Cumulative impacts of a gravel road and climate change in an ice-wedge polygon landscape, Prudhoe Bay, Alaska

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ARCTIC INFRASTRUCTURE SCIENCE TALK

T-MOSAIC/RATIC INFRASTRUCTURE ACTION GROUP

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Three RATIC papers in process to *Arctic Science* T-MOSAiC Special Issue

1. Cumulative impacts of a gravel road and climate change in an ice-wedge-polygon landscape, Prudhoe Bay, Alaska (accepted for publication)

Donald A. Walker, Martha K. Raynolds, Mikhail Z. Kanevskiy, Yuri S. Shur, Vladimir E. Romanovsky, Benjamin M. Jones, Marcel Buchhorn, M. Torre Jorgenson, Jozef Šibík, Amy L. Breen, Anja Kade, Emily Watson-Cook, Georgy Matyshak, Helena Bergstedt, Anna K. Liljedahl, Ronald P. Daanen, Billy Connor, Dmitry Nicolsky, Jana L. Peirce

2. Vulnerability of ice wedges and reversible nature of ice-wedge thermokarst in areas affected by road infrastructure, Prudhoe Bay Oilfield, Alaska (accepted for publication)

Mikhail Kanevskiy, Yuri Shur, D.A. (Skip) Walker, Torre Jorgenson, Martha K. Raynolds, Jana L. Peirce, Benjamin M. Jones, Marcel Buchhorn, Georgiy Matyshak, Helena Bergstedt, Amy L. Breen, Billy Connor, Ronald Daanen, Anna Liljedahl, Vladimir E. Romanovsky, and Emily Watson-Cook

3. Arctic roads and railways: environmental and social consequences of transport infrastructure in the circumpolar north (in review)

Olga Povoroznyuk, Warwick F. Vincent, Peter Schweitzer, Roza Laptander, Mia M. Bennett, Fabrice Calmels, Dmitri Sergeev, Christopher Arp, Bruce Forbes, Pascale Roy-Léveillée, and Donald A. Walker

Better cumulative impact assessment guidelines are needed for new Arctic infrastructure in regions with ice-rich permafrost

Prudhoe Bay Oilfield. Photo: Courtesy of Pam Miller

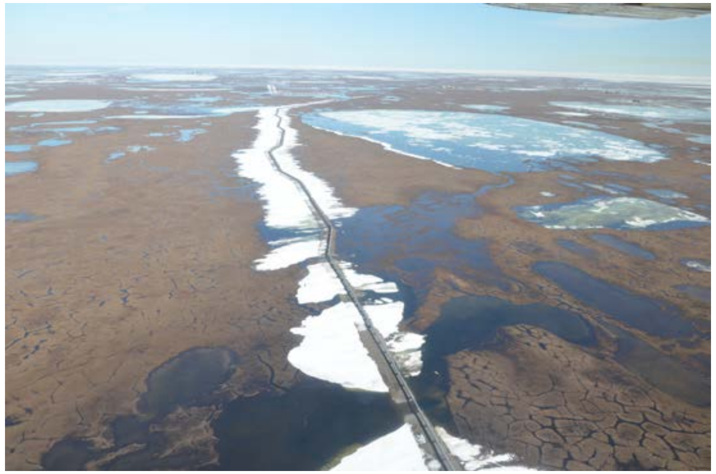
There is a scarcity of long-term environmental studies that have monitored changes after infrastructure was built.

Objectives

- Document 70 years (1949–2019) of cumulative effects of climate- and road-related impacts of a heavily traveled road in the Prudhoe Bay Oilfield (PBO) with an aim toward improving cumulative impact assessments for future roads.
- Focus on the often-ignored indirect impacts that follow the direct impact (footprint) of new roads.

Typical infrastructure and climate-related disturbances to landforms & vegetation

Flooding and snowdrifts



Dust disturbance

Ice-wedge thermokarst

Enhanced shrub growth

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

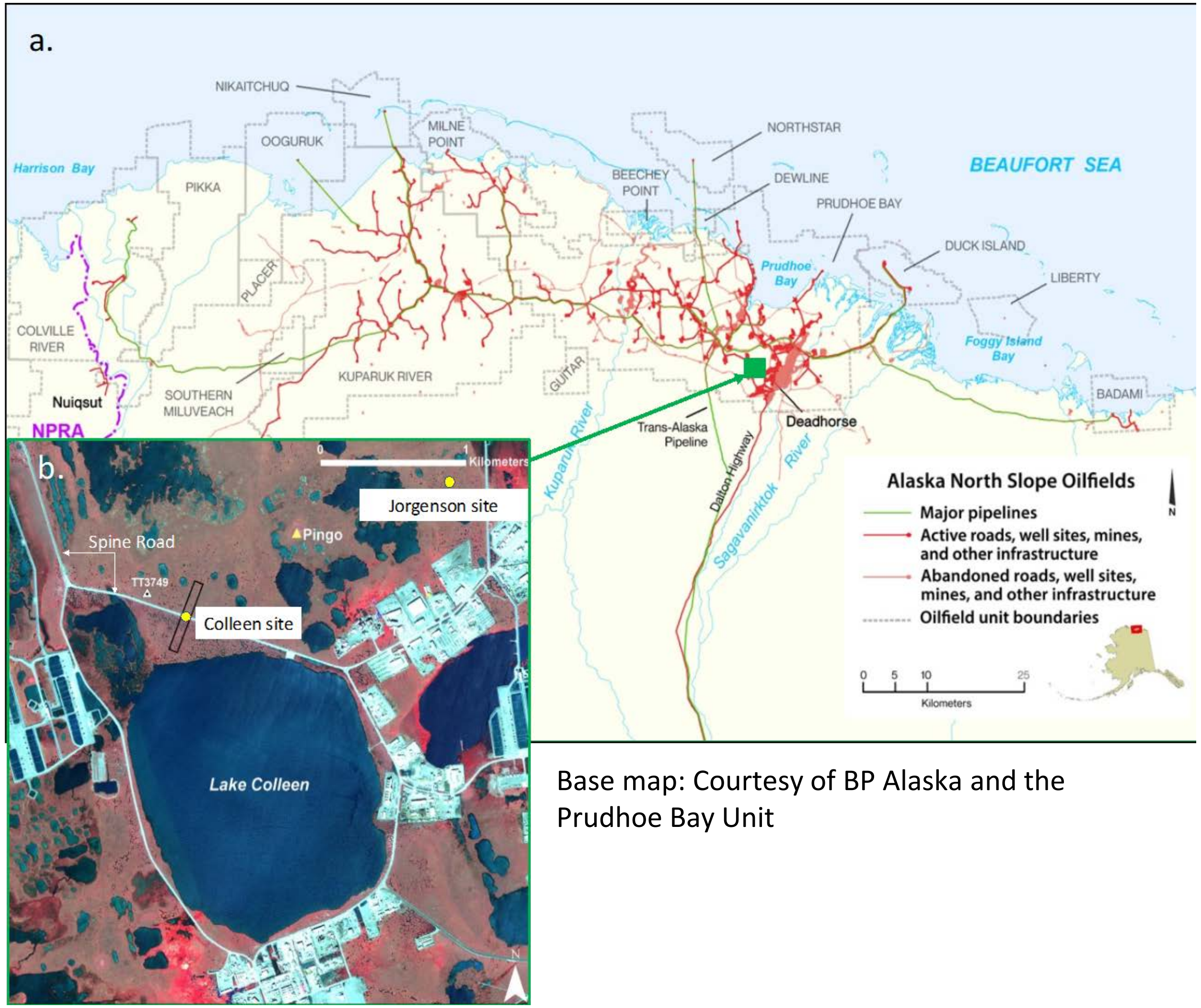
U.S. definition of cumulative impacts

"...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 other action. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time."
(Council on Environmental Quality, 1997).

- CIs are difficult to predict because of the complexity of ecological interactions, the scarcity of environmental baseline data, and the difficulty in defining the spatial and temporal boundaries for meaningful assessments (Clark 1994).
- Objective rules for conducting CIAs are also generally lacking (Jones 2016).
- CIAs are generally not integrated into comprehensive regional planning processes, so it is difficult to follow through on generated recommendations (NRC 2003).
- Nonetheless, CIAs are often mandated for large projects despite these difficulties because of the potential large long-term consequences that would likely occur in the absence of a thorough consideration of cumulative impacts

Site description

The Alaska North Slope oilfields, major infrastructure, and location of study areas



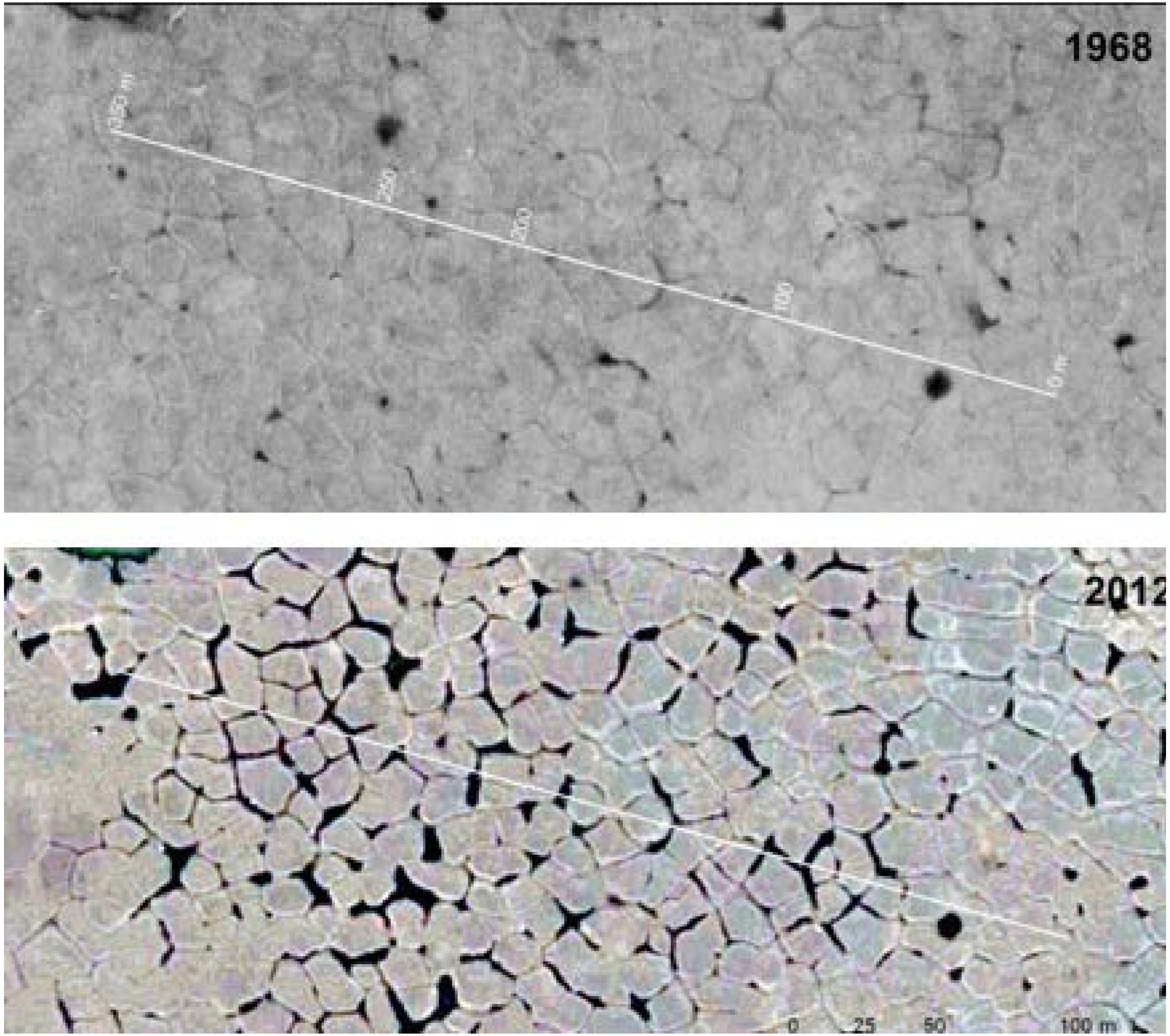
Colleen and Jorgenson sites within the Deadhorse Service Area

Base map: Courtesy of BP Alaska and the Prudhoe Bay Unit

Site description

Jorgenson Site (JS):

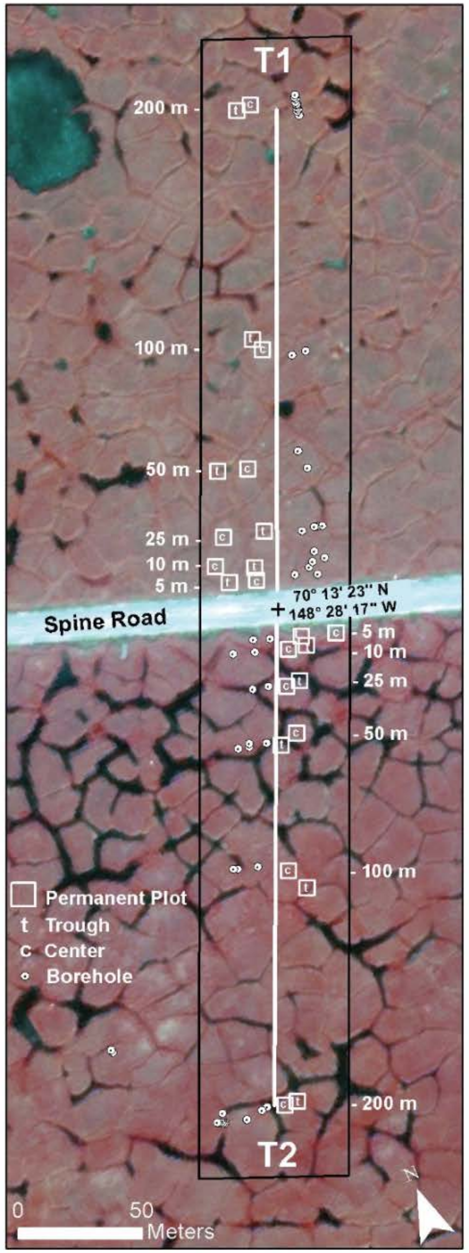
Impacted by climate-related change, relatively isolated from infrastructure-related change



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

Site description

Colleen site (CS): Impacted by climate- and infrastructure-related (change)



Northeast, upwind, heavy dust non-flooded side of road

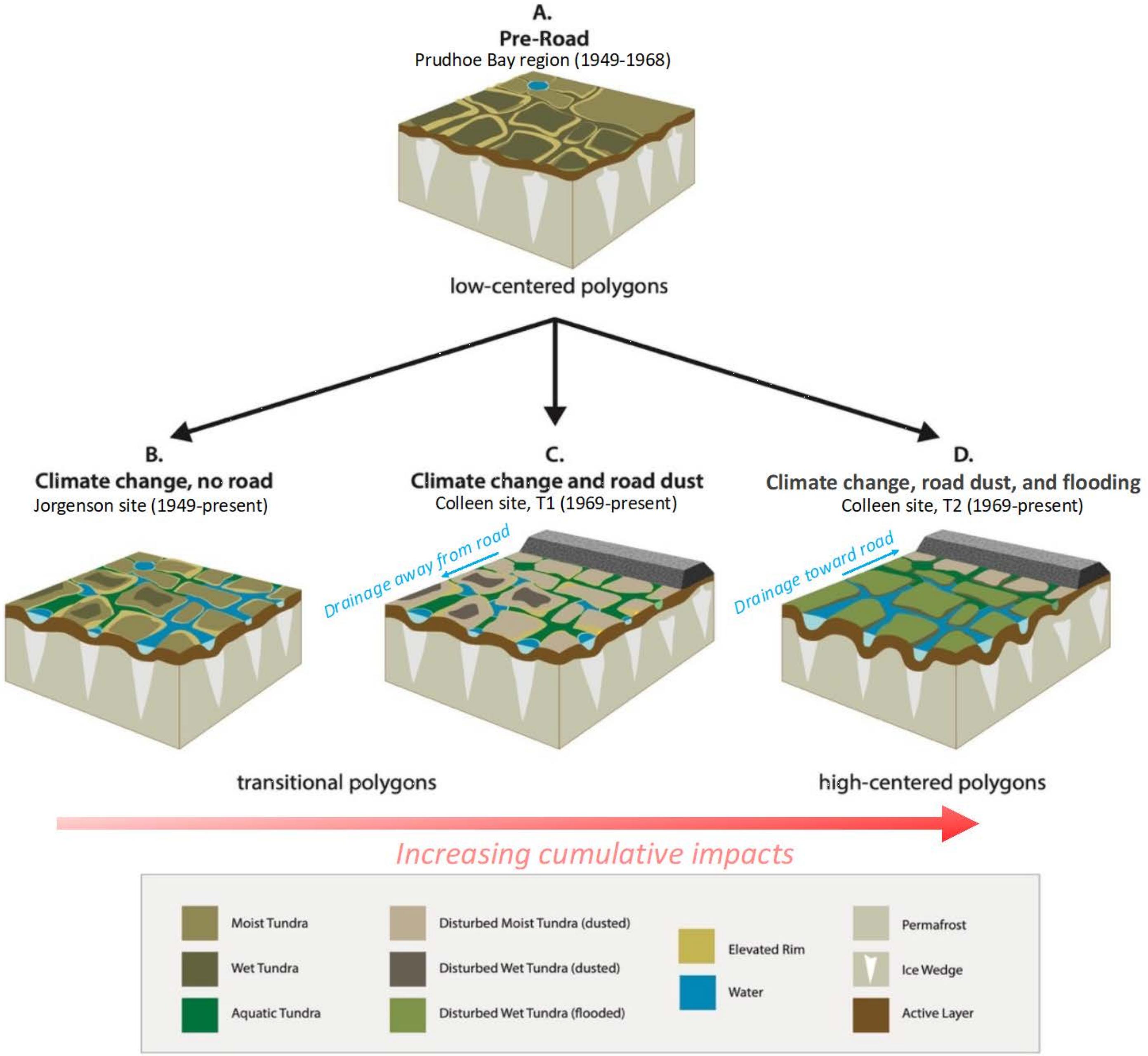
Southwest, downwind and upstream, flooded side of road

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

Methods

Trajectories of change

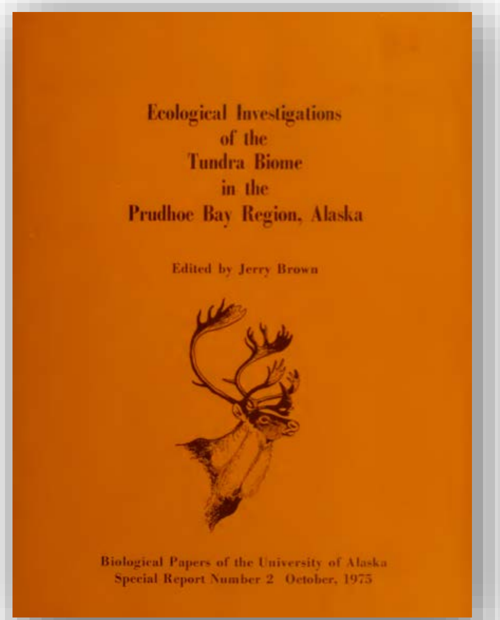
Cumulative impacts of climate- and road-related impacts at the Jorgenson and Colleen sites



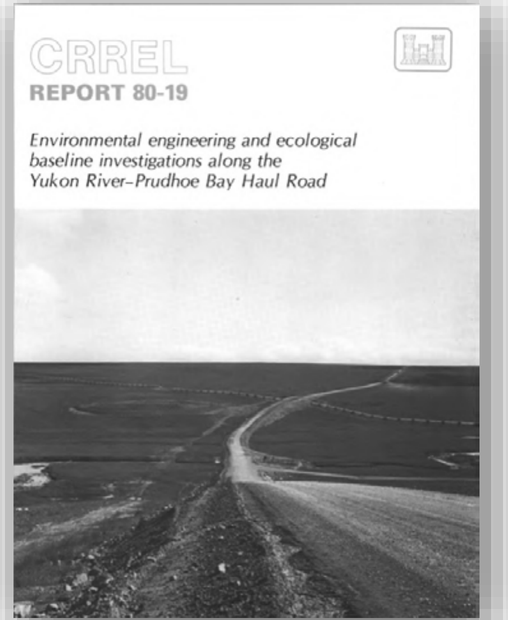
Methods

Comparison with historical (1970s) geoecological baseline studies

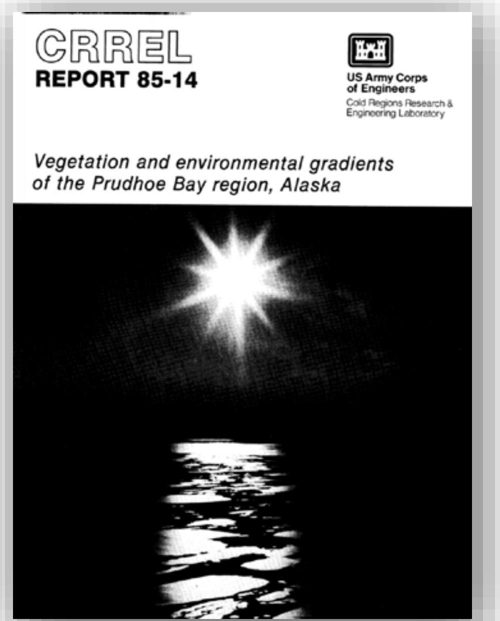
- International Biological Program (IBP Tundra Biome)
- U.S. Army Cold Regions Research and Engineering Laboratory (CRREL)



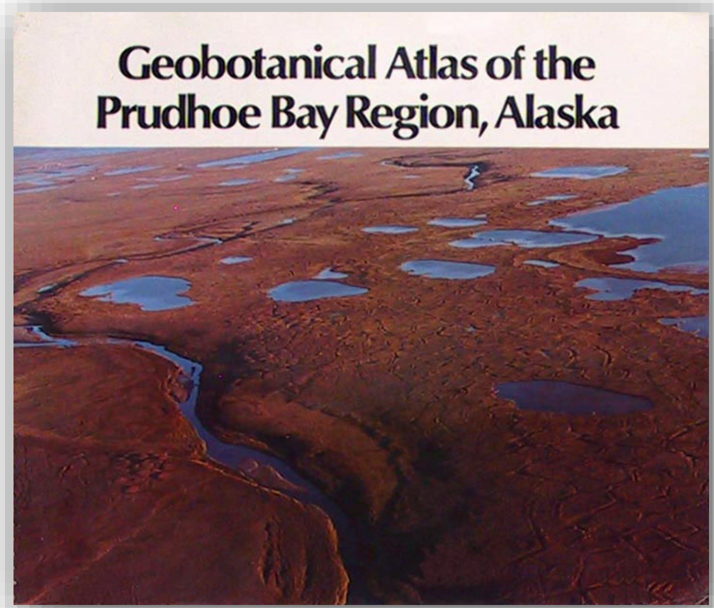
Brown J. (Ed.), 1975



Brown J. & Berg (Eds.), 1980



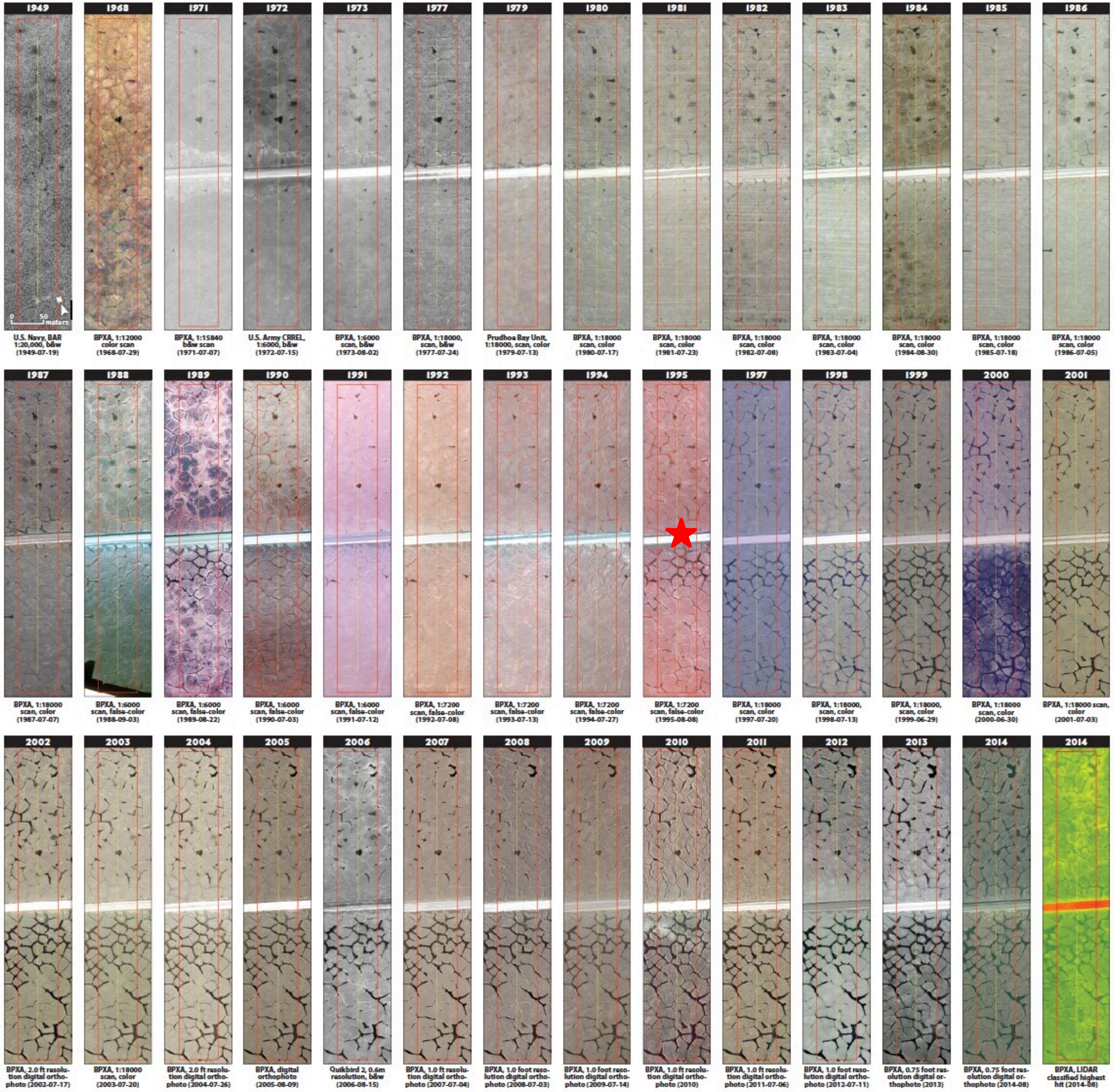
Walker, 1985



Walker et al. 1980

Methods

Historical (1949–2014) aerial photo record



Courtesy of BP Alaska Prudhoe Bay Unit, and Quantum Spatial, Anchorage

★ Large changes in thermokarst at the at the Colleen site began in mid-1990s

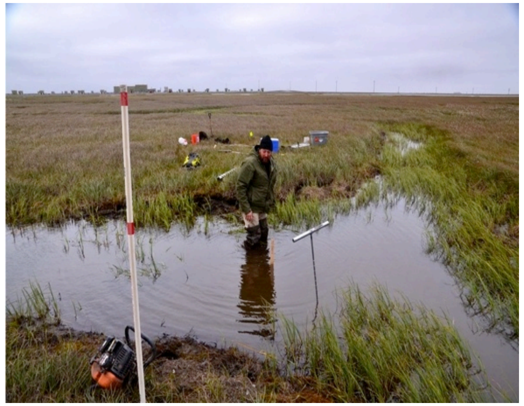
Methods

Integrated geoecological/ permafrost field observations (2014)

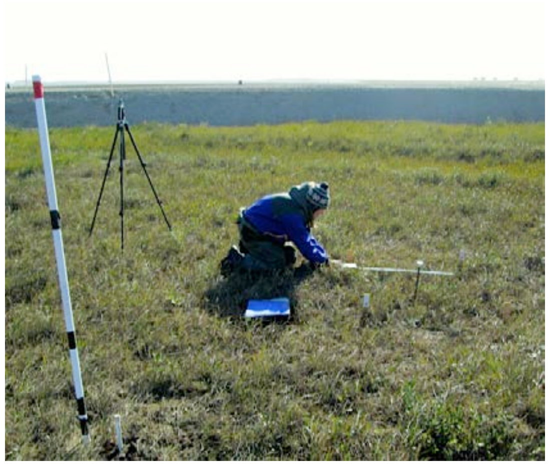
Transects perpendicular to the road

Micro-topography surveys

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



Vegetation plots: species composition, soils, environmental factors

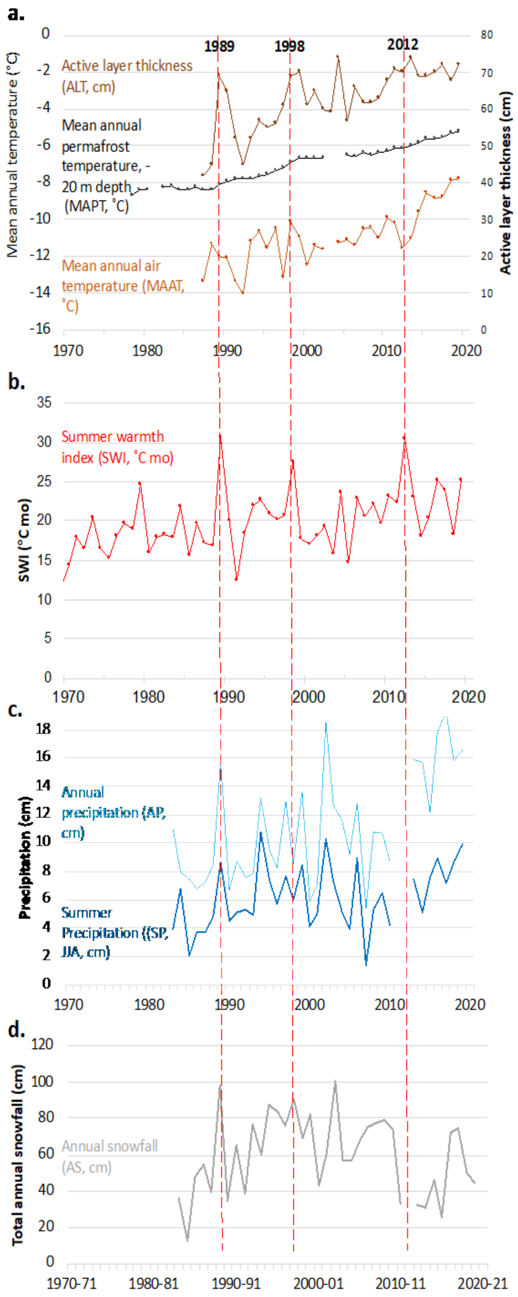


Soil dust layers

Permafrost cores

Methods

Changes in climate



Climate trends

Romanovsky Deadhorse site (1987-2019)

- ↑ **Active layer thickness** (30 cm increase)
- ↑ **Mean annual permafrost temperature** (3.2 ˚C increase)
- ↑ **Mean annual air temperature** (5.6 ˚C increase)

NWS, Deadhorse and Prudhoe Bay (1987-2019)

- ↑ **Summer warmth index** (7.9 ˚C mo), peaks in 1989, 1998, 2012 correspond to years with deep thaw

NWS, Kuparuk station (1982-2019)

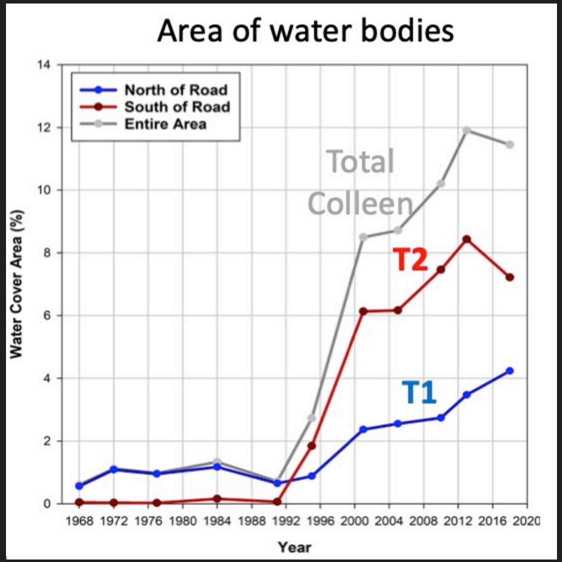
- **Annual precipitation** (no trend, recent increase)
- **Summer precipitation** (no trend, recent increase)

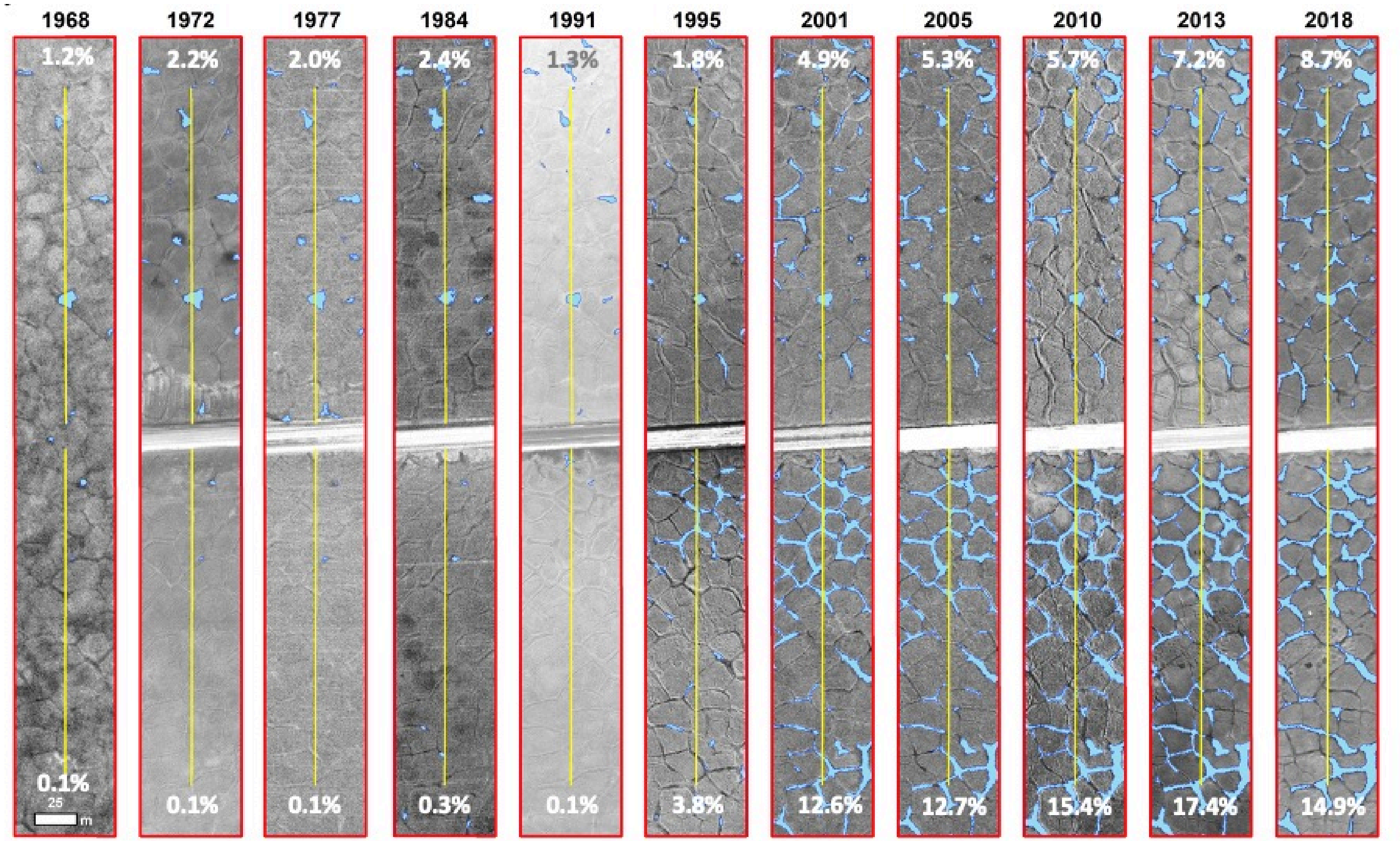
- **Snow depth** (no trend)

1949-1968: Barrow record relatively stable, slight cooling trend

Results

Waterbody distribution Colleen site (1968-2018)

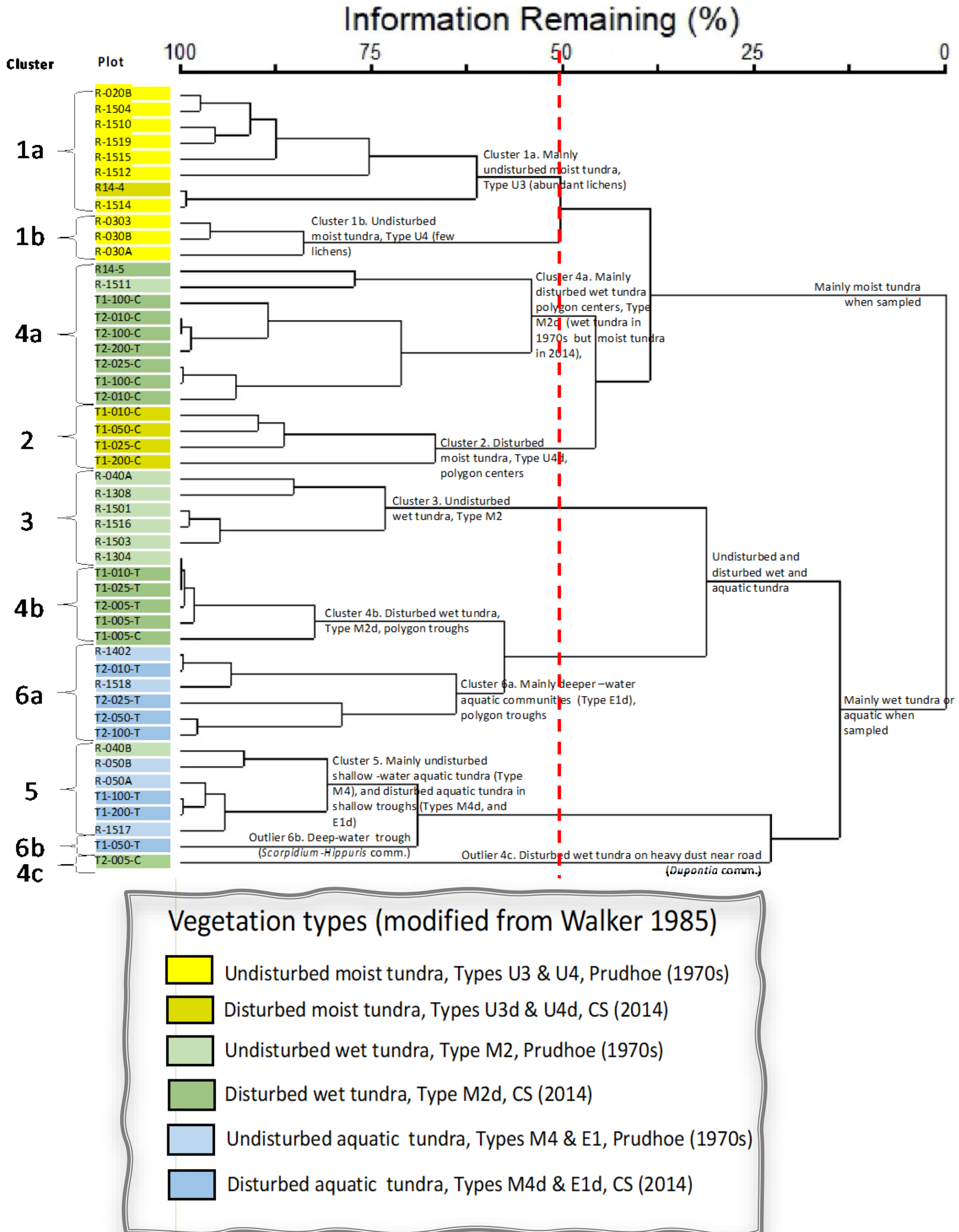




Results

Comparison of plots sampled in 2014 and 1970s

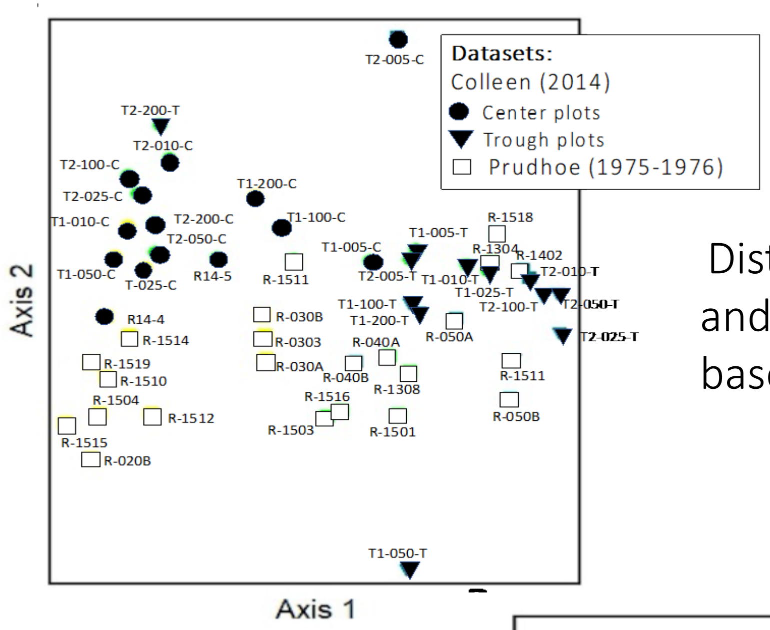
Classification



Results

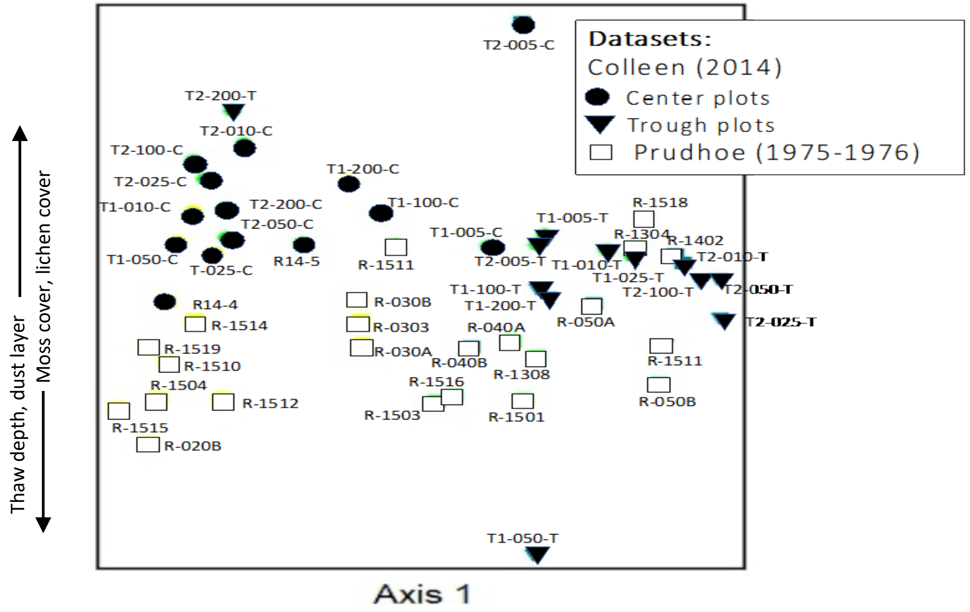
Comparison of plots sampled in 2014 and 1970s

Ordination



Distribution of Colleen (2014) and Prudhoe (1970s) datasets based on floristic similarities

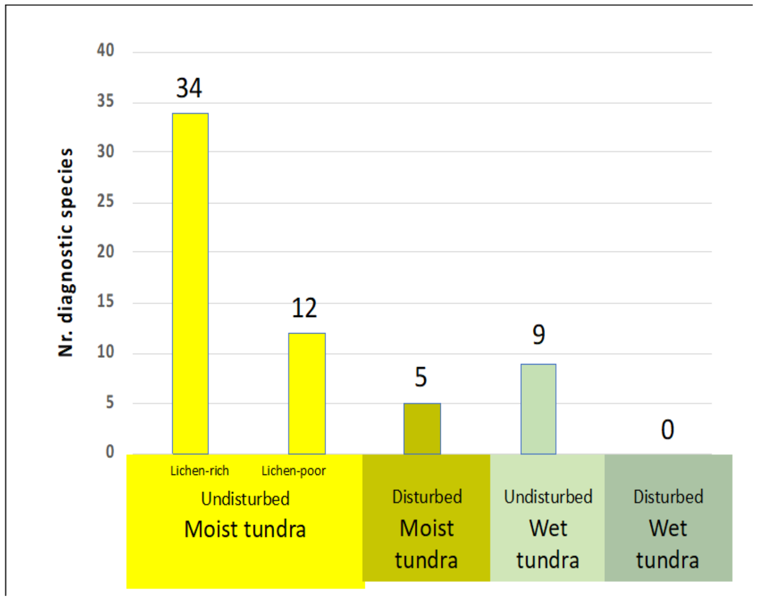
Relationship of plots and vegetation types to environmental gradients



Results

Comparison of plots sampled in 2014 and 1970s

Loss of diagnostic species:



Diagnostic species: Species with high fidelity to a given vegetation unit, i.e., they are regularly found in the given vegetation unit and are not regularly found in other units. Defined by the phi value:

$$\Phi = \frac{N \cdot n_p - n \cdot N_p}{\sqrt{n \cdot N_p \cdot (N-n) \cdot (N - N_p)}}$$

N ... number of relevés in the data set,
N_p ... number of relevés in the target vegetation unit,
n ... number of occurrences of the species in the data set,
n_p ... number of occurrences of the species in the target vegetation unit.

Common diagnostic species (phi values)

Moist tundra:

Undisturbed (lichen-rich) (34): *Pedicularis lanata 85.1, Lecanora epibryon 85.1, Tephroseris frigida 78.3, Hulteniella integrifolia 77.0, Thamnolia vermicularis s. subuliformis 69.4, Flavocetraria cucullata 68.3, Hypnum bambergeri 67.8, Salix rotundifolia v. rotundifolia 58.7, Papaver macounii 58.7, Hypnum procerrimum 58.7, Draba alpina 58.7, Arctagrostis latifolia 58.7, Dactylina arctica 56.7, Saxifraga oppositifolia s. oppositifolia 52.9, Carex membranacea 50.4, Ditrichum flexicaule 49.7, Oncophorus wahlenbergii 49.0, Sanionia uncinata 47.5, Minuartia arctica 47.5, Masonhalea richardsonii 47.5, Didymodon asperifolius 47.5, Cassiope tetragona 47.5, Carex scirpoidea 47.5, Cardamine digitata 47.5, Abietinella abietina 47.5, Encalypta species 46.2, Solorina species 44.7, Meesia uliginosa 43.3, Cetraria islandica 42.6, Tomentypnum nitens 40.1, Salix reticulata 39.7, Peltigera canina 38.1, Dryas integrifolia s. integrifolia 37.4*

Undisturbed (lichen-poor) (12): *Blepharostoma trichophyllum v. brevirete 66.2, Plagiochila arctica 65.5, Timmia austriaca 62.2, Cratoneuron filicinum 60.3, Orthothecium chryseum 57.3, Calliergon megalophyllum 52.8, Campylium stellatum 50.1, Cinclidium arcticum 50.0, Carex marina 50.0, Ditrichum flexicaule 49.7, Salix reticulata 49.5, Pedicularis albolabiata 42.9*

Disturbed (5): *Braya glabella s. purpurascens 72.7, Tortella tortuosa 49.5, Carex bigelowii 46.0, Salix richardsonii 38.6, Dryas integrifolia s. integrifolia 37.4*

Wet tundra:

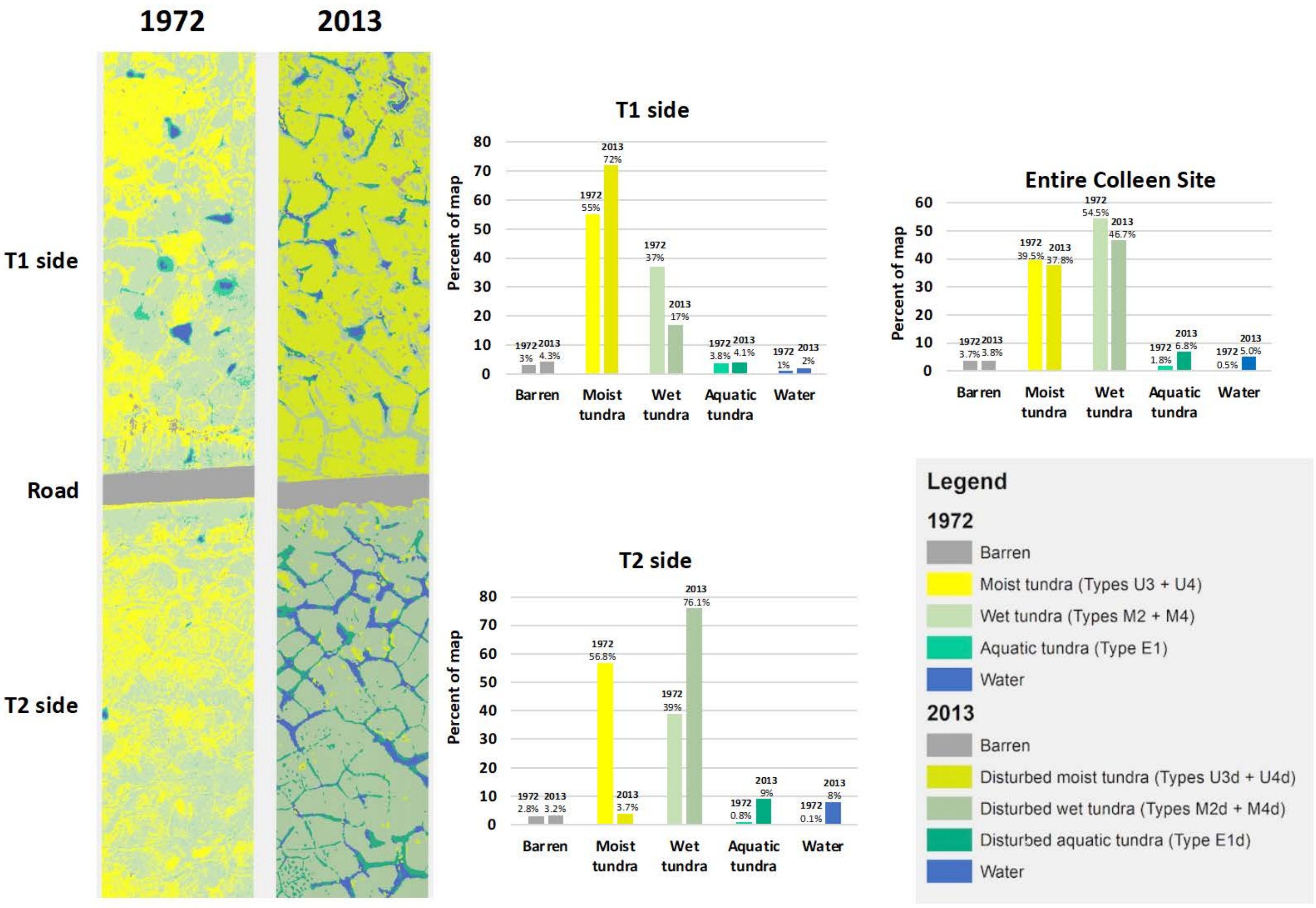
Undisturbed (9): *Cinclidium latifolium 68.6, Salix ovalifolia v. ovalifolia 67.7, Dupontia fisheri 67.7, Carex saxatilis s. laxa 56.9, Calliergon megalophyllum 52.8, Campylium stellatum 50.1, Juncus biglumis 45.3, Meesia triquetra 41.2, Orthothecium chryseum 40.9*

Disturbed (0):

Results

Comparison of Colleen site vegetation patterns in 2013 and 1970s

Mapping



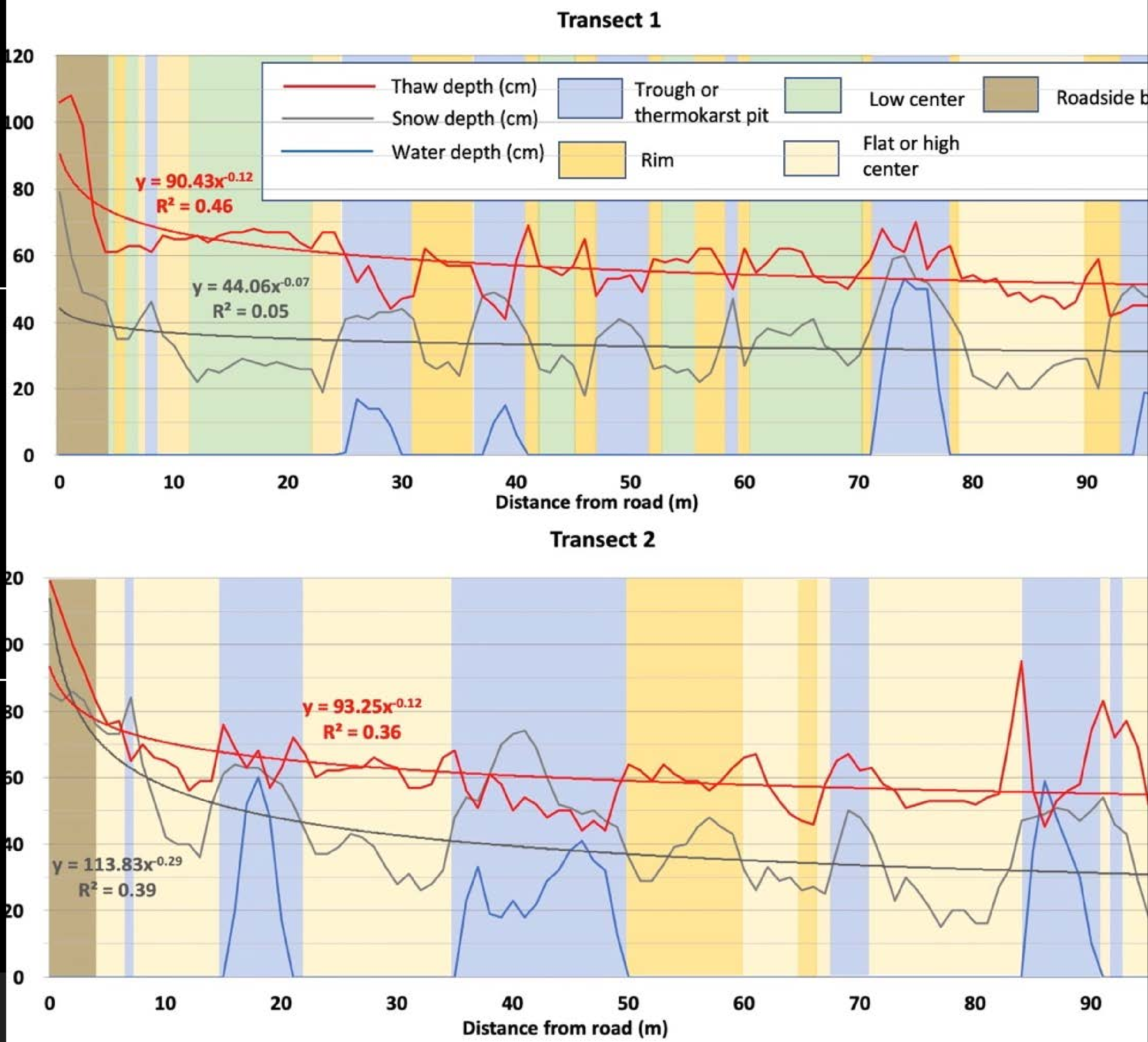
Disturbed aquatic tundra, Types M4d & E1d, CS (2014)

Results

Variation with distance from road

Coleen transects T1 & T2:

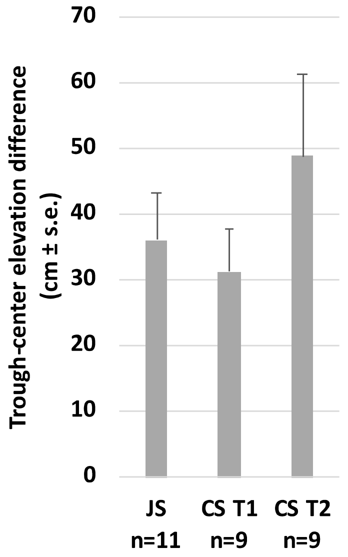
Thaw depth, snow depth, water depth, patterned ground features



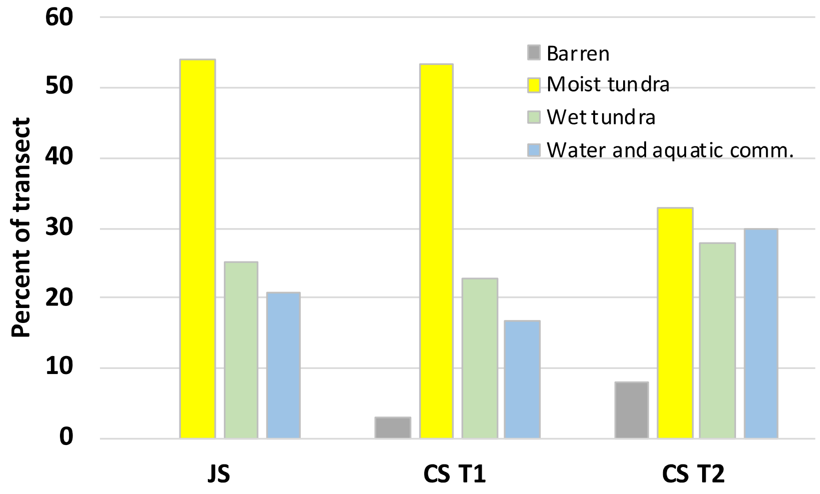
Results
Comparison of Jorgenson and Colleen transects

Comparison of key site factors along JS and CS transects:

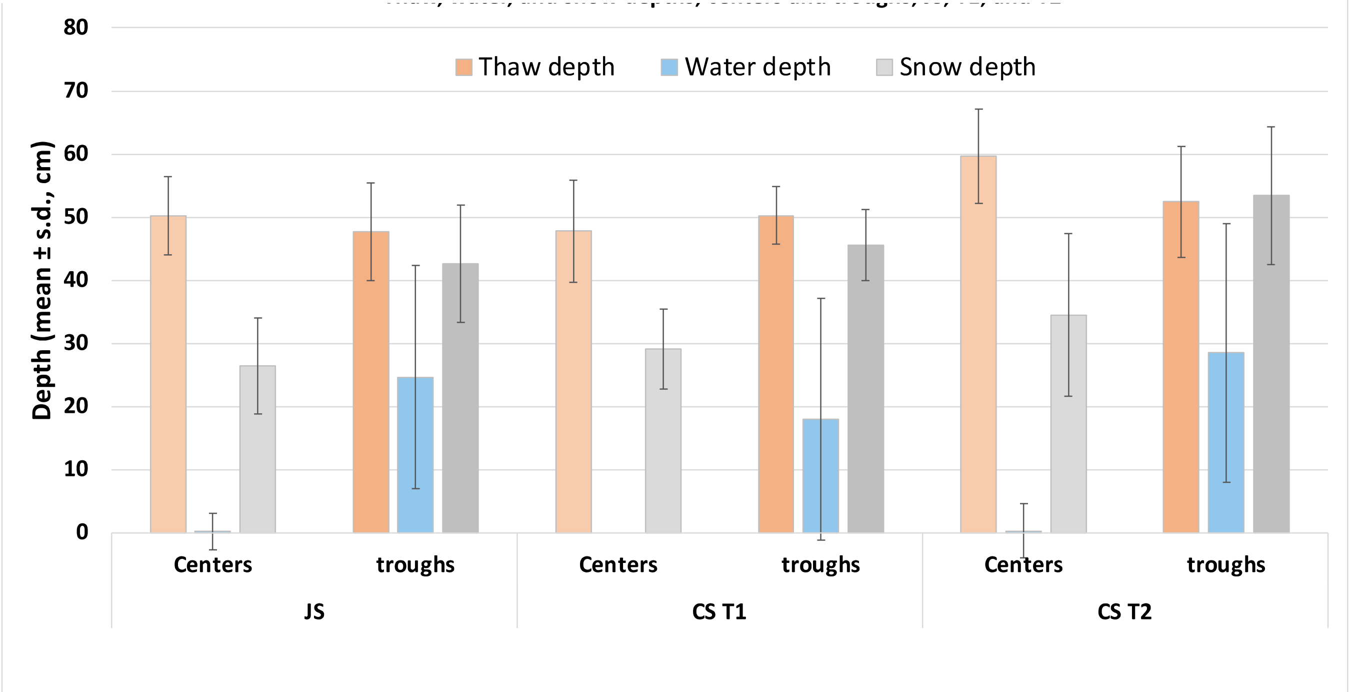
Center-trough elevation difference



Vegetation-type distribution



Thaw, water, and snow depths in polygon centers and troughs



Φ

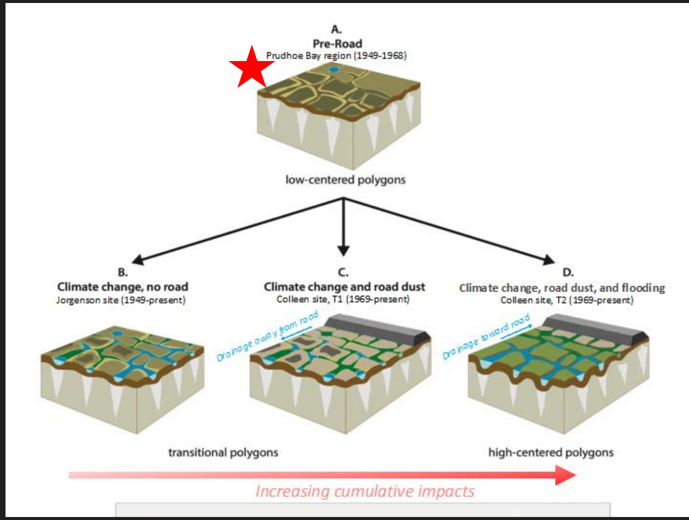
Results

Summary of of the four trajectories of change

Trajectory A:

Pre-road

Jorgenson and Colleen sites (1949–1968)



Drivers of change

Climate:

- Climate data from Barrow (1949 and 1968)
- Mean annual air temperature: -12.6 ± 1.2 ˚C; a slight cooling trend

Other:

- Natural landscape-evolution processes (e.g., annual frost heave, successional processes related to pond expansion and drainage, small annual input of eolian dust from the Sagavanirktok River).

Trajectory A cumulative impacts

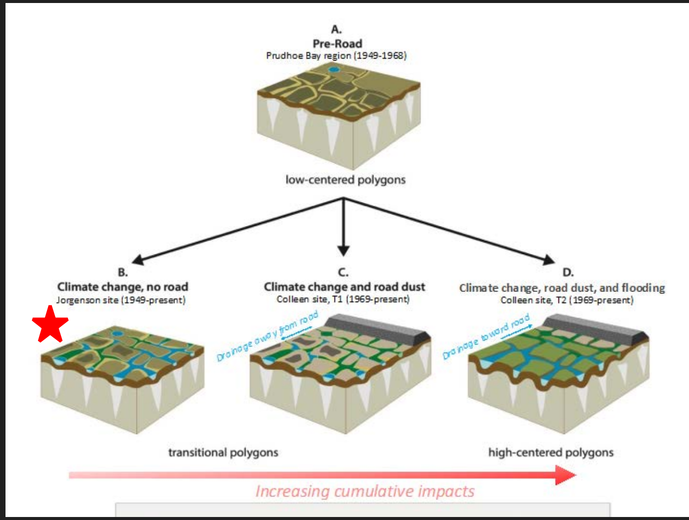
- Little detectable change in thermokarst ponds (l< 1% change at Jorgenson and Colleen sites), landforms, or vegetation patterns.

Results

Summary of of the four trajectories of change

Trajectory B:

Mostly climate change (1969–present) Jorgenson site



Trajectory B cumulative impacts

Climate change

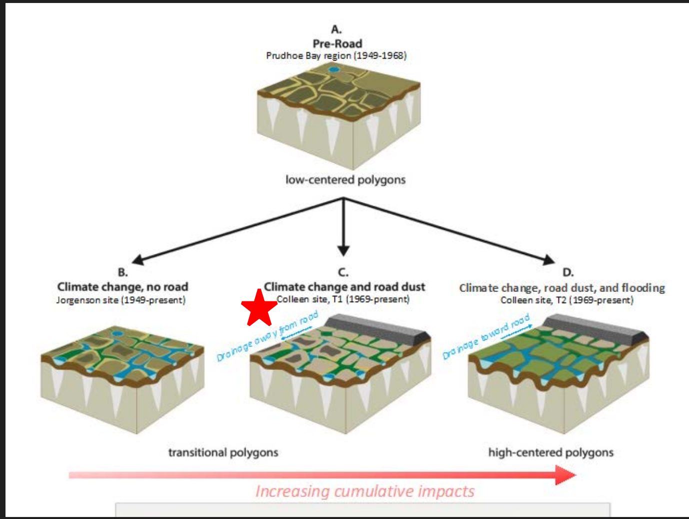
- ***Increase in water-body area:*** Approximately 7.5-fold increase in waterbodies since 1949; approximately 5-fold increase between 1988 and 2012.
- ***Changes to polygon morphology***: (a) Conversion from dominantly low-centered polygons to transitional and high-centered polygons; (b) more heterogenous vegetation (more ponds in troughs, drier tundra in polygon centers); (c) increase in snow and water depths in the polygon troughs, deeper active layers in polygon centers.
- ***Changes to ecosystem processes:*** (a) Water quality and microbiology in thermokarst-impacted water bodies (Vonk et al. 2015); (b) trace gas fluxes (Wickland et al. 2020; Kade, in prog.), (c) changes to polygon morphology (larger rims, more thermal cracking; profound changes in regional hydrology, and a much more heterogenous landscape) (Abolt et al. 2018, 2021); (d) large changes in pond communities and impacts to soil temperatures, ALT, and permafrost (Watson-Cook, in prog.); (e) extensive but unmeasured impacts to wildlife.
- ***Increased abundance of deciduous shrubs compared to areas sampled in the 1970s:*** 4.1-fold more in moist tundra and 5.6-fold more in wet tundra.

Results

Summary of of the four trajectories of change

Trajectory C:

Colleen Site T1 side of road
Climate change and road dust
(1969–present)



Trajectory C cumulative impacts:

Climate change

- Similar changes in pond area, microtopography, snow, thaw layers as the Jorgenson Site.
- **Greater cover of deciduous shrubs** near roads is likely due to a combination of warmer climate and disturbed soils.

Dust

- **Large dust impacts to vegetation** included much less cover of evergreen shrubs, forbs, mosses, and lichens compared to undisturbed vegetation types sampled in the 1970s. Loss of many diagnostic species, particularly lichens in undisturbed lichen-rich moist tundra.

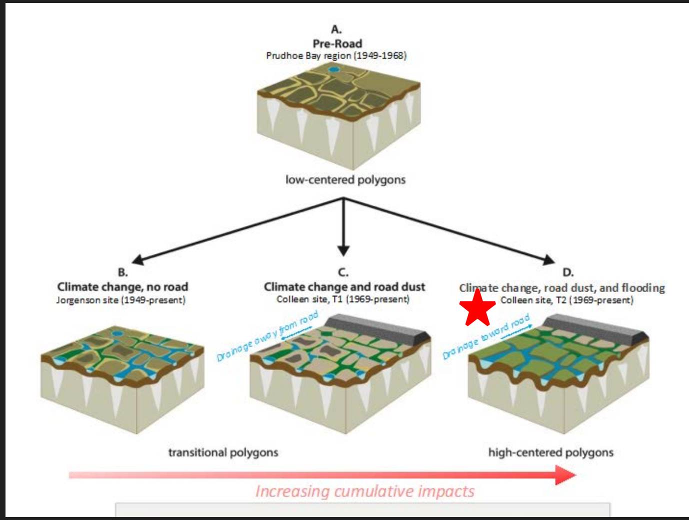
- **Accumulation of dust in troughs near roads reduced center-trough elevation contrasts and thermokarst** compared to the JS.

Results

Summary of of the four trajectories of change

Trajectory D:

Colleen site, T2 side of the road
Climate change, road dust, and flooding
(1969–present)



Trajectory D cumulative impacts

Climate change

- Impacts of climate change to ponding are difficult to tease apart from flooding impacts

Dust

- **Heavier volumes of dust on the Colleen T2 (downwind) side of the road created a barren margin to the road with sparse plant communities dominated by halophytic (salt-tolerant) plant species.**

Flooding

- Cumulative landscape effects of flooding on the T2 side compared to the other trajectories include **the thickest active layers in polygon centers, and deepest thaw depths, snow depths, and water depths in polygon troughs.**
- **The leaf area index (LAI) was overall 34% higher in vegetation plots on the flooded side of the road compared to the T1 side and 2.1 times higher in polygon centers on the T2 side compared to T1 centers**. The higher productivity is likely due to wetter early-summer soil moisture regimes, deeper thaw, higher rates of organic-matter decomposition, more nutrients from the dust, and high inputs of feces and decayed organic matter from the waterbirds that persistently graze the area.
- **Enhanced productivity and erosion of mineral material into the troughs is adding to the deeper litter layers and helping to protect ice wedges from further thaw** (Kanevskiy et al. 2017, 2022).

Φ

Conclusions

Climate change impacts

- The explosive growth in the numbers and size of small ice-wedge thermokarst ponds during the past 30+ years has transformed local microtopography, drainage patterns, vegetation, and ecosystem processes in ice-rich permafrost areas with near-surface ice-wedges.

- The increase in erect-shrub cover since the 1970s near roads and at over 200 m from the roads is likely a consequence of a combination the warming climate and road-related disturbances. This increase of shrubs in cold coastal landscapes is occurring more slowly than in inland areas.

Φ

Conclusions

Dust impacts

- Road dust has changed the distribution of common plant growth forms and the occurrence of many diagnostic species, especially small forbs, mosses, and lichens.

- Many dust-related impacts have logarithmic relationships to distance from the road and now evident in areas that are over 200-m from the road, especially on the downwind side of the road.

- Road dust has complex relationship with snow drifts, affecting ground temperatures, active-layer thickness, the timing of snow melt and green-up, and ice-wedge degradation near roads.

Conclusions

Flooding impacts

- Flooding at the Colleen site is attributed to combination of several factors related to both climate change and infrastructure, including (1) thermal degradation of ice-wedges in polygon troughs due to warmer air temperatures, (2) blockage of natural drainage patterns by the Spine Road, and (3) variations in the water level in Lake Colleen.

- The road-related flooding has magnified the climate-related thermal degradation in polygon troughs, changes to polygon morphology, snow distribution, maximum thaw depths, and vegetation patterns.

- The primary vegetation impact of flooding to vegetation is increased productivity of sedges, with corresponding impacts to LAI, increased grazing by waterfowl, increased litter, and increased protection to ice-wedges from thermal degradation.

Φ

Conclusions

Analysis of cumulative impacts (1)

- Historic baseline data were useful for examining the long-term cumulative impacts to the landforms and vegetation at the Colleen site and are needed for CIAs in new areas of proposed new development.

- A wide variety of local factors influence the trajectory of thermokarst, dust, and flooding (e.g., In this case, the proximity of Lake Colleen on the T2 side of the road greatly influenced the total area and interconnectivity of thermokarst features and the use of this area by waterfowl).

- Studies in other climates, geologic and topographic setting, and different types of road construction methods are needed to develop a broader understanding of the ecological consequences of building roads in areas with ice-rich permafrost.

Φ

Conclusions

Analysis of cumulative impacts (2)

- The full consequences of the major changes in thermokarst and hydrology to other components of the system, such as aquatic plant communities, invertebrates, birds, and other fauna, still need to be documented.
- Predicting the likelihood and extent of cumulative impacts of future development scenarios and climate change is currently very difficult. Much more work is needed to model the complex interactions of climate and infrastructure factors.
- Broader application of newer remote-sensing tools will greatly improve landform and vegetation-change detection at landscape and plot scales.

Eight recommendations for future cumulative impact assessment of roads in areas with ice-rich permafrost

1. Consider the likely consequences of climate-change and infrastructure-related impacts to permafrost, landforms, vegetation and ecosystems in areas with ice-rich permafrost.
2. Landscape sensitivity maps are needed for thermokarst risk assessment (e.g., Kanevskiy et al. 2017, 2022). Multi-year baseline of preconstruction geoecological and geotechnical conditions are needed, including details of the micro-topography, distribution and structure of ice-rich permafrost, snow, and vegetation.
3. Include impact of activities during the early phases of development, including leasing and seismic exploration, as well as the much more impactful exploration and development phases.
4. Use a hierarchical perspective to consider the cumulative consequences of climate change and land-use actions at local scales (e.g., this study), landscape and regional scales (e.g., Raynolds et al. 2014, Bergstedt et al. 2021), and global scales (e.g., Bartsch et al. 2020).
5. Better methods are needed to decrease the effects of road dust, roadside snow drifts, and flooding.
6. New remote sensing tools will improve monitoring permafrost terrain dynamics and infrastructure impacts.
7. Avoid construction in landscapes with very high risk of ice-wedge degradation <u>and</u> high conservation and/or subsistence land-use values.
8. After construction, continue monitoring the effects of the infrastructure and climate change to inform future CIAs.

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