Navigating the New Arctic: Toward a new era of infrastructure and climate change cumulative impact assessment

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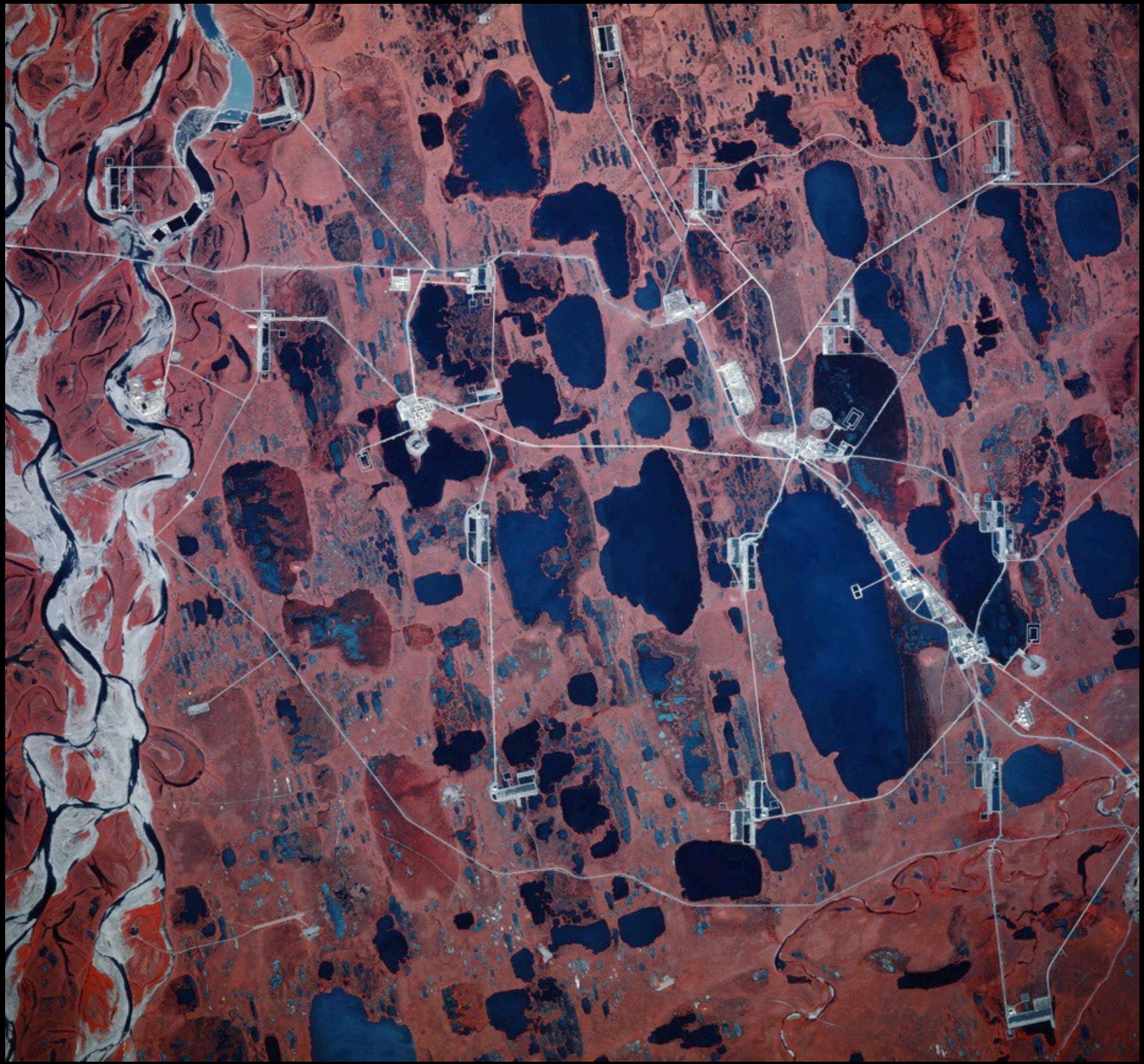
ARCTIC SCIENCE SUMMIT WEEK 2023, VIENNA; SESSION ID 40, 22 FEB.



The western half for the Prudhoe Bay Oil Field.
NASA 1982 false-CIR aerial photo, 1:60,000 scale.

Introduction

"Are we entering a new era for predicting cumulative impacts of climate change and infrastructure in the Arctic?"

- This talk is about the IASC Rapid Arctic Transitions due to Infrastructure and Climate change (RATIC) initiative.
- One of RATIC's goals is 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.
- Much of the talk is focused at the Prudhoe Bay Oilfield, AK.

Definitions

Cumulative impacts

"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." (CEQ 1987).

- **First 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

Definitions

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

Definitions

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)

Definitions

Ice-rich permafrost

- 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

Baseline Studies

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

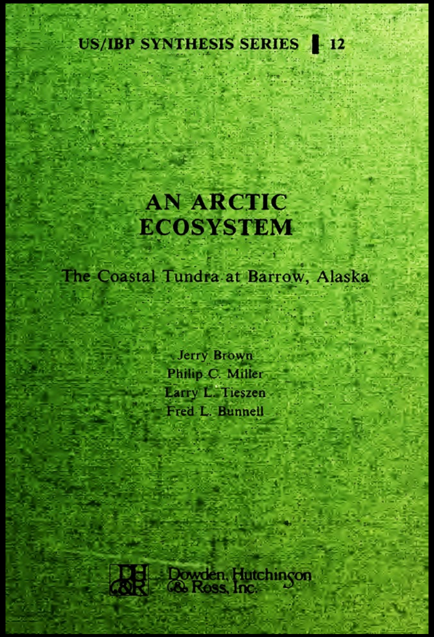
Prudhoe Bay Oilfield. Photos: Courtesy of Pam Miller

RATIC background

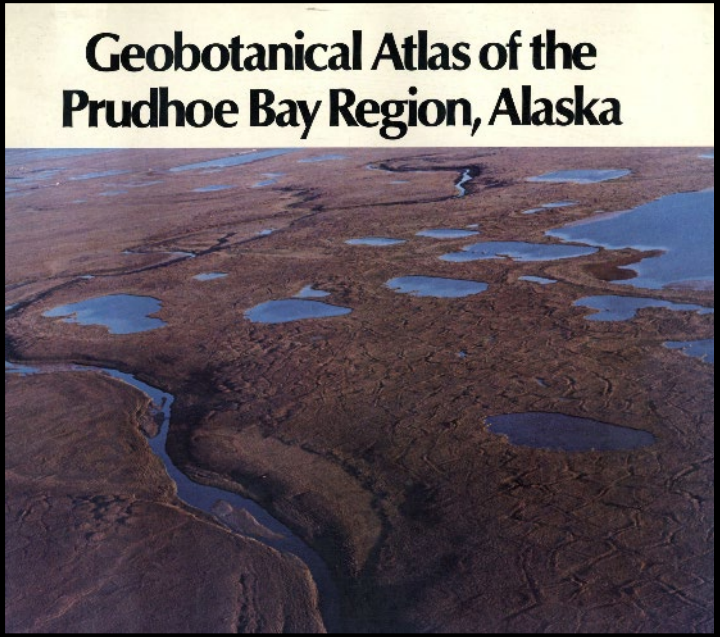
IBP Tundra Biome and U.S. Army CRREL investigations at Barrow, Prudhoe Bay, and the Dalton Highway

1970s-1980s

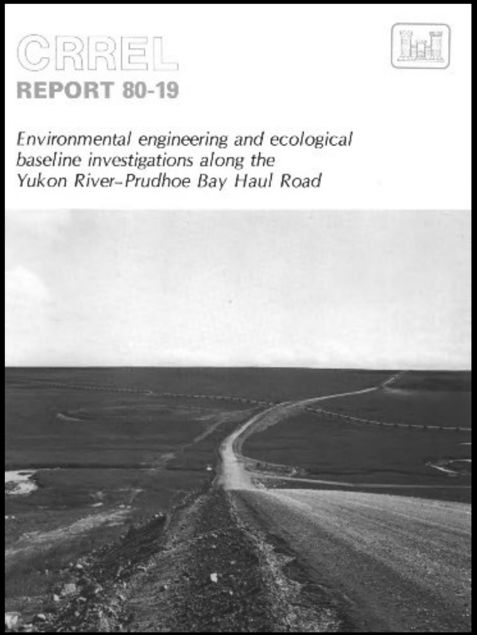
Baseline environmental studies



Brown et al. 1980 An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska.



Walker, D. A., K. R. Everett, P. J. Webber, and J. Brown. 1980. Geobotanical Atlas of the Prudhoe Bay Region, AK, CRREL Report 80-14.



Brown, J., and R. Berg. 1980. Environmental engineering and ecological baseline investigations along the Yukon River-Prudhoe Bay Haul Road. CRREL Report 8-19.

Key studies for examining change.

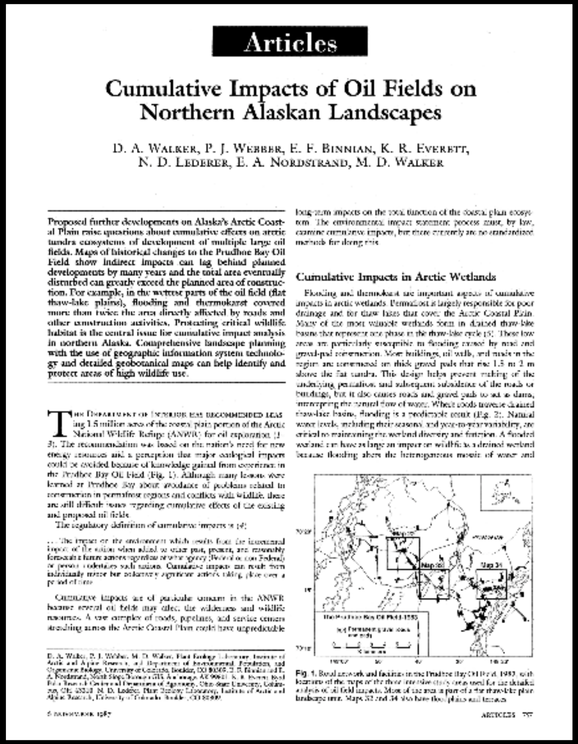
RAPID ARCTIC TRANSITIONS DUE TO INFRASTRUCTURE & CLIMATE
RATIC

RATIC background

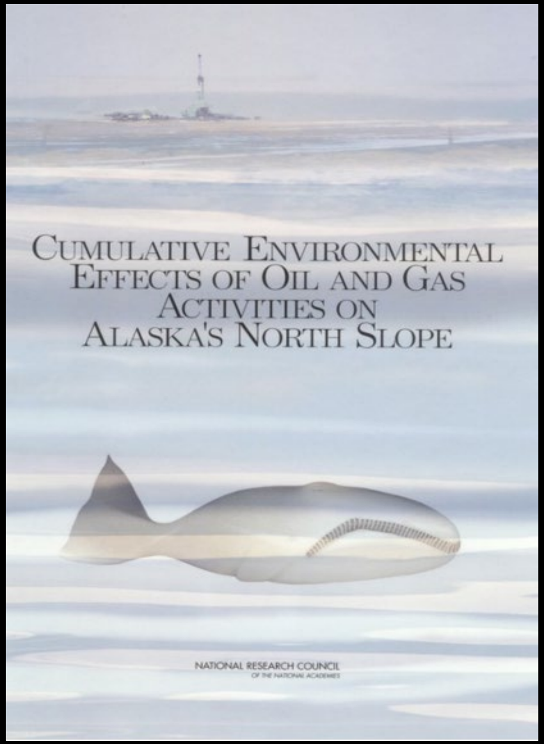
Cumulative impacts in the Prudhoe Bay region 1980s, 2000s, 2010s

1970s-2000s

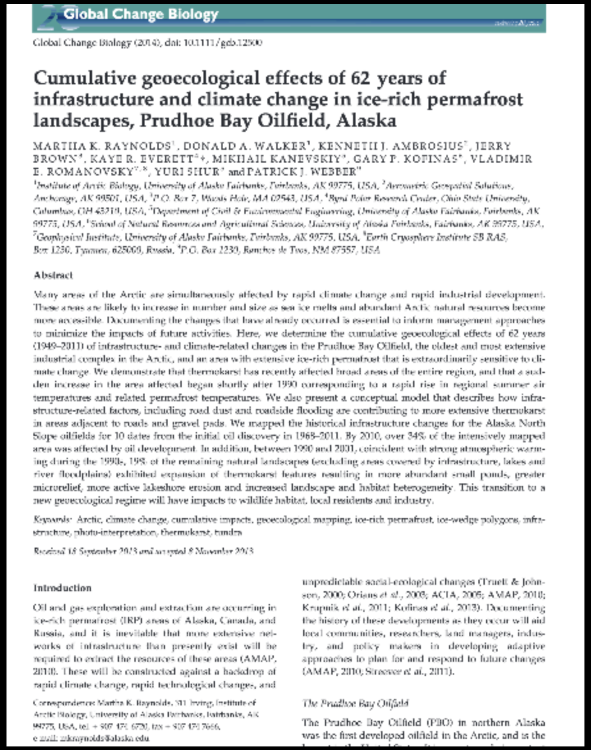
Cumulative-impact studies



Walker et al. 1987. *Science*.



National Research Council, 2003.



Raynolds, MK, et al. 2014. *Global Change Biology.*

Cumulative impacts as defined by the Council on Environmental Quality:

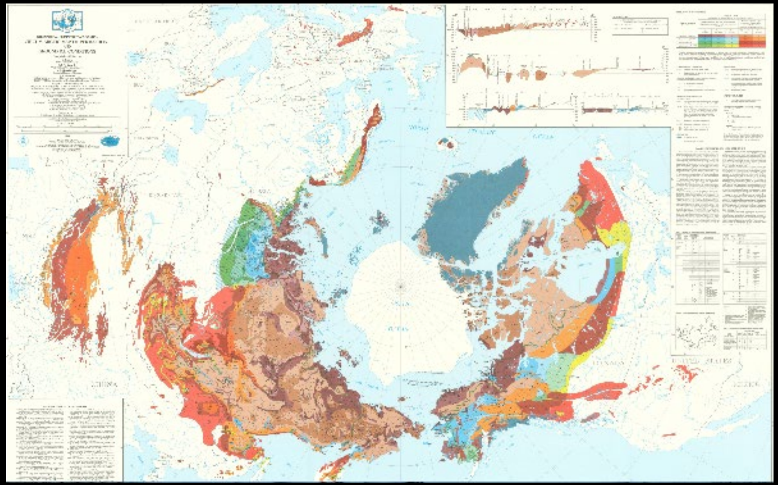
"The impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time." (40 CFR ~ 1508.7, 1979).

RATIC background

1990s-2010s

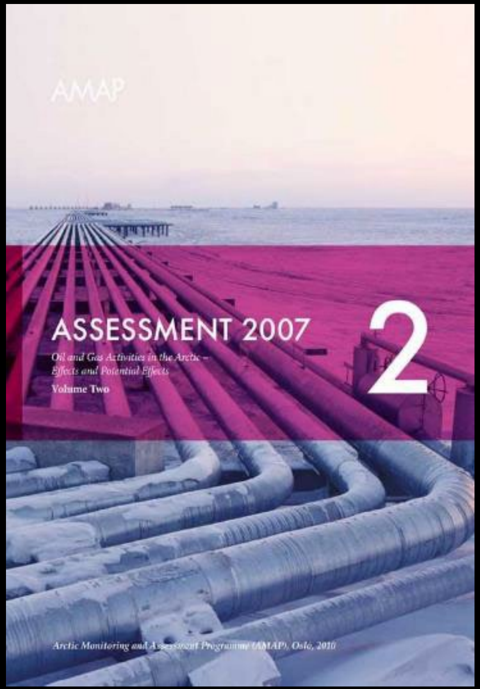
Pan-Arctic landcover and infrastructure assessments

Pan-Arctic permafrost



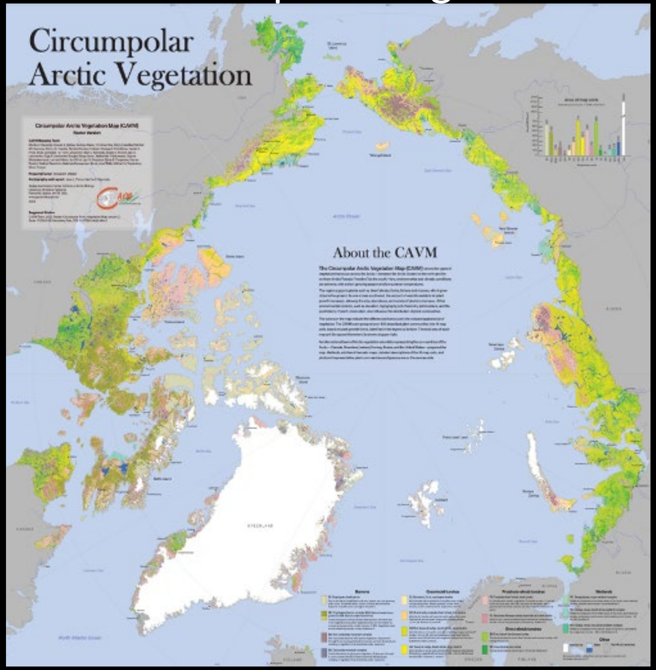
Brown et al. 1997.

Pan-Arctic assessment of oil and gas



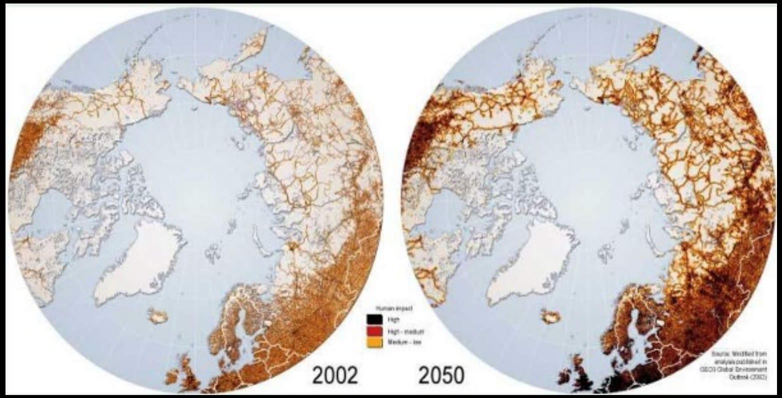
AMAP. 2010. Assessment 2007: Oil and Gas Activities in the Arctic — Effects and Potential Effects. Vol 1 and 2.

Circumpolar vegetation



CAVM Team 2003 and 2023.

Pan-Arctic transportation corridors



Nellemann et al. GLOBIO 2001. global methodology for mapping human impacts on the biosphere: The Arctic 2050 scenario and global application. UNEP.

RATIC background

Sustainability research Russia and U.S. Arctic oilfields

1990s-2010s

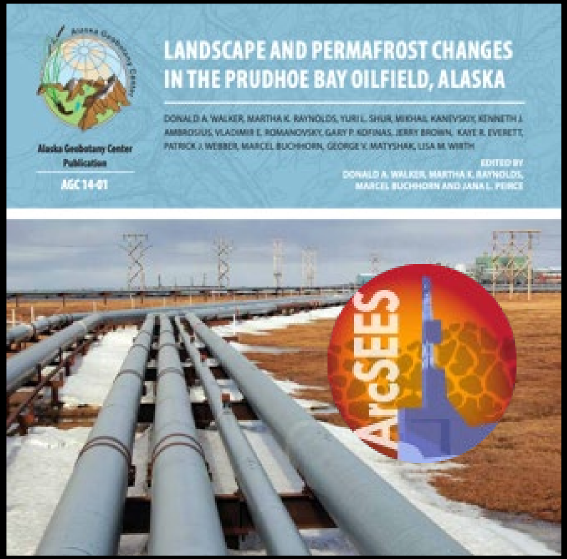
International sustainability research

Finnish Academy/ Arctic Center project: "Environmental and Social Impacts of Industrialization in Northern Russia (ENSINOR, 2004–2007)"


High resilience in the Yamal-Nenets social–ecological system, West Siberian Arctic, Russia

NASA Land-Cover Land-Use Change program (LCLUC) and Northern Eurasia Earth Science Partnership Initiative (NEESPI) two projects: Eurasia Arctic Transect (2007-2013) and SYN-YAMAL (2014–17)

NSF program, Arctic Science Engineering and Education for Sustainability (ArcSEES), UAF project: "Cumulative Effects of Arctic Oil Development: planning and designing for sustainability (2012-2021)"

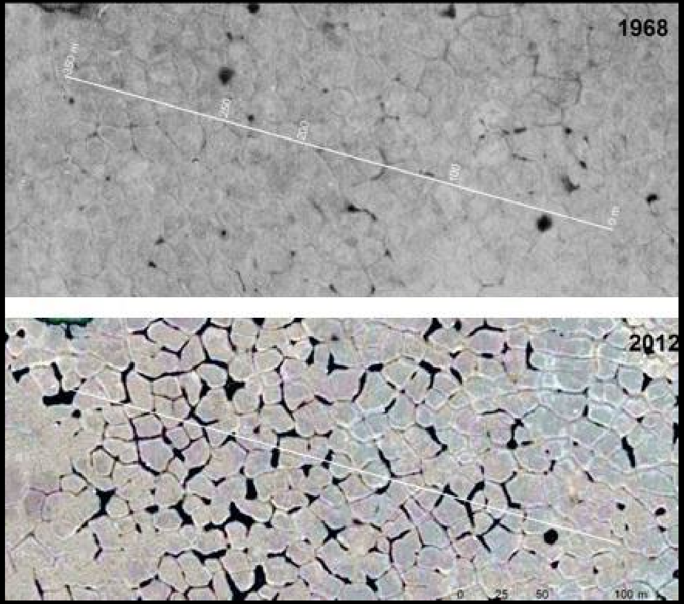


RATIC background

1980s-2020s

Hierarchy of studies of ice-wedge degradation

Abrupt ice-wedge degradation in natural systems due to climate change

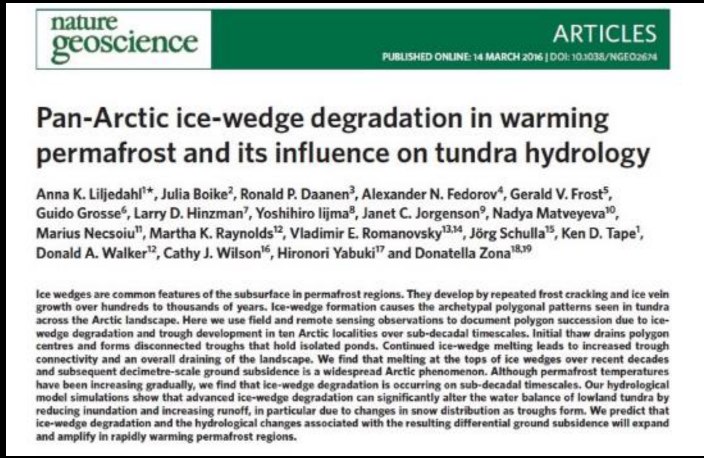


Jorgenson et al. 2006. Abrupt increase in permafrost degradation in Arctic Alaska. *Geophysical Research Letters* 25:L02503.

Ice-wedge degradation due to infrastructure and climate change

Kanevskiy 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.*

Pan-Arctic ice-wedge degradation



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

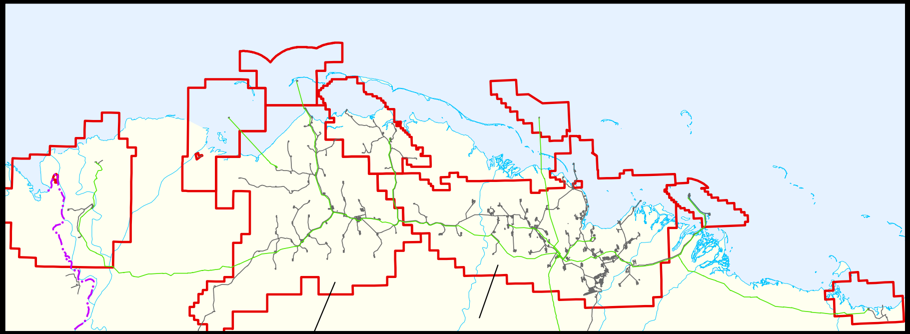
Anna K. Liljedahl[1*], Julia Boike[2], Ronald P. Daanen[3], Alexander N. Fedorov[4], Gerald V. Frost[5], Guido Grosse[6], Larry D. Hinzman[7], Yoshihiro Iijma[8], Janet C. Jorgenson[9], Nadya Matveyeva[10], Marius Necsoiu[11], Martha K. Raynolds[12], Vladimir E. Romanovsky[13,14], Jörg Schulla[15], Ken 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. *Nature Geoscience*

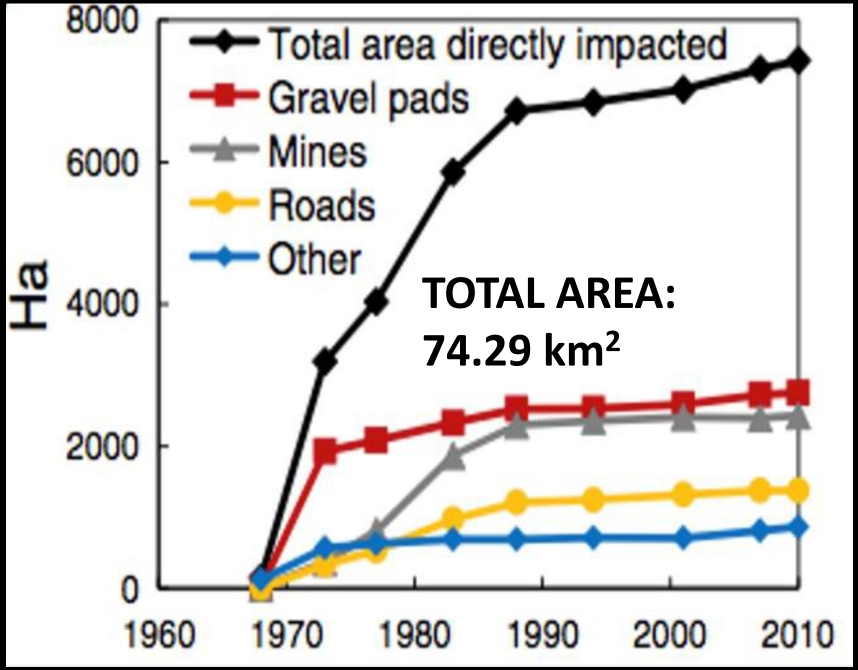
Cumulative impacts in the Prudhoe Bay Region

Oil-industry air photos, topographic 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, 1968–2010



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

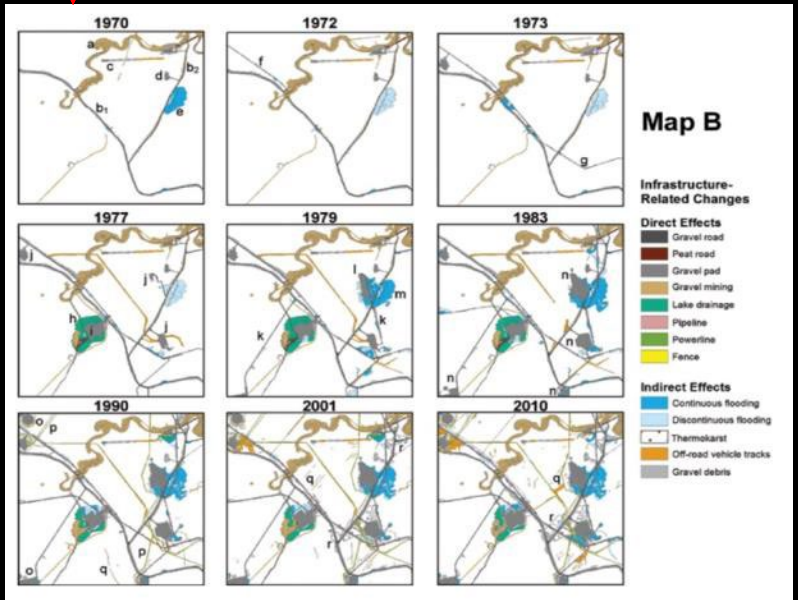
Raynolds et al. 2014, *Global Change Biology*

Landscape-level impacts

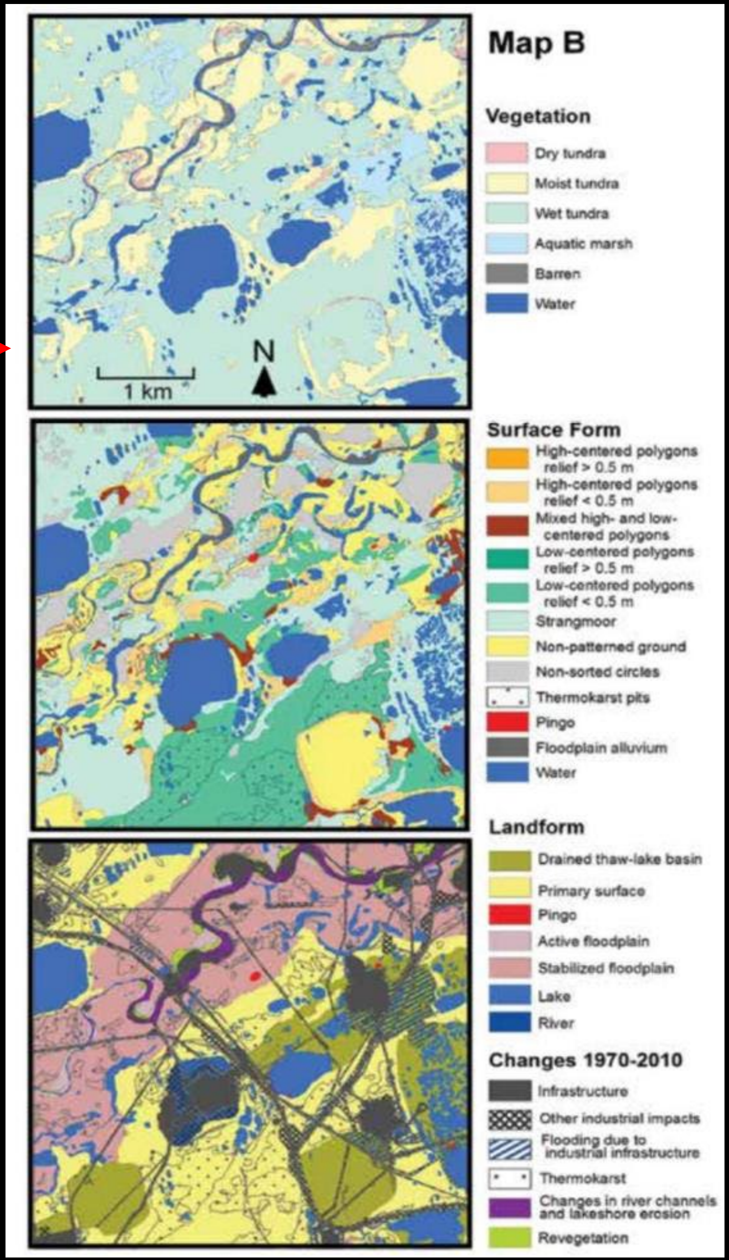
Cumulative impacts in the Prudhoe Bay Region

Master Map

Historical-change Maps



Geo-ecological Maps



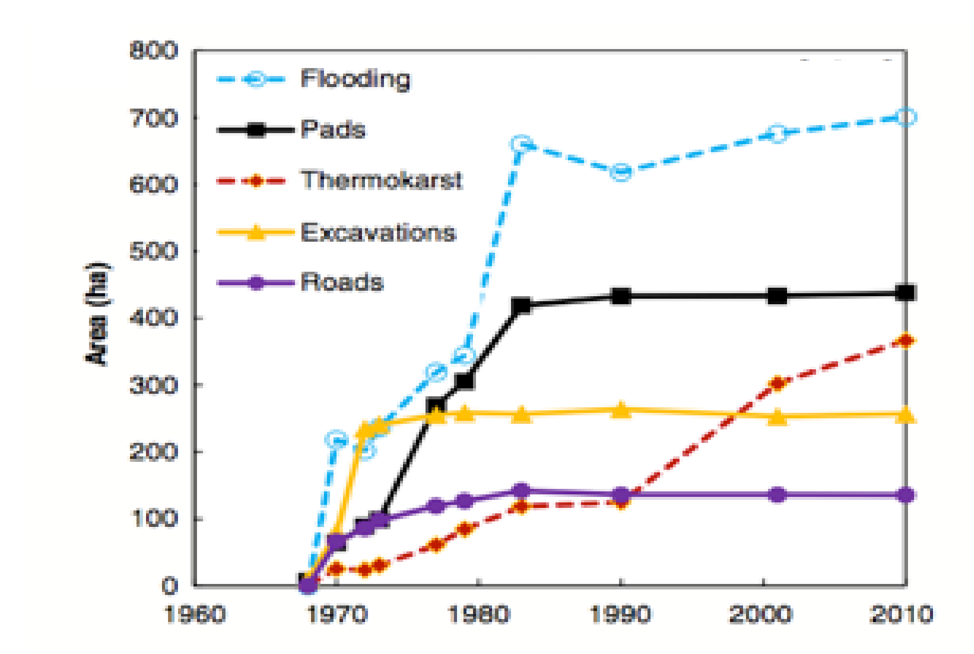
Landscape-scale integrated geo-ecological and historical change mapping (IGHCM) (1980s-2010s) also relied on oil-industry maps of infrastructure and topography and time series aerial photo industry aerial photos of the oilfield.

Raynolds et al. 2014, Global Change Biology

Cumulative impacts in the Prudhoe Bay Region

These analyses showed that by 2010, within 3 mapped 25-km^2 areas, the indirect impacts were nearly double the area of the direct impacts.

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



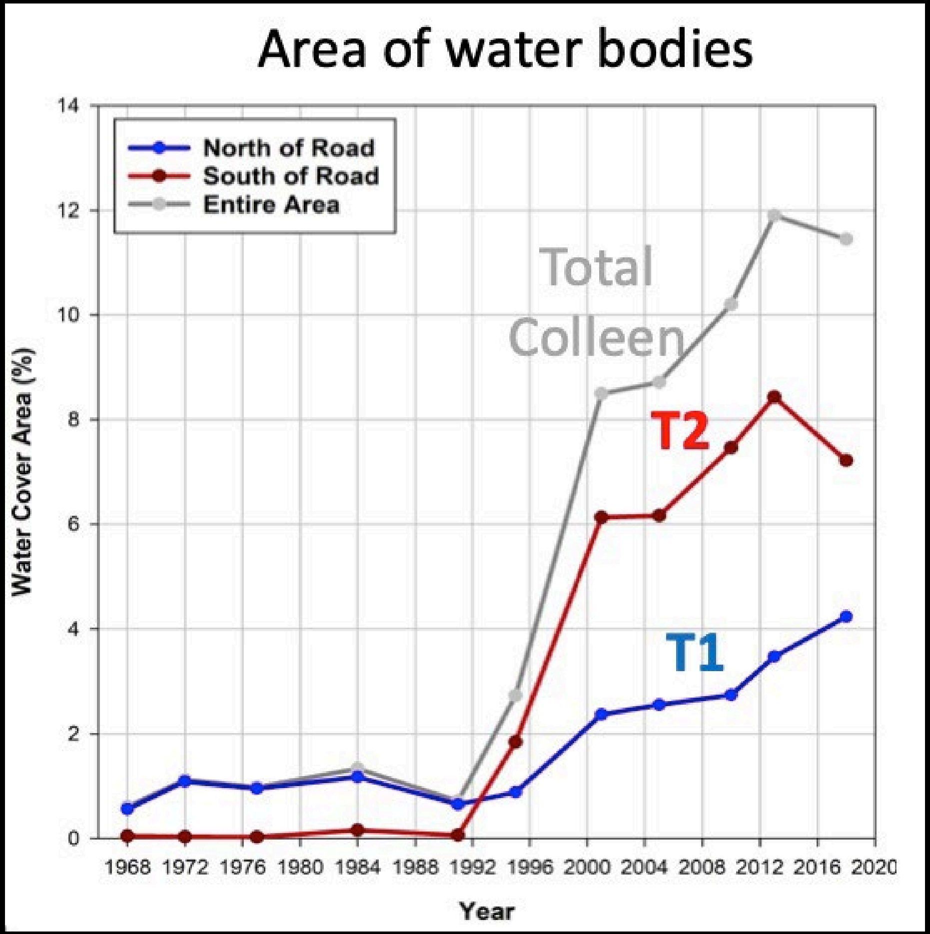
Direct impacts (solid lines): 919 ha (15% of mapped area) Leveled off after 1980.

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

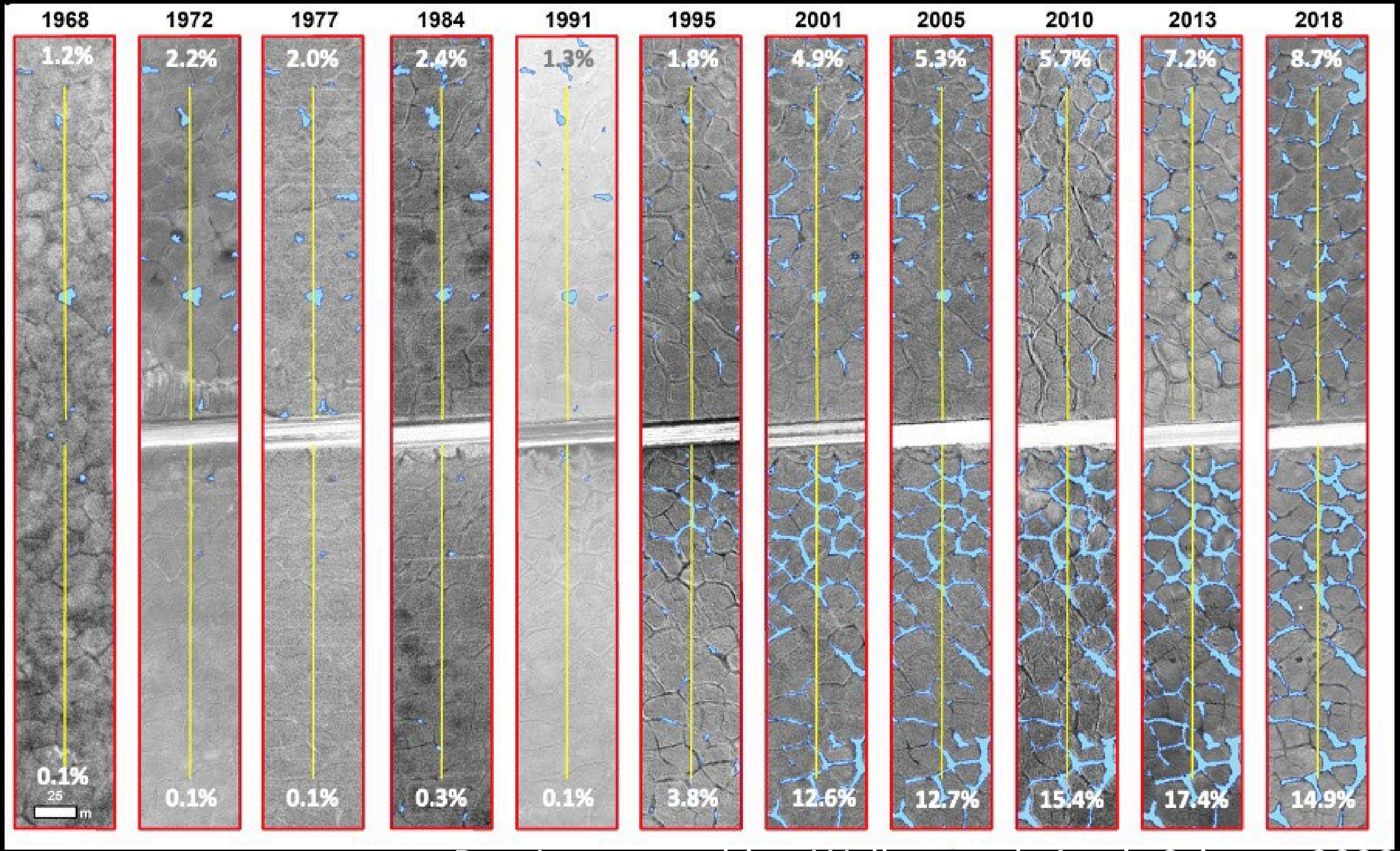
Thermokarst (red dashed line): increased 250% after 1990. Includes only infrastructure-related thermokarst.

Raynolds et al. 2014, *GCB*.

Cumulative impacts in the Prudhoe Bay Region



Growth of ice-wedge thermokarst ponds 1968-2018



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

Nearly all these historical regional,- landscape-, and plot-level analyses of cumulative impacts of infrastructure and impacts to adjacent tundra up to about 2010 relied on detailed infrastructure maps, historical high-resolution aerial photographs of the oil-industry.

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.

RATIC history

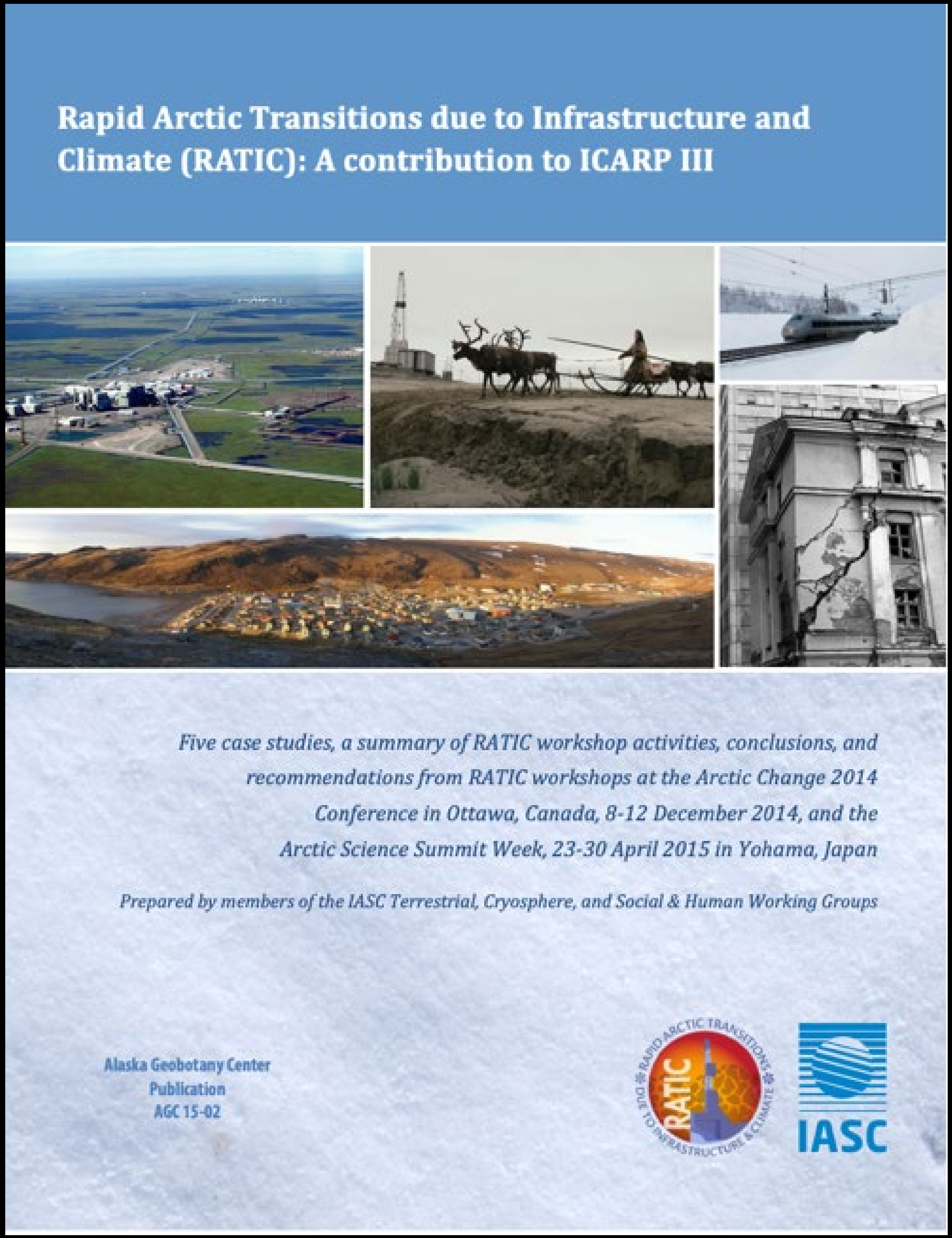
2015

ICARP III, Yohama

RATIC White Paper

- RATIC defined as a “Forum for developing and sharing new ideas and methods to facilitate the best practices for assessing, responding to, and adaptively managing the cumulative effects of Arctic infrastructure and climate change.”

- **A call for funding and new** tools to delineate, monitor, and model the cumulative impacts of Infrastructure and climate change.



High-resolution satellite data (Sentinel 1 and 2) to map Pan Arctic infrastructure

T-MOSAiC-RATIC Highlights

Circumpolar-scale infrastructure mapping and monitoring

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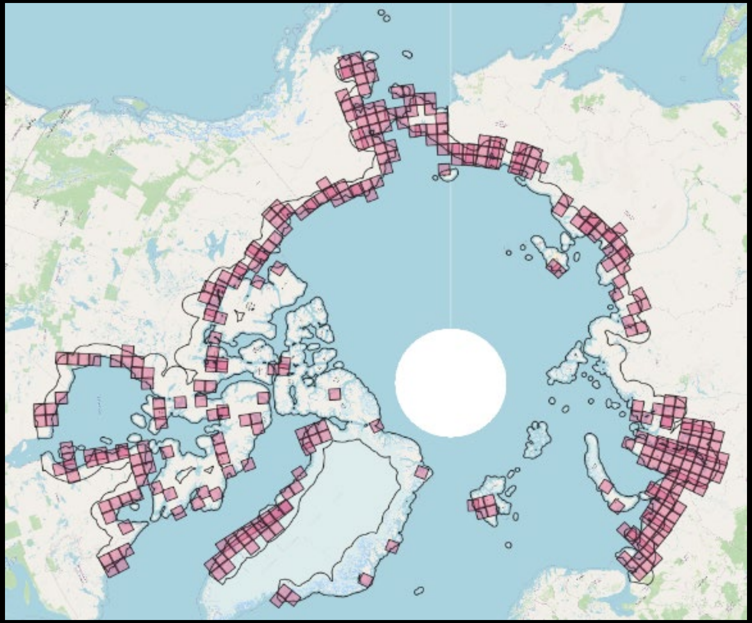
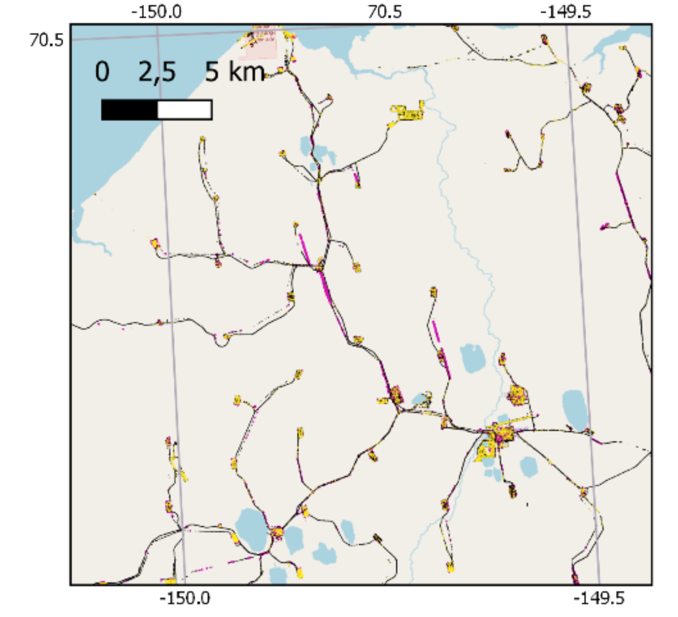
b·geos

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.

Graphic by Melanie Rohr, Walker et al. 2022, *Arctic Science*.

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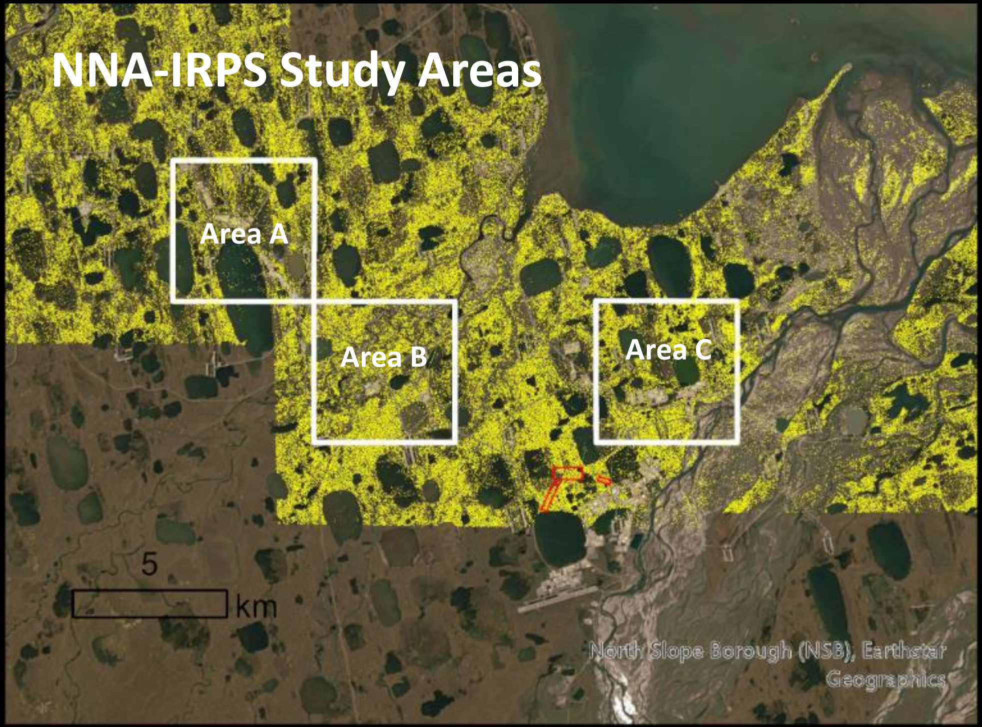
Examining Arctic change through big data, neural networks, artificial intelligence, and cyberinfrastructure

RATIC Highlights

Circumpolar-scale infrastructure mapping and monitoring

Permafrost Discovery Gateway

Mapping ice-wedge polygons in the Prudhoe Bay Oilfield at landscape to regional scale

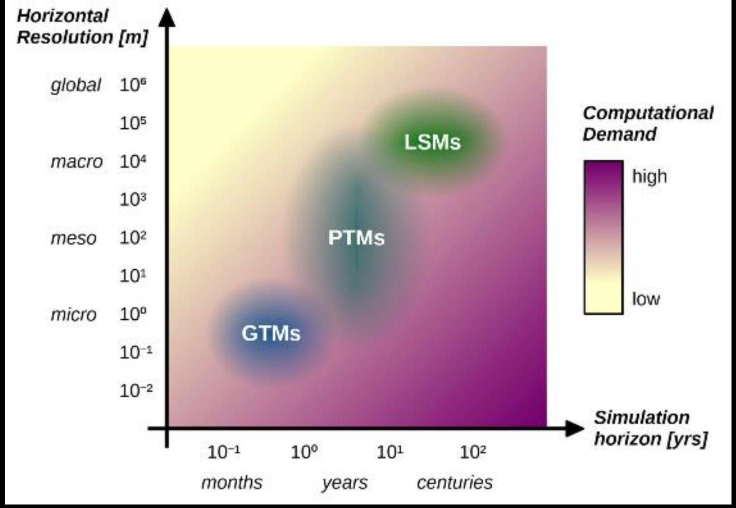


Witharana, et al.. 2021. An Object-Based Approach for Mapping Tundra Ice-Wedge Polygon Troughs from Very High Spatial Resolution Optical Satellite Imagery. Remote Sensing 13:558. doi: 10.3390/rs13040558

Use of hierarchy of spatial data sets to bridge the model gap between regional and engineering scales

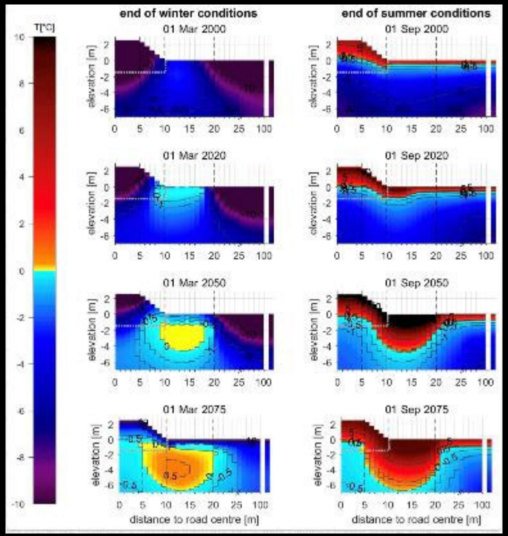
RATIC Highlights

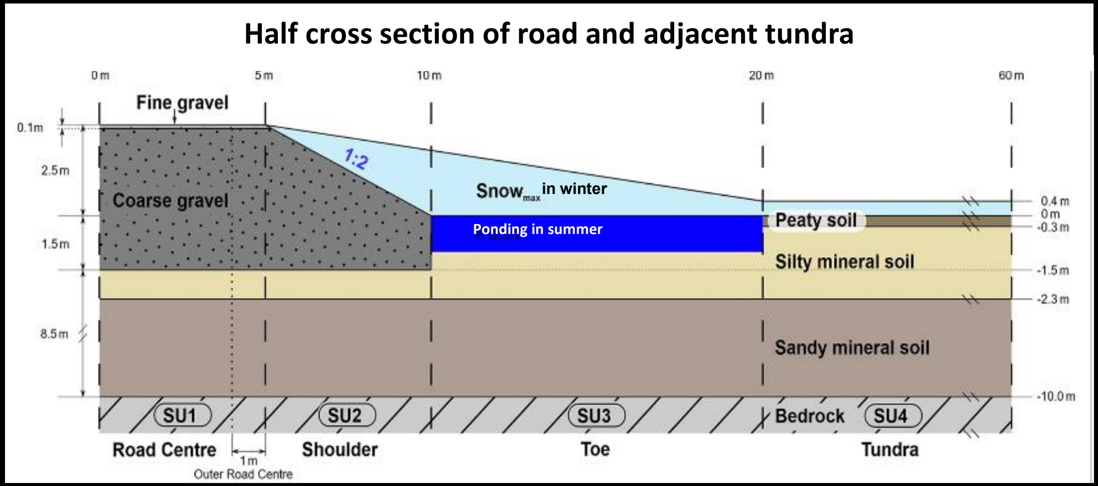
Hierarchical modeling for predicting impacts of infrastructure



Spatial and temporal scales for models

Process-based tiling model (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.

Alfred Wegener Institute

CONCLUSIONS

Are we entering a new era for predicting cumulative impacts of climate change and infrastructure in the Arctic?

- 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).

End of talk

RATIC history

2014

Birth of RATIC

ARCTIC CHANGE 2014

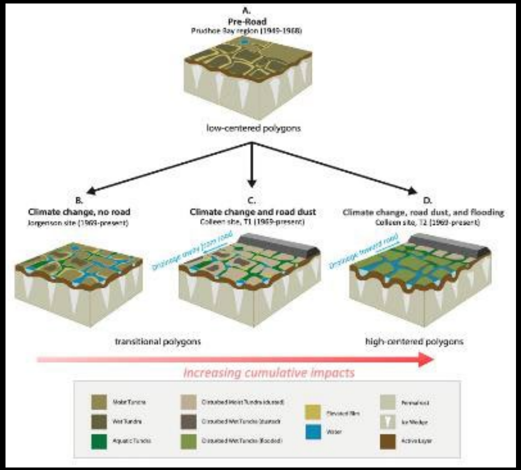
8-12 DECEMBER - OTTAWA CONVENTION CENTRE - OTTAWA, CANADA

First RATIC session and workshop

Result of IASC TWG Scoping Workshop at ASSW 2013 (Krakow) to examine the Social-Ecological Effects of Rapid Transitions in Arctic Permafrost Landscapes. Cross-cutting proposal: TWG, SWG, and CWG (Skip Walker and Gail Fondahl leads)

Cumulative impacts in the Prudhoe Bay Region

Integrated ground-based geo-ecological studies during NSF Navigating the New Arctic research at Prudhoe Bay, AK



4 scenarios of change

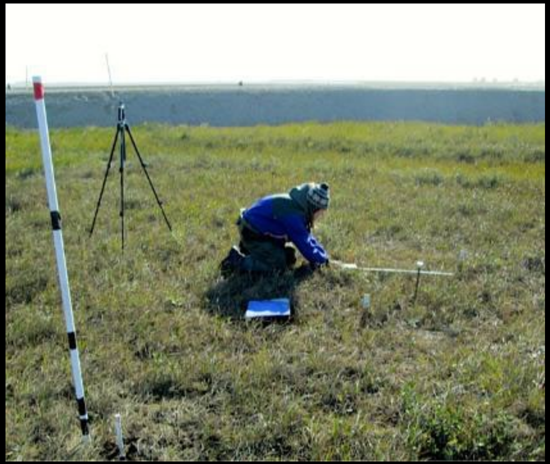
Plot-scale cumulative-impact field studies (2014–present)

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