70-year retrospective of remote sensing applied to cumulative impact assessments, Prudhoe Bay Oilfield Alaska

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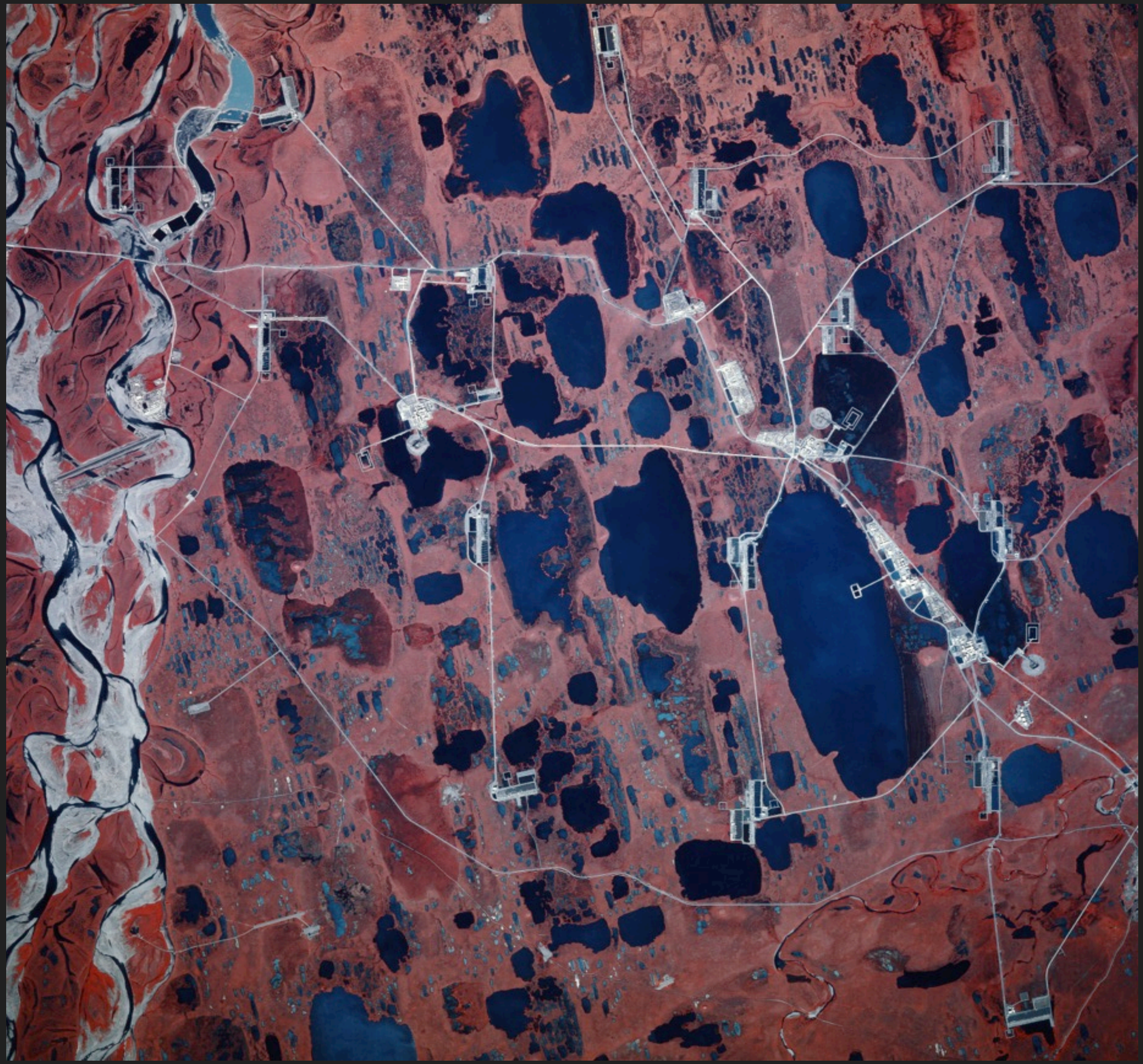
16TH INTERNATIONAL CIRCUMPOLAR REMOTE SENSING SYMPOSIUM, FAIRBANKS, AK 16-20 MAY 2022



NASA 1982 false-CIR aerial photo, 1:60,000 scale.

Introduction

"Are we entering a new era for using remote sensing to help predict cumulative impacts of climate change and infrastructure in the Arctic?"

Rapid Arctic Transitions due to Infrastructure and Climate change

- This talk is a product of the Rapid Arctic Transitions due to Infrastructure and Climate change (RATIC) initiative.
- Conceived at the Third International Conference on Arctic Research Planning (ICARP III, 2015, Toyama, Japan).
- To examine the combined cumulative impacts of infrastructure and climate change using an interdisciplinary, whole-system, and panarctic approach that includes the social and human dimensions.

Cumulative impacts definitions

- **Defined by U.S.** Council on Environmental Quality, 1987
- **Most countries have similar definition that generally,** include:
  - Direct and indirect impacts
  - Impacts over large regional areas outside the area of direct impacts
  - Complex interactions from multiple sources over long periods of time
  - Non-linear responses and critical thresholds
  - Impacts to human social systems
- Here, I focus on cumulative impacts to natural landscapes in the PBO.

Direct landscape impacts

The ”footprint”

Include areas covered by roads, pipelines, gravel pads, gravel mines, other semi-permanent structures

Photo: Grid Arendal, Peter Prokosh: http://www.grida.no/photolib/detail/prudhoe-bay-oil-field-alaska-1986_12be

Indirect landscape impacts

- Impacts that accompany or follow the main impact
- Include the interactions with climate change.

Flooding and snowdrifts adjacent to infrastructure

Road-dust disturbance

Infrastructure-related ice-wedge thermokarst

Enhanced shrub growth due to disturbance and climate change

Photo credits: Ben Jones (upper left), Skip Walker (others)

Seismic trails are a special class of indirect impact

Trails left by 3-D seismic exploration, North Slope, Alaska, 2019.

Photo: Courtesy of Heather Buelow.

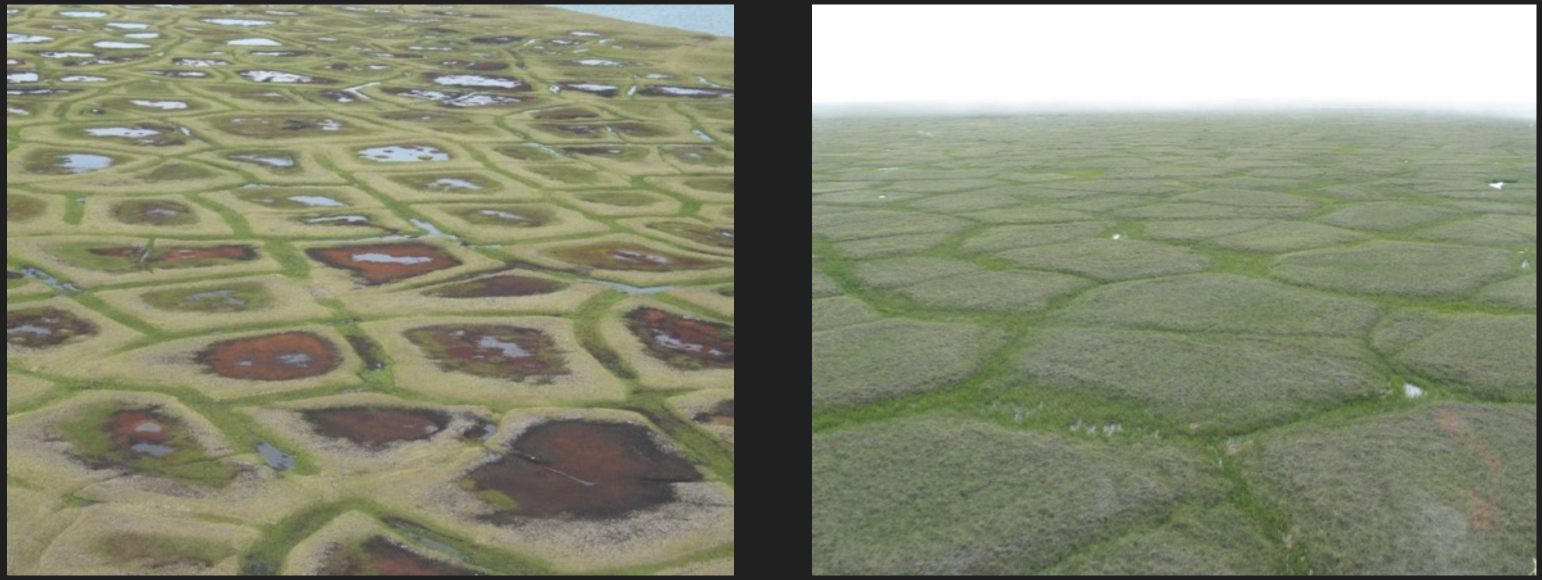
Raynolds, M. K., et al. 2020. Landscape impacts of 3D-seismic surveys in the Arctic National Wildlife Refuge, Alaska. *Ecological Applications* 30:e02143. https://doi.org/10.18739/

Potential impacts to ice-rich permafrost are not adequately addressed in most CIAs

- IRP is permafrost with *excess ice* (ice that exceeds the volume of the pore spaces in the soil).
- Includes areas with ice-wedges, tabular ice, lens ice, pingo ice.

Ice wedge, Misha Kanevskiy

Coastal erosion of Ice wedges, USGS

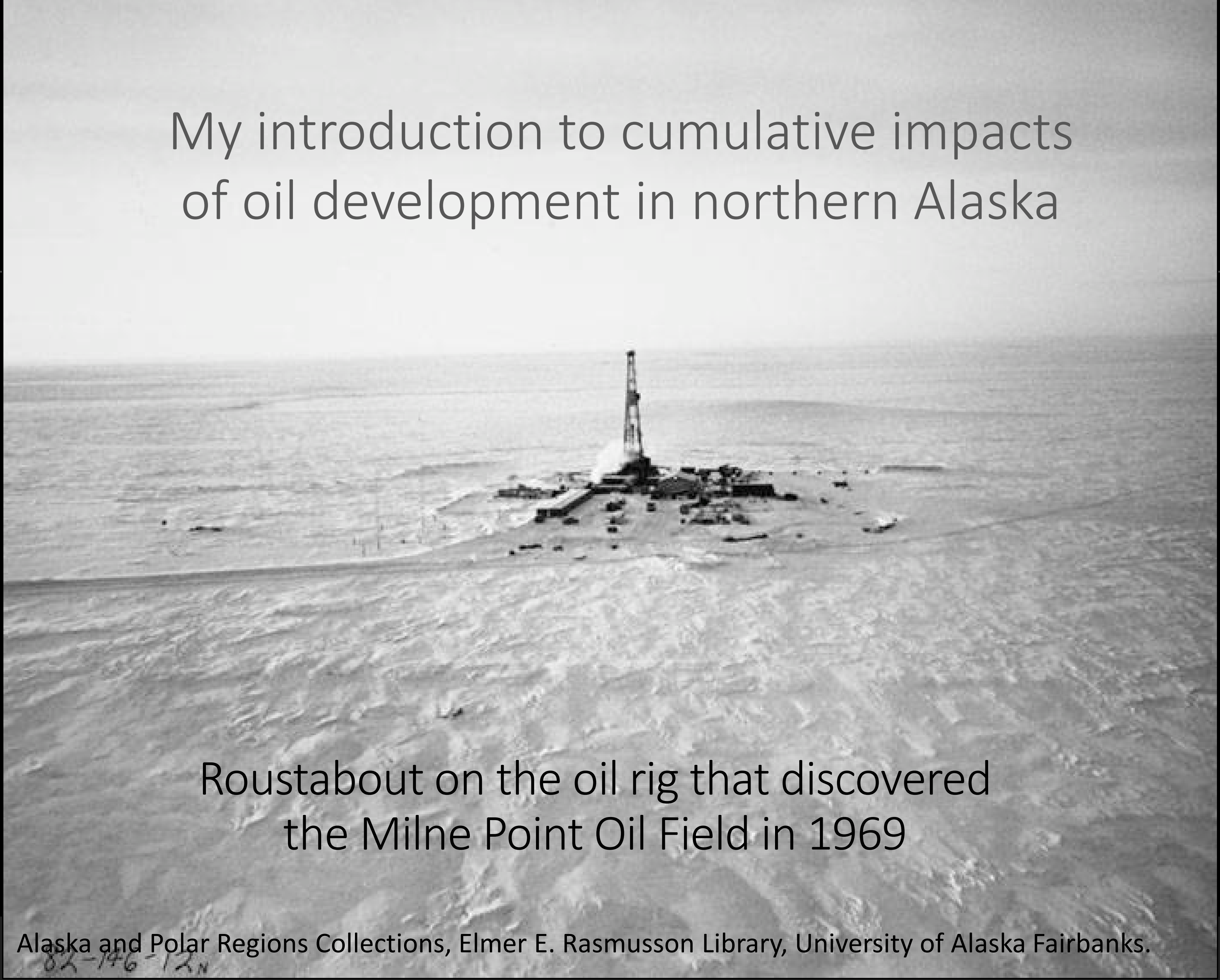


Low-centered and high-centered ice-wedge polygons, Misha Kanevskiy

There is a scarcity of long-term environmental studies after infrastructure was built in areas with IRP.

Prudhoe Bay Oilfield. Photos: Courtesy of Pam Miller

My introduction to cumulative impacts of oil development in northern Alaska

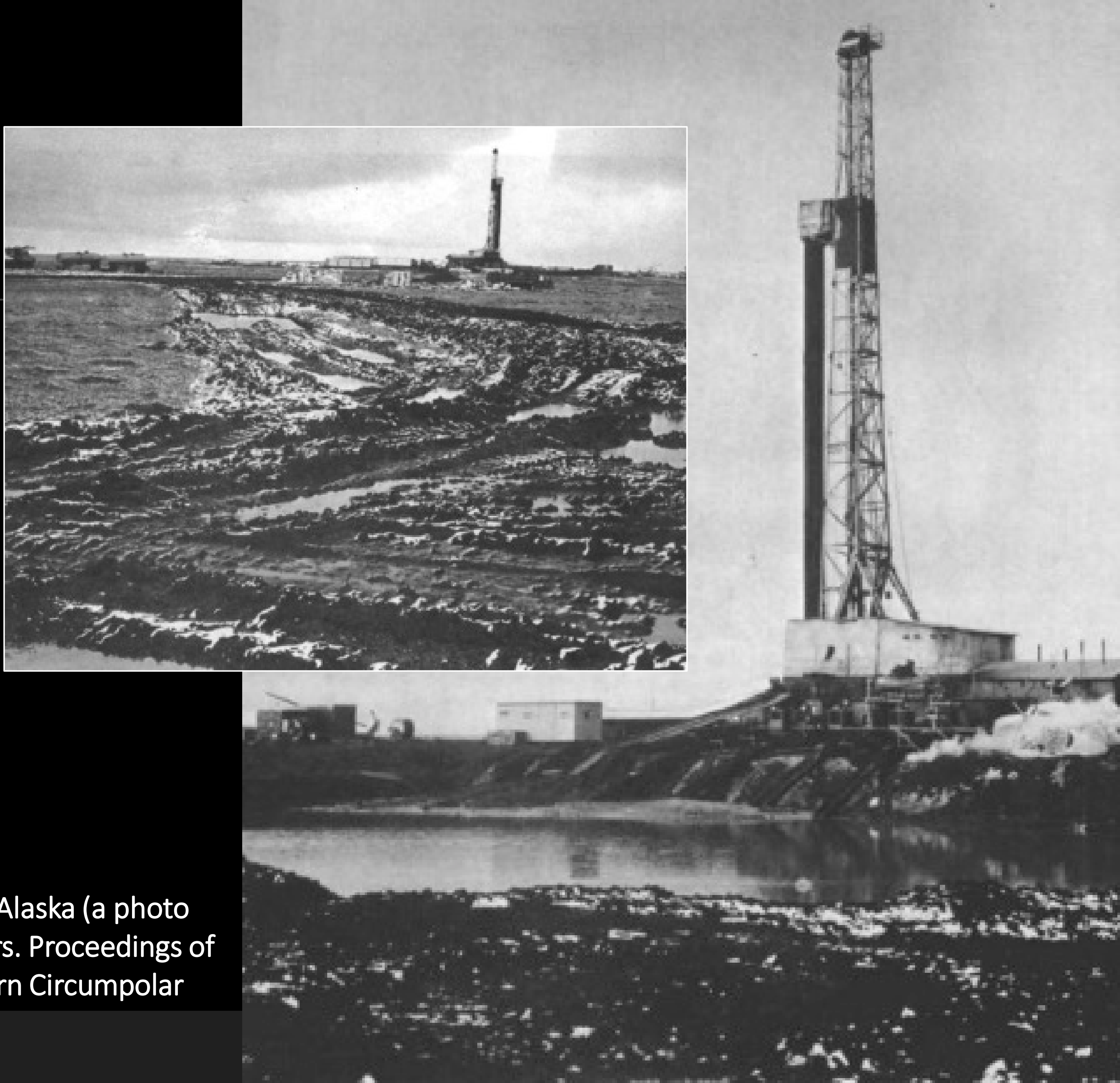


Roustabout on the oil rig that discovered the Milne Point Oil Field in 1969

Alaska and Polar Regions Collections, Elmer E. Rasmusson Library, University of Alaska Fairbanks.

Point Storkerson oil rig

This prompted my decision to go back to college to study Arctic and alpine environments.



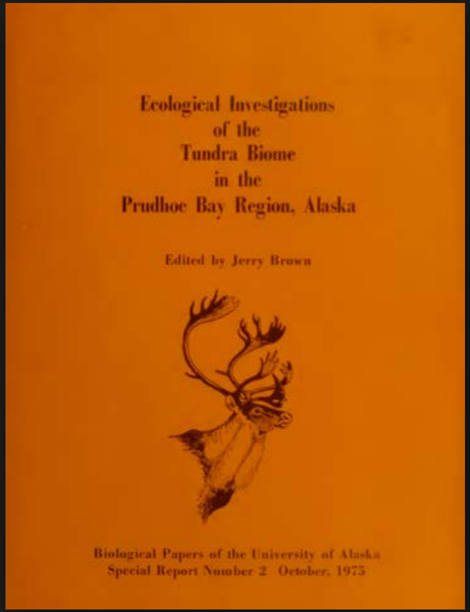
Photos: Klein, D. R. 1969. The impact of oil development in Alaska (a photo essay). Pages 209–242 *in* W. A. Fuller and P. G. Kevan, editors. Proceedings of the Conference on Productivity and Conservation in Northern Circumpolar Lands.

An early view of the PBO tells a lot about problems to come related to hydrology and permafrost

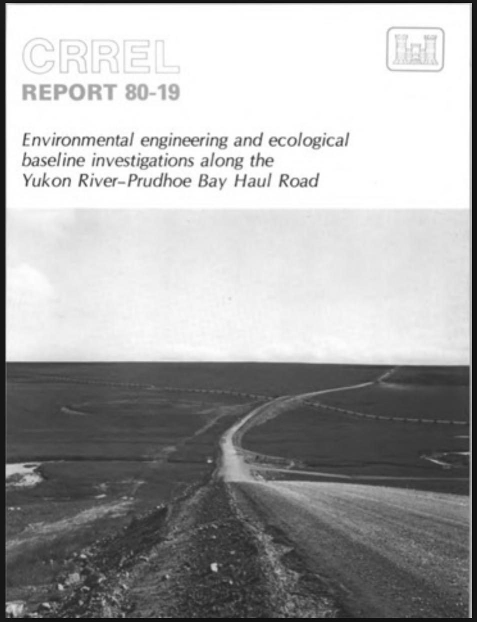
ARCO airstrip and base camp, Prudhoe Bay Oilfield, June 1971. Photo courtesy of USFWS.

Geo-ecological baseline studies at Prudhoe Bay (1970s)

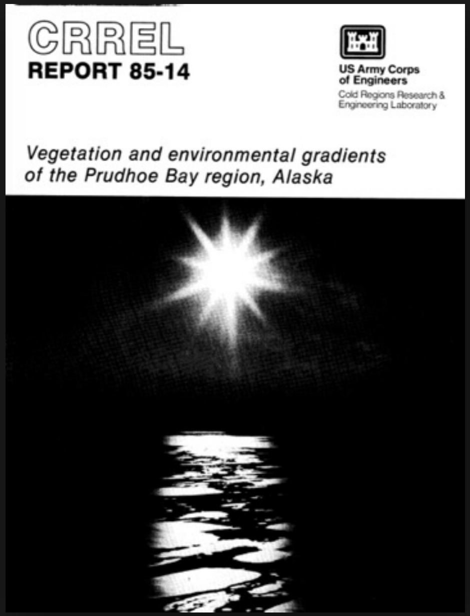
- International Biological Program (IBP) Tundra Biome
- U.S. Army Cold Regions Research and Engineering Laboratory (CRREL)



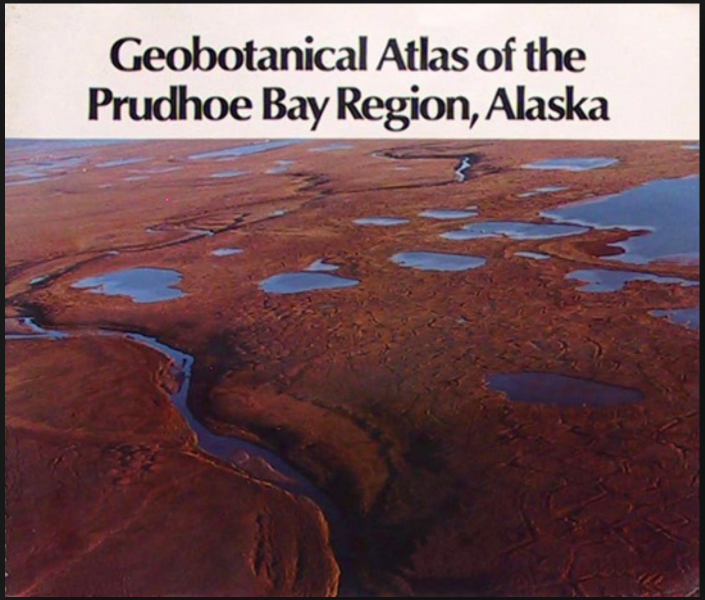
Brown J. (Ed.), 1975



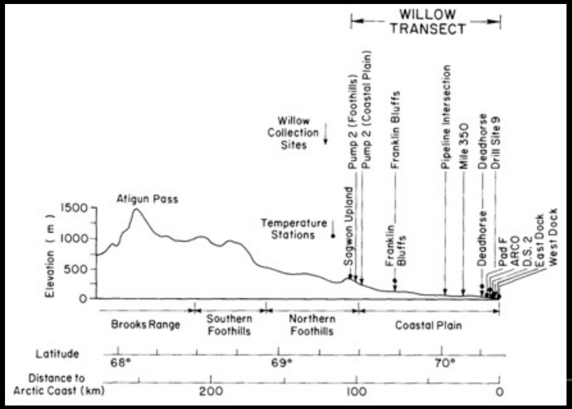
Brown J. & Berg (Eds.), 1980



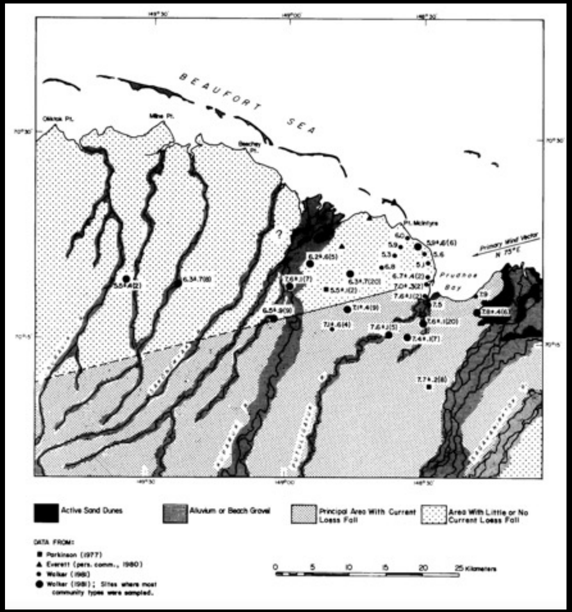
Walker, 1985



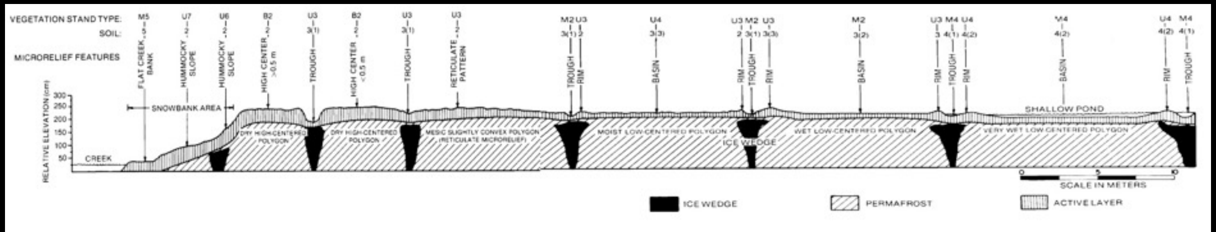
Walker et al. 1980



North Slope climate gradient



Loess gradient downwind of the Sag R.



Micro-topography/ soil-moisture gradient

The PBO baseline studies characterized vegetation variation at three scales:

Regional-scale

Coastal climate gradient, bioclimate subzones

Landscape-scale

Hillslope toposequences, riparian and coastal chronosequences, loess gradient downwind of major rivers

Plot-scale

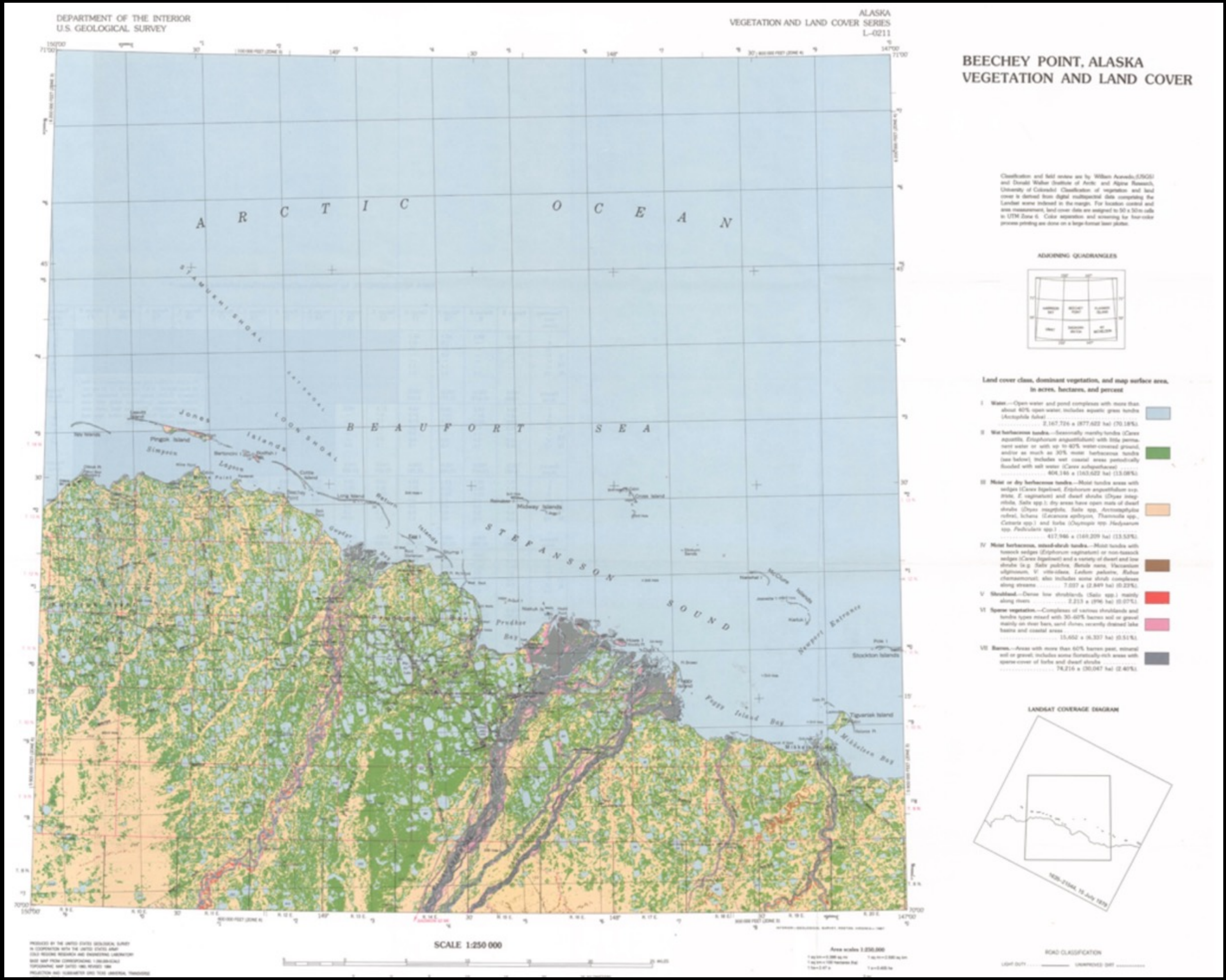
Patterned-ground features

Walker, D.A. 1985. *Vegetation and environmental gradients of the Prudhoe Bay region, Alaska*,CRREL Report 85-14. https://erdc-library.erdc.dren.mil/jspui/handle/11681/9420.

Regional-scale landcover mapping 1980s

Landsat MSS landcover map of the Prudhoe Bay region, 1987

EOS satellite-based remote sensing products were useful for broad-scale delineation of vegetation patterns but minimally useful for delineating patterned ground features or monitoring many infrastructure-related direct impacts because of the scale of the pixels (30-70 m).

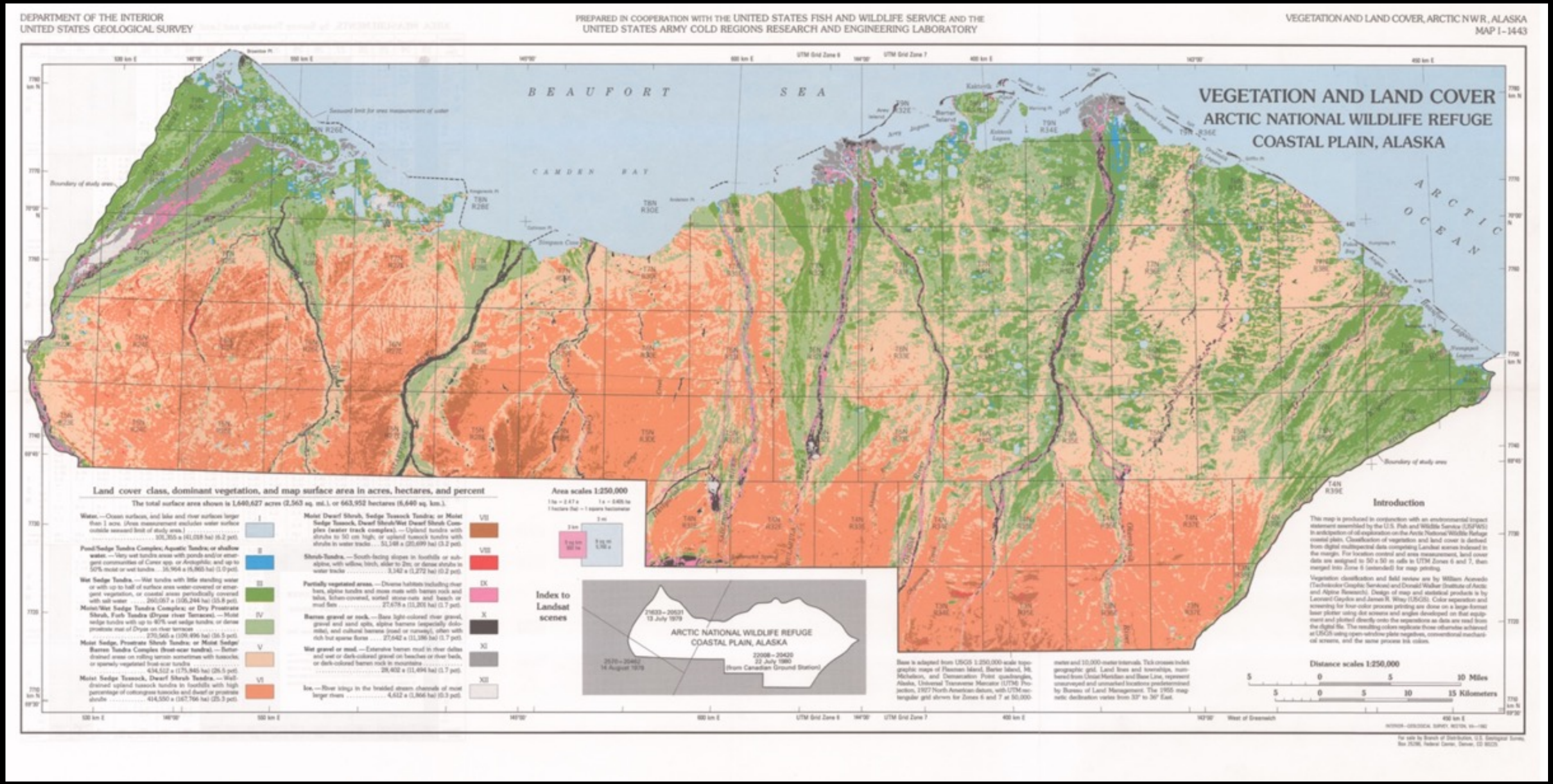


Walker, DA and Acevedo, W. 1987. CRREL Report 87-5.

Regional-scale landcover mapping 1980s

Landcover map of the 1002 Area of the Arctic National Wildlife Refuge (1982)

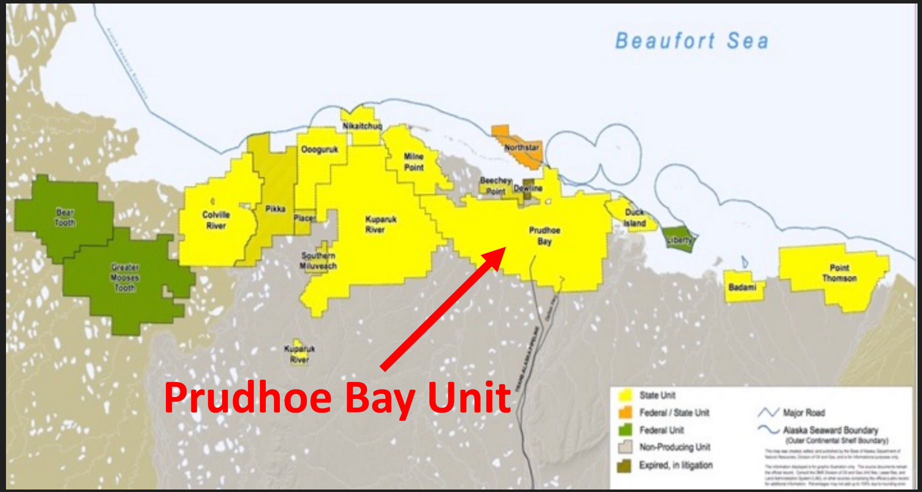
A strong contrast with the impacts of development in the PBO.

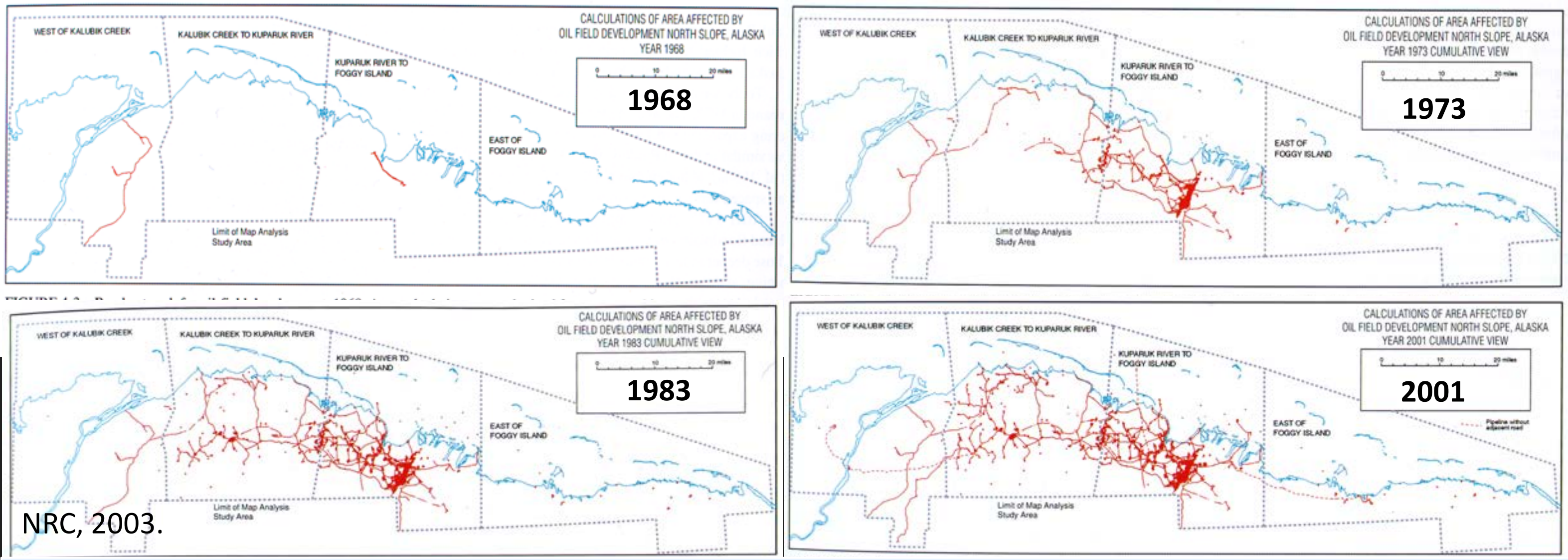


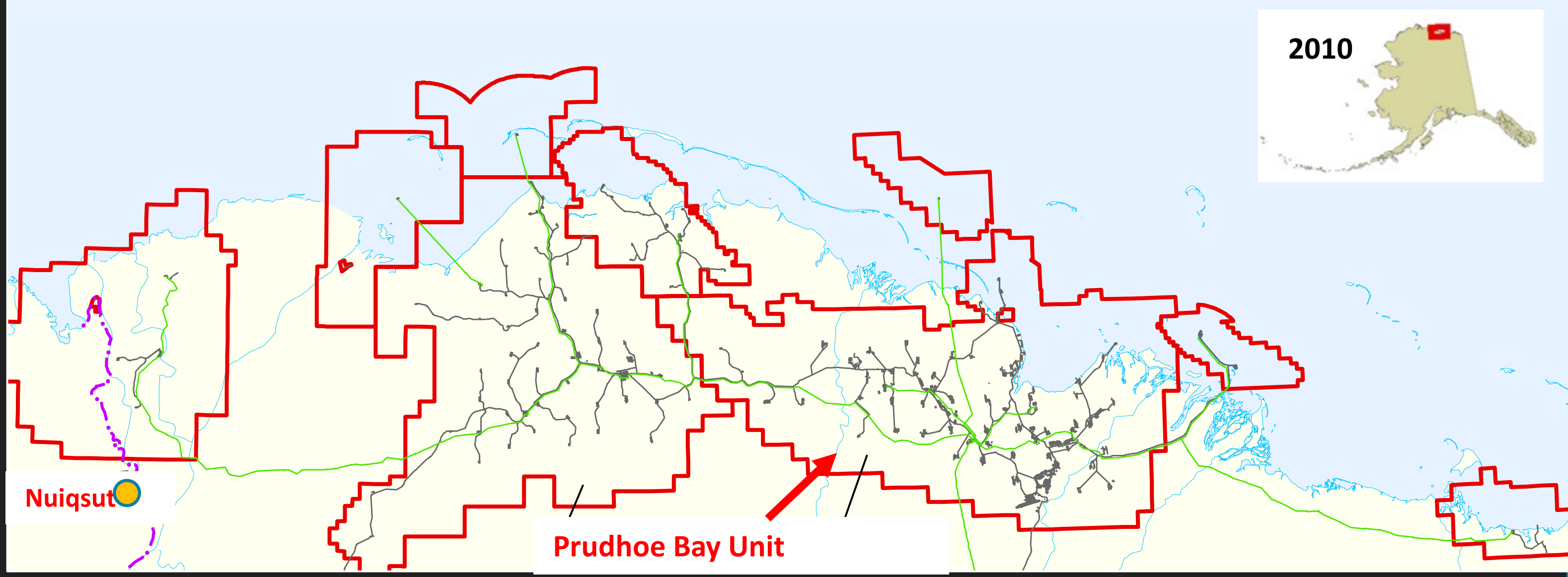
Acevedo and Walker. 1982. USFWS and CRREL, Map I-1443.

Regional-scale infrastructure mapping 1968-2010

Rapid growth of North Slope oilfields





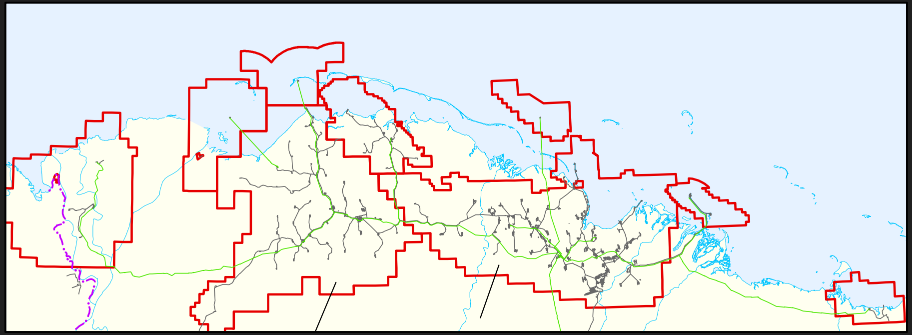


150 km

Courtesy of BP Alaska, Inc. and NV5 Geospatial, Anchorage, AK

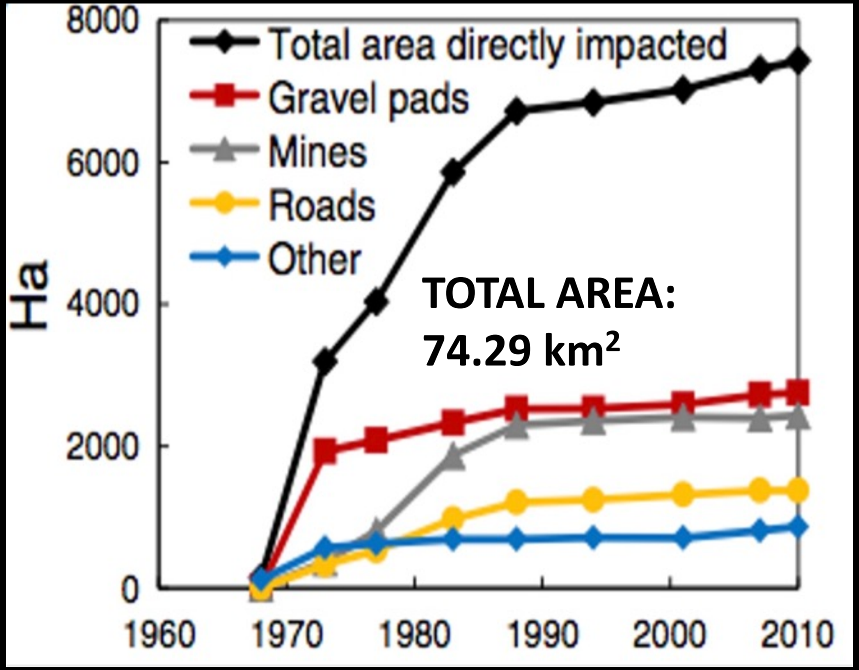
Regional-scale infrastructure mapping, 1968-2010

Oil-industry maps and GIS databases were used to map extent of infrastructure for regional cumulative-effects assessments in 1987, 2003, and 2014



Courtesy of BP Alaska, Inc. and NV5 Geospatial, Anchorage, AK

Regional footprint, 2010



Number of features
103 exploration sites
127 production pads
145 support pads
25 proc. fac. pads
13 off-shore islands
9 airstrips
4 exploration airstrips
2037 culverts
78 Other (bridges, caribou crossings, landfill)
TOTAL: 2510 mapped items

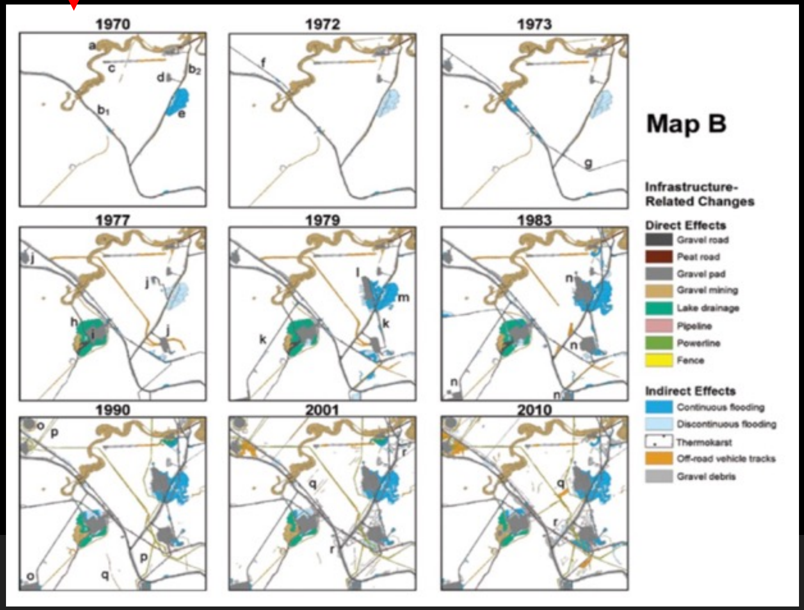
Length of linear features
669 km gravel roads
154 km abandoned roads
12 km causeways
96 km old tractor trails
54 km exploration roads
790 km pipeline corridors
541 km powerlines
TOTAL: 2316 km of mapped linear items

Raynolds et al. 2014, *Global Change Biology*

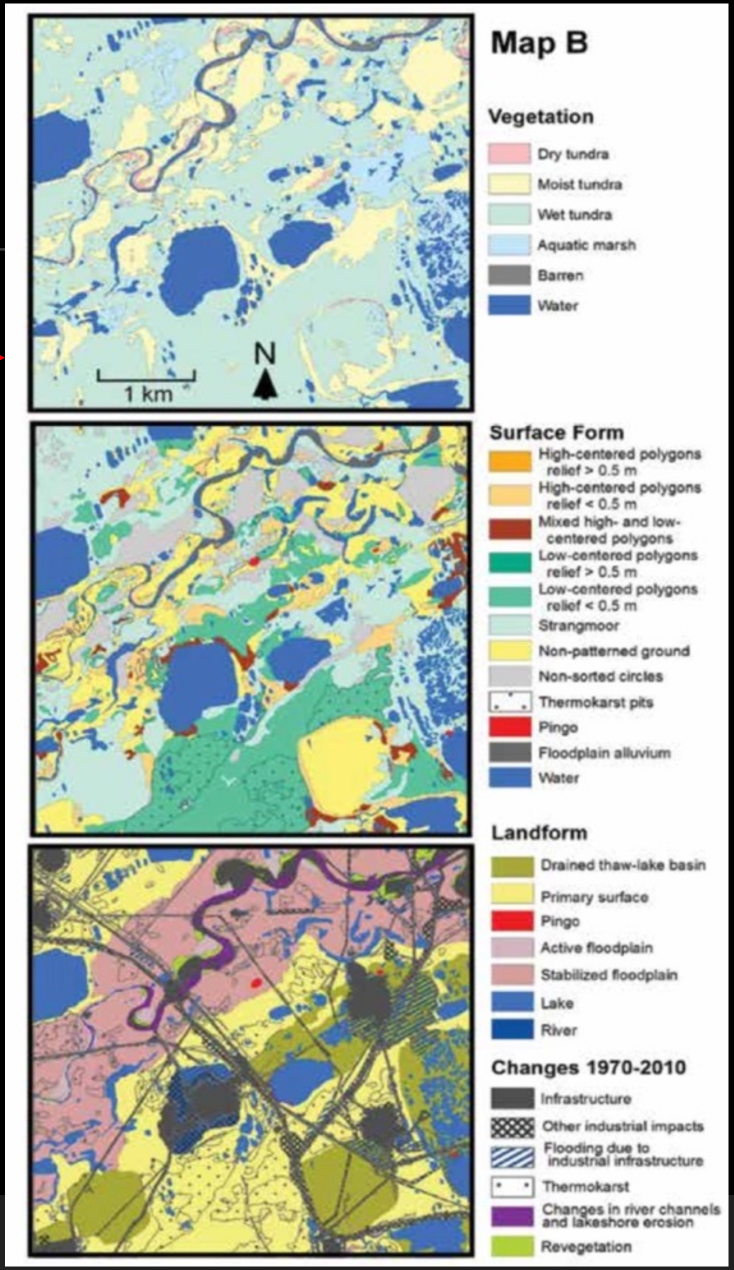
Landscape-scale integrated geo-ecological and historical change mapping (IGHCM) (1980s-2010s)

Master Map

Historical-change Maps



Geo-ecological Maps



Master maps:

1.ESRI Integrated terrain unit mapping (ITUM)

2. Baseline topography from oil-industry topographic maps.

3. Baseline terrain and vegetation information fom IBP Tundra Biome studies

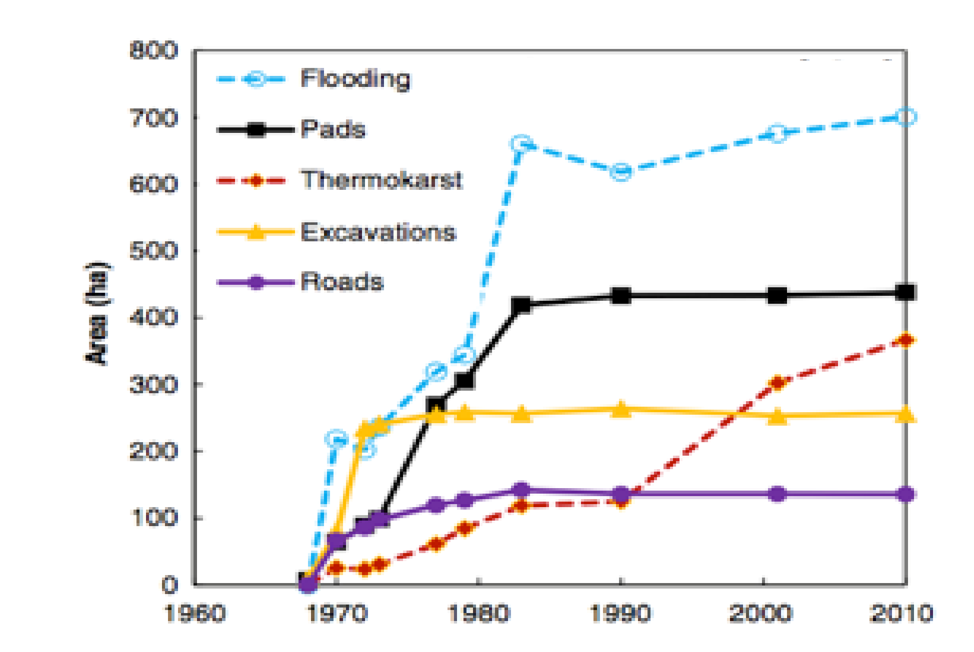
4. History of infrastructure from oil industry's historical high-resolution images.

Raynolds et al. 2014, Global Change Biology

Landscape-scale cumulative impacts

By 2010, within 3 mapped 25-km^2 areas the area indirect impacts was nearly double the area of the direct impacts.

Direct and indirect infrastructure-related impacts (1968–2010)



Direct impacts (solid lines): 919 ha (15% of mapped area) Leveled off after 1980.

Indirect impacts (dashed lines): 1794 ha (28.6% of mapped area) Continued to increase after the 1980s.

Thermokarst (red dashed line): increased 250% after 1990. Includes only infrastructure-related thermokarst.

Raynolds et al. 2014, *GCB*.

Numerous publications described recent abrupt changes in Ice-wedge degradation and ascribed it to warming climate

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 temperatures (annual means −6 to −12°C). The risk for thaw subsidence in arctic lowlands is substantial, however, because of the high volume of ground ice at the top of the permafrost [*Nelson et al.*, 2001]. Under the cold climatic conditions in the Arctic, a polygonal network of wedge-shaped ice bodies form beneath a thin layer of seasonally thawed soil due to contraction cracking caused by large fluctuations in winter temperature [*Leffingwell*, 1919; *Lachenbruch*, 1962; *Mackay*, 1990]. Between the active layer and the ice wedges is a very thin transient layer [*Shur*, 1977] of usually frozen soil that adjusts in thickness to 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-to-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 remains. Thaw depths were determined with a metal tile probe.

[4] For the photo-interpretation of ice-wedge degradation over time, we delineated and classified thermokarst pits on photography from 4 July 1945 (1:45,000 scale, B&W), July 1982 (1:63,000 scale CIR), and 14–15 July 2001 (1:18,000 scale, color orthophoto mosaic by Aeromap, Inc., Anchorage, Alaska) to assess temporal changes in various stages of thermokarst within the two intensive sites. To compensate for differences in visibility of pits due to the

Jorgenson et al. 2006:
Abrupt ice-wedge degradation
North Slope, AK

Global Change Biology

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

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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 warming during the 1990s, 19% of the remaining natural landscapes (excluding areas covered by infrastructure, lakes and river floodplains) exhibited expansion of thermokarst features resulting in more abundant small ponds, greater microrelief, more active lakeshore erosion and increased landscape and habitat heterogeneity. This transition to a new geoecological regime will have impacts to wildlife habitat, local residents and industry.

Keywords: Arctic, climate change, cumulative impacts, geoecological mapping, ice-rich permafrost, ice-wedge polygons, infrastructure, photo-interpretation, thermokarst, tundra

Received 18 September 2013 and accepted 8 November 2013

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

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.

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

Plot-scale cumulative-impact field studies 2011–present

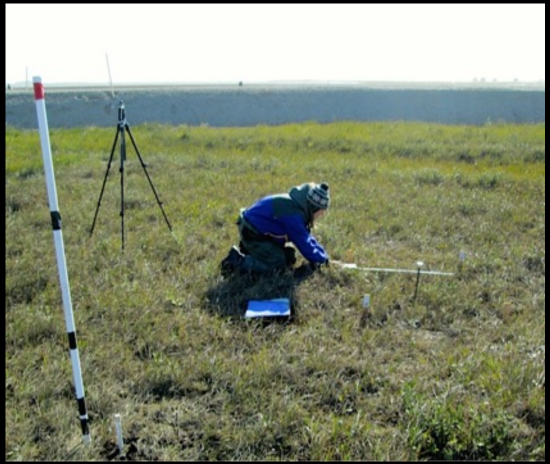
Integrated ground-based geo-ecological studies

Transects perpendicular to the road

Micro-topography surveys

Thaw, water depth, vegetation height, leaf area index, NDVI

Vegetation plots: species composition, LAI, soils, environmental factors

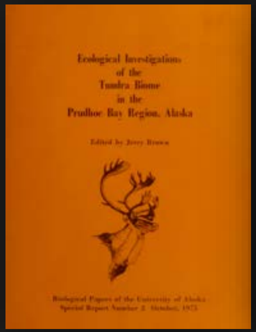


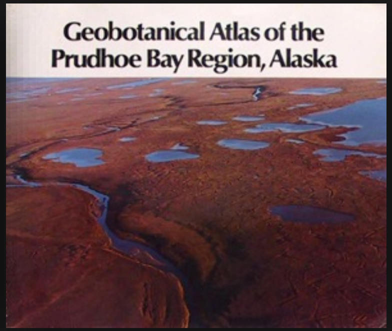
Soil dust layers

Permafrost cores

Plot-scale studies

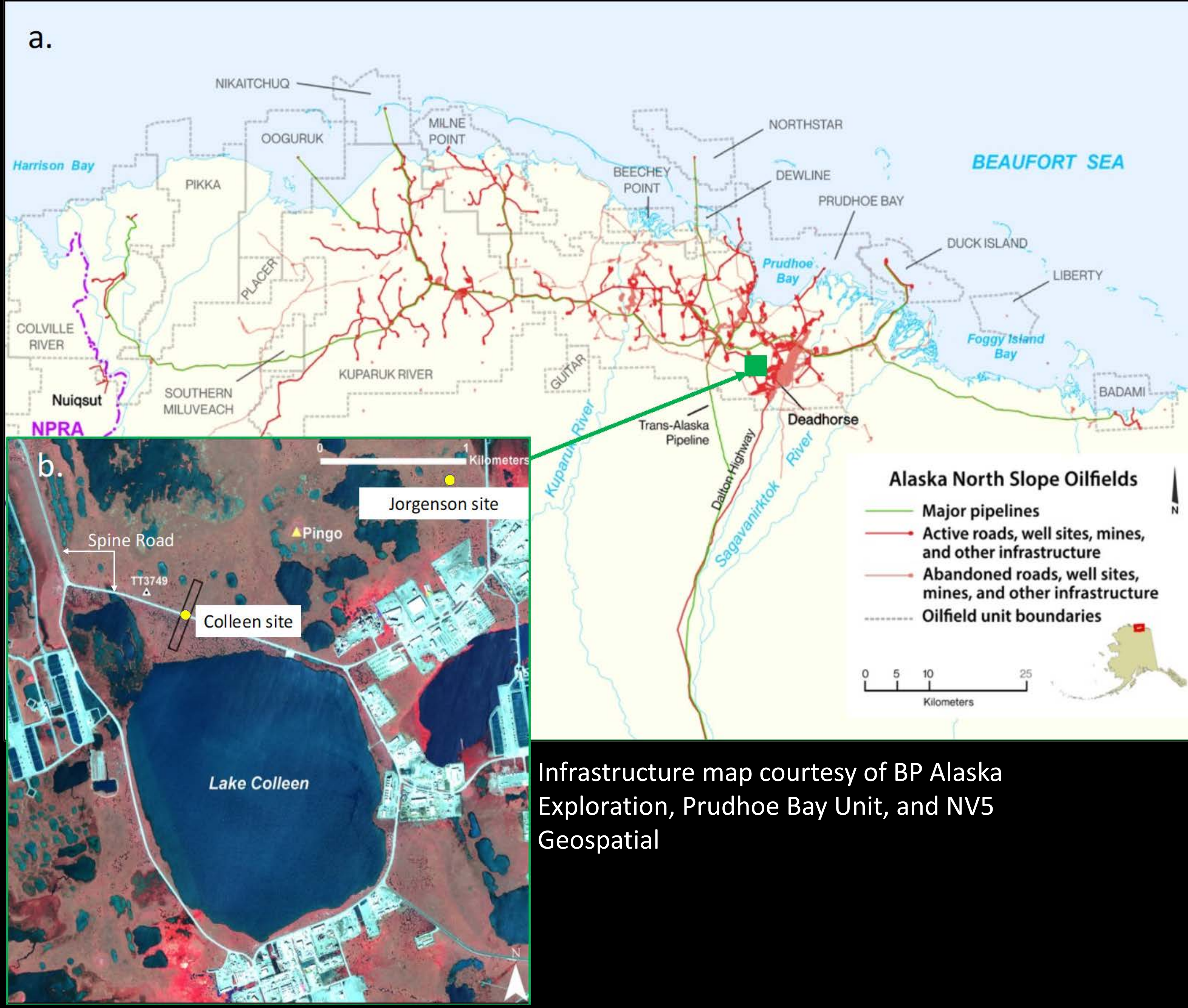
Comparison of data from 1970s and 2010s





1970s: IBP Tundra Biome studies

2010s: Plot and transect data from the Jorgenson and Colleen sites



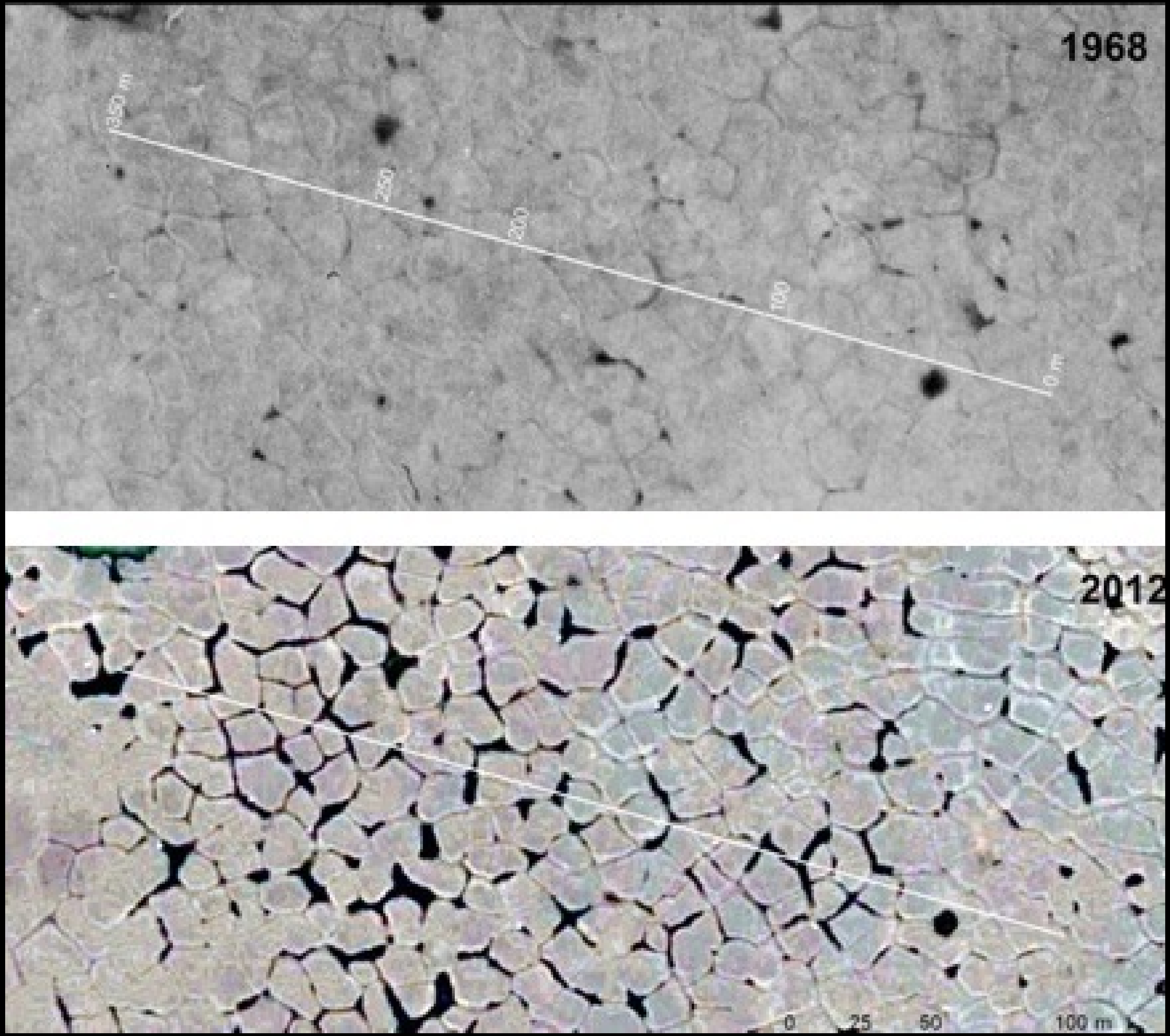
Infrastructure map courtesy of BP Alaska Exploration, Prudhoe Bay Unit, and NV5 Geospatial

World View image, July 9, 2010.

Plot scale field studies 2011-present

Jorgenson Site (JS):

- Impacted mainly by climate-related factors
- Relatively isolated from infrastructure-related change

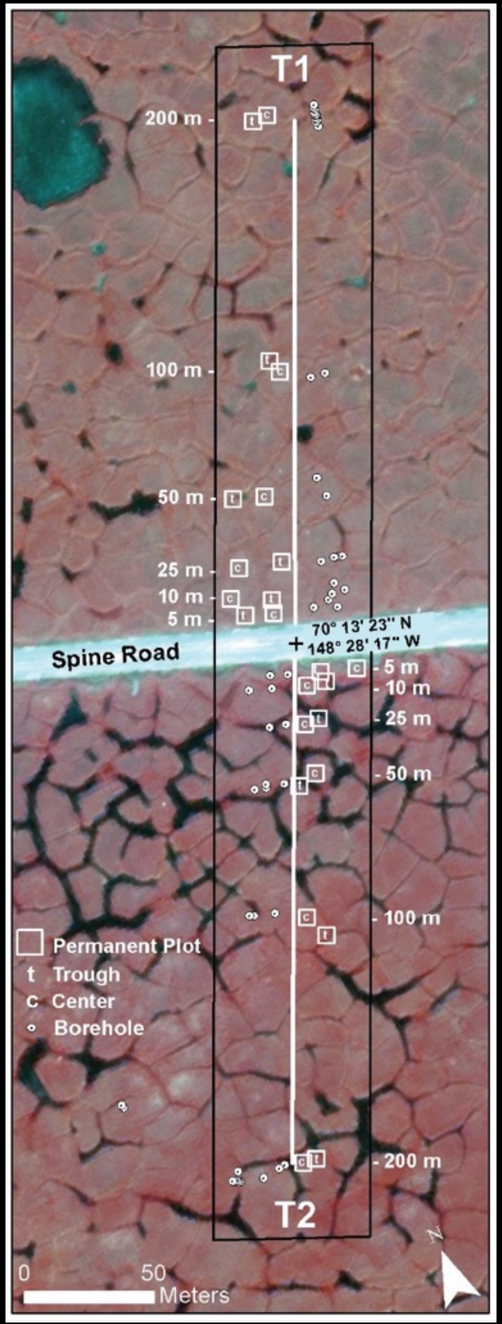


Jorgenson et al. 2015. J. Geophys. Res.-Earth, 120: 2280-2297.

Plot scale field studies 2014-present

Colleen site (CS)

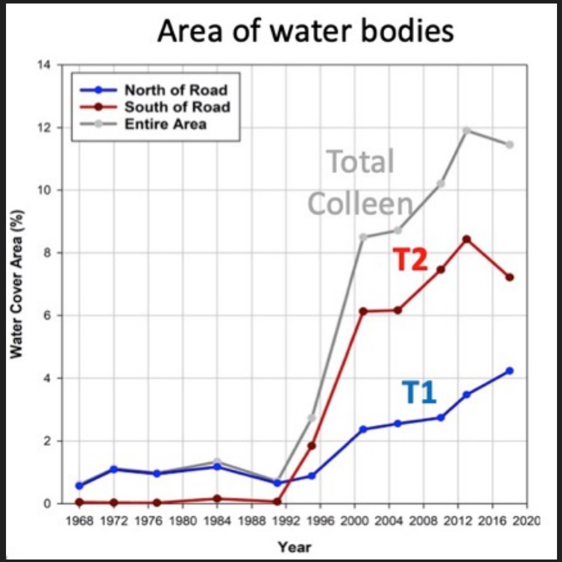
- Impacted by climate- and infrastructure-related change

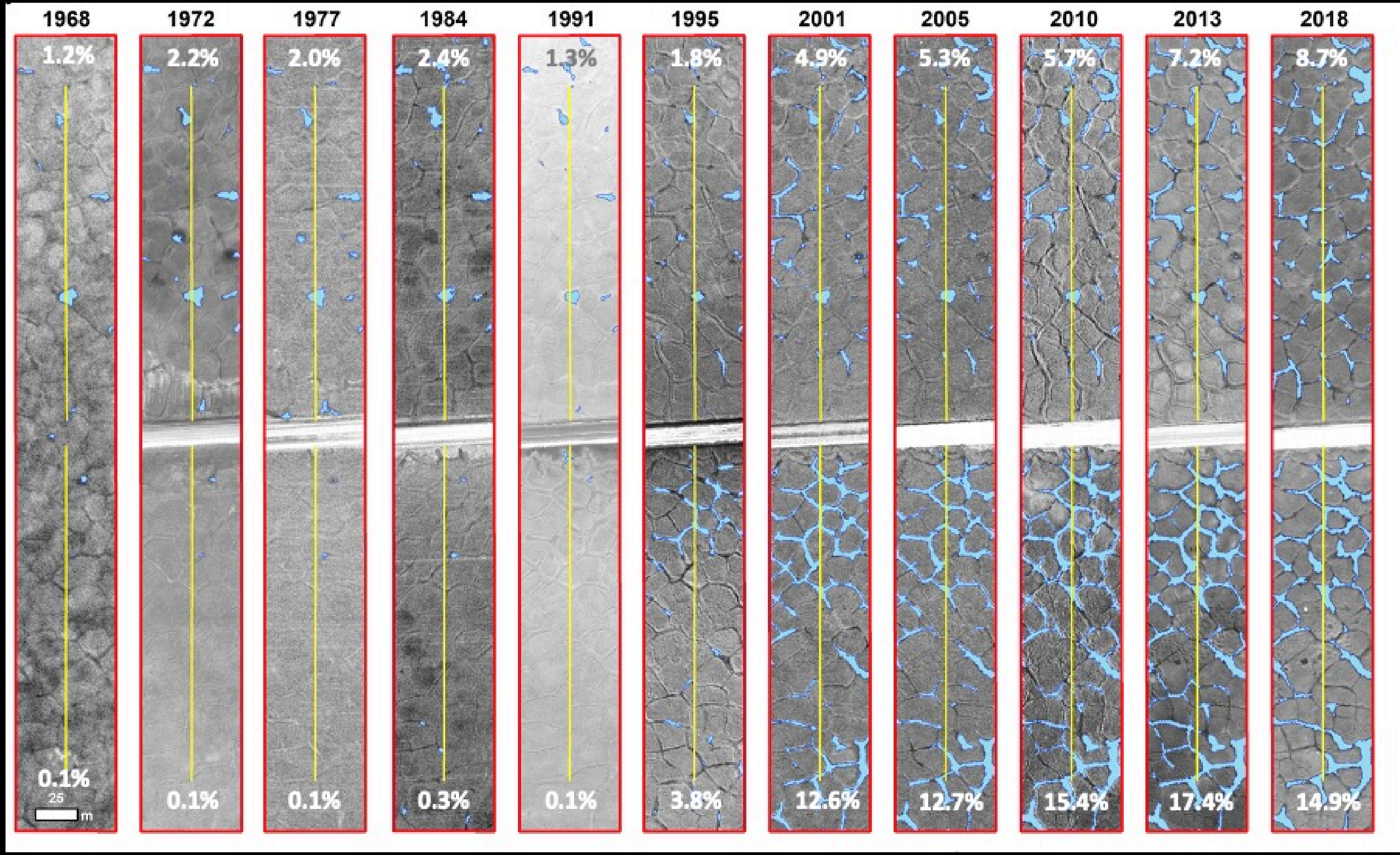


Base image: 2013 CIR digital orthophoto, Quantum Spatial, Anchorage, AK, courtesy of BP Alaska Prudhoe Bay Unit. Photos: D.A. Walker

Plot-scale cumulative impacts
1968-2018

Waterbody distribution Colleen site





Ben Jones graphics, Walker et al. *Arctic Science.* 2022.

Plot-scale trajectories of change

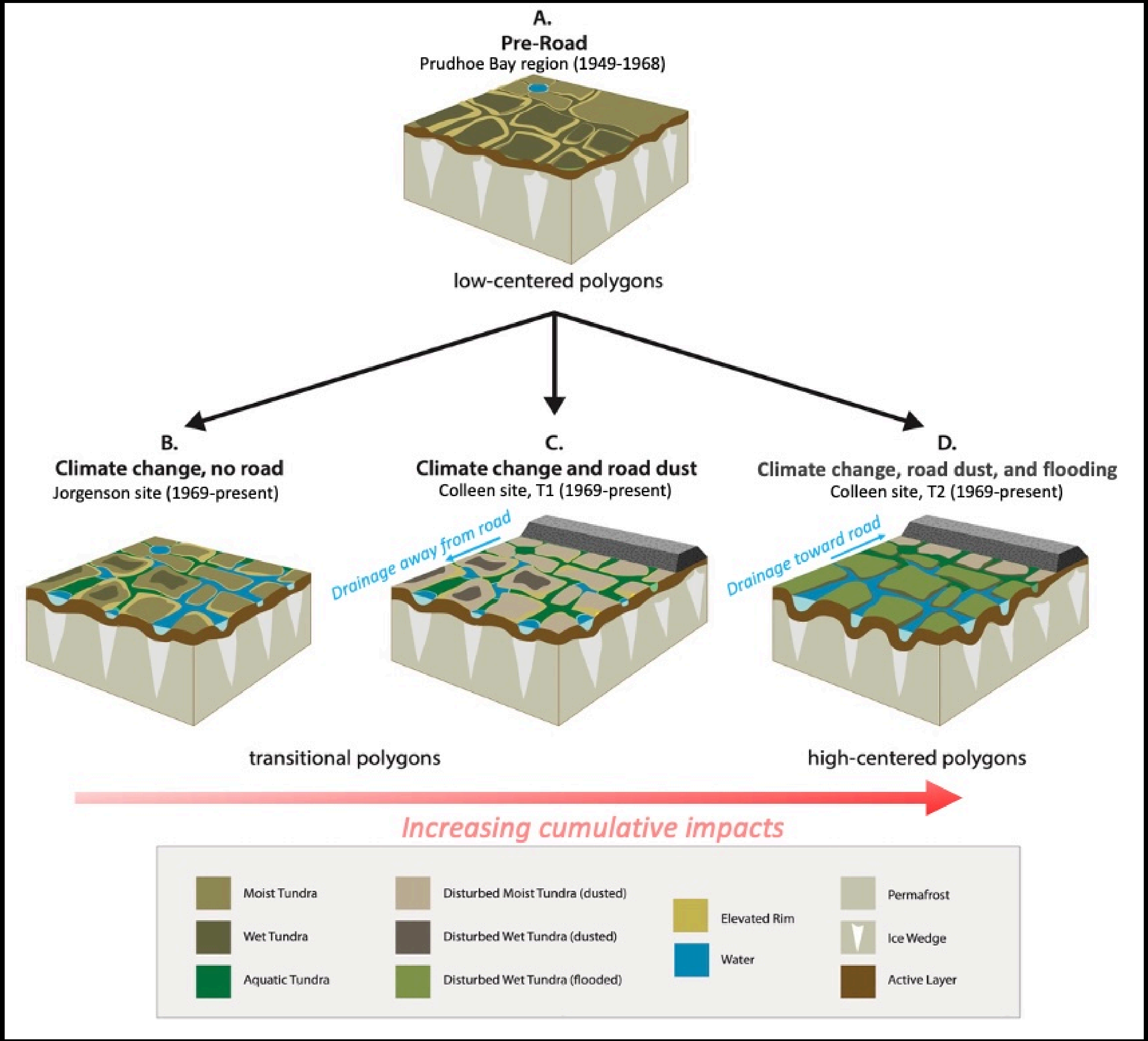
Cumulative impacts of climate- and road-related impacts at the Jorgenson and Colleen sites

Trajectory A examined conditions prior to road construction (1949–1968) using historical aerial photographs and literature sources from before and shortly after the Spine Road was constructed in 1969.

Trajectory B assessed the impacts of climate change after discovery of the oilfield (1969–present) based mainly on data from the JS, which is relatively isolated from road-related effects.

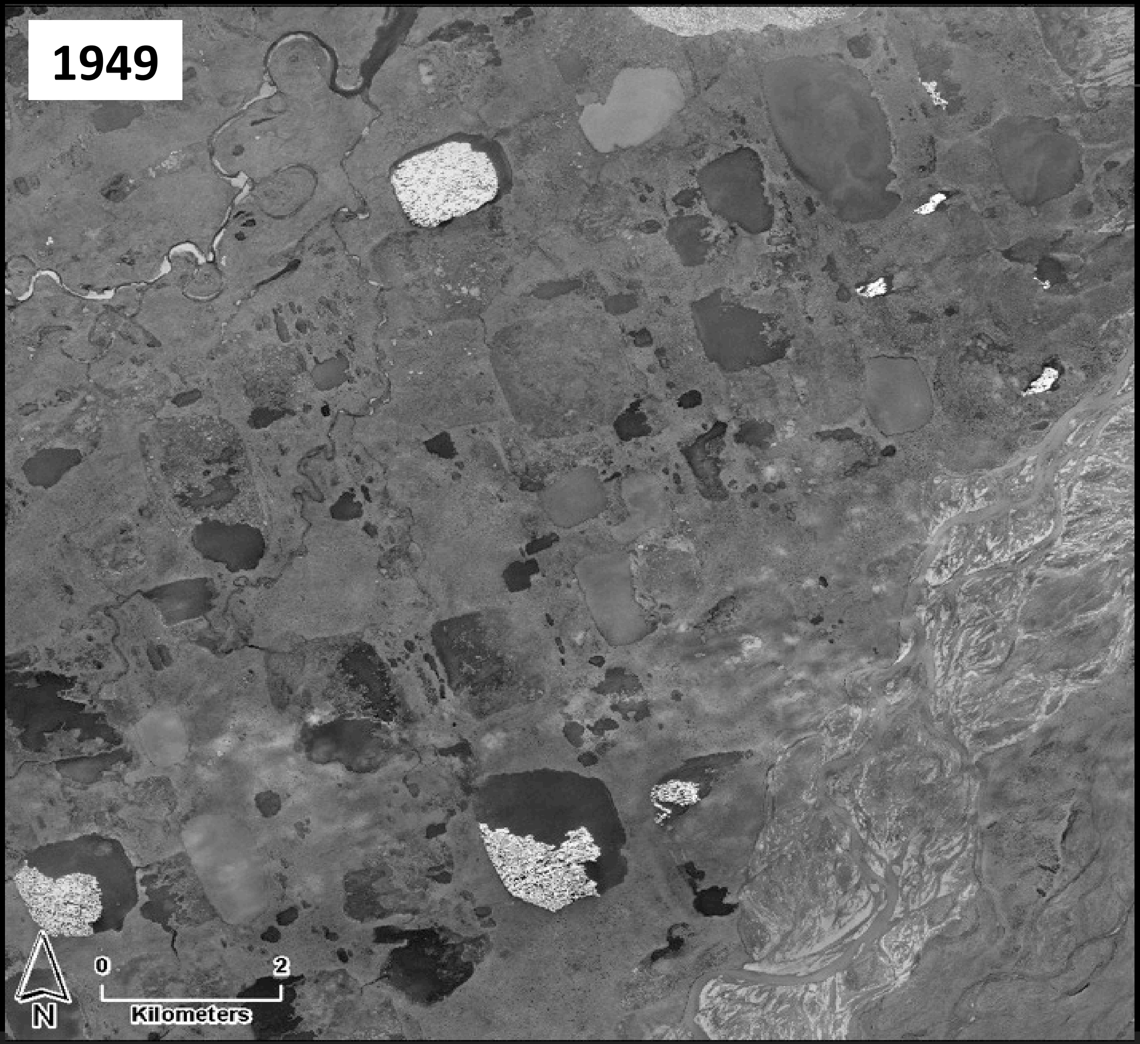
Trajectory C focused on the climate and dust impacts after road construction (1969–present) on the northeast, non-flooded side of the road along Transect T1.

Trajectory D examined the impacts of climate change, road dust, and flooding on the southwest, flooded, side of the road along Transect T2.



Walker, D. A., et al. 2022. Cumulative impacts of a gravel road and climate change in an ice-wedge polygon landscape, Prudhoe Bay, AK. *Arctic Science*. doi: 10.1139/as-2021-0014.

To date, CIAs in the PBO have relied on aerial photographs, manual photo-interpretation, and comparison to the historic baseline studies conducted by the Tundra Biome to document most changes to landscapes and infrastructure.



Deadhorse vic., U.S. Navy BAR photography, 1:20,000 scale

Courtesy of Lisa Wirth, GINA

NASA Worldview-2 image. 0.5 m resolution

Historic challenges for assessing cumulative impacts using remote sensing in northern Alaska

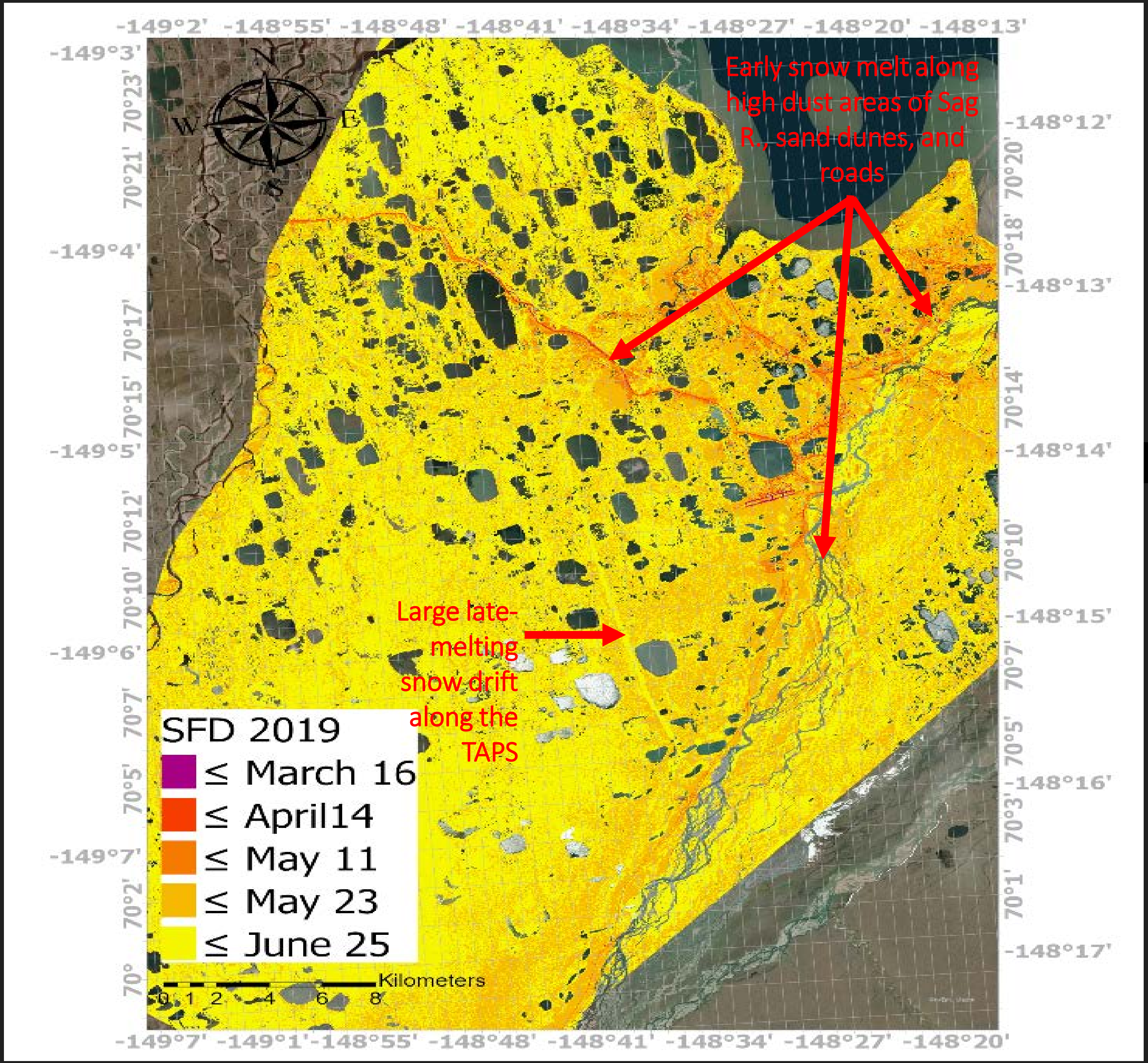
- Scarce baseline environmental information.
- Insufficient spatial resolution to detect many impacts.
- Insufficient temporal resolution.
- Analyses of Pan-Arctic changes to infrastructure were not possible.
- Lack of modeling tools to span the scale differences between most remote sensing imagery and the scale of information needed for engineers and land-use planners.

Recent CI investigations using RS

Use of Sentinel 1 and 2 imagery to map dust impacts on timing of snow-melt/ NDVI/ hydrology

Helena Bergstedt et al. 2022: Submitted to *Arctic Science.*

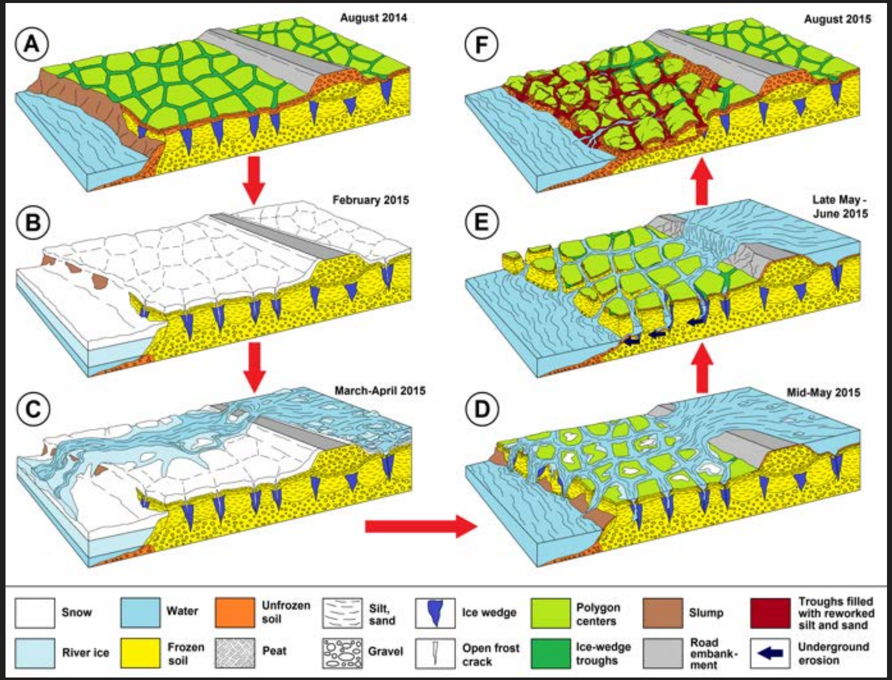
b•geos



Helena Bergstedt et al. 2022: Submitted to *Arctic Science.*

River flooding is a major issue for oilfield operations

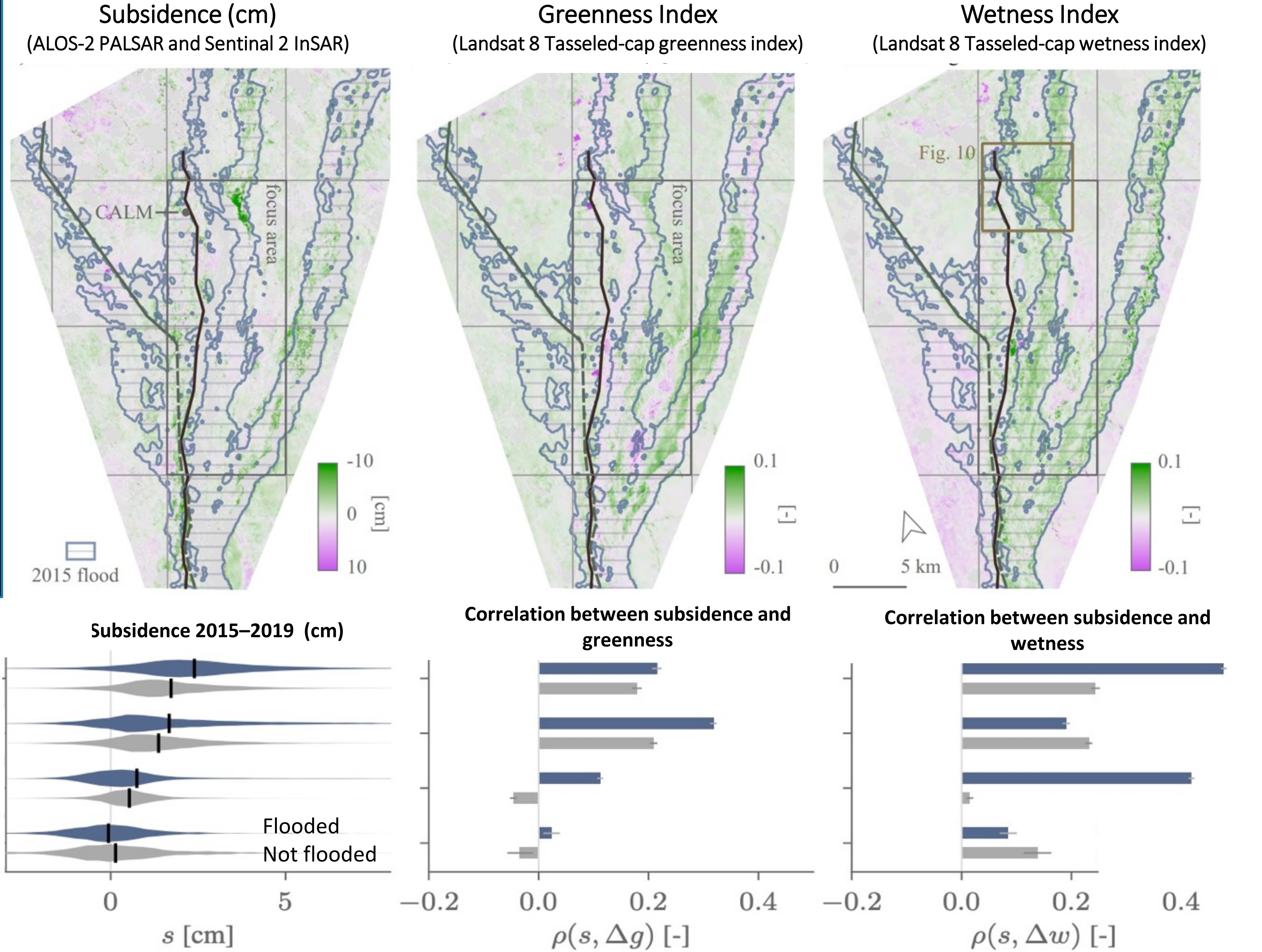
Underground thermal erosion of ice wedges



M. Kanevskiy diagram in Shur et al. 2016. 11th ICOP Proceedings

Courtesy of AKDOT & PF

Post-flood terrain changes (2015–2019) using InSAR, optical satellite imagery and sparse field observations

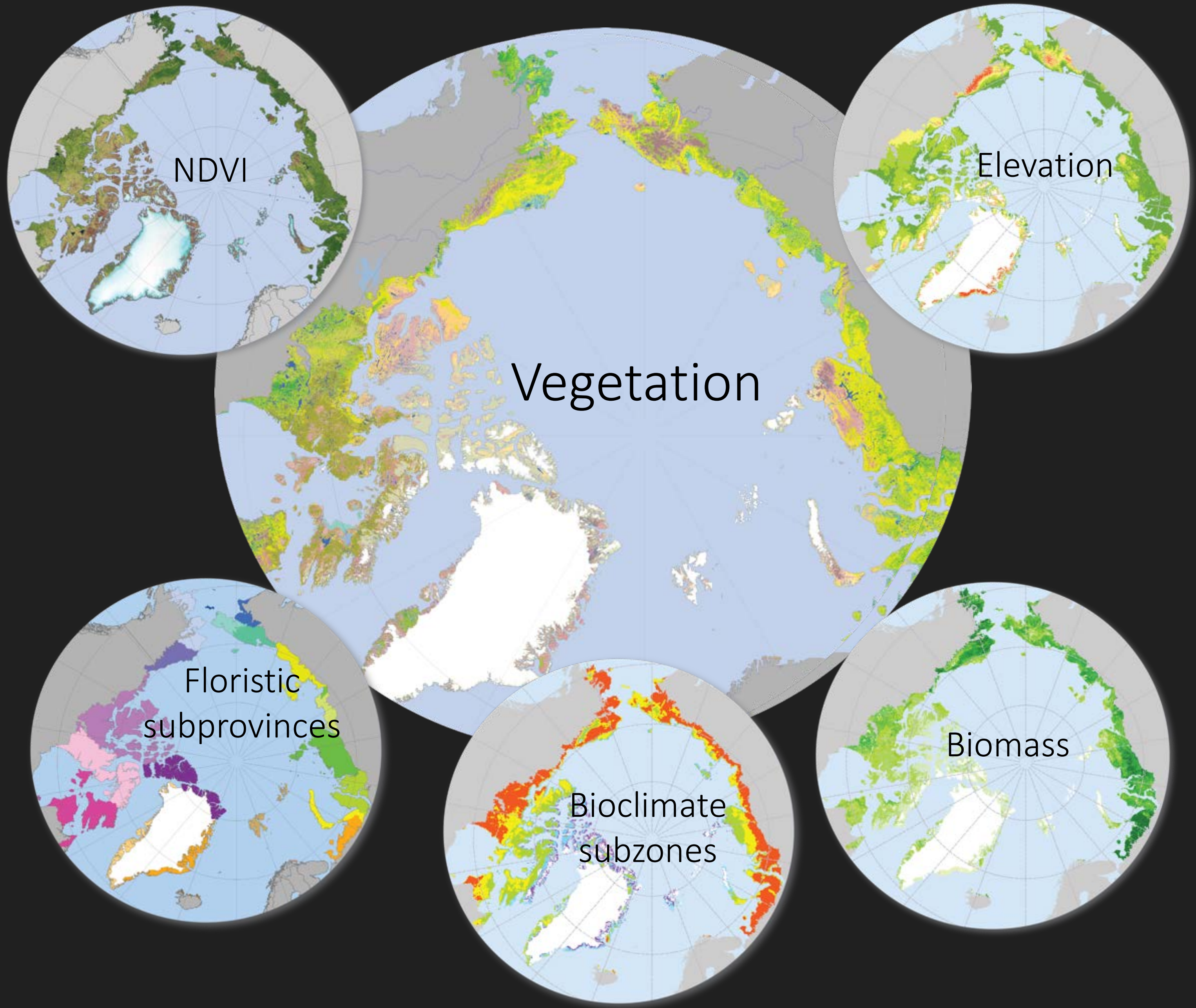


Zwieback, S. et al. 2022 in prep. Disparate permafrost terrain changes after a large flood observed from space. *International Journal of Applied Earth Observation and Geoinformation.*

Circumpolar-scale efforts

Pan Arctic Landcover mapping: The Circumpolar Arctic Vegetation Map

- Provides a consistent vegetation framework to look at panarctic vegetation change.
- Original map photo-interpreted from AVHRR imagery (CAVM 2003) based on the PBO and North Slope AK experiences. Minimum polygon area polygon area ≈ 200 km^2.
- New raster version derived from MODIS imagery (Raynolds et al. 2019) raster ≈ 1 km^2



Raynolds, M. K., et al. 2019. A raster version of the Circumpolar Arctic Vegetation Map (CAVM). *Remote Sensing of Environment* 232:111297.

Circumpolar-scale efforts

NUNATARYUK

b·geos

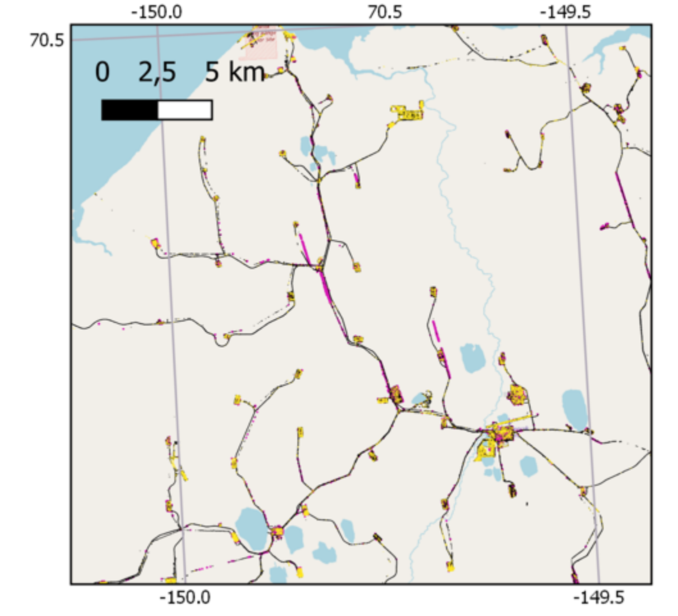
Pan-Arctic infrastructure mapping

- SACHI is a hybrid of two pattern-recognition modeling approaches using SAR (Sentinel 1) and multispectral (Sentinel 2), 10-m resolution data
- PBO data provided a high resolution dataset for validation of the SACHI data.

Sentinel 1/2 Arctic Coastal Human Impact data set (SACHI)

Areas of Sentinel-1/2 data processed for mapping infrastructure

Example, western Prudhoe Bay Oilfield



Method development:

Bartsch A. Pointner G, Ingeman-Nielsen T, Lu W. 2020. Towards Circumpolar Mapping of Arctic Settlements and Infrastructure Based on Sentinel-1 and Sentinel-2. *Remote Sensing*, 12, 2368. https://doi.org/10.3390/rs12152368.

Results:

Bartsch, A, Pointner G, Nitze I, Efimova A, Jakober D, S Ley, Högström E, Grosse G, Schweitzer P. 2021. Expanding infrastructure and growing anthropogenic impacts along Arctic coasts. *Environmental Research Letters*, 16: 115013. https://doi.org/10.1088/1748-9326/ac3176.

Circumpolar-scale efforts

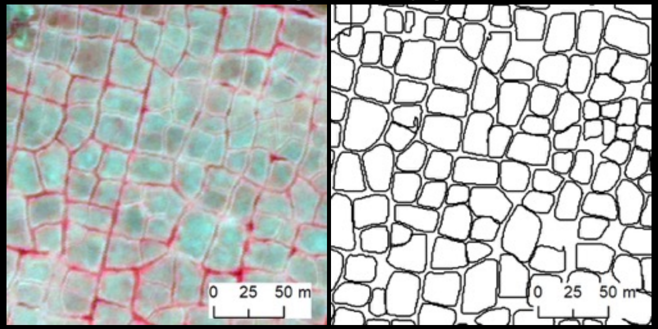
Permafrost Discovery Gateway (PDG)

Examining Arctic change through big data, artificial intelligence, and cyberinfrastructure

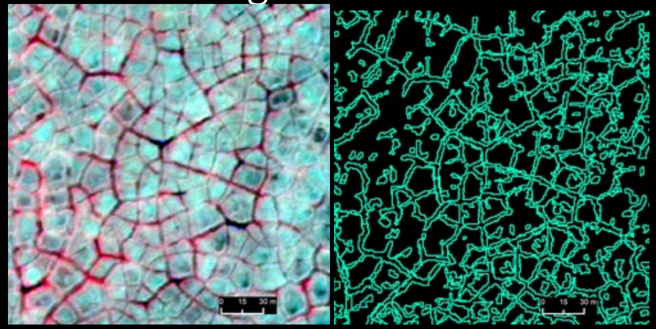
Anna Liljedahl, Chandi Witharana, Kenton McHenry, Aiman Soliman, Matt Jones, Amber Budden, Ben Jones, Jennifer Moss, Michael Brubaker, Jason Cervenec, Aaron Wilson, Guido Grosse, Ingmar Nitze, Galina Wind

Pan-Arctic sub-meter resolution products

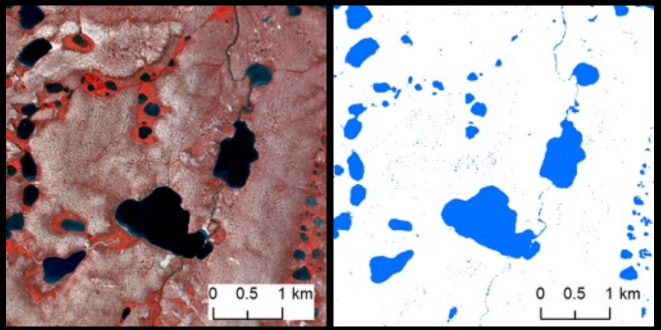
Ice-wedge Polygons



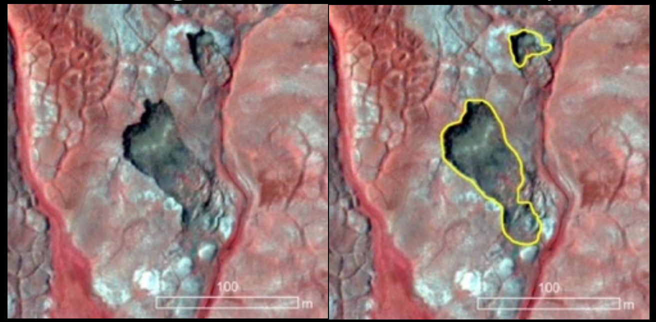
Trough Networks



Water Bodies



Retrogressive Thaw Slumps

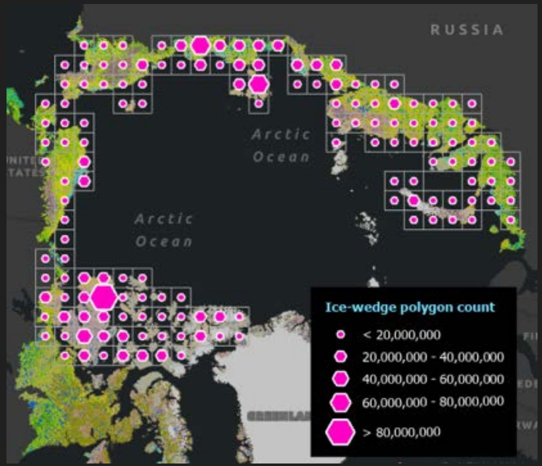


Human-built Infrastructure

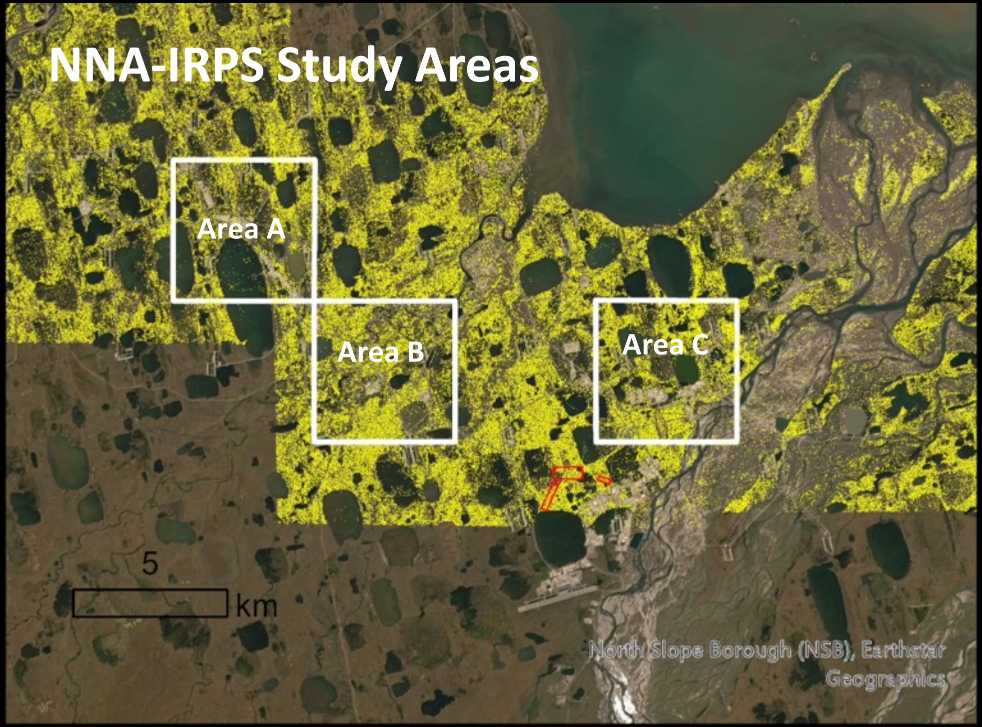
Application of PDG at the regional and landscape scales

Automated recognition of ice-wedge polygons from Maxar Imagery in the PBO

So far, > 1 billion individual ice-wedge polygons have been mapped in the pan-Arctic

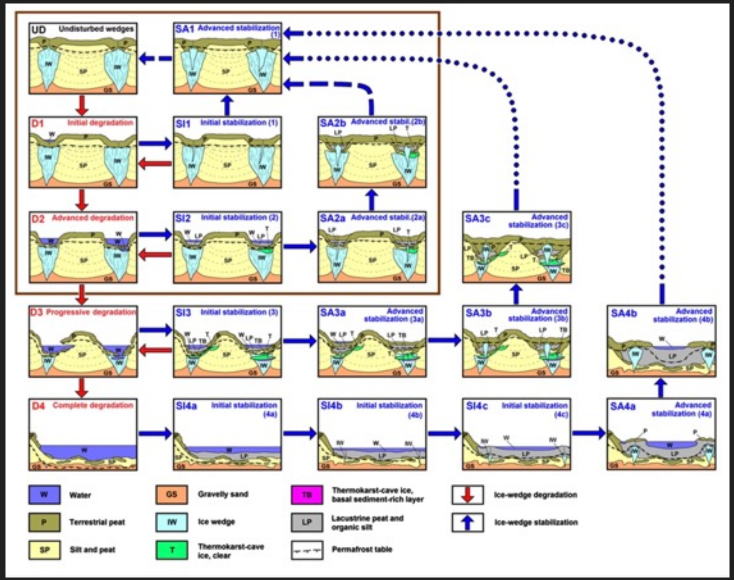


Maps of Prudhoe Bay ice-wedge polygons

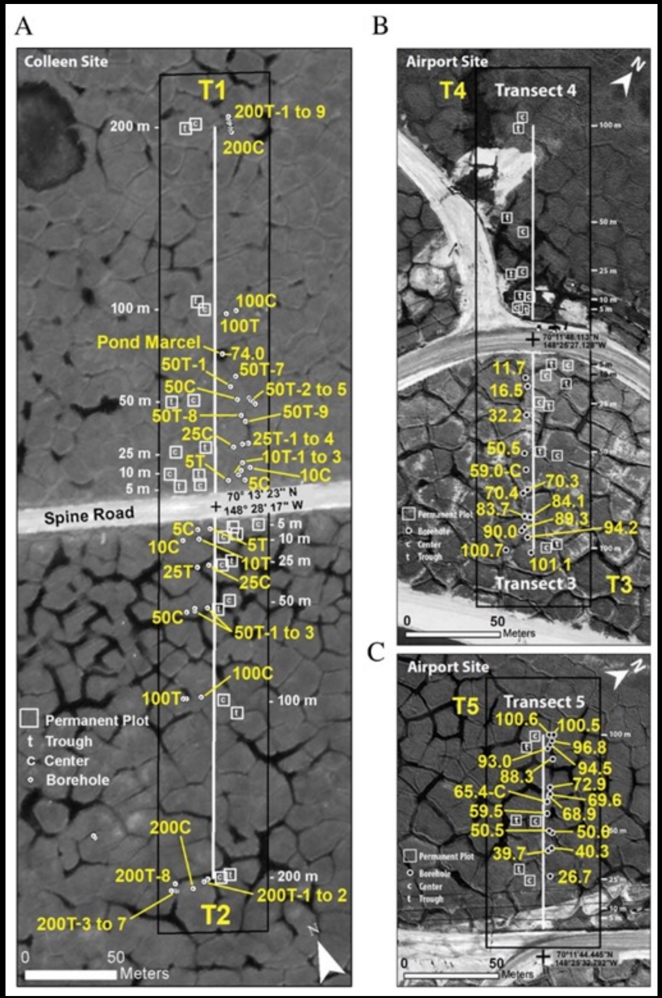


Modeling permafrost degradation risk

Permafrost-degradation risk assessment



Kanevskiy boreholes at Colleen and Airport sites

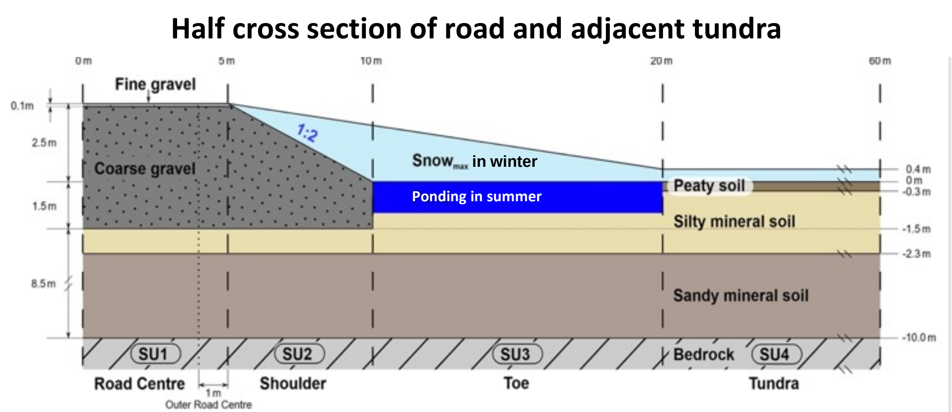


Vulnerability of ice-wedges to degradation

Vulnerability level	Thickness of protective layers, cm PL1*	PL2**	PL3*	Notes
1. Active degradation	0	0	0	No protective layers; the top part of the ice wedge is currently*degrading; degradation of the ice wedge of up to 5 cm is expected by the end of warm season
2. Very high	1-5	0	0	Degradation of the top part of the ice wedge is expected by the end of warm season
	=PL3	0	1-5	Thin intermediate layer is currently*degrading; degradation of the top part of the ice wedge is expected by the end of warm season
3. High	5-10	1-5	0	No intermediate layer, thin degrading transient layer; minor degradation of some parts of this ice wedge is possible by the end of warm season
	5-10	1-5	1-5	Partial degradation of the intermediate layer is expected by the end of warm season; minor degradation of some parts of this ice wedge is possible by the end of warm season
	=PL3	1-5	5-10	Intermediate layer is currently*degrading; minor degradation of some parts of this ice wedge is possible by the end of warm season
4. Moderate	10-20	5-15	1-5	No significant degradation of the intermediate layer and no ice-wedge degradation are expected during the current year
	10-20	5-15	5-10	Partial degradation of the intermediate layer is possible by the end of warm season; no ice-wedge degradation is expected during the current year
	=PL3	5-15	10-20	Relatively thick intermediate layer is currently* degrading; no ice-wedge degradation is expected during the current year
5. Low	20-30	15-25	5-10	No degradation of the intermediate layer is expected during the current year
	20-30	15-25	10-20	No significant degradation of the relatively thick intermediate layer is expected during the current year
	=PL3	>15	>20	Thick intermediate layer is currently* degrading
6. Very low	>30, >PL3	>25, >PL3	>20	The ice wedge is well protected by thick and stable intermediate layer; ice-wedge degradation is possible only due to a strong impact on the surface (flooding, vegetation removal) or after accumulation of wedge ice within the intermediate layer

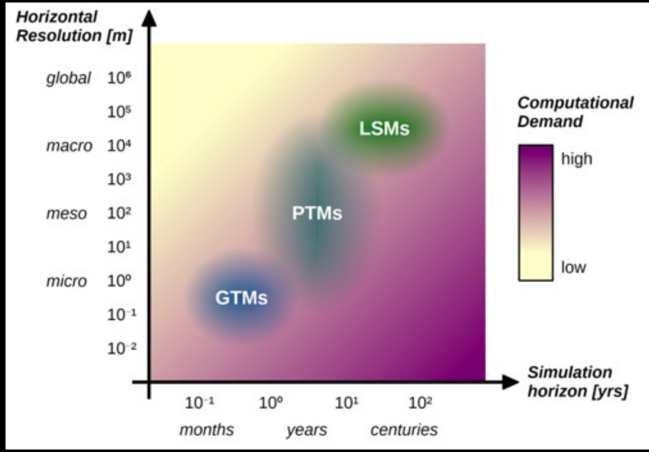
Kanevskiy, M. K. et al. 2022. The shifting mosaic of ice-wedge degradation and stabilization in response to infrastructure and climate change, Prudhoe Bay Oilfield, Alaska, USA. *Arctic Science*. doi.org/10.1139/as-2021-0024

Modeling permafrost degradation



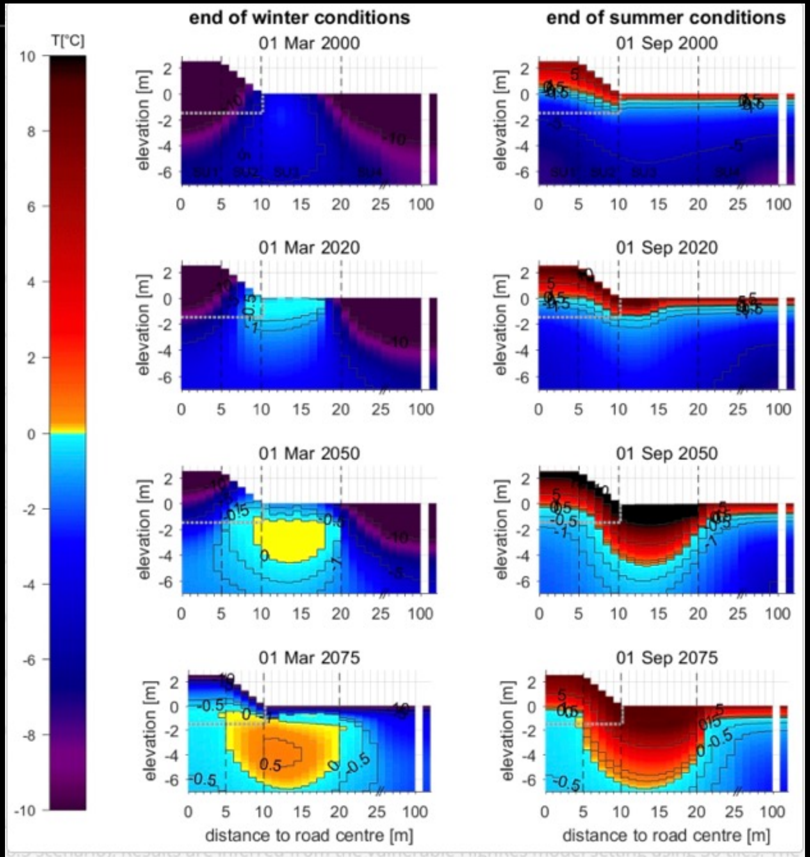
Process-based Tiling Models (PTMs) bridge the scale between available climate and land-cover maps and the scale of information needed for engineers and land-use managers.

Spatial and temporal scales for models



GTMs: Geotechnical Models
LSMs: Land Surface Models (hor. Resolution ~100km) and long timescales (climate relevant)
PTMs (Process-based Tiling Models) scalable to a specific modelling problem computational efficiency allows long-term simulations to investigate climate-change impacts.

PTM of road and adjacent permafrost



Schneider von Deimling, et al. 2021. Consequences of permafrost degradation for Arctic infrastructure – bridging the model gap between regional and engineering scales. *The Cryosphere* 15:2451–2471.

Are we entering a new era for remote sensing to help predict cumulative impacts of climate change and infrastructure in the Arctic?

CONCLUSIONS

- Recent advances using remote sensing products and models have greatly expanded the capability to monitor and predict change in IRP landscapes from fine-scale changes within patterned-ground features to circumpolar changes.

- However, the full consequences of major ongoing changes in thermokarst and hydrology to other components of the system (e.g. aquatic plant communities, invertebrates, birds, other fauna, and local people) still need to be documented.

- Studies in other climate regimes, geologic and topographic setting, and different types of construction methods are needed to broaden the knowledge base and improve models that are useful to engineers and land-use managers.

- Predictions of the full likely cumulative impacts of future development and climate change in areas with IRP remains a grand interdisciplinary research challenge. A follow-up to RATIC is needed at the next ICARP (ICARP IV, 2025, Boulder, CO).