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

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

- NSF NNA Concept
- Ice-rich permafrost systems (IRPS), some background
- How IRPSs are changing
  - Climate change
  - Infrastructure
- History of change at Prudhoe Bay and Point Lay
- IRPS Observatories
- Adaptive housing at Point Lay
- RATIC and T-MOSAiC initiatives
Navigating the New Arctic (NNA): 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.
Major goals of NNA

- Improved understanding of Arctic change, its local and global effects, and its effects on the natural, social, and built environments.
- Development of new research communities at the intersections of the natural, social, and built environments.
- Research that inform U.S. security, and economic development needs and enables resilient sustainable Arctic communities.
- Studies of feedbacks between the infrastructure and changes in natural ecosystems.
- Studies that advance STEM education through Arctic research activities.
The mission of our NNA project

To understand the structure, processes, evolution, and degradation of ice-rich permafrost (IRPS) in relationship to Arctic ecosystems, the people of the North, and the built environment.

To convey to students, government institutions and the public the role of IRPS and its function in Arctic and global social-ecological systems.

To use the acquired knowledge to promote better living conditions, methods of construction, and land-use policies in the North.

“To heal the planet we first need to understand it.”

Mark Hansen
Maine seaweed harvester
Focus: Ice-rich permafrost system

Conceptual model places ice-rich permafrost at the center of a web of changing Arctic system component — similar to a keystone biological species — if IRP is removed or drastically reduced, the system is totally transformed.
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 landscapes with continuous and discontinuous permafrost (darker purple areas in this figure) are extraordinarily sensitive to climate change.
Ice-Rich Permafrost

- IRP is permafrost with *excess ice* (ice that exceeds the volume of the pore spaces in the soil).
- Nearly 50% of the Arctic is underlain by ice-rich permafrost.
- Includes ice-wedges, tabular ice, lens ice, pingo ice.
- Many arctic landforms, such as ice-wedge polygons, tabular ice, and pingos are the result of various forms of massive ground ice.
IRP is the most susceptible element of Arctic systems to disturbance and climate change. If the ice in IRP melts, the soil becomes liquid and collapses!

**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 gullies.
Ice-rich-permafrost systems (IRPS)

Ground ice is at the center of a web of ecosystem properties and processes

- **Infrastructure**: Roads, gravel pads, pipelines, gravel mines, seismic lines, off-road trails
- **Landforms**: Micro-topography, periglacial landforms
- **Soils**: Soil moisture, texture, organic layer thickness, pH, nutrients
- **Micro-climate**: Ground temperature
- **Ground ice**: Permafrost temperature, active-layer thickness, ice content, cryostructure
- **Snow**: Depth, hardness, phenology
- **Hydrology**: Water depth, temperature, velocity
- **Vegetation**: Species diversity, canopy structure, thickness of moss layer, phenology
- **Other biota**: Microbes, insects, birds, mammals, fish

**Cryostratigraphy**: Patterned ground, vegetation, and trace gas fluxes

**Regional climate**: Mean annual temperature, summer warmth, summer precipitation, snowfall

**Economic and social impacts**: Fish and wildlife connections

**Hydrological connections**

Key Questions

• Where, why, and how is ground ice accumulated in IRPS?
• How do IRPS evolve 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 does the loss of ground ice change these systems and their components?
• How can people and their infrastructure adapt to the changes?
Variety of ice-wedge polygon forms

- Poorly developed low-centered polygons with <0.5 m relief in drained lake basin
- Poorly developed low-centered polygons with <0.5 m relief
- Well developed low-centered polygons with >0.5 m relief
- Well developed low-centered polygons with <0.5 m relief
- Mixed low- and high-centered polygons with >0.5 m relief
- Well developed high-centered polygons with >0.5 m relief
- Well developed high-centered polygons with >0.5 m relief

Well developed low-centered polygons

Poorly developed low-centered polygons

Well developed low-centered polygons

Mixed low- and high-centered polygons

Well developed high-centered polygons

Well developed high-centered polygons
Old residual surface with two recent drained thaw lakes

Recent drained lake, no ice wedges

Older drained lake surfaces with weakly developed ice-wedge polygons

Residual surface, well developed low-centered polygons

Residual surface, well developed low-centered polygons & thermokarst pits

Degrading residual surface

Photos: Walker, 1980 and Air Photo Tech, Inc. 1973
Abrupt increase in permafrost degradation in Arctic Alaska

M. Jorgenson, V. L. Shur, and E. R. Ralph

Received 10 October 2005; revised 25 November 2005; accepted 1 December 2005; published 26 January 2006.

[1] Even though the areal extent of continuous permafrost has relatively cold mean annual air temperatures, we found an abrupt, large increase in the rate of permafrost degradation in northern Alaska since 1982, associated with record warm temperatures during 1998–2000. Our field studies reveal that the recent degradation has occurred as a result of increased ice-wedge degradation in multi-decade-old ice-wedge polygons that have been stable for centuries. Analyses of snowdepths from 1949, 1982, and 2002 revealed large increases in the area (95%, 6.6%, and 4.0% of area, respectively) and density (68, 13%, and 1363% per decade) of degraded ice wedges in two study areas on the arctic coastal plain. Spectral analyses across a broader landscape found that newly degraded ice wedges are spatially associated with road infrastructure, vegetation, and climate. Recent changes in these indicators suggest that road infrastructure is contributing to increased climate warming and degradation of permafrost.

2. Methods

[2] We evaluated the degradation of ice-wedge polygons in northern Alaska at three spatial scales that included (1) field surveys within two small, intensive sites (64 km²) and (2) photo-interpretation of time-series of aerial photographs at the two intensive sites, and (3) image processing of the spectral characteristics of a suite of permafrost polygons in the three larger areas (14,314 km²). Field surveys in 2001 and 2002 at the intensive sites [Jorgenson et al., 2006] (Figure 1) and (C) 114–170 km west of the Cuverville River and closer to the coastal plain region indicate that the rate of degradation is occurring rapidly in vegetation, microgeomorphology, and soils associated with ice-wedge degradation in the landscape. For vegetation, the areas of dominant decay and dead vegetation is usually 11m wide. In assessing changes in vegetation, temperatures and related permafrost temperatures. We also present a conceptual model that describes how infrastructure-related factors, including road and railroads and pipeline, are contributing to more extensive degradation in areas adjacent to roads and roads. We mapped the historical infrastructure changes in the Alaska North Slope-ecological for 10 days from the initial discovery of 1980–2001. In 2001, over 35% of the impacted mapped areas were affected by oil development. In addition, between 1950 and 2001, correlated with significant atmospheric warming during the 1980s, 2001, the existing rendering complex includes areas covered by infrastructure, lakes and river facilities exhibited expanded extent of infrastructure degradation enabled in areas adjacent to the original land. This expansion to a new georegional regime will have impacts to wildlife habitat, local residents and industry.

[3] Abrupt increase in permafrost degradation in northern Alaska

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

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

Recent abrupt changes in thermokarst

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

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

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

Ice-wedge degradation is a common features of the thermokarst region. They develop by repeated freezing and thawing, and ice wedge growth hundreds to thousands of years. Intermittent thawing causes the arctic polygonal networks across the Arctic Landscape. Here we use field and remote sensing observations to document polygonal succession due to ice-wedge degradation and through development in the whole Arctic. We use the observed polygons and oriented for seasonal, while chipping connectivity and overall an understanding of the landscape. We find that melting at the top of ice-wedge polygons over decade and seasonal-decades-scale ground subsidence is a widespread Arctic phenomenon. Although permafrost temperature have been increasing gradually, in particular the recent warming onset in the time during a period, our hypothesis suggests that, increasing and increasing snowfall, in particular due to changes in snow accumulation in the form of snow, we predict that ice-wedge degradation and the hydrological changes associated with the reduced permafrost and ground subsidence will expand and amplify in rapidly warming permafrost regions.
Lake Colleen observatory: Abrupt thermokarst expansion, Prudhoe Bay Spine Road
Climate change at Prudhoe Bay

Time-series of temperature and thaw depth

SWI: $\uparrow 5^\circ C$ mo in 47 years

MAPT: $\uparrow 3.7^\circ C$ in 39 years

MAAT: $\uparrow 3.1^\circ C$ in 29 years

ALT: $\uparrow 20$ cm in 30 years

Data:
MAPT, MAAT, & ALT: Romanovsky, Deadhorse station
Thermokarst collapse due to flooding along the Dalton Highway.

Underground thermal erosion of ice wedges.


Shur et al. 2016. TICOP and in prep.

Photos: Courtesy of AKDOT & PF.
2015 Sagavanirktok River Icing and Flood

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

Repeat of aufeis and flooding in 2016

Photo: AK DOT&PF, Feb 26, 2016

Flooding & thermokarst are major issues 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.
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

3D-seismic white paper
Change at Point Lay:

- Rapidly changing ice-wedge polygons
- Eroding coastal bluffs
- Changing drainage systems
- Loss of water source
- Unstable housing
- Compromised utilities
Major impacts to housing due to ground subsidence at Point Lay, Alaska

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

Photo: Courtesy of CCHRC.
Cumulative impact analyses of oil and gas activities

1987: Prudhoe Bay: Walker et al., Science

2003: North Slope, 2003 NRC report

2008: Arctic wide, AMAP report
Current areas of active development, northern Alaska, 2018

Map courtesy of Alaska Division of Oil and Gas, Showing 2018 activity in yellow boxes.
Area of regional-, landscape--scale studies

Alaska North Slope Oilfields
- Major pipelines
- Active roads, well sites, mines, and other infrastructure
- Abandoned roads, well sites, mines, and other infrastructure
- Oilfield unit boundaries

Fig. 4 detail map areas
Trends at regional-scale direct impacts (footprint)

Area impacted
• 27.4 km² gravel mines
• 23.5 km² gravel drill sites & construction pads
• 12.6 km² gravel roads
• 10.8 km² other (airstrips, off-shore drilling islands, peat roads, etc.)

74.3 km² total footprint

Rate of increase
• Reduced rate during production phase to 2010.
62 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


- **2010 Historical change analysis:** Raynolds et al. (2014) *Global Change Biology*, 20: 1211–1224
Comparison of direct, indirect infrastructure- and climate-related impacts in Areas A, B, C

- Area of indirect impacts exceeded area of direct impacts after 1982.
- Anthropogenic direct impacts slowed rate of increase after about 1983.
- Indirect impacts slowed in 1983 but continued to increase.
- 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
Network of NNA-IRPS observatories

Barrow Environmental Observatory
Sloan et al. and others (NGEE)
Scott, Liljenedahl, Sturm (snow)

Point Lay Village Observatory (proposed)

Prudhoe Bay Oilfields
Jorgenson et al.

Jago River

Romanovsky permafrost boreholes

Prudhoe Bay
Jorgenson et al.

Dalton Highway
NaturalIRPS (proposed)

Jorgenson et al. Jago River

National Petroleum Reserve - Alaska

Arctic National Wildlife Refuge
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
Ground-ice characterization and evolution

### Boreholes

![Boreholes Image]

### Profiles

![Profiles Image]

### Scenarios of IRP change

![Scenario Diagram]
Adapting to change at Point Lay:
Cold Climate Housing Research Center (CCHRC)

Working with village stakeholders, the school, and the IRPS 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.
CCHRC housing prototypes

Anaktuvuk Pass prototype: Super insulated home with thermal-raft foundation

Atmautluak prototype: Integrated truss house, adjustable piling foundation

Buckland prototype: Thermal raft foundation, integrated truss house with single-piece, floor, walls, roof adjustable piling foundation

Quinhagak octagon prototype

Point Lay, thermal raft piles

Photos courtesy of the Cold Climate Housing Research Center
International collaboration: RATIC
Rapid Arctic Transitions due to Infrastructure and Climate

- IASC-sponsored forum for developing and sharing new ideas and methods regarding sustainable development in the face of rapid arctic change
- White paper

[Link to RATIC White Paper]

RATIC white paper:

Five international case studies of infrastructure impacts to social systems

- Road & pad impacts, Prudhoe Bay oil field, AK
- Nenets subsistence, Bovanenkovo gas field, RU
- Roads & airstrip stability, arctic villages, CA
- Rail corridors, NO
- Urban infrastructure, RU
MOASiC: One of Science magazine’s 10 stories likely to make headlines in 2019
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.
NNA-IRPS 2020 Summer Field Course

• 17-day expedition along the Dalton Highway
• Instructors: Members of the NNA-IRPS team.
• Focused on ice-rich permafrost systems, infrastructure, landscape evolution, arctic ecosystems, arctic plants
Co-investigators and collaborators

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Native Village of Point Lay

Kali School

Taġiuģmiullu Nunamiullu Housing Authority (TNHA)

NSB Department of Planning and Community Services

BP Alaska (now Hillcorp)

International collaborators
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   Helga Bültmann, Germany
   Warwick Vincent, Canada
NNA-IRPS proposal:
Our NNA-IRPS proposal
Major themes and linkages

**LANDSCAPE EVOLUTION**

Drivers of change:
- Climate change

Arctic systems:
- Ice-rich permafrost system (IRPS)

Major research topics:
- Characterization and evolution of natural IRPS

**ADAPTATIONS TO CHANGE**

Adaptive approaches to manage change
- Infrastructure

Arctic Social Ecological System (ASES)

Geographic foci:
- Node: Prudhoe Bay Oilfield
- Corridor: Dalton Highway
- Village Housing: Point Lay

Drivers of change:
- Climate change
- Infrastructure
Climate Sensitivity of High Arctic Permafrost Terrain Demonstrated by Widespread Ice-Wedge Thermokarst on Banks Island

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Abstract: Ice-wedge networks underlie polygonal terrain and comprise the most widespread form of massive ground ice in continuous permafrost. Here, we show that climate-driven thaw of hilltop ice-wedge networks is rapidly transforming uplands across Banks Island in the Canadian Arctic Archipelago. Change detection using high-resolution WorldView images and historical air photos, coupled with 32-year Landsat reflectance trends, indicate broad-scale increases in ponding from ice-wedge thaw on hilltops, which has significantly affected at least 15,000 km² of Banks Island and over 3.5% of the total upland area. Trajectories of change associated with this upland ice-wedge thermokarst include increased micro-relief, development of high-centred polygons, and, in areas of poor drainage, ponding and potential initiation of thaw lakes. Millennia of cooling climate have favoured ice-wedge growth, and an absence of ecosystem disturbance combined with surface denudation by solifluction has produced high Arctic uplands and slopes underlain by ice-wedge networks truncated at the permafrost table. The thin veneer of thermally-conductive mineral soils strongly links Arctic upland active-layer responses to summer warming. For these reasons, widespread and intense ice-wedge thermokarst on Arctic hilltops and slopes contrast more muted responses to warming reported in low and subarctic environments. Increasing field evidence of thermokarst highlights the inherent climate sensitivity of the Arctic permafrost terrain and the need for integrated approaches to monitor change and investigate the cascade of environmental consequences.

Keywords: permafrost; climate change; ice-wedge polygons; Landsat; Banks Island; Arctic; terrain sensitivity

Thermokarst on Banks Island

Extensive ponding at top of ice-wedges in previously barren sparsely vegetated upland terrain with large ice-wedge polygons.

Northern Alaska oilfields, Dalton Highway & Point Lay
Another Point Lay climate change story

Walrus haulout on barrier island since 2007 due to no sea ice.
International Collaboration

Modern (2019-2020) repeat of Nansen’s (1893–1896) Fram Expedition

Polarstern

Route

Science observations
Bridging Science, Art, and Community in the New Arctic

Organizers – UVa:
Matthew Burtner: Dept. Music
Howard Epstein: Dept. Env. Sci.
Leena Cho & Matthew Jull: Dept. Architecture

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