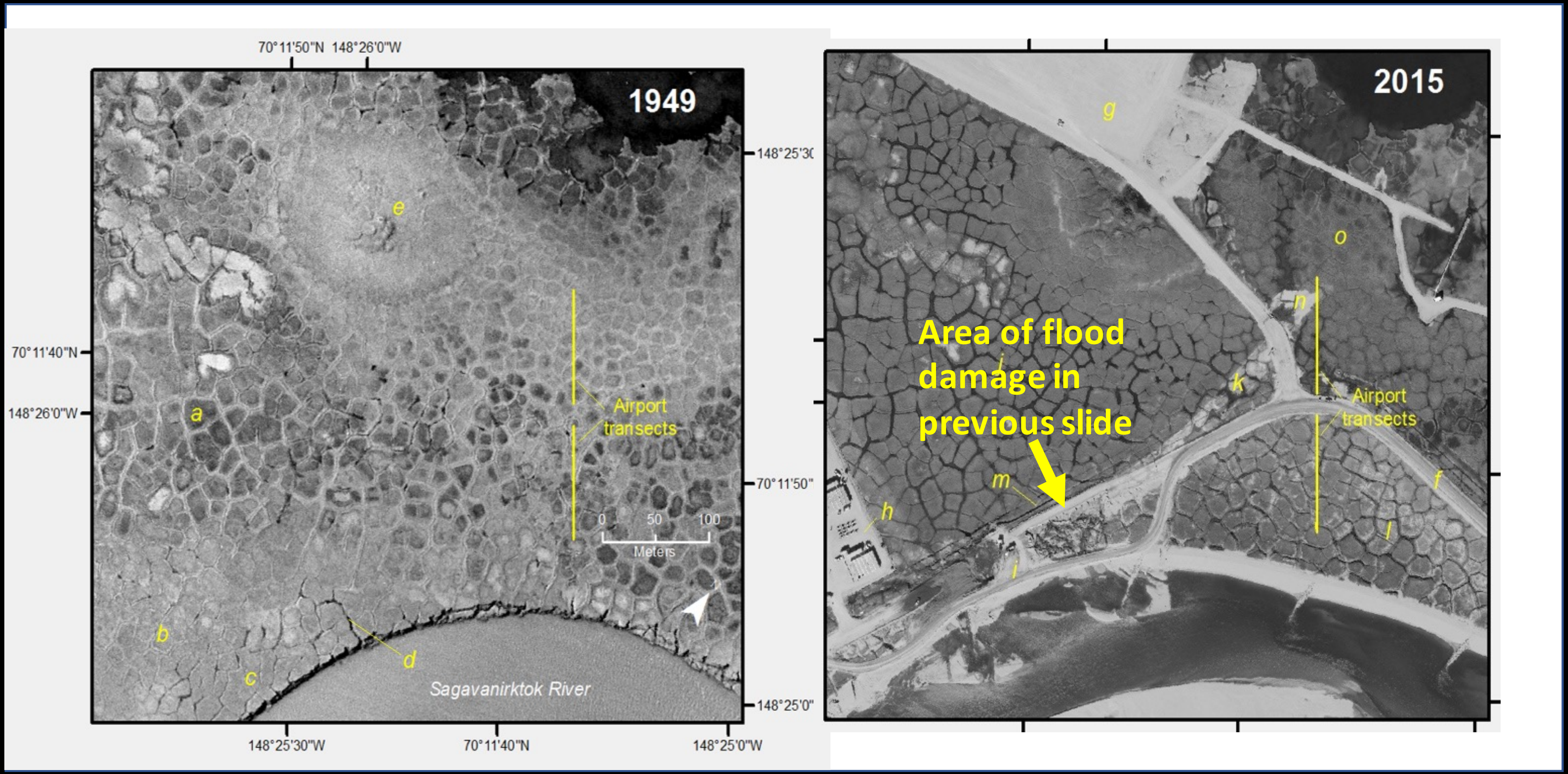
Underground thermal erosion of ice wedges

Photos: Courtesy of AKDOT & PF.

Dalton Highway near Deadhorse, May 25, 2015.

Shur et al. 2016. TICOP and in prep.

Airport observatory: Dalton Highway
Site of major flooding in 2015



Example of unpredictable cumulative effects:

2015-2016 Quintillion fiber-optic cable

- Cable to deliver high-speed telecommunication services.
- The cable was buried in a trench, much of which was dug in summer with extensive damage to the vegetation and permafrost.
- Especially visible in tundra of North Slope parallel to the Dalton Highway.
- Cable trench provided a pathway for flood waters to penetrate to the base of ice-wedge facilitating very rapid thermal erosion.
- Decision letter by AK-DNR permitted the project without a thorough environmental review.

3D-seismic surveys:

Seemingly minor initial impacts cover large areas but with unknown long-term consequences to hydrology, vegetation, and permafrost regimes

2D-seismic trail from 1960s.
Photo: Matt Nolan

3D-seismic grid south of Prudhoe Bay.
Photo: Heather Buelow

New natural thermokarst,
Arctic National Wildlife Refuge, Alaska
hoto: Matt Nolan

Walker, D. A., M. T. Jorgenson, M. Kanevskiy, A. K. Liljedahl, M. Nolan, M. K. Raynolds, and M. Sturm. 2019. Likely impacts of proposed 3D-seismic surveys to the terrain, permafrost, hydrology, and vegetation in the 1002 Area, Arctic National Wildlife Refuge, Alaska.
Alaska Geobotany Center Publication AGC 19-01..
https://www.geobotany.uaf.edu/library/pubs/WalkerDA2019_seismic_exploration_whitepaper.pdf

3D-seismic white paper

NNA-IRPS proposal:

www.geobotany.uaf.edu/library/pubs/NNA-IRPSproposal2019.pdf