Rapid Arctic Transitions due to Infrastructure and Climate (RATIC): A contribution to ICARP III

Five case studies, a summary of RATIC workshop activities, conclusions, and recommendations from RATIC workshops at the Arctic Change 2014 Conference in Ottawa, Canada, 8-12 December 2014, and the Arctic Science Summit Week, 23-30 April 2015 in Yohama, Japan

Prepared by members of the IASC Terrestrial, Cryosphere, and Social & Human Working Groups

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On the cover

Clockwise from top left: (1) Prudhoe Bay Oilfield, Alaska, photo: Pam Miller. (2) Nenets reindeer herder navigating the Bovanenkovo gas field, Russia, photo: Brian and Cherry Alexander. (3) Frost heave slows trains in Norway, photo: TU newspaper. (4) Building destroyed by thaw subsidence, Norilsk, Russia, photo: Zapolyarnaya Pravda, *foto.gazetazp.ru/77*. (5) Village of Salluit, Nunavik, Canada, photo: Mickael Lemay.

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Executive Summary

The Rapid Arctic Transitions due to Infrastructure and Climate (RATIC) initiative is 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. This white paper is provided as input to the Third International Conference on Arctic Research Planning (ICARP III).

Much of the information presented here is summarized from the RATIC activities at the Arctic Change 2014 conference, 8-12 December 2014, in Ottawa, Canada, and meetings during the Arctic Science Summit Week, 23-30 April 2015, in Toyama, Japan. The RATIC Ottawa meetings were organized so that international scientists who have been working independently on issues related to Arctic infrastructure in several areas of the Arctic could network with each other and share their findings. The activities included a workshop on 9 December and two topical sessions on 11 and 12 December 2014. During the Toyama meeting, a RATIC writing workshop was held on 25 April to consolidate new material and to discuss how to proceed with the white paper.

This white paper consists of five infrastructure case studies, a summary of the messages that emerged from the case studies and RATIC workshops, and recommendations for the ICARP III process. The case studies include: (1) the effects of oilfield infrastructure on landscapes and permafrost in the Prudhoe Bay region, Alaska; (2) analysis of the effects of gas- and oilfield activities on the landscapes and the Nenets indigenous reindeer herders of the Yamal Peninsula, Russia; (3) a summary of two Canadian initiatives that address multiple aspects of Arctic infrastructure called Arctic Development and Adaptation to Permafrost in Transition (ADAPT) and the ArcticNet Integrated Regional Impact Studies (IRIS); (4) an analysis of road infrastructure and climate change in subarctic Norway; and (5) a study of urban infrastructure in the vicinity of Norilsk, Russia.

Key conclusions

The key messages emerging from the case studies and workshops are:

1. There is a need to examine the cumulative effects of infrastructure in the context of Arctic social-ecological systems. Understanding the emergence and consequence of cumulative effects of infrastructure and climate change on high-latitude social-ecological systems requires the consideration of a number of dimensions. These include 1) accounting for the drivers of infrastructure and infrastructure change including the interaction of biophysical and social dynamics in Arctic Social-Ecological Systems; 2) evaluating the effects on ecosystem services, human residents and industry; and 3) crafting effective systems of governance to support adaptation to and mitigation of change. Framing these dimensions holistically requires transdisciplinary approaches that link science with policy.

2. Permafrost response to a combination of infrastructure and climate change is a pressing ecological issue that has large social costs. Permafrost thawing and its associated impacts on natural and built environments were clearly identified as priority issues across all regions of the Arctic, but the specific issues related to permafrost differ in each region studied. In communities and urban environments, changes to the thermal regimes of soils that support houses, roads, airports, and large buildings have large economic and social consequences. Ecological changes caused by thermokarst and other permafrost-related geomorphic processes are exacerbated by the soil-warming affects of infrastructure and are affecting the structure of landscapes, hydrological patterns, snow distribution, ecosystems, and the use of the land by northern residents and industry. These cumulative permafrost changes come at a time of intense demographic and socio-economic development in the Arctic.

3. The indirect effects of infrastructure exceed the direct effects of the planned footprints. Evaluating and predicting the effects of infrastructure and climate must extend beyond the direct area covered by roads, pipelines and facilities. Assessments of effects should include cumulative impacts of climate change and infrastructure on the adjacent ecosystems, local communities, regions, and areas outside the Arctic.

4. New tools are needed to monitor infrastructure and landscape changes and to develop sustainable approaches for future development. These include but a are not limited to: 1) integrated, interdisciplinary, whole-system approaches for examining the drivers and effects of infrastructure and climate change; this echoes the conclusions from the 2003 report by the U.S. National Research Council calling for regional ecosystem-level studies; (2) advanced GIS and remote sensing tools for studying change over large areas and in landscapes beyond the direct footprint of the infrastructure, for tracing small-scale disturbances that individually cover relatively small areas but which in total affect large landscapes, and for detecting changes to permafrost-related landforms such as landslides and thermokarst; (3) new techniques to model and predict the effects of fragmentation of large intact ecosystems, which have potentially large, long-term effects on fish and wildlife habitat, subsistence use of the land by indigenous people, and wilderness values; and (4) new scenario modeling approaches that involve the details of the affected landscapes and ecosystems, as well as foreseeable changes due to climate, economies, politics, demographics, land-use, and technological factors.

5. Infrastructure issues are not adequately addressed by any of the IASC working groups nor in many national-level Arctic science plans. IASC and ICARP III could play a key a role in helping to promote international projects and programs focused on sustainable methods of infrastructure development. Several programs in different countries provide examples of scientific approaches to sustainable infrastructure. The case studies cited in this paper provide some examples, including the Integrated Regional Impact Studies (IRIS) and the Arctic Development and Adaptation to Permafrost in Transition (ADAPT) program in Canada; the Finnish-sponsored Environmental and Social Impacts of Industrialization in Northern Russia (ENSINOR); the U.S. interagency North Slope Science Initiative (NSSI); and the National Science Foundation (NSF) Arctic Science, Engineering, and Education for Sustainability (ArcSEES) initiative in Alaska. Many other examples are available from industry and governments that are continuing to explore and develop useful approaches for sustainable infrastructure development.

Recommendations

Several steps were suggested to develop scientific research plans aimed at sustainable infrastructure development. The scope of the challenge includes: (1) examining the drivers of Arctic infrastructure in different Arctic cultures, economic systems, political environments, and ecological systems; (2) monitoring and understanding the vulnerabilities, resilience and full cumulative effects of Arctic infrastructure on the diverse group of Arctic social-ecological systems that are currently undergoing change; (3) planning, managing, and shaping future Arctic infrastructure; and (4) involving the Association of Polar Early Career Scientists (APECS) in the process to provide new energy and new ideas and to assure continuity of the effort through the next decade of Arctic research. Future planning needs to include consideration of the widely divergent political systems, economies, cultures, communities and landscapes present in the Arctic, fragmentation of presently intact natural landscapes by large networks of roads and pipelines, Arctic urban infrastructure, engineering of sub-arctic infrastructure, and Arctic off-shore infrastructure.

As first steps, the RATIC group recommends that the combined IASC Cryosphere, Social & Human, and Terrestrial Working Groups work together to: (1) Finish the RATIC white paper and post it on the ICARP III website as a product of the ICARP III planning process; (2) publish a summary of the white paper and follow-up synthesis activities in an appropriate peer-reviewed journal; (3) develop an interdisciplinary IASC Infrastructure Action Group that includes participation by members of all IASC working groups and APECS; (4) incorporate infrastructure-related issues more explicitly in the IASC working groups' research priorities; (5) promote regular infrastructure workshops at international scientific meetings; (6) emphasize the need for social-ecological-system studies in relationship to infrastructure; and (7) promote infrastructure-related themes in future international research initiatives.

Members and fellows of three IASC Working Groups proposed the following resolution for ICARP III:

Whereas:

- Northerners and Arctic socio-ecological systems are strongly impacted by changes in infrastructure;
- The drivers and consequences of infrastructure development in the Arctic are not adequately addressed by the Arctic research community; and
- The complexity of the Arctic infrastructure challenges requires a multidisciplinary and circumpolar collaboration approach involving all Arctic countries and implementation of an integrated social-ecological-system approach.

Therefore:

We propose that ICARP-III identify **sustainable infrastructure development** as a key research theme that requires a multidisciplinary collaborative approach involving scientists, local communities, governments, and industry.

This issue was adopted as one of the overarching messages from Arctic Science Summit Week 2015.

Acknowledgments

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Introduction

During the next few decades, the Arctic will see a continuation of warming and widespread expansion of infrastructure associated with extraction of Arctic resources. Climate change has drawn the attention of most of the Arctic scientific community, but the interacting effects of climate change and expanding infrastructure have received relatively little scientific research, despite increasing evidence that anthropogenic activity and climate change are interacting in complex ways to alter large areas of the Arctic. Several factors point to the need for coordinated interdisciplinary studies to examine infrastructure-related issues, including: (1) The large scale and differing nature of infrastructure and climate change impacts in different parts of the Arctic; (2) the complex, multidisciplinary and cumulative nature of the impacts to social and ecological systems; and (3) the need for new methods to assess cumulative effects and promote sustainable methods of infrastructure expansion.

The Rapid Arctic Transitions due to Infrastructure and Climate (RATIC) initiative is a forum for developing and sharing new ideas and methods to assess, respond to, and adaptively manage the cumulative effects of Arctic infrastructure and climate change. IASC helped support a RATIC workshop and two topical sessions at the Arctic Change 2014 conference in Ottawa, 8-12 December 2014. This white paper describes the RATIC initiative and summarizes five case studies, the first four of which were presented in Ottawa. The fifth was presented at the Arctic Science Summit Week in Toyama, 23-30 April 2015, as was much of the concluding material.

Overview of the RATIC workshops at Arctic Change 2014 and Arctic Science Summit Week 2015

The RATIC workshop at the Arctic Change 2014 conference included approximately 40 participants. Workshop talks were grouped into three case studies: (1) Cumulative effects of infrastructure and climate, North Slope, Alaska; (2) Russian Arctic oil and gas development and climate change interactions; and (3) Canadian Arctic development. The two topical sessions on December 11-12 included 10 oral presentations and 17 posters that included first-authored papers and posters from the U.S. (9 papers), Russia (9 papers), Canada (6 papers), Finland (2 papers), and Norway (1 paper). The agenda for the workshop and 27 abstracts of the topics presented during the conference can be found at the website: *www.geobotany.uaf.edu/yamal/workshops/ratic2014.php*

A RATIC writing workshop at Arctic Science Summit Week 2015 in Toyama, Japan (23–30 April) involved members and APECS fellows of the IASC Cryosphere, Social & Human, and Terrestrial working groups. The group developed a resolution aimed at recognizing sustainable infrastructure development as a priority issue for the Third International Conference on Arctic Research Planning (ICARP III).

Case Study 1: Cumulative effects of infrastructure and climate in the permafrost landscapes of the Prudhoe Bay oilfield, Alaska

Figure 1. The Prudhoe Bay oilfield, North Slope, Alaska. *(Photo: Courtesy of Pam Miller)*

Alaska's North Slope oilfield complex (Figs. 1 and 2) is the most extensive industrial complex in Arctic North America. Several studies have examined the cumulative effects of the oilfield development (Walker *et al.* 1987; National Research Council 2003; AMAP 2010; Raynolds *et al.* 2014). The report by the National Research Council was the most comprehensive and included a detailed history of development and an assessment of the effects to the physical environment, vegetation, animals, and the human environment (National Research Council, 2003).

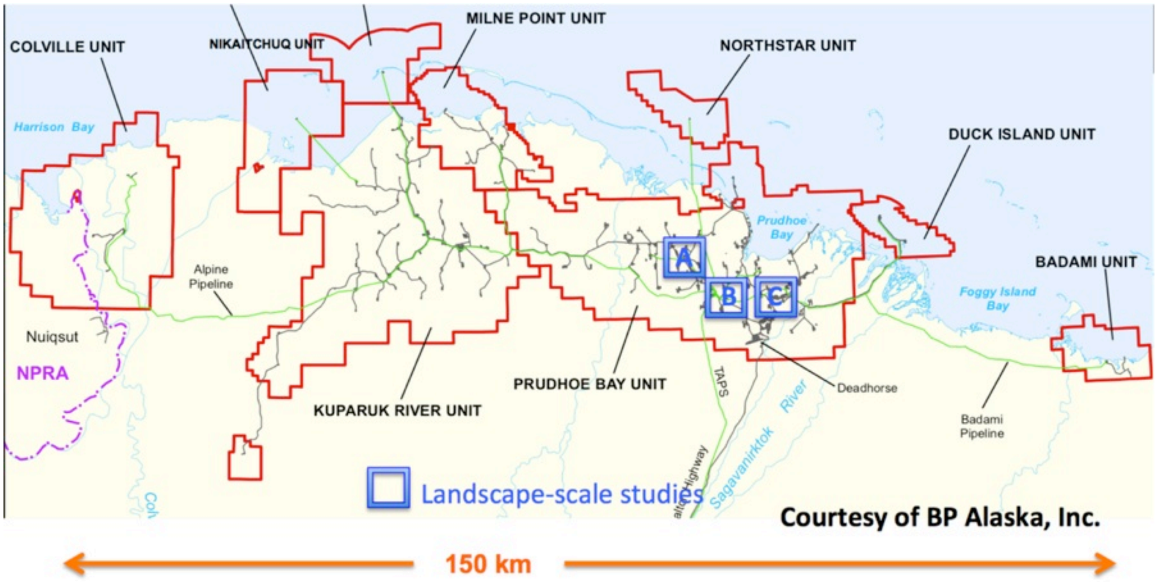

***Figure 2. Alaska North Slope oilfields. Red boundaries**: major oil production units including the Prudhoe Bay unit in the central part of the diagram. **Gray lines**: gravel roads, airstrips, and construction pads. **Green lines**: major pipelines. Note the Iñupiat village of Nuiqsut in the National Petroleum Reserve–Alaska (NPR-A). The Trans-Alaska Pipeline System (TAPS) and the Dalton Highway link the oilfields to Fairbanks, Alaska. Analyses of historical infrastructure changes between 1968 and 2010 have been done for the entire area of the map excluding TAPS and the Dalton Highway system. **Blue boundaries A, B, and C** are locations of the landscape-level analyses. (Courtesy of BP Exploration Alaska.)*

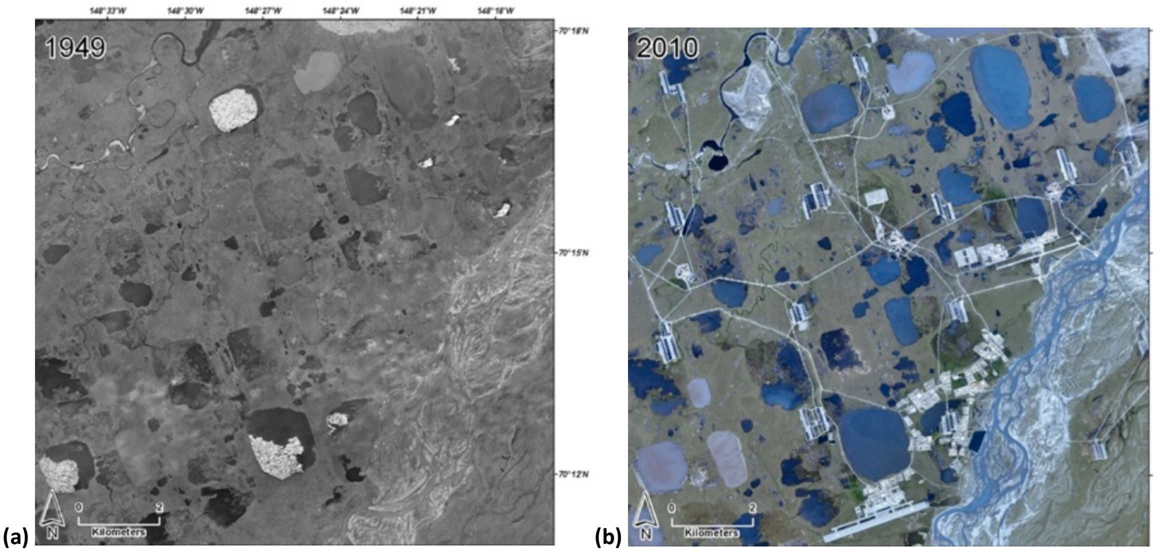

__Figure 3. Eastern portion of the Prudhoe Bay Oilfield: (a)__ 1949, prior to development (U.S. Navy, July 6, 1949, 1:20,000-scale BAR photography). __(b)__ 2010, World View satellite image, false color-infrared (CIR) composite with 0.5 m pixel resolution. Prominent features in both images include Lake Colleen (the large, partially ice-covered lake in the lower center of the 1949 image), the braided Sagavanirktok River on the right side of the images, and the Putuligayuk River in the upper left. Also visible are several thaw lakes and partially drained thaw lakes. Prominent features in the 2010 image include numerous gravel pads that support service and contractor facilities for the oilfield, and the network of roads and pipelines that connect the various facilities. The Deadhorse Service Area includes the Deadhorse Airport south of Lake Colleen and the concentration of facilities between Lake Colleen and the Sagavanirktok River.

Following completion of the NRC report, more recent observations noted an abrupt increase in the occurrence of thermokarst near Prudhoe Bay (Jorgenson *et al.* 2006). This case study describes large changes in landscapes and ecosystems in the Prudhoe Bay oilfield that are a consequence of a combination of a warmer climate and the thermal effects of oilfield infrastructure. The implications of these changes for local people and the industry are the topics of ongoing social science studies.

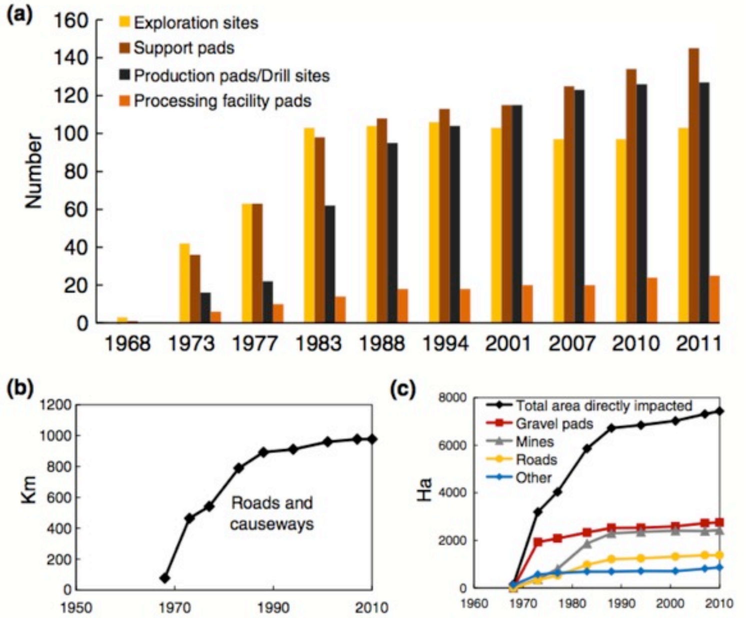

__Figure 4. History of North Slope oilfield infrastructure__ (direct effects, 1968-2011). The data exclude the Dalton Highway and the Trans-Alaska Pipeline; __(a)__ number of infrastructure items; __(b)__ total length of roads; __(c) total area of__ direct impacts. (Data courtesy of Aerometric, Inc. and BP Exploration Alaska)

Direct and indirect landscape effects of infrastructure at Prudhoe Bay

The history of industrial development in northern Alaska is documented in a time series of aerial photographs and satellite images obtained by the oil industry and U.S. government agencies since 1949 (Figs. 3 and 6). Essential prerequisites for the analyses were baseline geoecological studies conducted during the 1970s by the International Biological Program (IBP) Tundra Biome (Brown 1975, Walker *et al.* 1980, and Everett *et al.* 1973). The direct effects of oilfield development are the expanding footprints (area covered) of engineered infrastructure (Ambrosius 2003). These are captured in the oil industry's GIS database (Figs. 2 and 4), which includes the extent and year of construction of all gravel pads, exploration sites, exploration islands, airstrips, culverts, bridges, roads, major trails, gravel mines, pipelines, and major power transmission lines. The industry's database was used to complete a time-series analysis of the direct effects of development.

The number, length, and extent of infrastructure features increased rapidly during the early phase of development (1968-1983), leveled off between 1983 and 2001, and has shown another surge in recent years as oilfields expand westward (Fig. 4). As of 2011, there were 973 km of roads, causeways, and trails, 790 km of elevated-pipeline corridors, 507 km of transmission lines, 2,037 culverts, and 27 bridges. These various forms of infrastructure covered 7,429 ha (74.3 km^2), the total area directly impacted in Fig. 4c (Ambrosius 2014). The total area encompassed by this network of infrastructure was approximately 2,600 km^2.

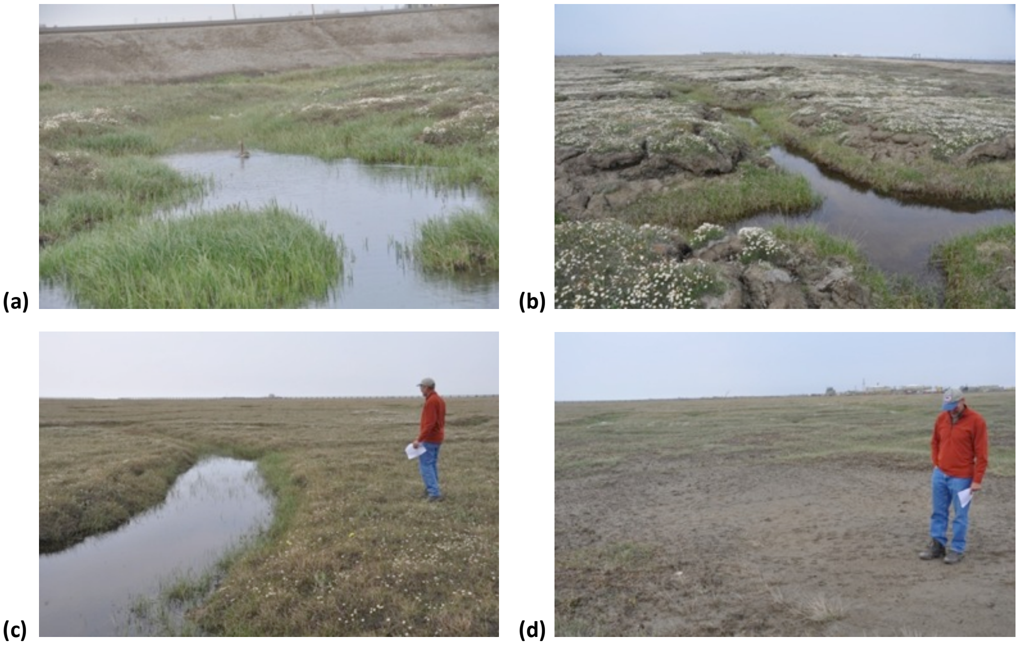

Figure 5. Examples of thermokarst and road dust effects, Prudhoe Bay Alaska. (a) *Changes in the surface thermal conditions near infrastructure often lead to warmer soils, deeper summer soil thaw—which in warm summers can penetrate to the ice wedges, leading to melting of the top surface of the ice-wedges—subsidence of the ice wedges, accumulation of water in polygon troughs, and development of wetland habitat.* ***(b)*** *The subsidence of the polygon troughs creates large microtopographic changes with the centers of ice-wedge polygons often becoming relatively well-drained habitat. Here, the pale-yellow-flowered* Dryas integrifolia *covers large areas of high-centered ice-wedge polygons. Prior to construction of the Spine Road these were low-centered polygons.* ***(c)*** *Example of climate-driven thermokarst in an area distant from infrastructure.* ***(d)*** *Area of heavy dust downwind of the Spine Road. (Photos: D.A. Walker, July 1, 2013).*

Indirect impacts are less predictable effects that occur after infrastructure is in place, such as roadside dust, flooding, snow drifts, off-road vehicle trails, and thermokarst (examples in Figs. 5, 6, and 7). Analysis of indirect landscape effects required construction of a separate GIS database at a finer scale using detailed photo-interpretation of high-resolution aerial photographs and knowledge of the geoecological characteristics of the landscapes. This was done as of 1983 for three portions (A, B and C in Fig. 2) of the Prudhoe Bay oilfield (Walker *et al.* 1987) and recently updated (Raynolds *et al.* 2014, Walker *et al.* 2014).

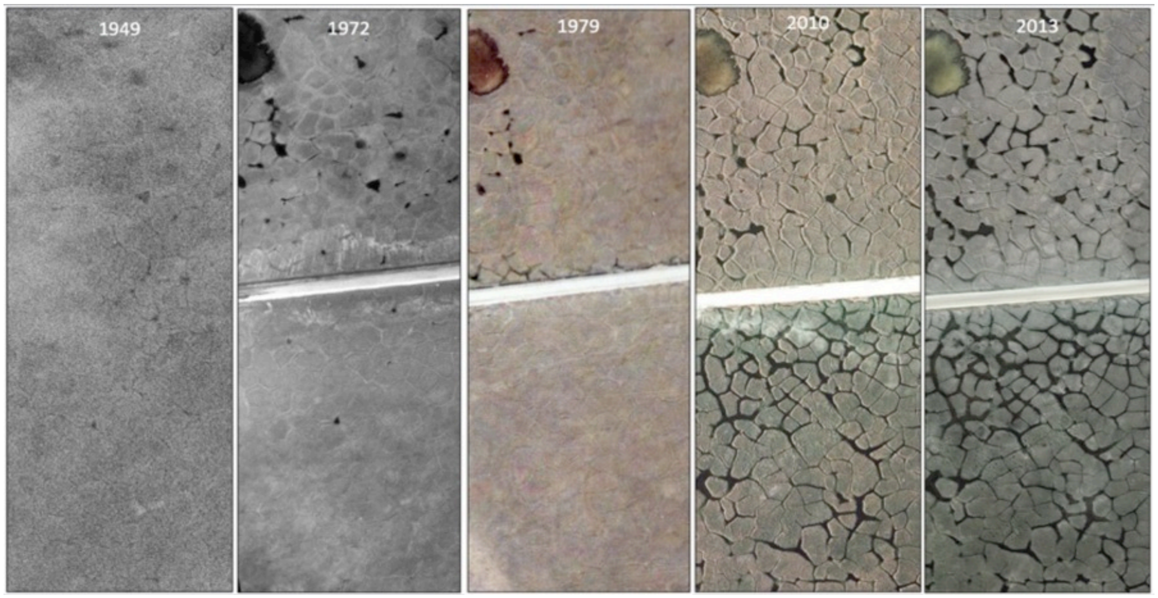

Figure 6. Progression of indirect roadside impacts along the Prudhoe Bay Spine Road near Lake Colleen. *Time series of aerial photographs of Colleen Site A, 1949-2013. The Spine Road was constructed in 1969 so it does not appear on the 1949 image. Thin cloud cover obscures the small lake in the upper left corner of the photo, but most of the thermokarst pits that were present in 1972 are also visible on the 1949 image. In 1972, gravel from road construction occurs on both sides of the road. In 1979, some roadside thermokarst is visible near the road on the north side (above the road in the photo). By 2010, extensive thermokarst is present on both sides of the road, but is most developed south of the road due to periodic flooding from a nearby lake. By 2013, most thermokarst on the south side of the road was connected to Lake Colleen by continuous channels of water in the polygon troughs (Walker* et al. *2014).*

Within the three areas of detailed analysis (Fig. 2 A, B, and C), the total area of direct effects as of 2010 was 919 ha or 14.6% of the mapped area, ranging from 12.2% in map A to 19.3% in map C (Raynolds *et al.* 2014). The largest direct effects were those of gravel pads, which covered 438 ha, followed by excavations (257 ha), roads (136 ha), and pipelines (79 ha) (Fig. 7a).

By 1977, the indirect effects exceeded the direct effects and have shown an almost linear rate of increase of about 23 ha y^{-1} in the most recent twenty years (1990–2010). As of 2010, the area affected by indirect effects was 1,794 ha (28.6% of the area of the three maps), or about double the area of direct effects. Flooding covered the most area (701 ha), followed by infrastructure-related thermokarst (367 ha), gravel and debris adjacent to roads and pads (332 ha), and off-road vehicle trails (291 ha).

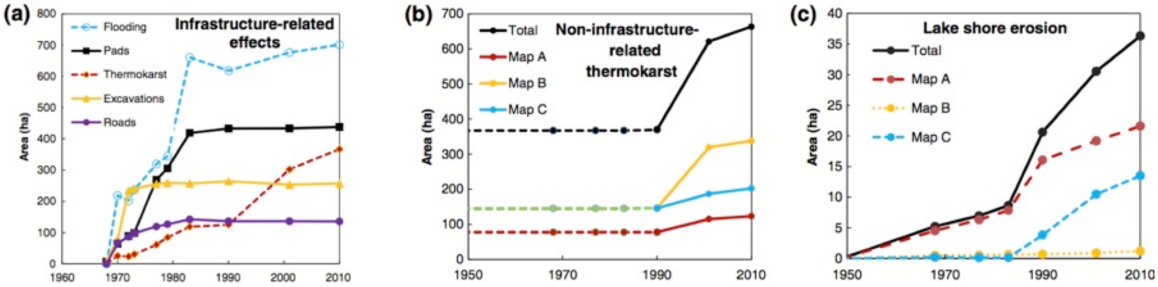

Figure 7. History of changes (1949–2010) *in three 22-km^2 mapped areas within Prudhoe Bay Oilfield, North Slope, Alaska:* ***(a)*** *History of most common infrastructure-related effects. Solid lines: direct infrastructure effects including roads, excavations [gravel mines] and gravel pads. Dashed lines: indirect effects [flooding (blue dashed line) and thermokarst (red dashed line)]. Note:* ***(b)*** *History of non-infrastructure-related (regional) thermokarst for three 22-km^2 areas (A, B, C, see Fig. 2) and total. The portions of lines between 1949 and 1990 that are dashed showed minor but unquantified changes between 1949 and 1990.* ***(c)*** *History of lakeshore erosion for maps A, B, and C and for the total mapped area. (Raynolds* et al. *2014)*

Flooding and road dust

Roads and gravel pads in the Prudhoe Bay region are elevated up to a 1.5 m above the tundra in order to minimize subsidence due to thawing permafrost. These elevated structures dam the flow of runoff water during the spring melt season. Extensive flooding is especially likely wherever networks of infrastructure intersect drained thaw-lake basins. Most of the main roads and pipelines in the Prudhoe Bay oilfield were built by 1983, when road-related flooding also leveled off (Fig. 7a). By 2010, the area flooded due to infrastructure occupied nearly as much area (701 ha, 11.2%) as the infrastructure itself (919 ha, 14.6%) (Fig. 7a), and ranged from 25.1% of map A, an extremely flat area with large areas of drained thaw-lake basins, to 2.0% of map C, a relatively well-drained area close to the Sagavanirktok River with relatively few thaw-lake basins.

Figure 8. Soil plug taken from low-centered polygon in a roadside area*. Note the 13-cm thick mineral surface horizon, which is the dust layer above the original organic surface horizon.*

Road dust is another infrastructure-related factor contributing to changed ecosystems at Prudhoe Bay. Traffic has generated high volumes of dust over the 45-year history of the road network (note the dust plume from a vehicle in Fig. 5b, 2010). Soils within about 50 m of the Spine Road now have mineral surface horizons composed largely of road dust and gravel that overlie the original organic soil horizons (Fig. 8) (Walker *et al.* 2015). Surface mineral horizons up to 18 cm thick cover the original organic horizons. The mineral surface horizons decrease in thickness away from the road, but even at 200 m from the road the underlying organic materials have a gray color indicating leached dust. Vegetation in areas within approximately 25-50 m of the road have much diminished diversity of vascular plants, mosses, and lichens compared to species composition in similar nearby areas surveyed in 1975. Bare soils and sparse moss carpets have replaced the original thick moss and lichen carpets.

Thermokarst

During the early years of the oilfield, thermokarst affected rather small areas immediately adjacent to roads, but by 2010 thermokarst had spread well beyond the road margins (Fig. 5). Infrastructure-induced thermokarst is now the second most extensive indirect effect next to flooding (Fig. 7a). Flooding, road dust and snowdrifts associated with the roads, and the generally sparser plant communities, all contribute to higher soil temperatures and thicker active layers (the layer of ground subject to annual thawing and freezing) near roads. All of these factors contribute to roadside thermokarst. Over the 42-year history of the study, infrastructure-related thermokarst eventually covered 367 ha (5.9%) of the total area of Maps A, B and C. Most noteworthy was the 2.3-fold increase of infrastructure-related thermokarst in the 11 years between 1990 and 2001. The rate of increase slowed somewhat during the decade between 2001 and 2010 (Fig. 7a).

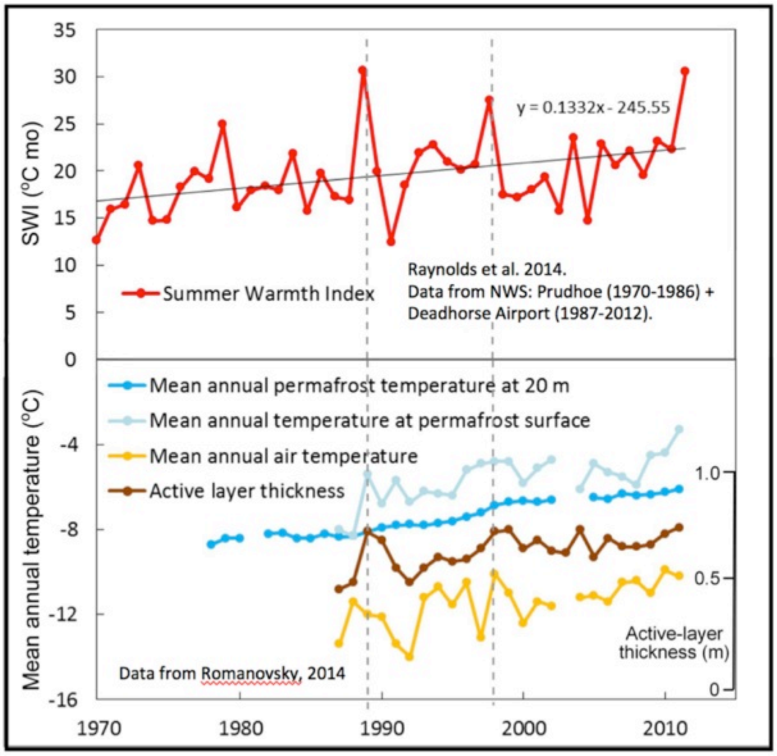

Figure 8. ***Climate and permafrost data from Prudhoe Bay. Top graph:*** *Summer warmth index (SWI = Sum of the monthly mean temperatures above freezing, °C mo). Data are from the Western Regional Climate Center, Prudhoe (1970–1986) and Deadhorse (1987–2012).* ***Bottom graph:*** *Mean annual air temperature at 2 m height (MAAT, yellow line), mean annual permafrost temperature at 20-m depth ($MAPT_{20}$, cyan line), mean annual temperature at the upper surface of permafrost (MAPTs, light blue line); and active layer thickness (ALT, brown line and scale on right). Data in lower graph are from Osterkamp and Romanovsky Deadhorse station. The climate station and maps (A, B, and C) are within 15 km of each other. Active layer depth was measured by interpolation of soil temperature data from several depths for 1987–1996 and by using a metal probe for 1997–2011. Note the corresponding peaks in SWI, ALT, and $MAPT_S$ in the extreme warm summers of 1989 and 1998 (gray dashed lines), which are within the period of the GIS analysis of Areas A, B, and C. (Raynolds* et al. *2014)*

Non-infrastructure-related (regional) thermokarst in areas distant from roads and pads also showed rapid growth during the 11 years between 1990 and 2001, when thermokarst increased 1.65 times (Fig. 7b). Lakeshore erosion increased 1.45 times during the same time period, further illustrating the effects of erosion of the ice-rich terrain (Fig. 7c). The rapid regional increases in thermokarst and lakeshore erosion between 1990 and 2001 are consistent with the records for summer air temperature, permafrost temperature and active-layer depth, which all showed rapid increases during the 1990s (Fig 8). Similar abrupt increases in thermokarst were reported west of Prudhoe Bay during the period 1982 to 2001 (Jorgenson *et al.* 2006). The most important factor is thought to be the depth of the active layer (brown line in Fig. 8), which peaked in 1989 and 1998-1999.

Two scenarios of thermokarst change are presented in a model (Shur *et al.* 2014) (Fig. 9), and are being examined during ongoing field studies at Prudhoe Bay (Walker *et al.* 2014, 2015). The first process, shown by the blue arrows in Fig. 9, is reversible and appears to be most common under conditions of climate-only driven thermokarst in decades prior to 1990. In this situation, thermokarst can be triggered during summers with exceptionally warm temperatures when the active layer exceeds the thickness of the sediments protecting the ice wedges. This process is reversible because the flooding of the polygon troughs also induces increased vegetation production, which increases the yearly increment

t of organic matter, creating an insulative layer that pro-

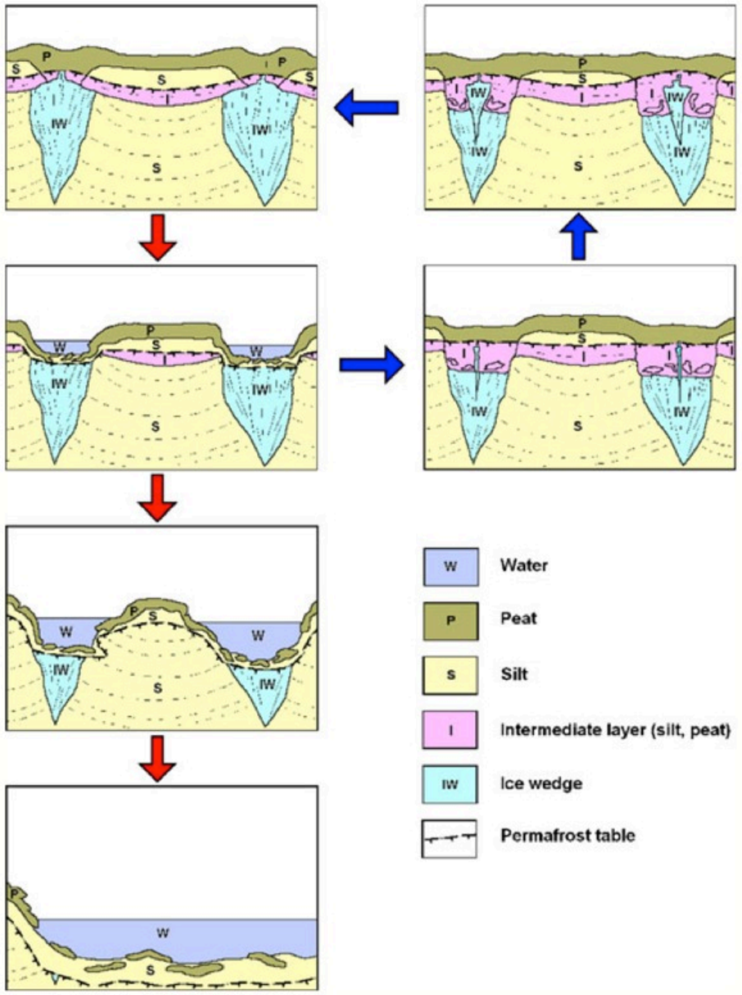

Figure 9. Two possible scenarios associated with thermokarst ice-wedge polygon terrains. Blue arrows: *A stable or reversible process is often observed in natural environments. The centers of polygons remain stable because the protective, insulative mat of vegetation and organic soils remains undisturbed.* ***Red arrows:*** *An unstable or irreversible pathway leads to larger water bodies and thaw lakes if the central parts of the polygons experience thaw settlement. This can occur when the thermal insulating properties of the vegetation and organic soils are reduced due to the accumulation of road dust, infrastructure-related flooding, or other disturbance, resulting in increases in the thickness of the active layer (Shur* et al. *2014)**.***

tects ice wedges in future years.

Irreversible thermokarst (red arrows in Fig. 9) can occur when the thermal and organic soils are reduced due to disturbance resulting in increases in the thickness of the active layer in the centers as well as the troughs of the ice-wedge polygons. This could lead to the gradual destruction of areas between the ice wedges and eventually to the formation of larger ponds and possibly new thaw lakes.

The prospect of future oil and gas development in northern Alaska

A synthesis of existing, planned, and proposed infrastructure and operations supporting oil and gas activities and commercial transportation in Arctic Alaska has recently been completed as a prelude to future scenarios planning (Hillmer-Pegram 2014). The following synopsis regarding future development in Alaska presents a picture of impending changes that will require an integrated and collaborative approach between agencies, local communities, and industry to manage cumulative effects of oil and gas development:

> *Today, the existing estimated footprint of oil and gas infrastructure totals well over 18,000 acres [7284 ha]. At the time of this writing, expansion of oil and gas infrastructure continues as the industry develops specific projects located at the outer edges of the existing infrastructural complex. For example, infrastructure is expanding to the east in the form of the Point Thomson project and to the west through the ongoing development of the Colville River and Greater Mooses Tooth Units within NPR-A. Simultaneously, oil and gas exploration activities continue to the north (in multiple offshore environments) and to the south of existing infrastructure (in the foothills of the Brooks Range). Commercial transportation infrastructure is also expanding, as construction crews build the road from the Manley Hot Springs area to Tanana. These construction projects and others are categorized as "planned infrastructure" in this report. They are relatively modest in scope and size, adding to the extent of existing infrastructure by only a few percent. Nonetheless, these projects represent the latest stages of a long-term trend of incremental expansion of industrial infrastructure in the region….[I]t is impossible to predict which projects will go forward, what they will look like, and when they will be developed. However, if "proposed infrastructure" projects develop in the manner described in state and federal analyses, the extent of Arctic Alaska's industrial infrastructure would increase significantly. The number of structures would almost double, from 460 to 816. The number of wells would increase by around one third, from 6,215 to 8,673. Miles of road would more than double, from 1,138 [18,208 km] to 2,503 [4005 km]. Miles of pipeline would more than quadruple, from 901 [1442 km] to 4,667 [7467 km]. Lastly, the infrastructure footprint would increase by about half, with over 27,000 acres [10,926 ha] of Arctic Alaska ultimately being directly covered or excavated for industrial development. The area and resources affected by that infrastructure footprint—what the NRC refers to as "zones of influence"—would be considerably greater.*
>
> *Importantly, the numbers in the preceding paragraph do not take into account potential infrastructure from a number of significant proposed projects. For example they do not include a North Slope gas pipeline or trucking project, development of unconventional resources in the Central North Slope, a road across NPR-A to support OCS production, construction of a deep-draft port along the west coast, or a rapid boom in trans-Arctic*

shipping. If some or all of those proposed projects go forward, it would further increase the expansion of infrastructure in Arctic Alaska (Hillmer-Pegram 2014).

Implications for ecosystems

The road networks and infrastructure associated with present and proposed oil and gas activities have numerous effects on ecosystems adjacent to the roads caused by dust, flooding, snowdrifts, and thermokarst (Walker & Everett 1987, Raynolds *et al.* 2014, Walker *et al.* 2014). Earlier snow melt, warmer soil temperatures, and extensive new wetlands near the roads affect the phenology of vegetation and use of the roadside areas by wildlife. Large flocks of waterfowl forage in the roadside areas during the melt period until other areas become snow free. Other animals, including ground squirrels and caribou, also concentrate near the roads during the snowmelt period. A new zone of reduced moss and lichen cover and noticeably high cover of taller, erect dwarf willows (*Salix lanata*) occurs in many roadside areas. The changes in microtopography are of greatest consequence (Fig. 5). Large areas adjacent to roads and in open tundra far from infrastructure, which were previously covered by homogeneous networks of wet, low-centered polygons with trough-rim relief of less than 0.5 m, have been converted to more heterogeneous, high-centered-polygon landscapes with greater than 0.5 m of relief. These more heterogeneous landscapes have deep ponds, extensive channels of waters in the polygon troughs, and well-drained polygon centers.

The full implications of these ecosystem transitions have not been studied, but many new questions were generated, including: (1) Is it possible to develop models that link hydrological processes to ice-wedge melting to better predict pathways of thermokarst and erosion processes in networks of ice-wedge polygons? (2) How are the diversity and distribution of tundra organisms including plants, invertebrates, small mammals, shorebirds, waterfowl, fish, caribou, and predators affected by thermokarst? (3) How do the warmer soils associated with most forms of infrastructure affect a suite of key ecosystem processes, such as plant water uptake, plant productivity, decomposition rates, and trace-gas fluxes? (4) How do heavy dust loads from the roads affect mosses, lichens, biological soil crusts, and the diversity of soil microorganisms that help stabilize and insulate the permafrost? (5) Will thermokarst continue to expand, possibly leading to formation of larger thaw ponds and lakes, or will the transformations lead to generally drier landscapes? In either case, the transformations will be mainly toward more diverse landscapes.

Implications for social systems and adaptive management of infrastructure expansion

Several questions related to Prudhoe Bay development activities are driving current human dimensions studies on Alaska's North Slope: (1) Do landscape changes associated with infrastructure expansion and climate change have implications for local people, including industry and North Slope oilfield workers? (2) Do these factors affect local-use subsistence resources, including summer and winter travel, and access to subsistence resources? (3) How are infrastructure changes affecting ecosystems services and important subsistence-cash economies at the community level? (4) How do local people evaluate their capacities to respond to change, given the projections for future industrial development and climate change? (5) Can the knowledge gained from such studies improve future construction of ice roads, pads and pipelines, the process of tundra restoration following the removal of gravel roads and pads? (6) Can increased knowledge and documentation of the historical changes and the processes improve adaptive management and planning for future oilfields? (7) What are the prospects of operationalizing "adaptive management" (AM) in decision-making regarding exploration, development, and production of oil fields?

In the context of North Slope oil and gas development, the implementation of AM has been the expressed goal of several agencies, including the Alaska Department of Natural Resources (DNR) as well as collaborative regional efforts, such as the North Slope Science Initiative (NSSI) and the Arctic Land Conservation Cooperative (LCC). The NSSI has undertaken this effort by building metadata sets, developing emerging issue papers, and most recently initiating scenarios analyses (Streever *et al.* 2011). At the agency level the results of these efforts have been mixed. For example, a study by DNR's Northern Regional Office found a number of organizational and informational constraints in the implementation of AM and cumulative effects assessment, including the problem of limited staff size, high turnover of agency personnel, limitations in handling the high number of applications, a lack of standardized policies and guidelines for addressing applications, limited engagement with a greater community such as university researchers and regional assessment teams, and inadequate GIS capacity (Wishnie 2003). In other cases problems have followed from legal constraints in undertaking environmental impact assessments, which do not provide opportunities for simulation modeling and structured decision support tools.

The 2003 NRC Cumulative Effects report summarized these issues, but to our knowledge no recent evaluations of the effectiveness of AM in addressing possible cumulative effects has been completed for the North Slope oilfields. Larger oilfield development firms at Prudhoe Bay do have several AM principles in place as corporate operating procedures. Tundra rehabilitation and restoration, netting waste pits, use of strobes to deter bird strikes, waste management (from dumping to injection), pipeline heights for caribou movement, reuse of gravel, spill response protocols, and management of sedimentation near causeways are a few examples of where monitoring, research and learning through time has led to the modification of practices.

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Case Study 2: Russian Arctic oil and gas development and climate change interactions

History of development

The Bovanenkovo Gas Field (BGF) was discovered in 1972 in the central Yamal Peninsula (Fig. 10), about 500 km from the contemporary road and rail network of West Siberia. The BGF is one of the largest in Russia in terms of proven reserves. The first construction phase began in the mid-1980s with several drilling sites and electrical power plants. In the early 1990s, construction plans were frozen as the Soviet Union collapsed and the new Russian economy declined. From 1993 to 2005, primarily maintenance activities were conducted in the field (Forbes & Stammler 2009; Forbes *et al.* 2009; Kumpula *et al.* 2010; 2011; 2012).

In 2002, Gazprom launched new plans for gas development in the region to include three main industrial zones: Bovanenkovo, Tambey, and Yuzhnaya. At present, the BGF infrastructure is rapidly expanding, with a massive influx of shift workers (Forbes *et al.* 2009, Kumpula *et al.* 2012). The railroad from Obskaya to Bovanenkovo (572 km) was one of the

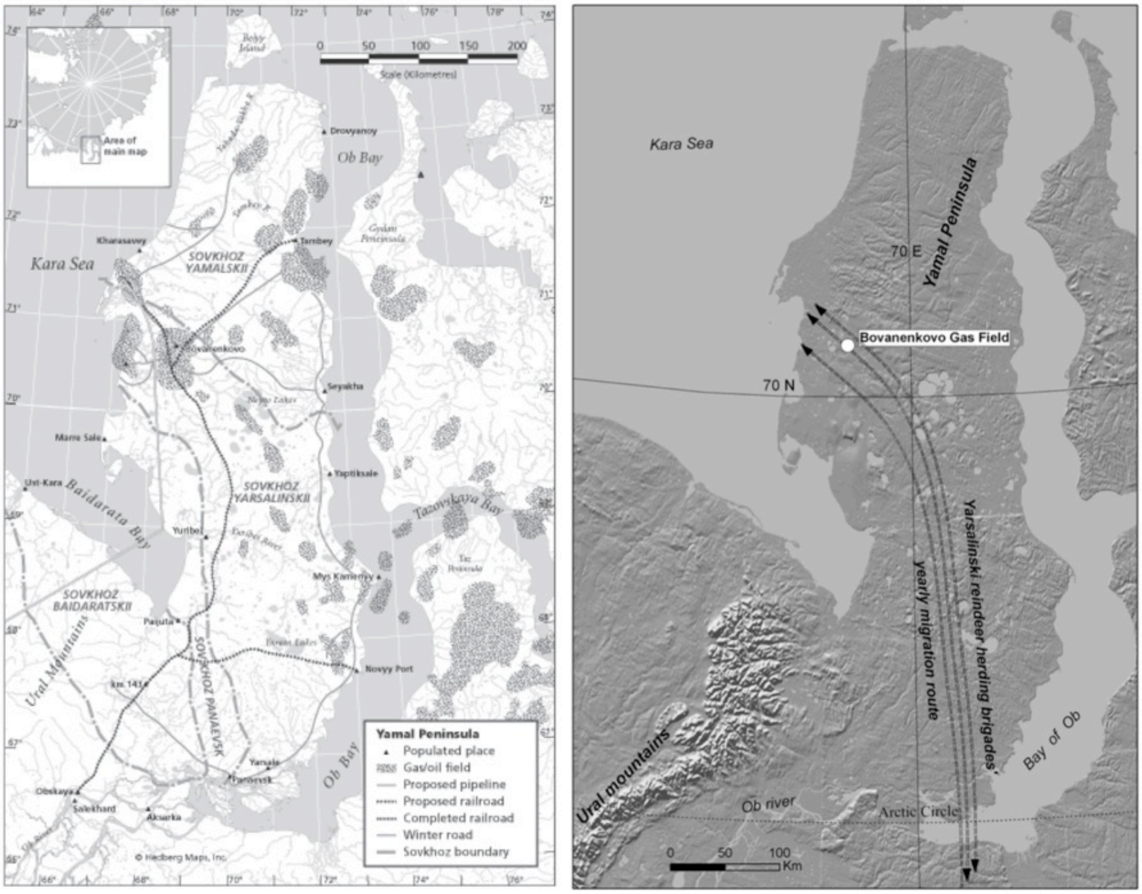


***Figure 10. The Yamal Peninsula. Left**: Hydrocarbon fields, and associated infrastructure. **Right**: Location of the Bovanenkovo Gas Field (white circle) at 70˚20' N, 68˚30' E. Arrows indicate the yearly migration paths of the Yarsalinski sovkhoz reindeer-herder brigades. The brigades travel 1,200–1,400 km between the most distant summer pastures by the Kara Sea coast and the winter pastures that lie south of the Bay of Ob.*

largest construction efforts. The railway was half finished by the early 1990s, but construction stalled south of the wide Yuribei River valley until 2009 when a 4-km-long bridge across the floodplain was completed (Fig 11). Construction of preparatory housing and transport began in 2007. The first gas pipeline was built from Vorkuta to Bovanenkovo by 2011, and the BGF opened for production at the end of 2012. (*www.yamaloilandgas.com/en/yamal-invest*).

***Figure 11. Cargo train on the bridge over the Yuribei River** floodplain traveling to the Bovanenkovo gas field. (Photo: T. Kumpula, July 7, 2010)*

Areas covered by permanent infrastructure in the main BGF include gas field facilities, stations, roads, airfields, and paved areas, which increased from 2.8 km² in 1984 to approximately 40 km² by 2014. The visibly affected area around the BGF, estimated from remote sensing imagery, later fieldwork, and interviews of gas field workers, increased rapidly from approximately 70 km² in 1984 to 320 km² by 1988. Expansion slowed between 1993 and 2001, but in 2010 the new development phase began and the affected area increased to almost 1,000 km² by 2014 (Fig. 12).

Landscape disturbances related to permafrost

Highly erodible sands and the presence of massive tabular ground ice near the tundra surface contribute to landslides and thermo-denudation of slopes in the Central Yamal Penin-

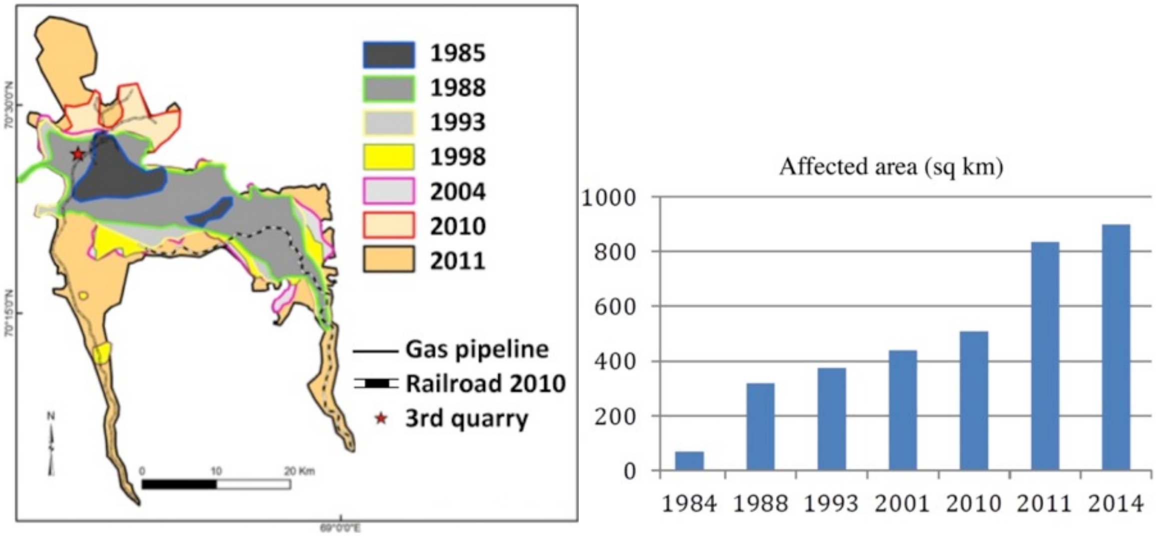


***Figure 12. Historical expansion of the Bovanenkovo gas field. Left:** Expansion of the BGF field from 1984 to 2014. Area affected by gas development as evaluated from the satellite imagery, field observation and interviews with reindeer herders and gas field workers. The gas field was discovered in 1972, and construction began in the late 1980s. Development slowed in the early 1990s as the Soviet Union collapsed. After only modest development from the mid-1990s to 2009, rapid infrastructure expansion occurred between 2010 and 2014. Since then pipeline construction has increased impacts significantly. **Right:** Historical stages of visibly affected area, including off-road tracks, roads, quarries and residential or other buildings. The main gas field no longer functions as an island since it now connects directly to southern transportation networks.*

sula (Fig. 13). A large set of cryogenic landslides occurred in the Bovanenkovo region in the late 1980s, which triggered major investigations of these phenomena that continue to the present day (Leibman 1994, Leibman *et al.* 2014).

Figure 13. Landslides of the Central Yamal Peninsula. (a) *and* ***(b)*** *Examples of typical cryogenic landslides and thermocirques of the Central Yamal Peninsula.* ***(c)*** *Yamal Peninsula and location of the key site of landslide research at Vaskiny Dachi.* ***(d)*** *Satellite image of highly dissected landscapes caused by cryogenic landslides that are typical of this region. (Images c and d: Google Earth, Digital Globe).*

The landslides create highly dissected landscapes typical of the central Yamal region (Fig. 13d) and present hazards to gas development and other land uses in this region. Marina Leibman and her colleagues have studied the strong impact of cryogenic landslides on all components of the geosystem including vegetation, soils, active layer, and ground water. Detailed information on these studies were mainly available in Russian, with only abstracts available in English at international permafrost conferences. Four chapters in a recent book describe the discovery, description, dating, and mapping of the Yamal landslides. The collected information addresses: mechanisms, forcing factors, triggers of landslide processes (Leibman *et al.* 2014); the erosional processes involved in formation of the complex drainage networks (Gubarkov & Leibman 2014); the geohazards and mapping of these features using remote sensing methods (Khomutov & Leibman 2014); and the complex relationships between permafrost, soils, and vegetation (Ukraintseva *et al.* 2014). Thermal denudation depends primarily on the depth of tabular ground ice occurrence. Tabular ground ice occurs closer to the surface within outliers of marine plains and deeper at the lowered surfaces subjected to thermokarst. Areas with massive ice at depths of less than 10 m are most sensitive to climate warming, primarily to extremes in summer temperatures like those in the summer of 2012, resulting in unusual deepening of the active layer and activation of thermal denudation.

The landslide processes have major ecosystem consequences. Studies by Natalya Ukraintseva and colleagues showed that landslide processes cause desalinization of the underlying marine sediments, which enriches the active layer with salts and triggers unique vegetation successional processes, eventually leading to colonization of landslide surfaces by extensive willow (*Salix lanata, S. glauca*) plant communities after about 200 years. This is an important peculiarity of cryogenic landslides in the regions with saline permafrost distribution. These willow communities are expanding under the influence of climate warming, and they present additional obstacles for reindeer moving through the landscapes (Forbes *et al.* 2010).

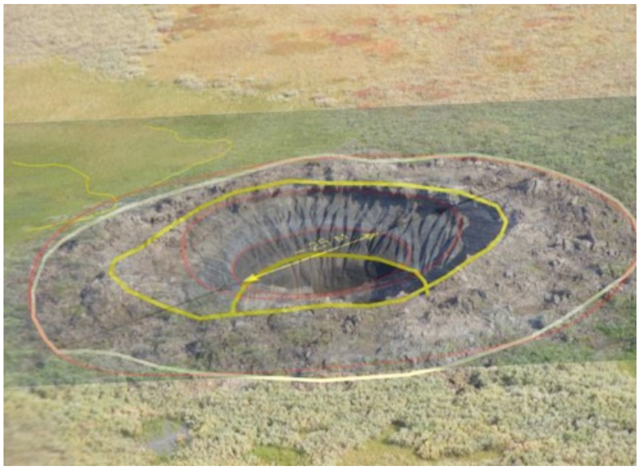


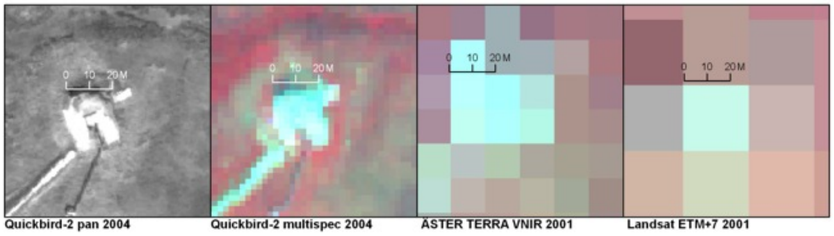
Figure 14. The Yamal crater. *The inner diameter of the crater in July 2014 was 20-25 m and the depth to the bottom of the interior lake that formed was 50 m.*

Concern over the stability of the permafrost on the Yamal Peninsula has increased with the recent discovery of a deep crater about 25 km southeast of the Bovanenkovo gas field (Fig. 14). The crater probably formed in autumn 2013 (Leibman *et al.* 2014a). The Yamal crater is now known to be one of three or four that appeared within the last two years. A parapet surrounds the crater resulting from the expulsion of ice and rocks from beneath the surface. The authors conclude that increased ground temperatures, combined with unfrozen water in the permafrost and expanding pockets of methane gas (from gas hydrate decomposition within the permafrost) created a pingo-like mound that burst due to high pressure. Similar temperature anomalies may increase in number in future decades, presenting risks for human activities in the region. This conclusion is supported by recent studies of gas hydrate behavior in the upper permafrost, as well as by subsea processes in gas-bearing provinces where an analogue mechanism is known to produce pockmarks and subsea depressions.

The Bovanenkovo gas field is situated in hilly terrain composed of several marine terraces, with mainly marine clays overlaid by alluvial sands and peat; the permafrost is composed of mainly tabular ground ice in the uplands, with extensive cryogenic landslides and thermocirques on slopes. The Prudhoe Bay oilfield is on a flat alluvial gravel floodplain overlain by ice-rich loess with extensive thaw lakes, and ice-wedge polygons with extensive ice-wedge thermokarst. These differences in the underlying surficial geology have resulted in very different permafrost conditions and hazards.

Use of remote sensing technology to detect landscape disturbances

Remote sensing is a practical way to trace rapidly expanding areas of infrastructure and extent of natural and anthropogenic disturbances in remote areas of the Arctic. However, small features such as vehicle trails and most patterned-ground features are impossible to detect with the course spatial resolution of common sensors, such as the Advanced Very High Resolution Radiometer (AVHRR, 1.1 km resolution), Moderate-Resolution Imaging Spectroradiometer (MODIS, 250 m), and Landsat Multi-Spectral Scanner sensor (MSS, 80 m) (Kumpula *et al.*, 2012). Moderate-resolution sensors, such as Landsat Enhanced Thematic Mapper plus panchromatic (ETM+, 15 m), Satellite *Pour l'Observation de la Terre* (SPOT panchromatic, 2.5 m), or Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER Visible and Near Infrared, 15 m), are capable of defining larger forms of infrastructure and landscape disturbances with high contrast and clear boundaries, such as roads, sand mines, construction pads, and recent large landslides (Fig. 15 top and Fig. 16).



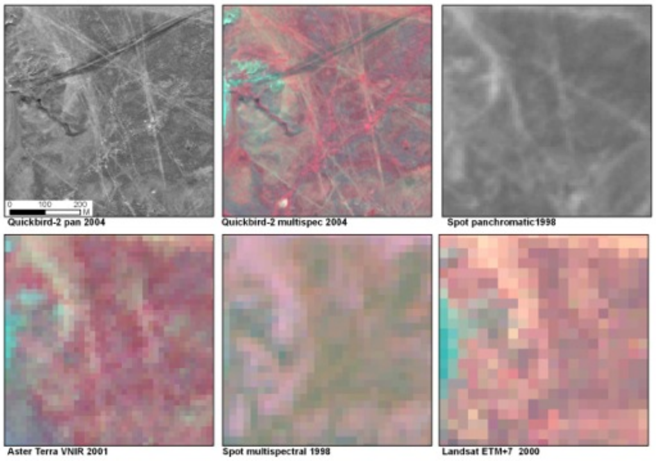
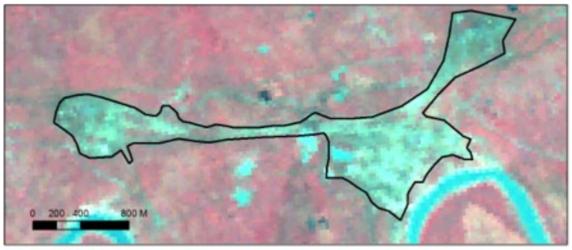
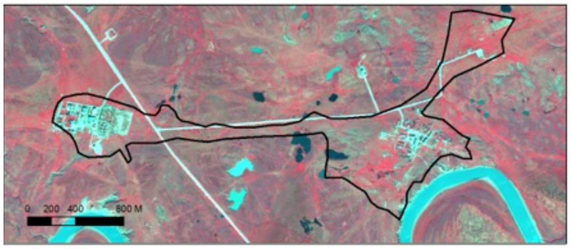


Figure 15. Use of remote sensing products to detect gas-field impacts. Top four images: *Use of remote sensing to detect larger impacts. With Quickbird-2 panchromatic imagery (pixel size 0.6 m), the size and the nature of most surface disturbances can be reliably determined. With multispectral Quickbird-2 imagery (2.5 m), details are detectable but more blurry. In ASTER imagery (pixel size 15 m), the size, shape and nature of objects are somewhat unclear, and with Landsat ETM+7 imagery (pixel size 15 m), the impact is barely observable.* ***Bottom six images:*** *The use of remote-sensing to detect finer scale features such as off-road vehicle trails.*

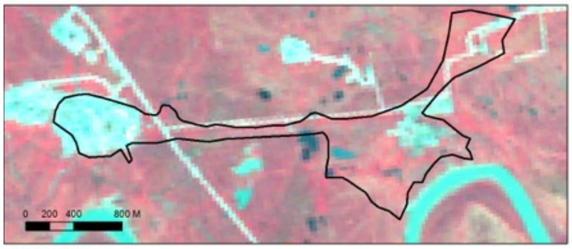
Only Very-High-Resolution (VHR) imagery—such as Quickbird (0.61 m resolution), Worldview (0.46 m), or Geoeye (0.41 m)—can sharply define common forms of indirect impacts such as off-road vehicle (ORV) trails and areas of thermokarst (Fig. 15, bottom six images, Fig. 16, and Fig. 3). In Fig. 16, ORV trails are easily detected with Quickbird-2 panchromatic imagery. When individual vehicle tracks are multiplied and spread out, they appear as medium-scale impacts and are therefore possible to detect using moderate-resolultion imagery such as ASTER, SPOT, Landsat ETM+, but impossible to detect with Landsat MSS (pixel size 80 m). The three images in Fig. 16 create a time series (1988, 2004, 2011) that traces natural revegetation following heavy off-road vehicle traffic in the late 1980s when the first gas worker settlement at Bovanenkovo was established in the vicinity. Note the much higher resolution of the Quickbird-2 image in the middle.



Landsat TM 1988



Quickbird-2 2004



Landsat TM 2011

Figure 16. Use of remote sensing to detect time-series change. *Three images trace revegetation in the vicinity of Kekh, the first gas worker settlement to be established at Bovanenkovo in the late 1980s. The top scene from 1988, when the development just began, reveals a large zone of exposed mineral soils (marine clay) denuded of vegetation by heavy off-road vehicle traffic and construction activities. The black polygon circumscribes the extent of disturbance beginning in 1988 and remains consistent across all three images for spatial reference. In the middle scene, a VHR Quickbird-2 image clearly defines the extent of revegetation after 14 years of natural regeneration. The bottom Landsat TM scene indicates that much of the bare ground has been revegetated by 2011. In addition, a significant amount of new permanent infrastructure has been built since 2004, but the boundaries of the revegetated areas are indistinct.*

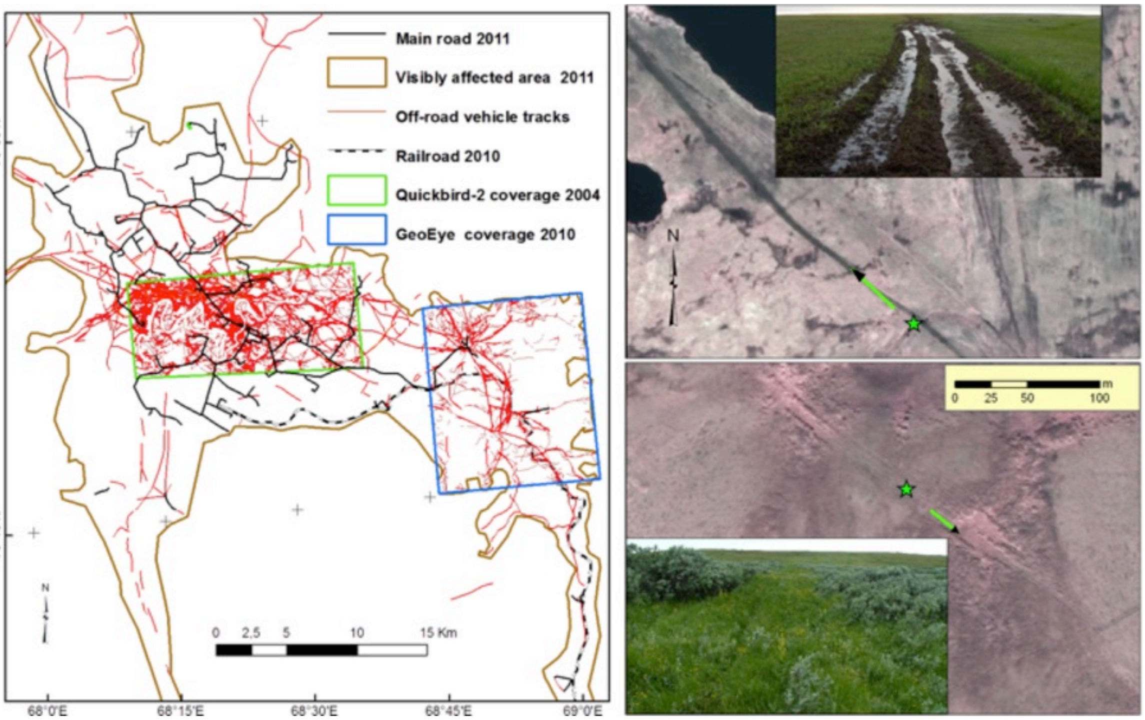


Figure 17. Off-road vehicle trails near BGF, 1988-2011. Left: The borders of Quickbird-2 (green) and GeoEye (blue) images show how VHR imagery improves detection of small-scale disturbances. ***Right:*** *Two zooms from a single Quickbird-2 image (05.08.2005) from Toravei research area are based on a combination of multispectral (2.4 m resolution) and panchromatic (0.64 m resolution) images.* ***(Top)*** *Recent track crossing a wet mire. Green stars show the locations and arrows show the direction of photographs.* ***(Bottom)*** *20-year-old off-road track through dense erect willows has naturally revegetated with graminoids, as willows (mainly* Salix lanata*) have not regenerated after initial disturbance. (Copyright Digital Globe & Eurimage. Photos: E. Kaarlejärvi, left, T. Kumpula, right, July 12, 2006)*

Indirect landscape effects of infrastructure: Off-road vehicle trails

Widespread summer off-road-vehicle trails are the most noticeable indirect effect of gas-field development on the Yamal Peninsula (Figs. 17 and 18). Individual tracks vary in width from 4 to 8 m, whereas patches resulting from multiple tracks can be up to 100 m (Khitun 1997). Until the early 1990s the trails were used so intensively that the original vegetation cover was destroyed. After the basic road network was built in the early 1990s most tracks naturally revegetated, albeit with different species composition and vegetation structure in many instances (Khitun 1997, Kumpula *et al.* 2010).

Much of the terrain affected by the network of trails at BGV has been transformed from erect- (*Salix* spp.) and dwarf-shrub vegetation to graminoid-dominated cover. Evidence from research at this site and similar situations elsewhere in the Arctic indicates that this shift to an alternative stable state will endure for many decades, if not centuries.

From space, it is possible to trace the history of many tracks using remote sensing technology (Fig. 17). Ground-based studies of ORV effects began in 1991 in connection with active gas field development and railway construction (Rebristaya *et al.* 1993, Khitun 1997). This information in combination with ground-based studies of vegetation recovery following disturbance provide a sound basis for developing sensitivity and resilience maps to off-road vehicle traffic.

For the 2012 field survey measurements, vehicle trails were subdivided according to vegetation types, degree of disturbance (one-pass tracks, multiple pass tracks, and undisturbed communities), time since disturbance, and time since impact—recent tracks (0-3 yrs.), old tracks (>20 yrs.), and natural landscape without impact (Khomutov & Khitun 2014) (Fig. 19, Table 1). Restoration of original plant communities occurred if the impact was low to moderate. After moderate to heavy impact there was often a long-lasting, graminoid-dominated stage. Shrubs of all types were sensitive to disturbance. Dwarf birch did not recover even 20 years after heavy impact (Fig. 18a, Table 1). Zonal communities (Fig. 18b, Table 1) were most resistant to impact but also took the longest to recover. Often hydrology changed after impact, with poorly drained sites becoming wetter. Wet sedge meadows or mires were easily disturbed, but they also easily recovered with the same sedges (*Carex concolor, Eriophoprum polystachyum*), though moss cover at old disturbances was sparse compared to the background vegetation (Fig. 18c, Table 1).

Similar studies have been conducted in Alaska with respect to winter seismic trails (Jorgenson *et al.* 2010). The trails on the Yamal Peninsula and the seismic trails in Alaska have a larger though less permanent footprint than all other human impacts combined. Both studies showed that plant community composition and structure was altered by species-specific responses to initial disturbance and subsequent changes in substrate. Long-term changes in both studies included increased cover of graminoids and decreased cover of shrubs and mosses. Trails with low levels of initial disturbance usually improved well over time, whereas those with medium to high levels of initial disturbance recovered slowly. Recovery to pre-disturbance communities did not occur where trail subsidence occurred due to thawing of ground ice. Both studies also showed that impacts following moderate to severe disturbance by vehicles can persist for two decades or more.

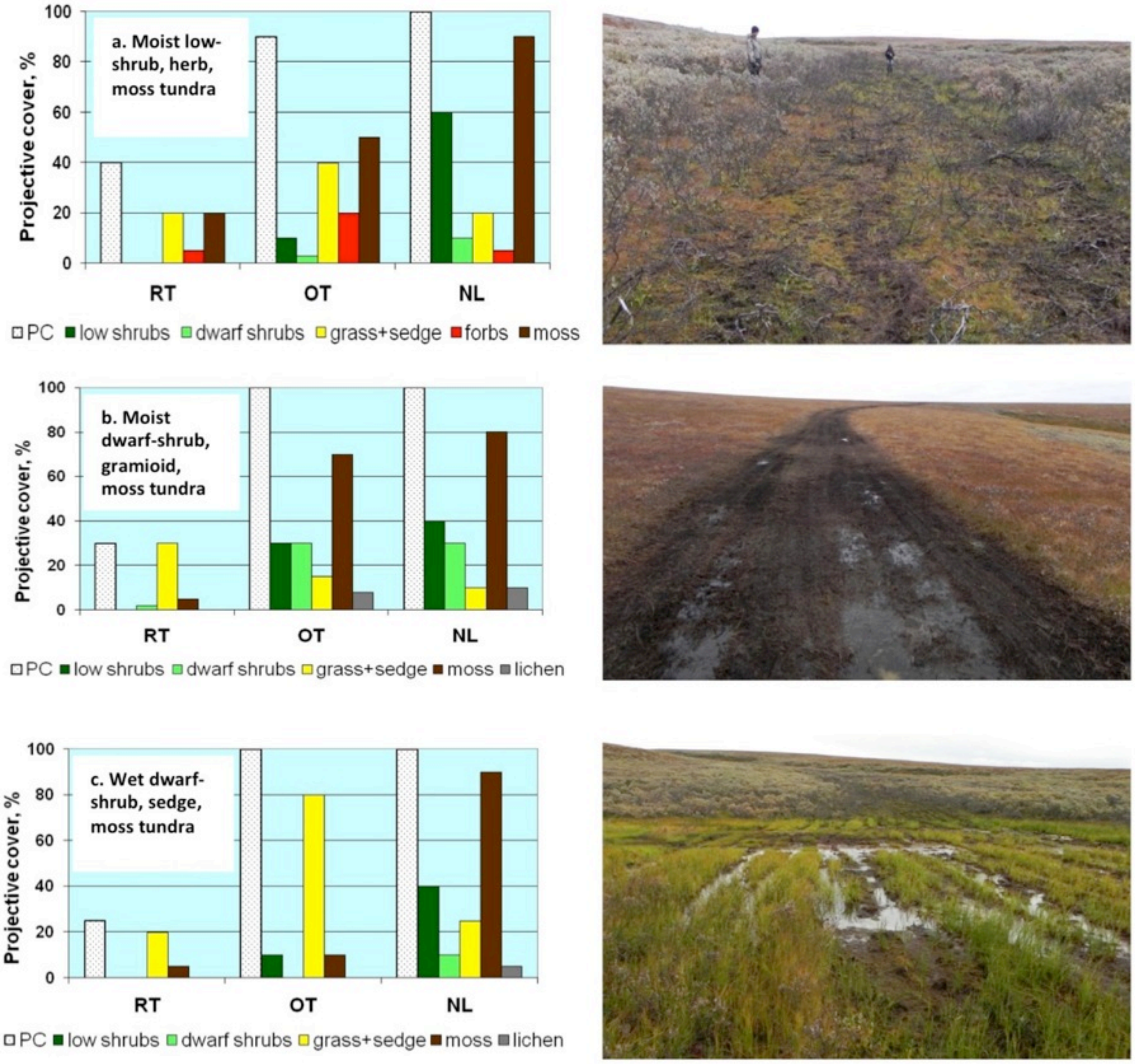


Figure 18. Recovery of multiple vehicle passes in three common tundra types near Bovanenkovo. Left: *Percentage cover of common plant functional types during three stages of recovery: RT = recent track (0-3 years); OT = old track (> 20 years); NL = natural landscape. PC = total plant cover (which cannot exceed 100%).* ***Right:*** *Examples of old tracks caused by multiple passes of off-road vehicles in the three community types.* ***(Top)*** *Trail through moist low-shrub, herb, moss tundra on moderately drained slope. The shrubs (*Betula nana, Salix glauca, Salix lanata, Salix polaris, Vaccinium vitis-idaea, *etc.) are fully degraded in the track.* ***(Center)*** *Track created by many vehicle transits along the watershed slope with moderately well-drained (zonal) moist dwarf-shrub, graminoid, moss tundra.* ***(Bottom)*** *Multiple tracks as a result of frequent transit of vehicles through a poorly drained wet dwarf-shrub, sedge-moss tundra. Sedges have replaced the original dwarf shrubs, and there is little recovery of mosses.*

Table 1. Summary of plant-community responses to ORV impact of differing intensity and periods of recovery near the Bovanenkovo gas field.

Intensity of impact	**Plant community type, drainage, and age of disturbance**					
	Moist low-shrub, herb, moss tundra (Fig. 18a)		**Moist dwarf-shrub, graminoid, moss (zonal) tundra (Fig. 18b)**		**Wet dwarf-shrub, sedge, moss tundra (Fig. 18c)**	
	Old tracks (ca 20 years)	**Recent tracks (2-3 years)**	**Old tracks (ca 20 years)**	**Recent tracks (2-3 years)**	**Old tracks (ca 20 years)**	**Recent tracks (2-3 years)**
Low (1-2 passages)	Restored completely.	Broken branches of willows, damaged moss sod, increased cover of horsetails.	Restored completely; does not differ from background.	Little damage; species diversity is preserved. Active layer is 1-3 % deeper than background.	Restored completely; wetter in some areas.	Shrubs damaged, moss layer damaged, active regrowth of sedges.
Medium (several passages)	Restored but still notable damage to shrubs; young growth of willows is present. Moss cover is practically restored.	Shrubs damaged. Grasses (*Poa alpigena, Arctagrostis latifolia*), *Carex stans,* and *Rubus chamaemorus* along with mosses are active colonizers.	Recovered, increased cover of grasses (*Calamagrostis holmii, Alopecurus alpinus*); moss cover almost completely restored but solely pioneer mosses (*Bryum* spp., *Psilopilum laevigatum*) were still present	Shrub and field layers damaged. Graminoids, horsetail and mosses from remnants of sod recover in the tracks. Active layer increased 5-30%.	Willows are partly restored; dwarf-birch is dying off; soils are wetter than background; increased cover of *Carex stans;* sparse moss cover without *Sphagnum*.	Shrubs damaged; moss cover damaged; extensive standing water, recovery by *Carex stans*: very few mosses.
High (multiple passages, transportation corridor)	Absence of old shrubs, but young willow growth is present; *Carex stans* and *Eriophorum polystachion* dominate; sparse moss cover.	Vegetation heavily damaged; soils are wetter; sedges, horsetail and mosses are active colonizers.	Revegetated; species diversity is almost restored, but structure is different; increased graminoids cover; fewer shrubs, but young willow growth is present.	Vegetation cover heavily damaged. Active layer depth is 0.3 m (>50%) deeper. Recovery by graminoids and horsetail, pioneer mosses (*Bryum sp., Psilopilum laevigatum*)	Notably wetter than background; re-vegetated as wet sedge meadow, lower species diversity; no dwarf-shrubs; almost no mosses.	Vegetation heavily damaged; thermokarst initiated inside tracks; recovery mainly by *Carex stans* (5-20% cover); pioneer mosses.

Effects of development on reindeer herding

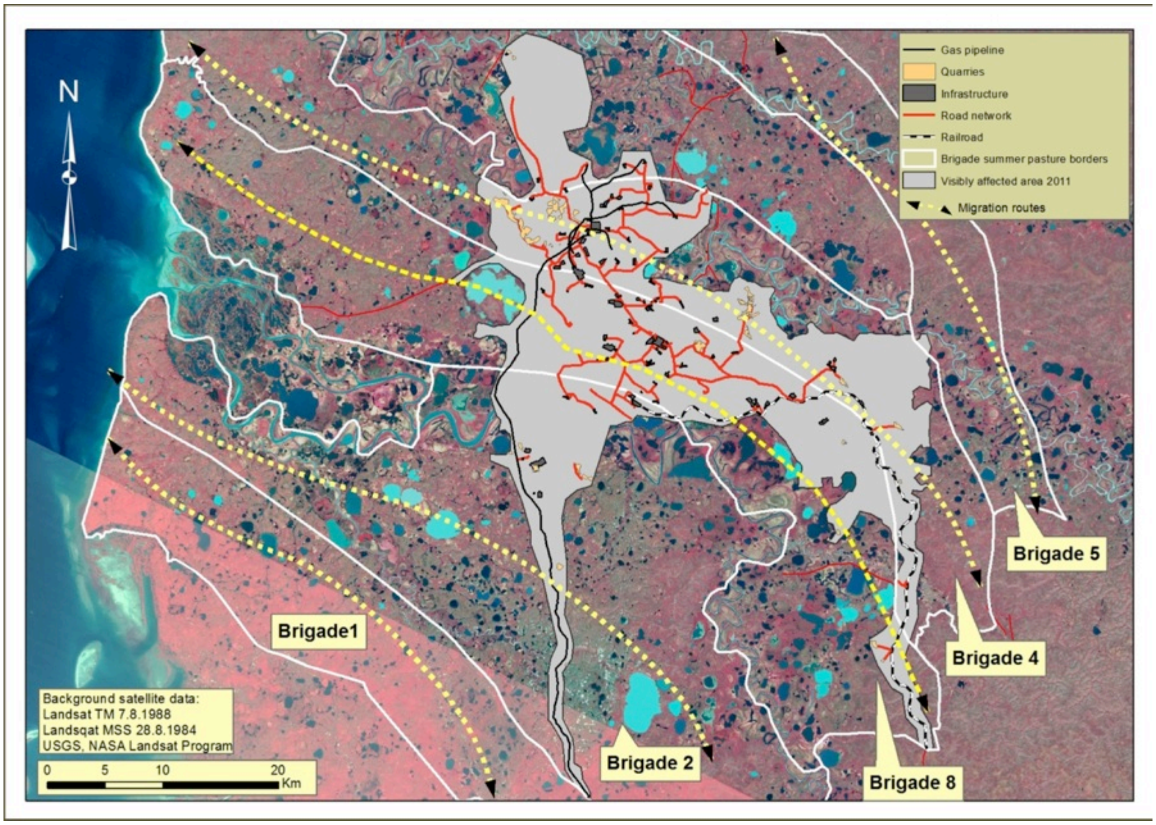


***Figure 19. Impacted area in the vicinity of the Bovanenkovo gas field,** showing the migration routes and summer grazing pastures of five Nenets reindeer brigades that use the area en route to summer grazing pastures north and west of the gas field. During the early phases of gas-field construction in the mid 1980s, direct and indirect impacts of the gas field affected summer reindeer pastures primarily on the territories used by brigades 4 and 8. Brigade 2 was relatively unaffected until 2011. Since then, pipeline construction has increased impacts significantly on lands used by herders south of the Mordy-yakha River, the delta of which empties into the Kara Sea (left center).*

The Yamal Peninsula is the homeland for the indigenous Nenets, who practice migratory reindeer husbandry. The Bovanenkovo gas field is on the migration path of two major Yarsalinski reindeer brigades or collective management units (Fig 19). Nenets herding in the Yamal Peninsula has so far survived rather well compared with other regions in post-Soviet Russia (Forbes & Stammler 2009, Forbes *et al.* 2009).

Each year, the brigades reach the gas field from the south in early to mid-July on their way to the Kara Sea coast, where reindeer are brought for insect relief and access to high-quality forage. Impacts of the Bovanenkovo field were rather local until 2007, when only two to three reindeer herding brigades were directly affected. After the recent surge in construction, most of the Nenets reindeer herding units are now affected. In the vicinity of the gas field, the herds encounter significant barriers at the Seykha River and obstructions due to the pipelines, roads, and rail corridors associated with the gas field (Forbes *et al.* 2009, Kumpula *et al.* 2010, 2011, 2012) (Fig. 20). The brigades return to Bovanenkovo in mid- to late August when they start the migration to their winter pastures on the south side of the Ob River.

Figure 20. Examples of gas field structure impacts to the Nenets herders' migration through the BGF. (a) *BGF is divided by the wide Seykha river, which has few suitable crossing sites for herders. Here part of the brigade begins the crossing inside BGF. Local gas field workers have been in the field for 20 years and help herders take children and elders across with larger boats.* ***(b)*** *Within the gas field, several "gates" and a route have been established where herders can pass under pipelines and through the gas field as quickly as possible.* ***(c)*** *Nenets camping site on hill that has a gas drill site as a new neighbor. Camps within BGF are necessary because the main part of the field is approximately 20 km wide, and the river crossing takes time and energy for both people and animals.* ***(d)*** *Reindeer herd resting in the BFG area. Huge piles of metal, concrete and trash have been gathered as part of the plan to clean up the gas field and its vicinity. Trash significantly devalues the pastureland because it can injure reindeer hooves, which can then be infected and possibly cause the death of animals. Herders try to avoid sites they know to be trashy. (Photos: T. Kumpula July 7, 2011)*

Climate-related factors influencing the migration include direct and indirect ecological impacts from expanding willow communities (Pajunen *et al.* 2009), possibly novel ecosystems enhanced by climate change (Macias-Fauria *et al.* 2012), changes in snow cover and rain-on-snow (ROS) events (Bartsch *et al.* 2010), and the timing of sea ice thawing and formation on the Bay of Ob, which is needed for crossing this major water body in spring and early winter (Nuttall *et al.* 2005). In Winter 2013-2014, Yamal reindeer herders experienced a pronounced ROS event that caused icing of pastures across a large part of central Yamal. ROS was experienced several times, and reindeer not able to dig lichen forage starved. Official reports from Yamal estimate that about 60,000 reindeer died during the winter.

Future directions of research on the Yamal

Petroleum industry expansion, increasing shrubification, permafrost melting, ROS events, and their relationship to the traditional reindeer-herding Nenets way of life pose a complex packet of questions without immediate answers:

1. How can development co-exist with reindeer herding in such a manner that traditional herding practices can continue? Future assessments of environmental and social impacts in the Arctic will benefit by deploying interdisciplinary teams and exer-

cising tighter integration across traditional disciplinary borders beginning at the planning stages. Involving local social scientists early in the planning process is necessary to ensure conservation of scarce research funds by focusing on the most relevant locations and issues. As petroleum development expands, Nenets need to be involved in decisions regarding alignments of roads, pipelines, and construction sites on traditional pasturelands. The solutions need to allow for the free movement of people, animals, and goods to increase the herders' capacity to respond to the combined ecological and social changes and to facilitate contacts between nomads and incoming workers with all the associated favorable and problematic consequences. Herders should be allowed to trade fish and reindeer meat in the gas fields. Investments by the gas industry must undergo a cost-benefit analysis that considers the ecological and socio-cultural situation in the tundra.

2. How are climate change and development interacting to affect traditional migratory herding practices? For example, climate change can create big problems to reindeer herding in the Yamal region, especially if rain-on-snow events tend to become more frequent and stronger, and if access to unaffected areas is hampered by extensive infrastructure. Restricted access to traditional grazing lands is a core source of problems, although the problem is complex. For example, the significant reductions in shrub biomass caused by construction in the Bovanenkovo field, eventually resulted in net increases in highly nutritious and digestible forage species common to early-succession- stages of revegetation, but herd access to these areas is restricted, and other hazards tend to make the Nenets avoid them.
3. How does development affect other aspects of traditional subsistence lifestyles? For example, herders expressed strong concern about the potential loss of fish as an essential source of protein during the long summer migration when they do not slaughter reindeer. They feel hunting and fishing by gas field workers should be banned.
4. How can researchers best interact with the field situation to bring ground-based knowledge into the analyses? New research should include on-the-ground surveys as a substantial component. Field surveys remain essential for reliable satellite-image interpretation, interpretation of complex geoecological patterns, and for understanding the sociological consequences of the changing land-cover patterns. This is best done by working closely with Nenets herders who have intimate knowledge of the land and ongoing changes. Although rapid changes are occurring to infrastructure networks, landscapes and climate, the Nenets have proven rather resilient to the changes and, by tradition, are very capable of adapting to changing environmental and social conditions.

Contributors: Timo Kumpula, Bruce Forbes, Artem Khomutov, Marina Leibman, Olga Khitun

Case Study 3: ADAPT and ArcticNet IRIS in Canada

Climate change and its impact on permafrost is a major concern for Canada given that much of the country is underlain by permafrost, and the integrity of many of its northern geosystems, ecosystems and engineered infrastructure is dependent upon the stability of these frozen lands. Canada is undertaking two large scale research projects that address the processes and implications of permafrost thawing and degradation: ADAPT and ArcticNet, the latter via its formulation of Integrated Regional Impact Studies (IRIS).

ADAPT

The permafrost region of Canada encompasses a vast area, accounting for around 50% of the county's landmass, with diverse landscapes and ecosystems. The NSERC Discovery Frontiers project ADAPT (Arctic Development and Adaptation to Permafrost in Transition) (*www.cen.ulaval.ca/adapt*) was formulated in response to the urgent need to understand how the structure and functioning of these northern systems are linked to permafrost behaviour and climate change. Additionally, the infrastructure and resources for northern settlements, from drinking water and exploited wildlife to runways, roads and housing, critically depend upon the state of the Arctic permafrost, and ADAPT is also addressing many of these issues.

ADAPT involves 15 laboratories across Canada, with many collaborations, including with the European program PAGE21 (page21.org) that is focused on carbon stocks and fluxes. The program is organized as four interlocking modules: 1) Permafrost dynamics in natural and engineered environments; 2) Permafrost and aquatic ecosystems; 3) Microbes and biogeochemical fluxes of nutrients and carbon, including via thaw lakes; and 4) Tundra permafrost ecosystems: vegetation and wildlife. The activities are integrated across modules by way of common protocols (*www.cen.ulaval.ca/nordicanaD*), community outreach activities, a conceptual three-layer model of permafrost systems, and a central hypothesis focused on the central roles of liquid water and snow in affecting all aspects of terrestrial Arctic systems (Vincent *et al.* 2013).

ArcticNet

The Network of Centres of Excellence ArcticNet (*www.arcticnet.ulaval.ca*) brings together scientists and managers in the natural, human health and social sciences with their partners in Inuit organizations, northern communities, federal and provincial agencies and the private sector to study the impacts of climate change in the coastal Canadian Arctic. Over 100 ArcticNet researchers from 27 Canadian universities and 5 Federal departments collaborate with research teams in the USA, Japan, Denmark, Sweden, Norway, Poland, the United Kingdom, Spain, Portugal, Russia, Greenland, South Korea and France. A central aim of ArcticNet is to develop a series of Integrated Regional Impact Studies (IRISs) for each of four regions of the Canadian Subarctic and Arctic.

In brief, an IRIS summarizes and combines knowledge and models of relevant aspects of the ecosystems of a region affected by change, with the objective of producing a prognosis of the magnitude and socio-economic costs of the impacts of change (Yarnal 1998).

ArcticNet is also significantly augmenting and updating the present observational base on which to develop regional models of change in the Canadian Arctic. The ArcticNet IRIS approach aims to lay the groundwork for regional models for the Mackenzie Shelf region, the Canadian Archipelago, the North Water, the terrestrial Eastern Canadian Arctic from Ellesmere Island to James Bay, and for Hudson Bay as a whole. The resolution of General Circulation Models (GCMs), typically 400 x 400 km, is too coarse to provide the regional and community-level information, which policy-makers in Northern governments and Federal agencies need, so finer-scale regional climate models need to be developed. These regional models of climate change impacts will ultimately provide the spatio-temporal resolution necessary to downscale knowledge of the impacts of change to the level of the community. The implementation of each ArcticNet IRIS includes the following steps (Fortier 2010):

1. Identify indicators of environmental, health and societal vulnerability with the input of stakeholders.
2. Document past and present changes in climate and different components of the regional environment.
3. Identify present environmental, health and societal vulnerabilities with the input of stakeholders.
4. Based on observations and experimental studies of processes, develop impact models that describe the response of an exposure unit (i.e. a natural component/ecosystem, a component of human health or a societal/economical sector) to external changes (climate and non-climate determinants). These models range in complexity from simple conceptual models or statistical relationships to sophisticated numerical simulations.
5. Identify linkages (including feedbacks) between environmental change and health/societal impacts.
6. Assemble the Impact Models into an Integrated Assessment Model through the linkage of individual impact models along predefined vertical “Impact Chains” and the horizontal integration of the vertical chains.
7. Downscale General Circulation Models (GCMs) to Regional Climate Models (RCMs).
8. Force the Integrated Assessment Models with the scenarios produced by the RCM to provide insights into future environmental, health and societal vulnerabilities;
9. Analyze the prognosis with stakeholders.

Permafrost research and adaptation strategies are an important part of this IRIS development process for each of the regions, given the wide-ranging impacts on northern communities and their surrounding environments.

Permafrost degradation and infrastructure in the Canadian North

Permafrost degradation is beginning to have broad effects across northern Canada. The landscape is changing through thermokarst that takes place mostly in the discontinuous permafrost zone and through increased active-layer depth and more frequent slope processes in the continuous zone. Vegetation, soil drainage and water bodies are greatly modified by these permafrost changes, which affect resources traditionally available for humans such as berries that are shaded in the understory of shrubs that expand in thermokarst hollows, and drinking water sources that are affected as nutrient and sediment loads increase due to increased upstream slope processes.

Canadian northerners are most directly impacted by permafrost change through its effect on the infrastructure that supports the well-being of residents, public safety and economic activity. These cumulative changes come at a time of intense demographic and socio-economic development in the Arctic. This is especially linked to the oil, gas and mining industries, which are growing rapidly and requiring new facilities such as roads, airstrips, railways, new housing units, and associated services. Given this dual context of climate and socio-economic change, permafrost degradation and its associated impacts on natural and built environments were clearly identified, through several consultations with communities, stakeholders and regional governments, as a priority issue across all ArcticNet IRIS regions. The stability and safety of infrastructure in the communities and on the land in Canadian Arctic is of central concern to residents, decision makers and industry.

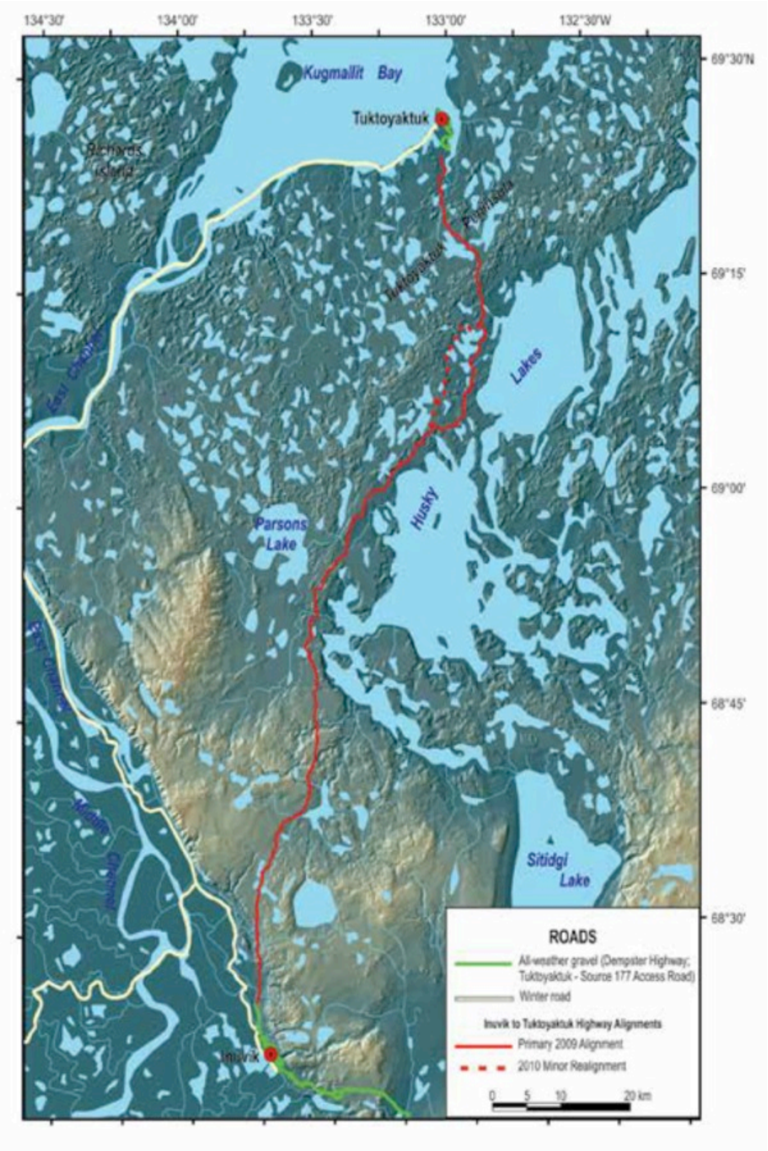


Figure 21. Proposed route of the Inuvik to Tuktoyaktuk Highway. *Photo: Smith and Duong 2012.*

The need for a better understanding permafrost behaviour and properties is crucial to secure major public investments that are planned in support of the socio-economic development of remote Arctic communities. For example, the expansion of the road network by the construction of an all-season road between Inuvik and Tuktoyaktuk in the Inuvialuit Settlement Region (ISR) represents an investment of 3 million CAD dollars (Fig. 21). This requires many operational, design, and potential mitigation considerations according to the diversity and complexity of sediment types, organic deposits, chaotic lake-filled thermokarst terrain, ground-ice content and structure (ice-wedge polygons, massive ground ice, etc.), and associated processes (retrogressive thaw slump, gullying, and thermoerosion, etc.) characterizing the region.

As a result of the growing concern across northern Canada, the first Pan-Territorial Adaptation Workshop focussed on permafrost degradation and related infrastructure issues was hosted in Yellowknife in 2013. It brought together frontline decision makers and permafrost researchers from Nunavut, NWT and Yukon to share knowledge, form connections, and look at possibilities for adaptation in the future (*www.northernadaptation.ca/news/pan-territorial-permafrost-workshop*).

There are three key areas in which infrastructure sensitivity occurs through climate-induced change: permafrost, hydrology and coastal conditions. Permafrost is especially vulnerable to changing climate where ice-rich permafrost occurs. When ice-rich permafrost thaws, the terrain often settles, soil drainage conditions are altered (either becoming dryer when water percolates deeper in coarse soils or wetter when the fine-grained ice-rich substrate remains impervious), various slope processes are triggered (such as active layer slides), hollows and ponds are created and lakes can be completely drained. Thaw subsidence may result in changes to the stability of various infrastructure components.

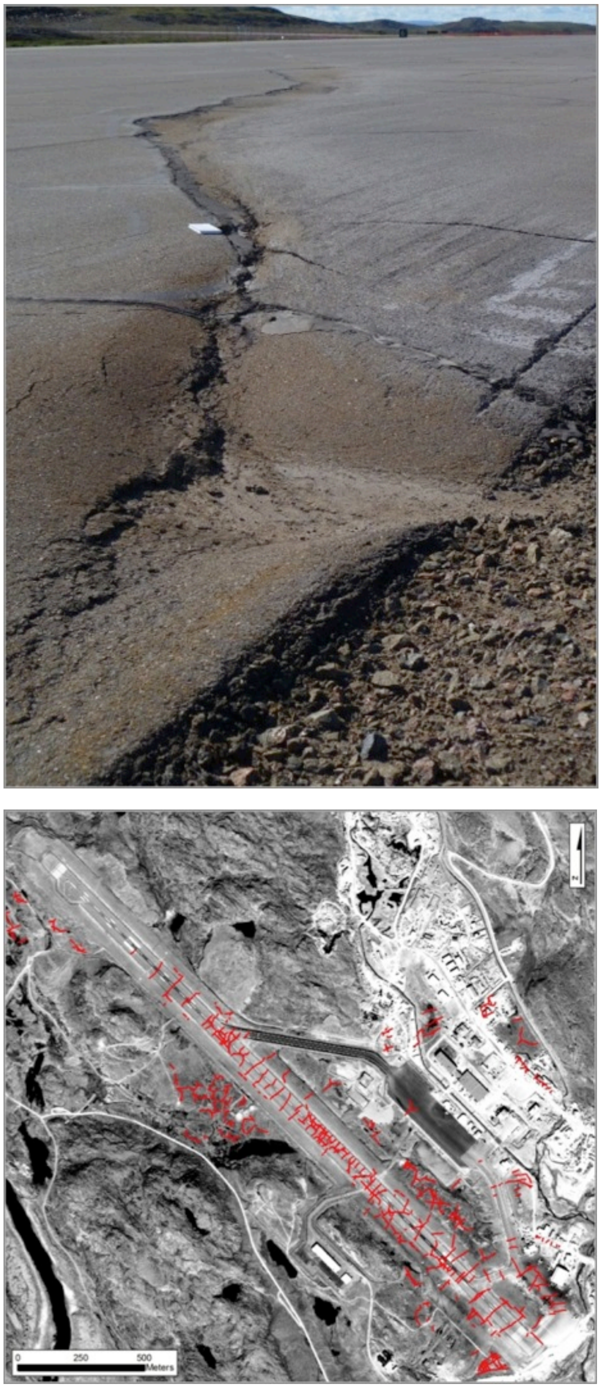


***Figure 22. Cracking and linear depressions** associated with ice wedge degradation at the Iqaluit Airport.*

Several permafrost-infrastructure issues encountered in Nunavut partly come from the fact that much of its infrastructure was built at a time where climate warming had not yet been observed in the region and permafrost was thought to be permanently stable ground. In addition, permafrost was a poorly known phenomenon and construction projects were often implemented without sufficient knowledge of permafrost conditions such as the type and amount of ground-ice content. Consequently, construction designs of many buildings and infrastructure are not necessarily appropriate to their underlying permafrost conditions and adapted to cope with the climate change observed in Nunavut since the 1990s. For example, the Iqaluit airport, the hub of the eastern Canadian Arctic, is currently affected by thawing permafrost. An ongoing project led by M. Allard's team in collaboration with Transport Canada revealed that the runway, taxiways and apron are affected by differential settlements resulting from the presence of localized ice-rich soils of the original terrain conditions prevailing before the construction of the airport (Fig. 22). Extensive geotechnical surveys of permafrost are being undertaken to support the repair and expansion plans of the airport.

Figure 23. The extreme peak discharge of the Duval River *in June 2008 resulted in the downcutting of the river bed, caused thermo-erosion and the collapse of the Hamlet's bridges (Photos Michel Allard's team).*

Additionally, land use changes may alter drainage patterns, further impacting infrastructure and potentially causing expensive repairs or failure in some cases. Hydrological changes will alter seasonal flow peaks and stress drainage infrastructure. In extreme cases, modifications of drainage patterns may trigger permafrost degradation processes such as landslides (active layer failures), gullying in ice wedges and rapid riverbank erosion (by thermal erosion), which can in turn severely damage infrastructure when it occurs in a community surroundings. These events occurring at critical places and times are often associated with extreme weather anomalies, for example a heat wave followed by intense rainfall (L'Héreault 2009) and may have significant implications for community functioning and safety. In Pangnirtung , Nunavut, the sudden peak discharge the Duval River in 2008 resulted in the downcutting of the river bed by thermo-erosion and in the destruction of the Hamlet's bridges (Fig. 23). This example of permafrost degradation, triggered by an extreme weather event (heavy rain in this case), that had immediate impacts on the community functioning and well-being (Carbonneau *et al.* 2012). Following this catastrophic event, a study of the permafrost conditions was undertaken in the Hamlet of Pangnirtung by the Geological Survey of Canada (GSC) and Université Laval's *Centre d'études nordiques* (CEN), under the Nunavut Landscape Hazard Mapping Initiative launched by the Canada-Nunavut Geoscience Office (CNGO).

In Nunavik and Nunatsiavut (Canadian Eastern Subarctic), many research projects have been conducted in collaboration with regional authorities to produce improved permafrost maps and prediction of permafrost behavior in order to protect and optimize the major investments required for the urban planning of communities. Permafrost degradation at temperatures near 0 °C appears to be affected by the unfrozen water content and heat brought to the thawing interface by groundwater. This process is also effective in accelerating localized thawing under human infrastructures. Collection and organization of permafrost information into geographic information systems (GIS) allows for the integration of a wide diversity of essential knowledge into the planning process. The GIS can then provide powerful tools for analysis and sharing of information with stakeholders and communities. An example is the adapting of foundation types to mapped permafrost conditions to ensure a prolonged service life of buildings (Fig. 24).

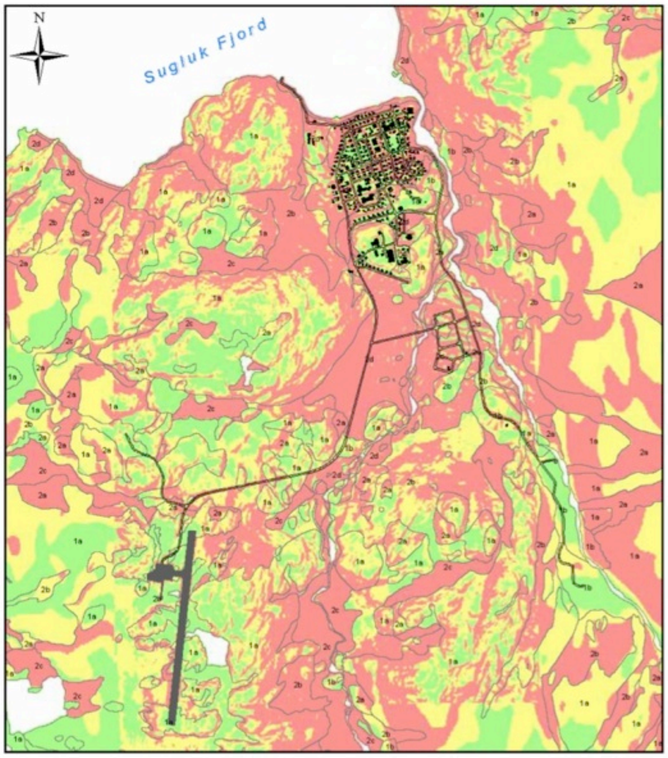
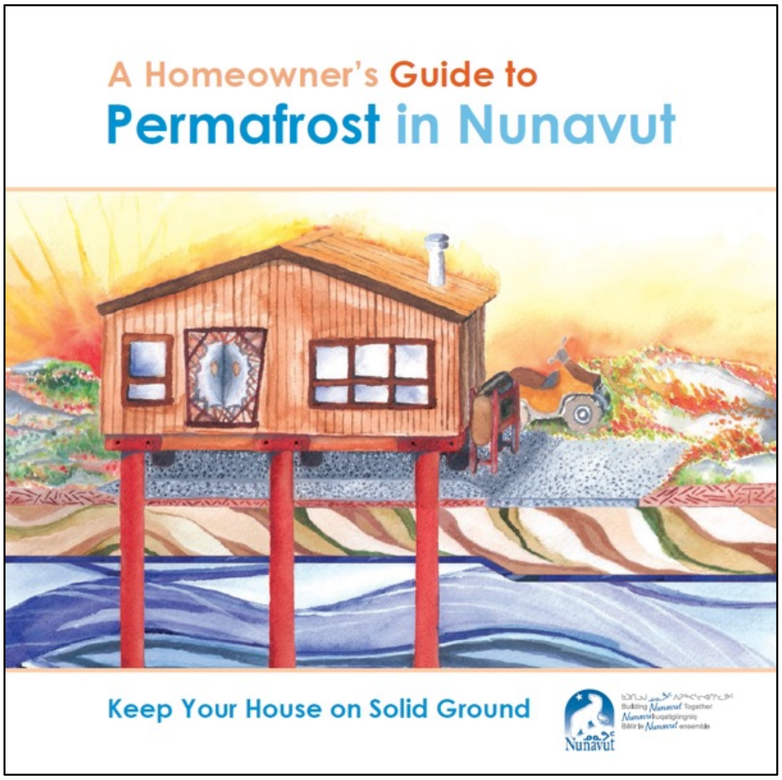


Figure 24. Risk management map *for potential construction development in Salluit, Nunavik (Allard & Lemay 2012). The red colors delineate areas with hazardous building conditions.*

In the coastal sector, decreased sea ice has resulted in increased wave activity. The strong waves rapidly erode exposed areas of massive ground ice. Coastal erosion is already occurring in some communities, while it threatens others based on projected climate change. Knowledge about the presence of ground ice and thaw-sensitive terrain, improved hydrological projections, and documenting emerging coastal processes and hazards provide the means to design appropriate infrastructure and to minimize potential risk.

In addition to the research projects noted above, there is now considerable local effort devoted towards information exchange with decision makers, environmental engineers and the public on this subject. For example, the Nunavut Climate Change Centre of the Government of Nunavut has produced a booklet in collaboration with permafrost scientists (Michel Allard *et al.* 2013) entitled 'A Homeowners Guide to Permafrost in Nunavut'. This document provides basic information about permafrost and how it is affected by change. It also provides practical advice on how a homeowner can determine if their house is built on ice-rich



A Homeowner's Guide to
Permafrost in Nunavut

Keep Your House on Solid Ground

Figure 25. Guide produced by the Government of Nunavut, Canada, *in collaboration with permafrost scientists, to help northern homeowners manage the effects of thawing permafrost.* *(*www.climatechangenunavut.ca/ sites/default/files/permafrost_ nunavut_eng_reduced_size_0.pdf *)*

permafrost, and how to properly maintain their foundation to reduce permafrost thaw (Fig. 25).

Finally, climate- and infrastructure-induced changes not only affect built environments, but also have impacts on natural permafrost environments and their ecosystem services. However, little is known about how permafrost degradation affects the various natural components of permafrost landscapes, and a multidisciplinary, system science approach is required. ADAPT is an example of one such approach in the Canadian North.

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Case Study 4: Road infrastructure and climate effects in Norway

Roads and climate change in Norway

This short case study from subarctic Norway illustrates some of the regional variation related to frost heave and effects of climate change on areas outside the permafrost zone. The scenarios for future climate in Norway all predict milder winters. While one might expect that frost-related problems will be less severe or perhaps disappear altogether in the subarctic, it is more likely that both single-winter and year-to-year variations will increase. Thus in most of Scandinavia, roads in regions that previously enjoyed stable winter conditions are now subject to several freeze-thaw cycles each winter (Ministry of the Environment 2010, Grendstad 2012).

The increase in freeze-thaw cycles will accelerate road deterioration and consequently increase maintenance costs. In general, cold-climate countries have to cope with pavement deterioration effects, which in countries such as Norway represent approximately 30% of the maintenance budget (PIARC 2010). Damages due to frost heave are particularly difficult to repair since frost-protective layers have to be placed deep in the road structure. For railways insulation of existing structures is costly, but possible, without replacing the entire structure.

Flytoget må kjøre i 80

Flytoget må redusere farten fra 210 til 80 km/t på grunn av telehiv.

Av Joachim Seehusen

Foto: Truls Tunmo

Ny motorvei ødelagt for alltid

Deler av riksveg 2, den nye firefelts motorveien mellom Kløfta og Nybakk, har omfattende telehivskader. – Veien er ødelagt for bestandig, bekrefter prosjekteringsleder i Statens vegvesen, Arvid Sagbakken.

Figure 26. Articles in Teknisk Ukeblad (TU), *Norway's leading engineering magazine, about frost heave problem for the airport train and for a new motorway.* ***Left:*** *"Airport express has to drive 80 km/h."* ***Right:*** *"New highway broken forever."*

The winters of 2009-2010 and 2010-2011 were cold, following some years of mild winters, and yielded frost-heave problems on sections of some newly constructed motorways, especially in the southeastern part of Norway. This gave rise to several reports in newspapers and the media that were negative for the national road authorities (Fig. 26).

After a large research program called "Frost i Jord" ("Frost in the Soil") (1976) ended nearly 40 years ago, very little research has been done in relation to frost heave. To identify the causes of the recent problems and to propose adapted national frost design specifications, the Norwegian Public Roads Administration established an expert group that raised a variety of questions requiring further research.

Changes in construction materials

Frost penetration information has to be reassessed due to outdated climate data as well as changes in the materials used in pavement structure over the last 2-3 decades. For example, the materials used in roadbeds have changed from mainly well-graded natural gravels to more coarse and openly graded crushed/blasted rock. At present, there is no good understanding of the thermal conductivity of materials currently used in Norway. As materials became coarser, convection and radiation became the dominant heat transfer processes, which is undesirable for road and rail-bed construction. Existing frost susceptibility criteria for soils and coarse material in Norway are mainly based on grain-size distribution and allowable fines content, while differences in heat transfer through the materials and mineralogy of the fines are not considered.

Many studies in cold permafrost areas show that natural winter convection in clean coarse rock-fill materials in roadbed embankments increases winter cooling and helps to prevent permafrost from thawing under highway and railway structures. At the same time, Lebeau and Konrad (2007) showed that convection heat transfer could lead to the formation of undesirable permafrost conditions in areas where there are no naturally occurring permafrost soils.

The Norwegian Research Council has funded a study of “Frost protection of roads and railways” (2015-2019) to determine modifications of existing national construction requirements. This project is a joint effort between the Norwegian University of Science and Technology (NTNU), the SINTEF research institute, and the University of Laval (Quebec, Canada), together with the Norwegian Public Road and Railway Administrations. A major focus of the project is to come up with recommendations that make use of local rock materials in the frost protection layer and that adapt existing design procedures to climate change.

It is important that materials for the upper layer in a roadbed have the right grading and mineralogy to ensure good frost protection. Local materials not fulfilling the requirements for use in upper layers or for surfacing can be used in lower layers, where stresses are lower than in the upper part. At the same time, the petrology of rocks used in this layer should be considered to insure that frost protection layer will be functioning as intended.

Contributor: Elena Kusnetsova

Case Study 5: Urban landscapes on permafrost: the Oganer district of Norilsk, Russia

Figure 27. View of Norilsk from Oganer District.

The effects of climate warming on the permafrost system are exacerbated in areas of intensive human activity, particularly in large industrial centers that result in the emergence of urban landscapes on permafrost and which are different from their environmental counterparts (Anisimov *et al.* 2014, Grebenets *et al.* 2012, Streletskiy *et al.* 2012a, 2014). The city of Norilsk, located above 69°N in the Russian Arctic is one of the largest urban landscapes on permafrost. It consists of the Norilsk city district, Oganer district (Fig. 27), two satellite city districts, Talnakh and Kayerkan, and the small settlement of Snejnogorsk.

It has a high population density, concentrated mining and metal production plants, developed infrastructure of various types and ages. Norilsk is known for exceptionally high pollution levels and represents a nucleus of technogenic impacts on the Arctic environment, including permafrost. Response of the permafrost system to these impacts was exacerbated by the climate warming observed in recent decades. The combined effects of warmer climate and human-induced changes in this urban environment led to accelerated deterioration of permafrost geotechnical properties and created potentially dangerous situations with respect to infrastructure and the population in the city. This case study examines the past, present and future state of permafrost geotechnical properties as an integrative component of urban landscapes, which reflect both climatic and technogenic changes in the environment.

Norilsk and Organer: Climate, population, permafrost conditions, and construction methods

Norilsk is characterized by severe climate, forest-tundra vegetation and continuous permafrost. The climate is characterized by cold winters and relatively warm, but short, summers. Mean annual temperature between 1980 and 2010 was -8.5 °C, The mean total annual precipitation was 465 mm per year, the majority being snow. Mean air temperature during the coldest month (January) was -26.8 °C, and +14.2 °C during the warmest month (July). Between the 1970s and 2000s, mean annual air temperature and precipitation increased by 1.4 °C and 10 mm, respectively (Fig. 28).

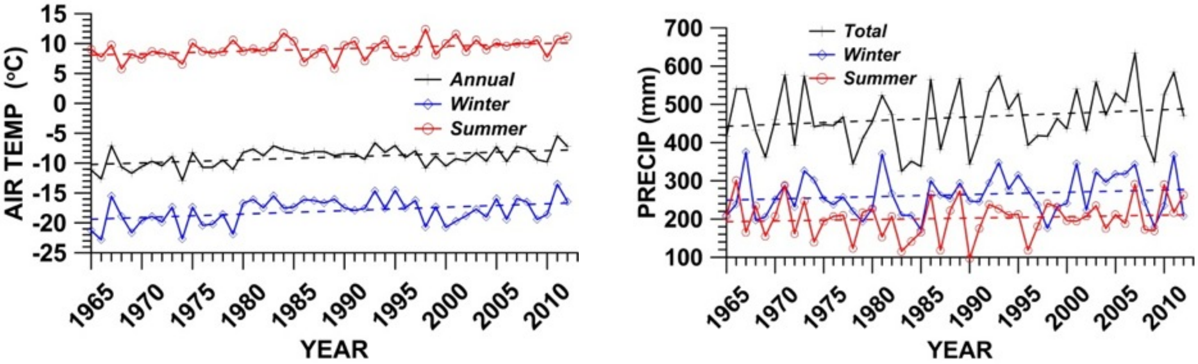

Figure 28. Mean annual, winter and summer temperature and precipitation observed in Norilsk.

The area is characterized by continuous permafrost. Permafrost temperatures in Norilsk city varied from from -6 to -0.5 °C prior to construction in 1940s and 1960s to -2.5 to -0.5 °C in 2000s (Fig. 28). Excessive heat from underground utility lines, leaks and breaks of water and sewage pipes lead to warmer permafrost and even talik development. The combined influence of climatic, environmental factors and rapid technogenic transformations of ground thermal regime after construction created highly heterogeneous permafrost temperature field (Grebenets *et al.* 2012). The active-layer thickness (ALT) data available only for 2005-2013 from the CALM monitoring site R32 Talnakh located near Norilsk in typical polygonal tundra landscape. The lowest ALT was in 2005 (0.81 m) and the highest was in 2012 (1.03 m), with an average of 0.92 m.

Despite the substantial population decline in the last ten years from 220,500 to 178,000 people, Norilsk population over the last three years was relatively stable and is projected to increase slightly over the next decade. Unlike some industrial centers, which are largely relying on shift-workers, the labor workers comprise only 72% of the total population of Norilsk. Moreover, only 10 to 13,000 workers (or less than 10%) are changing annually. Permanent population of Norilsk requires substantial number of residential housing, however only few houses were built in the last twenty years. Residential houses are typically designed for 50-year lifespan and with the majority of houses built prior to 1980s, Norilsk is heading towards a housing crisis. Approximately 50 nine- and five-story houses built in 1960s-80s were recently disassembled in Norilsk region and many others are waiting to be demolished. Another approximately 300 buildings in Norilsk industrial region have damage associated with the deterioration of permafrost-geological conditions; more than 100 facilities are in the state of failure.

The Norilsk administration is looking for ways ways to sustain the population and infrastructure in the city. One of the ways, outlined by strategic city planning committee of 2006 was to build new houses in Oganer District. Organer is one of several satellite districts, including Talnakh (population 48,000) and Kayerkan (population 23,000) that contribute to the total 178,000 current population of Norilsk. Oganer has a current population of about 7,000 people, but was originally designed to accommodate 50,000 to 80,000 workers involved in mining and production industries, but was never fully built. While other satellite cities, such as Talnakh and Kayerkan were able to accommodate growing Norilsk population, they both were more than 15 km away, requiring additional time and transportation costs to deliver workers.

The idea of a new satellite city became apparent in mid-80s, when Norilsk was unable to grow to the extent needed to accommodate large workforce required to maintain the growing production of mineral resources. Located in the valley, Norilsk was situated between two metallurgy plants and steep mountains slopes. The only direction of city expansion was east, but the area immediately adjacent to the city was previously occupied by structures without ventilated basements, such as machinery shops, garages and residential barracks. Poor insulation of these structures resulted in deterioration of permafrost conditions and thermokarst development was likely to occur with new construction. Near surface bedrock at a site, about 8 km east of the Norilsk, could support massive apartment buildings, which otherwise would be impossible in fine grained frozen sediments.

The first houses in Oganer were built around 1986 on piles, which are set in a combination of permafrost and near-surface bedrock. The bedrock supported the bases of the piles which were additionally frozen along the sides allowing large structural weights to be held by the foundations. Permafrost is commonly used as the base for foundations when it can be protected from thawing during construction and lifespan of the structure. This practice is known as the passive construction principle. The majority of buildings in the area were constructed on piles, which minimized disturbance of the permafrost regime and maximized the total potential structural load by redistributing the structural weight over multiple points (Fig. 29).

Figure 29. Building constructed using piling foundation on permafrost. *The same type of piles can be seen on the right from the building. Various heights of the piles are the result of differential frost heave processes over the construction site. (Photo: D. Streletskiy, July 2013)*

Piling foundations were advantageous in permafrost with low ice content and the near-surface bedrock; however, several additional geologic surveys in Oganer revealed that the bedrock extent was much smaller than expected prior to construction. Because roads were already built and utilities were in place, the construction continued, but had to deal with ice-rich (40-60%) permafrost in a river valley that was primarily sand and clay. Alternative types of foundations, such as the surface foundations with ventilated bases were implemented. This was a good solution considering presence of ice-rich permafrost; however problems with ventilation and overestimated structural weight of the structures resulted in deformation of the buildings on surface foundations (Fig. 30).

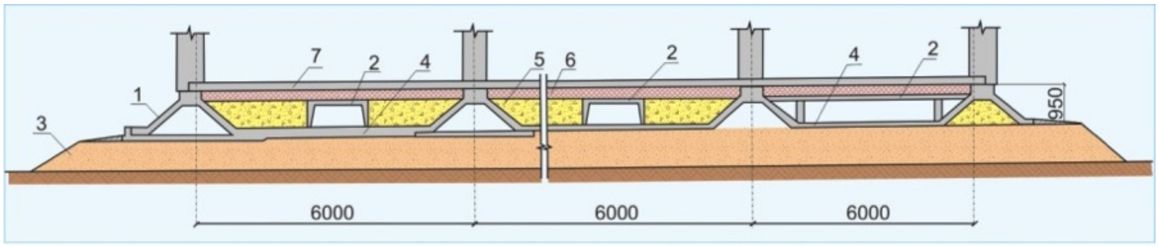

Рис. 4. Конструкция поверхностного пространственного фундамента-оболочки в сочетании с вентиляционными каналами:
1 – складка фундамента; 2 – вентиляционный канал; 3 – промежуточный слой; 4 – монолитный участок; 5 – засыпка под полом; 6 – утеплитель; 7 – бетонный пол.

***Figure 30. Profile of typical surface foundation** used on permafrost with high ice content **(top)** and example of building with such foundation in Oganer **(bottom)**.*

Difficult engineering conditions, presence of ice-rich permafrost and intensification of thermokarst processes due to vegetation and soil disturbances made construction expensive and problematic. Construction of Oganer faced additional difficulties in 1990s as the complicated economic situation, due transformation to a free market economy and the uncertain future of remote cities after collapse of the Soviet Union, resulted in substantial population emigration from many Arctic regions, including Norilsk. Oganer, originally planned as a large satellite city was never completed. Presently, it is represented by only one out of five planned districts, with several 9-story unfinished buildings, including a fire station, a school and a hospital.

Methods

We used a combination of modeling techniques and field observations to evaluate how changes in climatic conditions and human activities affected permafrost geotechnical properties in Norilsk and surrounding areas. Climatically driven changes in the permafrost-geotechnical environment were evaluated using a model designed to estimate permafrost temperature, active-layer thickness, and foundation bearing capacity, depending on changing climatic conditions, accounting for various land-cover and soil characteristics, and geometry of common piling foundations.

We used, as input into the permafrost-geotechnical model developed by Streletskiy *et al.* (2012b), average monthly temperature and winter precipitation from the Norilsk weather station, in combination with the results from experiments using six global circulation models (GCMs) in CMIP5 (Coupled Model Intercomparison Project Phase 5), The six models were chosen based on their ability to demonstrate the best performance in matching observed temperature trends in the Russian Arctic. These models were CanESM2 (CanESM), Canadian Earth Systems Model 2; CSIRO-Mk-3.6 (CSIRO), Commonwealth Scientific and Industrial Research Organization Mark 3.6; HadGEM2-ES (HadGEM), Hadley Centre Global Environment Model Version 2 – Earth System; GFDL-CM3 (GFDL) Geophysical Fluid Dynamics Laboratory Climate Model Version 3; IPSL-CM5A-LR (IPSL) for Institute Pierre Simon Laplace, Climate Model 5A – Low Resolution; and NorESM1-M (NorESM), Norwegian Earth System Model version 1-M. The projected experiments ran from 2006-2300 under RCP8.5 forcing, meaning that each square meter at the top of the troposphere will increase 8.5 Watts by 2100. Since each GCM had a different native horizontal resolution, the output was rescaled to a 1° x 1° spherical grid for the comparative purposes.

To evaluate historic changes in the permafrost-geotechnical environment, we used a 30-year reference climatology prior to construction. This procedure would have been required according to the Construction Norms and Regulations used to estimate foundation bearing capacity prior to construction (Streletskiy *et al*. 2012b). For example, if a building was constructed in 1975, the 30-year reference climatology used to estimate bearing capacity would have been obtained for period between 1945 and 1975. Likewise, a building constructed in 2005, would use reference climatology from 1975-2005.

Soil properties, such as texture, moisture, peat and ice content can be quite variable within relatively small areas, so several soil types, each characterized by high and low ice content, were used. Snow height is difficult to approximate in urban environments, as wind tunneling and snow removal result in large differences in snow height from the ones obtained in natural conditions. Foundations of buildings are usually protected from snow and should be zero, however snow commonly accumulates along the sides of buildings. To assess the effect of snow redistribution on permafrost temperature, two extreme cases were included: one in which no snow accumulates and a second with 0.6 m of snow accumulation by the end of the winter. In this way, temperature conditions of a particular year represent the initial model input for foundation bearing capacity, which varies depending on snow redistribution, soil conditions and presence of ice. For example, snow accumulation and presence of high ice content will result in high permafrost temperature and low bearing capacity, while lack of snow and low ice content will result in a better ability of permafrost to support foundations. A combination of various conditions was presented by 18 model cases for each year.

To evaluate future changes in permafrost-geotechnical properties, the decade between 1965 and 1975 (further 1970) was selected as a reference period, since a large number of structures were built around this period and because 30-year periods were too computationally demanding to model. Relative changes in climatic, permafrost and geotechnical parameters were calculated for the present 1995-2005 (2000), near-future 2015-2025 (2020), mid-century 2045-2055 (2050), and the end of the century 2085-2095 (2090).

Results and conclusions

According to the six models used in this study, the mean annual air temperature in Norilsk increased by 1.3^{o}C from 1970 to 2000, which agrees with the observational trend from the Norilsk weather station. HadGEM, IPSL and GFDL did the best job in representing the observed trend. According to the best three models, temperature increases of 4, 7 and 11^{o}C are expected by 2020, 2050 and 2090, respectively, under the RCP8.5 forcing (Fig. 31). There is large uncertainty in snow cover representation across the models, with IPSL predicting a 40 cm increase and HadGEM showing a 30 cm decrease. Overall, snow cover is predicted to increase slightly by the end of the century (Fig. 31).

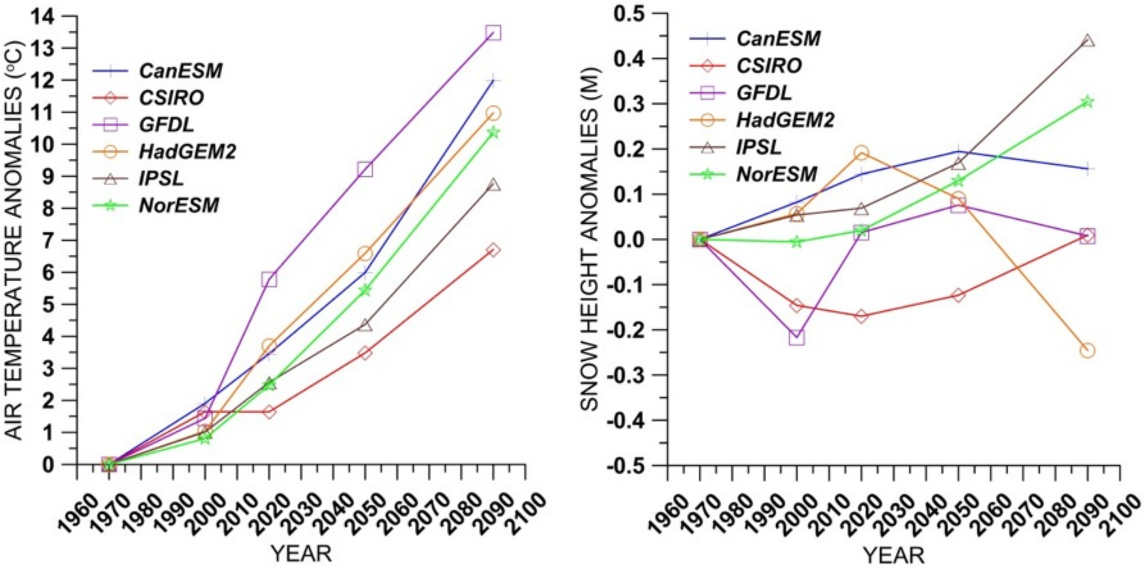

***Figure 31. Mean annual air temperature and snow height anomalies** are shown relative to decade of 1970s using six models.*

Active layer thickness was validated using the R32 Talnakh CALM site located within the climate grid. The average ALT over the observation period was 0.92 ± 0.21 m, which is within the range obtained by the model ensemble for the 2000s. The use of all 6 models showed that ALT in 2000 was 13 cm greater than in 1970 and is presently around 1 m. The ALT is projected to increase by an additional 40 cm by 2020. Two out of six models show that by 2050, the active-layer will no longer reach the permafrost layer. Instead, a layer of talik overlying the permafrost will increase. A layer of seasonal freezing will develop at the surface and the thickness of the frozen layer will progressively decrease by 2090. The remaining four models project an average increase of 1.8 m by 2050 relative to 1970. All models, except CSIRO, show near-surface permafrost disappearance by the end of the century. According to CSIRO, low temperature permafrost will persist throughout the century even under a scenario using the highest possible forcing.

Warmer winter air temperatures and increased snow cover height lead to an increase in permafrost temperature, while warmer summers and, possibly, the role of increasing summer precipitation, resulted in thickening of the active layer. The combination of these factors resulted in an overall decrease of bearing capacity by 2013, relative to previous years (Fig. 32).

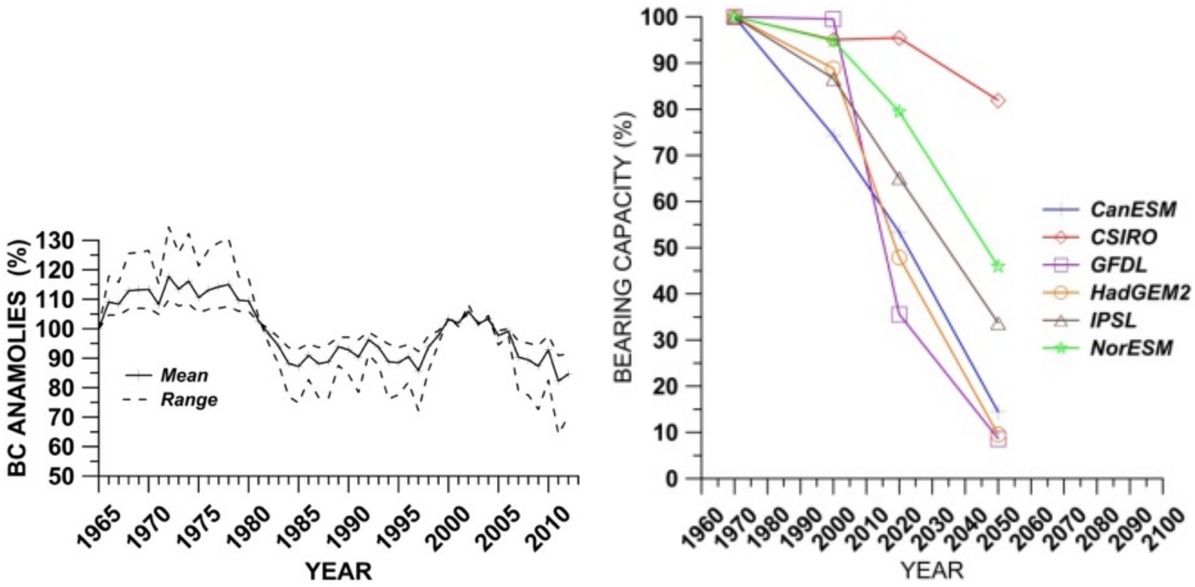

Figure 32. ***Left:*** *Foundation bearing capacity in 2013 relative to the year of construction.* ***Right:*** *Projected bearing capacity, using the six models.*

For buildings built around the 1960s, the decrease was, on average, 15% (9-30%), while the average for buildings built around the 70s and 80s, it was 21% (11-38%). This indicates that structures built in 1970s and 1980s are more prone to deformations due to climatic loss of bearing capacity than those built in 1960s.

The bearing capacity obtained by the six models show a decrease by 10±9% from 1970 to 2000 (Table 2), which is similar to the estimate of 12% obtained using observational data for the same time period. By 2020, a bearing capacity decrease is projected to be 36±21%, which is higher than safety coefficients for most buildings built in late 1970-80s in the Norilsk area. With a slow pace of new construction and "recycling" of old foundations, it is possible that some of the foundations will still be in place by 2050, in which case the ability of their foundations to support structural weight will decrease by two thirds, according to six models (67±28 %)

Table 2. Predicted changes in in climatic and permafrost characteristics in Norilsk area based on the six models.

	1970s	**2000s**	**2020s**	**2050s**	**2090s**
Annual Air Temp (^{o}C)	-12.03 ± 1.7	-10.72 ± 1.7	-8.77 ± 2.6	-6.20 ± 3.0	-1.68 ± 3.5
Relative* Snow Height (cm)	0.00	-3.39 ± 11.9	1.64 ± 9.8	8.27 ± 9.9	10.52 ± 23.5
Active Layer Thickness (m)	0.81 ± 0.4	0.98 ± 0.4	1.40 ± 0.5	0.46 ± 2.1	-1.35** ± 1.5
Temp of Permafrost Top (^{o}C)	-7.70 ± 1.8	-6.77 ± 2.1	-4.67 ± 3.2	-1.90 ± 3.3	1.73 ± 3.0
Relative* bearing capacity (%)	0.00	-10.27 ± 9.2	-36.28 ± 21.0	-67.43 ± 27.7	NA***

*Relative values from 1970s; **Positive values of ALT represent layer of seasonal thawing, negative – seasonal freezing ***Permafrost disappearing

Summary

The economic development of industrial centers on permafrost mandates that housing be adequate to sustain the workforce that dwells in these centers. The foundation bearing capacity used as a quantitative indicator of the ability of foundations to support the structural weight of houses depends on permafrost properties. These properties are, in turn, affected by changes in climatic and environmental conditions and human activities, making bearing capacity an important comprehensive indicator of changes in urban landscapes on permafrost. The combination of climate warming and human activities in the Norilsk area has resulted in increased permafrost temperature and a decrease in foundation bearing capacity. This trend is likely to continue in the future if adequate measures fail to be taken by the city administration.

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Conclusions and Recommendations

Conclusions from the RATIC workshops

The RATIC workshops at the Arctic Change 2014 meeting in Ottawa, and Arctic Science Summit Week 2015 in Toyama provided international discussions on issues related to infrastructure and climate change in the Arctic. The complexity of the Arctic-wide problem became evident when viewed from the perspective of different countries and in the context of the full Arctic Social-Ecological System (Fig. 33). The central question in all the case studies was, "Can we develop effective methods to sustainably manage future infrastructure in the Arctic?" The participants identified several key messages relevant to the ICARP III process:

1. There is a need to examine the cumulative effects of infrastructure in the context of and Arctic social-ecological systems.

Understanding the emergence and consequence of cumulative effects on high latitudes social-ecological systems requires the consideration of a number of dimensions. These include 1) accounting for the drivers of infrastructure and infrastructure change including the interaction of biophysical and social dynamics in Arctic Social-Ecological Systems (Fig. 33); 2) evaluating the implications of social-ecological changes on ecosystem services, human residents and industry, 3) crafting effective systems of governance to support adaptation to and mitigation of change. Framing these dimensions holistically requires transdisciplinary approaches that link science with policy.

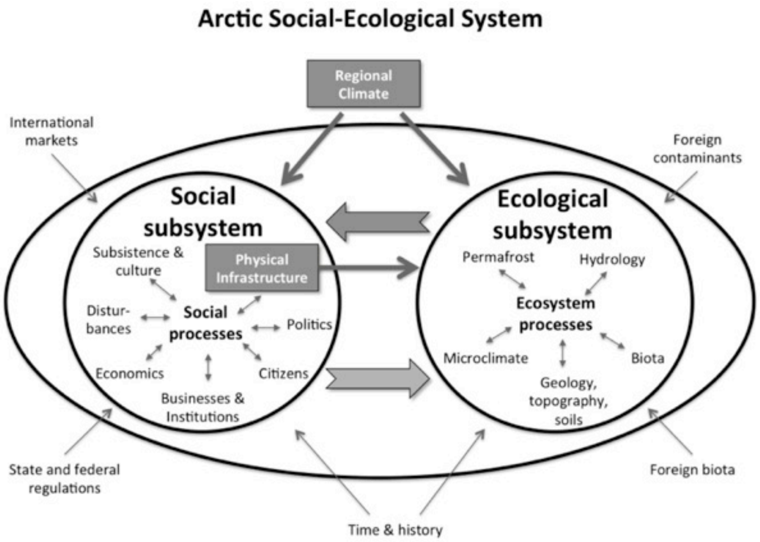

Figure 33. The Arctic social-ecological system (SES) *emphasizing the roles of climate and physical infrastructure, and the feedback to the social subsystem from the ecological subsystem. The Arctic SES consists of ecological and social subsystems that strongly influence one another at local and regional scales. For each subsystem there are external factors (e.g. regional climate and international markets) that are not influenced by local conditions (known as state factors by ecologists) and internal factors (e.g. institutions or disturbances), which respond to external factors and which both affect, and are affected by local processes (known as interactive controls by ecologists). Climate operates directly on both the social and ecological systems. Infrastructure is a product of the social system that influences other social processes and also directly influences permafrost, microclimates, biota, etc. of the Arctic ecological system. (Based on Whiteman* et al., *2004).*

Accounting for the drivers of change including the interactions of biophysical and social dynamics. The drivers of infrascture include Cumulative effects (CEs) suggest that drivers of change are not additive but interact, resulting in responses that are potentially non-linear, multi-scaled, and temporally lagged. While many regulatory regimes only consider CEs in the context of multiple land-use change activities, other drivers such as climate or human feedbacks, can be equally if not more significant. These include changes in economies, policy shifts, or changing human values. Stitching the elements of the system together to understand CE is, at best, challenging, limited by the typical conventions of science that promote, hypothesis testing, reductionism and simplification. As research efforts in this area move forward in the future, it will be necessary for researchers to fully engage in transdisciplinary science, such as resilience theory, complex adaptive systems, and vulnerability analysis. These approaches shift the focus to understanding possible regime shifts, critical thresholds of change, how human choice may transform the system in anticipation of change. How will land-use change and climate change interact? How may the consequence of those changes modify human behavior?

Evaluating the implications of social-ecological changes on ecosystem services, human residents and industry. Evaluation of the implications of industrial development and related cumulative effects to human well-being has been considered in many ways through several disciplinary perspectives. From a local community perspective, a key issue is the direct and indirect changes to ecosystem services, such as changes in the abundance and distribution of important harvested resources and local access to harvest areas. For example, local hunting parties are typically restricted from traveling through or harvesting in close proximity to industrial development sites for safety and security reasons. Environmental degradation in the form of contaminants, noise pollution, increased air traffic can also affect harvest areas. These potential problems can be framed in the context of food security, but should also be considered in light of the deep cultural significance of subsistence to indigenous peoples. Negotiated agreements with local communities for financial benefits mean that local communities are faced with difficult decisions and assessing trade-offs. Because of the inevitable winners and losers that result, internal community conflicts can add to the stress of community life and affect a community's sense of unity. Oil and gas extractive firms operating in the North are ultimately charged with securing a profit for shareholders, but have a legal duty to maintain environmental standards. In conditions of rapid climate warming, thawing permafrost, hydrological change, sea-ice retreat, coastal erosion, and ecological change create challenges for field management. For example, the seasonal duration of ice roads, water from lakes for the construction of ice roads, changes in spring flooding, and thermokarst are now managed with great uncertainty. What data are needed to assess novel conditions? Who should take responsibility of monitoring and to what extent should data be available to non-industry entities? University-industry partnerships in monitoring and research in oil field environments are underutilized.

Crafting effective systems of governance to support adaptation to and mitigation of change. By "systems of governance" we mean the broad set of processes that society (i.e., stakeholders) uses to make decisions. It is not restricted to the actions of government. Multiple drivers of change, possible cumulative effects, and conditions of uncertainly suggest that conventional approaches to decision making related to oil and gas development are inadequate. Alternative approaches, such as adaptive management, scenario analysis, and structured decision making (or decision analysis) may provide opportunities for the identification of optimal choices, experimentation, learning from past experience, and innovation. The extent to which systems of governance can accommodate such approaches is unknown, but there have been several initiatives recently launched (e.g., North Slope Science Initiative – Scenarios Project). These efforts, however, have a power politics dimension related to the involvement of more marginal actors, such as indigenous communities. While formal co-management arrangements (e.g., Alaska Eskimo Whaling Commission) and "home rule" (e.g., North Slope Borough) can help to level the playing field for decision making through greater democratization, experience on the Yamal shows how industry can articulate and adopt "Best Practices" that are sensitive to the needs of local resource users. More research is needed that assesses the conditions that make for equitable, effective, and resilient systems of governance of industrial activities that address the emergent sent of problems.

2. Permafrost response to a combination of infrastructure and climate change is a pressing ecological issue with large social costs.

Permafrost thawing and its associated impacts on natural and built environments were clearly identified as priority issues across all regions of the Arctic, but the specific issues related to permafrost differ in each region studied. As pointed out in the Norwegian case study, frost heave is changing even in boreal regions without permafrost. The Prudhoe Bay case study focused on the ecosystem consequences of ice-wedge degradation in the flat Arctic Coastal Plain of northern Alaska. The permafrost issues in the Yamal case study dealt with large landslides related to massive tabular ice and the recent discovery of new craters that appear to be caused by explosive release of methane trapped in the permafrost.

Infrastructure changes soil thermal regimes through local heating, shading, and destruction of the vegetation carpet, and through indirect changes to snow regimes, hydrology, addition of dust and other contaminants. In communities and urban environments, changes to the thermal regimes of soils supporting houses, roads, airports, and large buildings have enormous economic and social consequences.

The changes to local microtopography caused by of networks of infrastructure are affecting the structure of landscapes, ecosystems, and the use of the land by northern residents and industry. Northerners are impacted by permafrost change through its effect on community infrastructure and subsistence activities. Oil, gas and mining industries require extensive new facilities built on permafrost. These cumulative permafrost changes come at a time of intense demographic and socio-economic development in the Arctic.

3. The indirect effects of infrastructure exceed the direct effects of the planned footprints.

Both the Prudhoe Bay and Bovanenkovo studies emphasized that the eventual indirect landscape effects from such things as roadside flooding, thermokarst, and dust, often exceed the direct effects of the infrastructure itself. Evaluating and predicting the effects of infrastructure must extend beyond the direct footprint of roads, pipelines and facilities to the adjacent landscapes, local communities, regions, and areas outside the Arctic. Fragmentation of large intact ecosystems is a major impact that is generally not addressed. The case study from the Yamal demonstrated the impacts to migratory reindeer herders. Studies in Alaska have shown that indigenous hunters no longer can use large areas of tundra within the oilfields for subsistence hunting. Summer off-road vehicle trails, winter seismic trails and ice roads cover large areas that are not included in the planned footprint of developments. The indirect effects to wildlife and local communities are more difficult to assess and require more attention than they have received in the past. Other indirect effects that need study are the effects of light, sound, and odor emissions from infrastructure, changes in predator-prey relationships due to infrastructure, and the issues of restoration, revegetaion, and cleanup following removal of infrastructure.

4. New tools are needed to monitor infrastructure and landscape changes and to develop sustainable approaches for future development.

There is need for integrated, interdisciplinary research addressing infrastructure. The observations from infrastructure studies to date have strengthened the conclusions from the 2003 report by the National Research Council regarding the need for regional ecosystem-level studies:

> *Most ecological research in the Prudhoe Bay region has focused on local studies of the behavior and population dynamics of animal species. Patterns and processes at landscape scales, as well as nutrient cycling and energy flows, have received relatively little attention. Nevertheless, the research that has been done has identified the need for, and importance of studies of population dynamics over large areas and the need to assess how industrial activities on the North Slope are affecting the productivity of tundra ecosystems. Alterations of flow patterns of water across the Arctic Coastal Plain, thermokarsting of tundra adjacent to roads and off-road pathways, and changes of albedo attributable to dust are all likely to influence plant community composition, rates of photosynthesis and decomposition; and efficiencies of energy transfer between plants, herbivores, and carnivores. Thus, tundra within an oil field is likely to differ in many ways from that in an unaffected ecosystem, yet the extent of the differences and the processes that cause them are largely unknown (National Research Council, 2003).*

GIS and remote sensing are essential aspects of studying change and developing adaptive management of Arctic infrastructure. Both the Prudhoe Bay and Bovanenkovo studies built on extensive climate, permafrost, and geoecological baselines that were built during and following the IBP Tundra Biome studies in the 1970s. Much of this history was organized in historical GIS databases. At Prudhoe Bay, the oil industry uses the latest technology in a comprehensive GIS-based infrastructure-mapping program with high-resolution aerial-photo missions to provide annual updates of the GIS information. An emerging application of remote sensing is in detecting changes to landscapes beyond those of the footprint of the infrastructure. Very-high-resolution (VHR) satellite data can trace the cumulative effect of ORV trails and other types of small-scale disturbance that individually cover relatively small areas, but in total affect large landscapes. More intensive monitoring of old trails is needed to develop effective sensitivity models that can predict recovery from ORV traffic at the plant-community-level. The VHR imagery are also essential for detecting changes to historical changes to permafrost-related landforms such as landslides and new large craters on the Yamal peninsula and the thermokarst pits of the Prudhoe Bay studies.

Scenario modeling is a key aspect of adaptive management. New approaches are needed that involve the details of the affected landscapes and ecosystems, as well as foreseeable changes due to climate, as well as economic, political, demographic, land-use, and technological factors.

5. Infrastructure issues are not adequately addressed by any of the IASC working groups nor in many national-level Arctic science plans.

IASC and ICARP III could play a key a role in helping to promote international projects and programs focused on sustainable methods of infrastructure development. Several programs cited in this paper provide examples from different countries. In Canada, the Arctic Development and Adaptation to Permafrost in Transition (ADAPT) and ArcticNet Integrated Regional Impact Studies (IRIS) programs are the best examples of how large integrated national projects that include scientific understanding of permafrost dynamics in natural and engineered environments can be applied at the community level. The Finnish ENSINOR project deeply involves social scientists and the local people in helping to understand the complex social-ecological problems associated with gas development on the Yamal Peninsula. In the U.S., the NSF Arctic Science Engineering and Education for Sustainability (ArcSEES) program seeks “fundamental research that improves our ability to evaluate the sustainability of the Arctic human-environmental system as well as integrated efforts which will provide community-relevant sustainability pathways and engineering solutions.” The North Slope Science Initiative (NSSI) is an interagency, collaborative effort to address the research, inventory, and monitoring needs related to North Slope development activities in Alaska. Many other examples of scientific approaches to sustainable infrastructure are available from industry and governments that are continuing to explore and develop useful approaches for sustainable infrastructure development.

Recommendations for Arctic Research Planning

The RATIC workshop participants agreed that science plans emerging from ICARP III need to explicitly address rapidly expanding infrastructure networks. Recent studies indicate that combinations of industrial development and climate change have resulted in major changes to local ecosystems, including the permafrost, hydrology, vegetation, wildlife, and local people. The effects are both positive and negative with respect to biological resources and the local communities and economies. The effects of resource development and fragmentation of large intact ecosystems by extensive networks of roads, railroads, and pipelines are apparent and keenly felt by the indigenous people of the Arctic. The effects on broader regions are currently difficult to assess, but require more attention because of the cumulative effects beyond the areas of immediate impact. This topic is internationally important because mineral and hydrocarbon exploration have transnational effects that are broadly occurring across the circumpolar Arctic. The social, economic, regulatory, and political drivers of development vary across the Arctic. The national and international programs supporting research described in the case studies are examples that need to be built on for the next decade.

Next steps

The scope of the challenge includes: (1) examining the drivers of Arctic infrastructure in widely different Arctic cultures, economic systems, political environments, and ecological systems; (2) monitoring and understanding the vulnerabilities, resilience and full cumulative effects of Arctic infrastructure on the diverse group of Arctic social-ecological systems that are currently undergoing change; (3) planning, managing, and shaping future Arctic infrastructure, and (4) involving the Association of Polar Early Career Scientists (APECS) in the process to provide new energy and new ideas and assure continuity of the effort through the next decade of Arctic research. Future planning needs to include consideration of the widely divergent political systems, economies, cultures, communities and landscapes present in the Arctic, fragmentation of presently intact natural landscapes by large networks of roads and pipelines, Arctic urban infrastructure, engineering of subarctic infrastructure, and Arctic off-shore infrastructure.

As first steps, the RATIC group recommends that the combined IASC Cryosphere, Human and Social, and Terrestrial Working Groups work together to: (1) Finish the RATIC white paper and post it on the ICARP III website as a product of the ICARP III planning process; (2) publish a summary of the white paper and follow-up synthesis activities in an appropriate peer-reviewed journal; (3) develop an IASC interdisciplinary Infrastructure Action Group that includes participation by members of all IASC working groups and APECS; (4) incorporate infrastructure-related issues more explicitly in the IASC working groups' research priorities; (5) promote regular infrastructure workshops at international scientific meetings; (6) emphasize the need for social-ecological-system studies in relationship to infrastructure; and (7) promote infrastructure-related themes in future international research initiatives.

Sustainable infrastructure development resolution for ICARP-III

Arctic Science Summit Week 2015 in Toyama, Japan (23–30 April) brought together nearly 700 international scientists, students, policy makers, research managers, Indigenous Peoples and others interested in developing, prioritizing and coordinating plans for future Arctic research (www.assw2015.org). Members and Fellows of the IASC Cryosphere Working Group, Social & Human Working Group, and the Terrestrial Working Group drafted the following resolution on 25 April 2015.

Whereas:

- Northerners and Arctic socio-ecological systems are strongly impacted by changes in infrastructure;
- The drivers and consequences of infrastructure development in the Arctic are not adequately addressed by the Arctic research community;
- The complexity of the Arctic infrastructure challenges requires a multi-disciplinary and circumpolar collaboration approach involving all Arctic countries and implementation of an integrated social-ecological-system approach.

Therefore:

- We propose that ICARP-III identify **sustainable infrastructure development** as a key research theme that requires a multidisciplinary collaborative approach involving scientists, local communities, governments, and industry.

During the concluding ceremonies for the 2015 Arctic Science Summit Week, sustainable infrastructure was recognized as one of eight overarching messages that emerged from the conference:

> *New markets for Arctic resources and associated activities, including trade, tourism and transportation, will likely emerge faster than the necessary infrastructures on land and sea.*

> *Sustainable infrastructure development and innovation to strengthen the resilience of Arctic communities requires a collaborative approach involving scientists, communities, governments, and industry.*

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