Cumulative Effects of Arctic Oil Development – planning and designing for sustainability

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Table of Contents

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Summary

Intellectual merit: Developing arctic oil & gas resources requires extensive networks of roads, pipelines and other forms of infrastructure. The cumulative environmental and social effects of expanding developments are difficult to assess and impossible to predict — especially in the face of rapid climate change and unpredictable politics, oil markets, and social and economic changes. Previous analyses of the cumulative effects (CE) of oil and gas development in northern Alaska have recommended comprehensive adaptive planning approaches to 1) minimize the spread of infrastructure across land that is used by indigenous people for subsistence, and 2) reduce the indirect effects of infrastructure that result in the thawing of ice-rich permafrost (NRC, 2003; Streever et al., 2011). A sustainable approach to CE requires collaboration between indigenous people, industry, and scientists from a broad spectrum of disciplines to address these infrastructure-related concerns (NSF, 2012). This proposal does that with detailed ground studies, local community input, industry involvement and an international perspective. A three-pronged initiative is proposed: 1) A *case study of the cumulative effects of industrial infrastructure at Prudhoe Bay, Alaska* will focus on infrastructure-related effects associated with gravel mines, roads and other areas of gravel placement. The study will include ground-based studies, an examination of infrastructure and landscape change at multiple scales, and a human dimension component that includes evaluation of adaptive management planning for infrastructure in northern Alaska and CE studies associated with the Iñupiat village of Nuiqsut. The study will develop a process-based understanding of infrastructure-related permafrost/ landform/ vegetation succession in terrain undergoing thermokarst formation (the development of highly eroded landforms that result from the thawing of ice-rich permafrost). The study will help to answer the questions "What will these areas look like in 50-100 years?" and "Can adaptive management methods address the complex issues related to placement, usage and decommissioning of infrastructure in Northern Alaska?" 2) An *Arctic Infrastructure Action Group (AI-AG)* will bring the CE issues to greater prominence in the international Arctic research community. The AI-AG will consist of local people who interact with development infrastructure, permafrost scientists, ecologists, hydrologists, engineers, social scientists and educators seeking to develop adaptive management strategies that address the unique issues related to networks of infrastructure in arctic permafrost environments. Three workshops will bring panarctic participants together, first in a scoping workshop and then to focus specifically on the two most rapidly expanding areas of Arctic infrastructure, the North Slope of Alaska and the Yamal Peninsula, Russia. 3) An *education/outreach component* will train students in arctic systems and introduce them to the issues of industrial development and adaptive management approaches during an expedition along the Elliott and Dalton highways in Alaska. The course will include a section at Prudhoe Bay to learn firsthand about the issues with oilfield infrastructure, its impacts and vegetation rehabilitation practices. Students will also visit the village of Nuiqsut to experience village life and discuss CE issues with the local residents. ***Broader impacts:*** The proposed Prudhoe Bay case study will lead to better engineering solutions for building roads that minimize thermokarst. It will improve our understanding of climate-change related issues including how large developments affect patterns of vegetation change observed on remote-sensing imagery at multiple scales. The human-dimension aspect will have broad relevance to management and decision-making involved in placement, design, maintenance and decommissioning of infrastructure. The study will also contribute significantly to understanding infrastructure impacts on villages, where road-induced thermokarst is a growing hazard. The AI-AG focus on adaptive management methods will promote synergistic exchange of ideas among stakeholders including local Native people, industry, management agencies, NGOs, scientists and the general public. The project will be closely linked to the UAF EPSCOR Northern Test Case. The proposed course, scholarship support for two Alaska Native North Slope students, and outreach to APECS scientists will help entrain a new generation of scientists in CE research. Map and plot data from the project will have wide practical applications for future researchers at Prudhoe Bay. The project web site will promote outreach and education activities.

Project Description:

Part 1. Case study: A hierarchical geoecological and social analysis of infrastructure cumulative effects at Prudhoe Bay, Alaska

Background

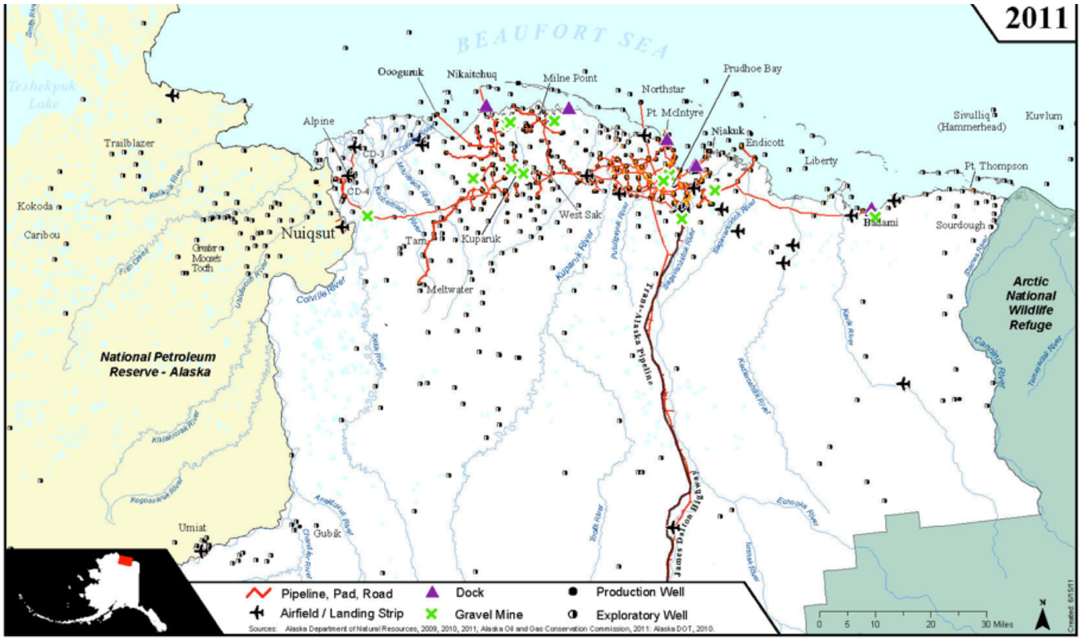

Figure 1. Existing, mines, roads, and aboveground pipelines (red), production and exploratory wells (black dots). Compiled by the Northern Alaska Environmental Center (2011).

The opening of Arctic lands and seas to transportation and development is occurring against a backdrop of sea-ice loss, dwindling resources elsewhere in the world, and competing geopolitical interests. It is inevitable that much more extensive networks of infrastructure than presently exist will be required to develop these areas. The first part of our research will focus on the issues related to infrastructure expansion and its relevance to the local ecosystems and people in the Prudhoe Bay region of northern Alaska (Fig. 1).

The North Slope oilfields currently hold about 16% of the total U.S. proven reserves of oil and gas (U.S. Energy Information Administration, 2012). The North Slope oilfields are by far the largest source of the oil and gas revenue for the State of Alaska, which in total account for about 92% of the Alaska state budget (Alaska Oil & Gas Association, 2012).

Figure 2. Roadside area along the Prudhoe Bay Spine Road. Within 10 m of the road vegetation has been buried by road dust. Water collected in the ice-wedge troughs is actively eroding the centers of some polygons and converting previous low-centered polygons to high-centered polygons. Photo is a 1983 road transect that would be resampled for this project (Walker and Everett, 1987). Thermokarst has spread much more widely in the 25 years since this photo was taken.

Prior to the discovery of oil at Prudhoe Bay in 1968, Iñupiat very sparsely inhabited the region. Since then a network of about 960 km of roads, 750 km of aboveground pipeline corridor, and 350 km of power transmission lines (Fig. 1, redlines) has spread across about 4000 km^2, an area about the size of Rhode Island (NRC et al., 2003). Gravel mines and gravel placement cover about 2.6% of the Prudhoe Bay Unit (Gilders and Cronin, 2000). As of 2001, the total gravel impacted area was 17,354 ha (NRC, 2003). A wide variety of indirect effects, such as roadside flooding, road dust, and thermokarst, affect additional areas of tundra (Walker et al., 1987b; NRC, 2003) (Fig. 2). The size of the developed area will increase as fields to the east, west, and south are added to the network and the Arctic Ocean becomes more ice-free and marine access to coastal areas improves.

The full cumulative effects (CE) of extensive networks of infrastructure needed for resource development are not adequately addressed in current international arctic initiatives, but the local residents most directly feel the effects of infrastructure and development. The definition of CE used here is:

> …The impact on the environment which result from the incremental impact of the action when added to other past, present and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time. (Council on Environmental Quality, 1987)

Iñupiat people of the North Slope recognize that there are trade-offs and some potential risks associated with the expansion of

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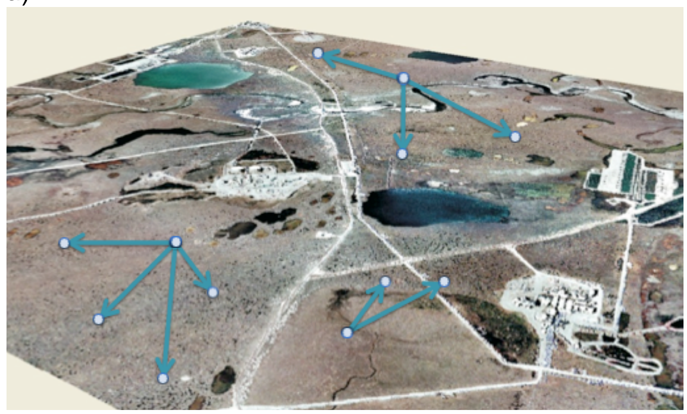

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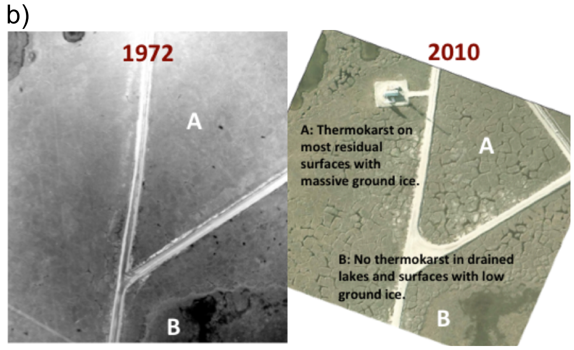

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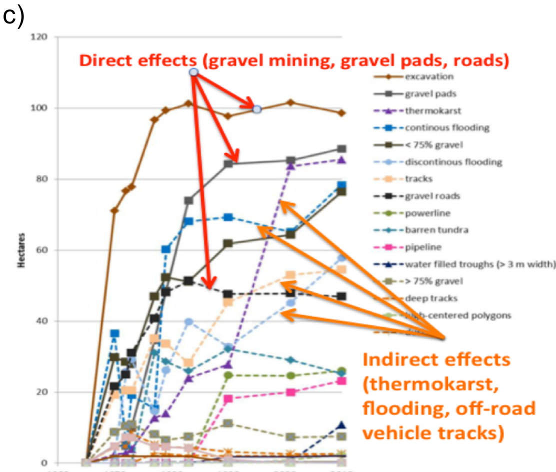

Figure 3. Infrastructure-related changes within a 21 km^2 area, central Prudhoe Bay oilfield (Raynolds et al., 2012). a) Digital color-infrared image overlaid on LIDAR DEM. Pump Station 1 of the Trans Alaska Pipeline is in the center of figure. Blue arrows point to areas of expanding thermokarst not present in earlier images prior to development. (Courtesy of Aerometrics Inc.) b) Detail of area of expanding thermokarst at road junction in center of a) in 1972 and 2010. c) Analysis of trends of direct effects (red arrows) and indirect effects (orange arrows) within the area shown from 1968 to 2010. Only infrastructure related thermokarst is shown in this graph. The study also revealed that an additional 287 ha in areas away from infrastructure were affected by thermokarst.

oil and gas development infrastructures but also that CE have not received enough attention (NRC 2003; Forbes et al. 2009) (Also see letter from Taqulik Hepa, Director North Slope Borough Department of Wildlife Management.) This proposal will first address the physical footprint and the effects to permafrost, and then address the social aspects of the changes and their effects on subsistence livelihoods. The study is divided into three primary parts: Part 1: Hierarchical change analysis; Part 2: Roadside thermokarst analysis; and Part 3: Human dimensions of infrastructure changes.

a. Hierarchical change analysis

Background:

The infrastructure development scenario that unfolded in the Prudhoe Bay oilfield was unique because it was the first large scale oil development in the Arctic. Oil-field drilling technology evolved rapidly during its expansion, reducing the amount of roads, gravel pads and other infrastructure required in later oilfields (Gilders and Cronin, 2000). However, many of the landscape and social consequences of development are universal and will occur in other areas despite technological advances. For example, permafrost is a panarctic phenomenon that greatly affects infrastructure construction, maintenance, and the ability of landscapes to stabilize after infrastructure is abandoned (e.g., Brown and Berg, 1980; Nelson et al., 2001; Kidd et al., 2006). Extremely ice-rich permafrost is common within the oil and gas fields of Alaska, Canada and Russia.

Recent studies indicate that natural thermokarst is expanding exponentially during periods of warmer summer temperature. Jorgenson et al. (2006) documented an abrupt increase in the occurrence of ice-wedge degradation and the formation of thermokarst pits in an area near Fish Creek, just west of the Prudhoe Bay oilfield. The increase is attributable to a Mean Annual Ground Temperature warming of up to 5 ˚C between 1989 and 1996. The thermokarst resulted in major rearrangement of hydrologic features. The authors speculated that if the trend continues 30% of the terrestrial landscape would be altered, resulting in major changes to the local biodiversity, plant communities, wildlife use, and other system services including sinks and sources of trace gases. Our preliminary studies of a portion of the Prudhoe Bay oilfield (described below and in Fig. 3) indicate that thermokarst has already extensively modified 14% of the landscape (Raynolds et al. 2012).

Many of the issues related to infrastructure occur at fine scale (sub-meter to tens of meters) and until recently have been difficult to analyze using remote-sensing technology. For example, thermokarst formation occurs at a scale of a few meters, and many infrastructure components such as culverts, which are sometimes improperly placed to drain road-related impoundments, are not visible on most high-altitude aerial photographs or intermediate-scale remote-sensing images such as Landsat or MODIS. Very-High Resolution (VHR) digital satellite imagery with sub-meter resolution, such as QuickBird and WorldView, enables detection of practically all direct and indirect landscape effects of infrastructure (Kumpula et al. 2012), but such imagery is still not available for all regions and time series of VHR images are still generally lacking.

The Prudhoe Bay oilfield is unique in the Arctic because a complete record of historical changes in infrastructure and the surrounding vegetation has been recorded in aerial photographs dating from 1949 (Walker et al. 2012 submitted). Furthermore, since 1977 the oil industry has contracted annual high-resolution photo missions that cover the entire area of the oilfield. These missions now use the latest advances in aerometric sensors and LIDAR-supported orthophoto-topographic mapping (Walker et al., 2012 submitted). A LIDAR-based digital elevation model (DEM) that covers much of the oilfield allows detailed analysis of changes in surface topography related to thermokarst. Time series of images from satellites with daily coverage (e.g. AVHRR and MODIS) are also useful for detecting regional- and global-scale changes in vegetation productivity patterns (e.g. Bhatt et al. 2010) and satellites with higher spatial resolution but less frequent coverage, such as Landsat and SPOT can analyze these trends with respect to landscape features and infrastructure (Raynolds et al. 2012 submitted). VHR imagery combined with LIDAR imagery now facilitate high-resolution multi-spectral analysis of infrastructure-related patterns of snow, dust, flooding topography and vegetation.

A detailed fine-scale (1:6000) time-change analysis of a portion of the Prudhoe Bay oilfield showed major increases in roadside and regional thermokarst (Fig. 3a (blue arrows) and Fig. 3b) (Raynolds et al., 2012). Areas of direct impacts (gravel mines, roads and construction pads), increased rapidly within 15 years of initial oilfield discovery (1968-1983) with only modest increases since (Fig. 3c, red arrows). However, indirect effects of thermokarst, flooding and off-road vehicle trails, have continued to expand (Fig. 3c, orange arrows). Thermokarst expanded exponentially between 1990 and 2001 (Fig. 3c dashed purple line), presumably due to a combination of changed roadside microclimate and regional climate warming, which matched the timing of rapid thermokarst expansion observed near Fish Creek, west of Prudhoe Bay (Jorgenson et al., 2006).

Table 1. Five-level hierarchic approach for land-cover/infrastructure changes in the Prudhoe Bay case study.

Level, scale, data type (Local prior examples)	Reso-lution	Extent	Time Scale	Purpose
5. Regional to global scale. AVHRR satellite sensor (Bhatt et al. 2010)	8 km	North Slope to global	1982 to present	Time series change in vegetation in relationship to climate change at regional scale and in relation to rest of Arctic.
4. Landscape to regional scale. Landsat ETM, ETM+ satellite data (Walker and Acevedo 1987, Raynolds et al. 2012 submitted)	30 m	50 x 50 km	1984 to present	Change in vegetation in relationship to infrastructure and climate at landscape scale to North Slope scale
3. Landscape scale. Integrated Geoecological and Historical Change Maps (IGHCM) (Walker et al. 1987a, b; Walker et al. 2012 submitted)	5 m (polygon data)	3 areas of Prudhoe Bay Oilfield, 4.5 x 4.5 km	1949 to present	Time-series change in industrial infrastructure and landscapes.
2. Plot to landscape scale. Very High-Resolution satellite data (e.g. GeoEye, Worldview, Ikonos)	1 m	15 km swath-width	2001 to present	Very detailed vegetation and disturbance mapping. Extrapolation of IGHCM information to larger areas.
1. Plot-scale. Ground studies (Walker 1985, Klinger et al. 1983; M.D. Walker 1990, Walker and Everett 1987, 1991; Walker et al. 1987a)	Sub-meter, plots and transects	Plots and transects within 1 km of Prudhoe Bay Oilfield roads	present	Detailed study of relationship between topography, permafrost and vegetation; topographic and vegetation changes relative to distance from roads.

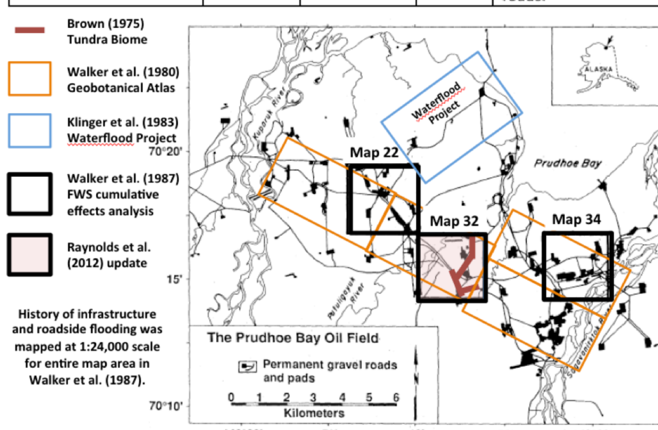

Figure 4. Areas of detailed geoecological mapping that will be used for the case study.

Research questions:

1. *What has been the historical pattern of infrastructure and infrastructure-related thermokarst formation in the Prudhoe Bay region? How do the patterns vary with respect to distance from roads, different types of roads, and in different types of terrain? How can infrastructure-related and climate-change related thermokarst be differentiated?*
2. *Are the changes in thermokarst affecting local patterns of plant productivity? If so, are the changes widespread enough to be detected using time-series of global-scale remote sensing products such as Landsat, MODIS, and AVHRR?*

Proposed work:

To answer questions 1 and 2, we propose a five-level spatial analysis of infrastructure-related changes within the oilfield (Table 1). Level 1 of the analysis will include the ground studies proposed for the roadside thermokarst study described in the next section. At higher levels we have identified a hierarchy of geoecological maps and images to aid the analysis at plot, landscape, regional and global scales.

Level 2 will use Very High Resolution (VHR) imagery and the Lidar imagery to construct digital vegetation classifications and DEMs that will be used in the roadside thermokarst studies (next section).

Level-3 analyses will develop Integrated Geoecological and Historical Change Maps (IGHCMs) that will replicate the analysis of Figure 3c for Maps 22 and 34 (Fig. 4), permitting a more thorough analysis of CE in other portions of the oil field with different landscape types. The IGHCM approach is a GIS-based mapping method specifically developed in the Prudhoe Bay region to examine cumulative effects of oil field development (Everett et al., 1978; Walker et al., 1980; Walker et al. 1986b, 1987b; Raynolds et al., 2012).

Level 4 will use a time-series of Landsat images obtained during the peak period of vegetation productivity (≅15-30 July) with 30-m resolution to examine trends in the normalized difference vegetation index (NDVI, an index of plant greenness and productivity) using methods based on Olthof et al. (2008). At this scale we will be able to determine the effect of landscape and infrastructure factors on productivity. We will examine areas within the oilfield and in nearby undisturbed tundra to separate the infrastructure-related trends in productivity from the regional trends.

Level 5 will use the global AVHRR (Advanced Very High Resolution Radiometer) data to compare the local and regional, and global trends in productivity (Bhatt et al. 2010).

b. Roadside thermokarst study

Background

A particularly challenging aspect of arctic development is how to construct roads in permafrost-rich wetlands. Roads have the greatest indirect impacts of any infrastructure feature because of secondary impacts from dust, off-road vehicle trails, roadside flooding and snow drifts and other impacts that develop adjacent to the roads (Fig. 2). Thermokarst often forms in areas of ice-rich permafrost following road construction, and its extent often grows as time passes (Fig. 3c). Another serious issue is related to how to minimize thermokarst in areas that are rehabilitated after decommissioning. At Prudhoe Bay as of 2003, about 3640 ha of wetlands had been filled with gravel for roads, airstrips, production pads and facility pads (NRC et al., 2003). Under the 1977 U.S. Clean Water Act, the oil industry is required to obtain federal permits to fill wetlands, and the permits are issued with stipulations for restoration upon site abandonment. As the oilfields age, some exploratory well sites, gravel roads, and other gravel-fill areas are no longer needed and are being decommissioned (Kidd et al., 2006). The gravel is removed and either treated for use in new pads, ground up for injection into the geological formations of the oilfield, or buried. Restoration techniques are then used to attempt to return the site to a semblance of the preexisting ecosystem (Galatowitsch 2012). Wetland sites underlain by large ice wedges are particularly difficult to rehabilitate to acceptable standards (Kidd et al., 2004).

Figure 5. Ice wedge exposed at the Beaufort Sea coast of Alaska.

Figure 6. Ataxitic cryostructure in the upper permafrost, Beaufort Sea coast of Alaska.

At present, it does not seem technically or economically feasible to rehabilitate all the eventually abandoned mines, roads, and gravel pads. A study by the National Resource Council Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope concluded:

"…although DRR [disturbance restoration and rehabilitation] is assumed in some permits and plans, it will almost surely cost much more than the amount of money available. Extrapolation from estimates for individual project plans suggests a total of billions of dollars. However, existing state and federal bonding requirement are not even remotely sufficient to underwrite potential DRR costs on the North Slope. Because the cost of the obligation to restore abandoned sites is unclear and the financial resources to do so are so uncertain, the committee judges it likely that, absent a change in those constraints, most of the disturbed North Slope habitat will never be rehabilitated or restored. What is needed is a slope-wide land-use plan and an understanding of the likely costs and effectiveness of various DRR approaches."
(NRC, 2003).

Much additional experimentation and knowledge about processes involved in landscape succession and revegetation in various wetland habitats has been done by the oil industry (e.g.,AOGA, 2001; Galatowitsch, 2012; Jorgenson and Joyce 1994; Jorgenson and Kidd, 1991; Kidd et al. 2006; McKendrick et al. 1992; McKendrick, 2000; Gilders and Cronin, 2000). But much more is required to develop reasonable practical approaches (Streever et al., 2011).

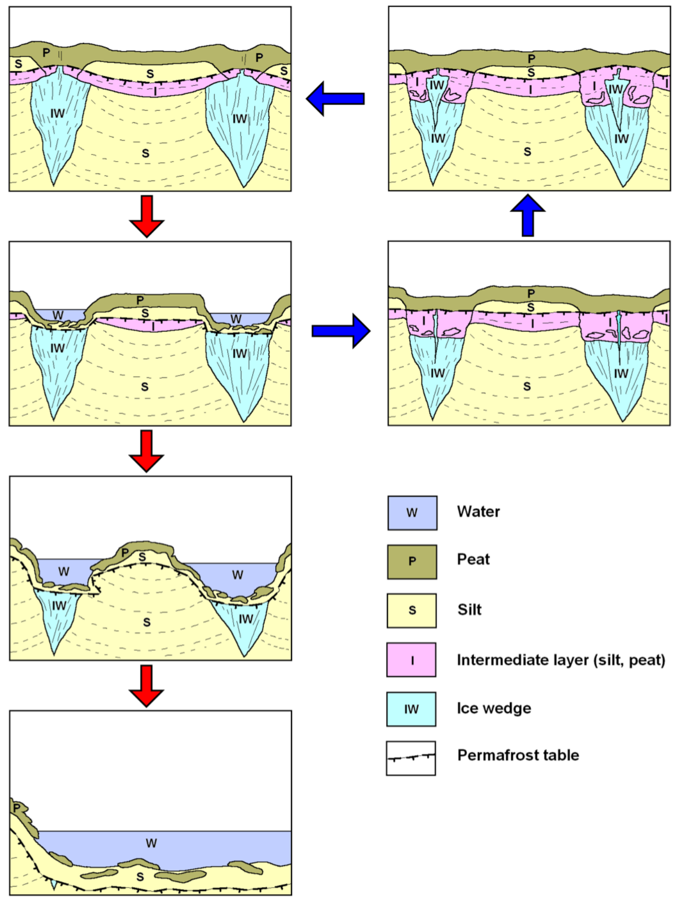

Figure 7. Two possible pathways of thermokarst associated with terrains with wide occurrence of ice wedges. A reversible process (blue arrows) is often observed in a natural environment. This reversible thermokarst associated with ice wedge melting occurs when central parts of polygons remain stable. The process can take a different pathway leading to larger water bodies and lakes if central parts of polygons experience thaw settlement (red arrows). This progressive thermokarst can start abruptly with increase in the thickness of the active layer as a result of change in vegetation on soil surface. It can be triggered by accumulation of dust, which changes thermal insulating properties at the soil surface and increases the rate of snow melting. Our previous work (Pullman et al., 2007)) showed that thaw strain of the upper permafrost of the Arctic Coastal Plain can vary from 0.25 to 0.7. Thaw settlement in central parts of polygons would depend on thaw strain and an increase in the active layer depth (Figure 8).

Recently, we studied ground ice of the upper permafrost at more than 60 sites along the Beaufort Sea coast from Barrow to the Canadian border (Kanevskiy et al., 2012). Ice-wedge polygons existed practically everywhere, varying in size from 10 to 25 m across with average width of 15 m, creating very ice-rich terrain. The maximum width of ice wedges (Fig. 5) at some sites was over 5 m, while their vertical extent usually did not exceed 4 m (Kanevskiy et al., 2012). Volumetric ice content (VIC) of organic and mineral soils between ice wedges varied from 37% to 91%. Mineral soils with the ataxitic (suspended) cryostructure (Fig. 6) prevailed at depths from 1 to 2 m below the permafrost table. These ice-rich soils had the highest VIC, reaching 95%. The visible ice content of these sediments varied from 50% to 80%. Lower ice contents were typically observed in sand and gravel. The average total volumetric ice content (TVIC) at the Arctic Coastal Plain, which includes wedge ice, segregated ice, and pore ice exceeded 80%.

High ground-ice content in the upper permafrost makes permafrost

sensitive to environmental changes. The first and main reaction to changes is thermokarst associated with partial melting of ice wedges and the formation of ponds (thermokarst pits) at ice-wedge intersections and along troughs. Jorgenson et al. (2006) reported preliminary observations of this process.
More detailed studies of ice-wedge thermokarst are now being performed at several sites of the Arctic Coastal Plain and Arctic Foothills. These contemporary studies are focused mainly on the ice-wedge thermokarst in relation to climate warming. ***Little is known about the impacts of infrastructure on this process.***

Our proposed studies will examine positive and negative feedbacks to the thermokarst process (Fig. 7). The positive feedback from surface water and the negative feedback from vegetation and organic matter accumulation have large implications on how permafrost will respond to climate change and infrastructure. An increase in the amount of initial thermokarst ponds along road embankments is usual, but it is not known how far from embankments the ponds trigger impacts on thermokarst. For example, we do not know how additional snow, water and dust accumulation associated with road embankments change ecosystem succession and as a result affect the rate of thermokarst. Our current studies of thermokarst in natural conditions indicate the process is normally limited mostly to areas occupied by ice wedges, while the ice-rich upper permafrost in the central part of polygons (Fig. 6) in most cases remains protected by the mineral soil and thick organic matter above it (Fig. 7 blue arrows).

However, thaw settlement can occur in the central parts of polygons if the polygon centers are affected by other disturbances such as dust, deep flooding, or warmer soils due to road-induced snow drifts (Fig. 7 red arrows). It is possible to compare areas of the direct impacts (footprints of infrastructures, S_d) with areas of the indirect impact (those affected by changes in hydrology, snow, and dust accumulation, S_{in}). Shur (1988) proposed the coefficient K to measure the impact of an infrastructure feature:

$$K = \frac{S_d + S_{in}}{S_d}.$$

The impact is minimal when $K = 1$, which means that there is no human-induced change outside of an infrastructure footprint. In reality, K is always greater than one. Along pipelines in West Siberia K reaches 10 even without taking into account human-induced fires, and in areas of gold placers in Northern Yakutia K reaches 7, without taking into account impacts on water quality in rivers and creeks (Shur,1988).

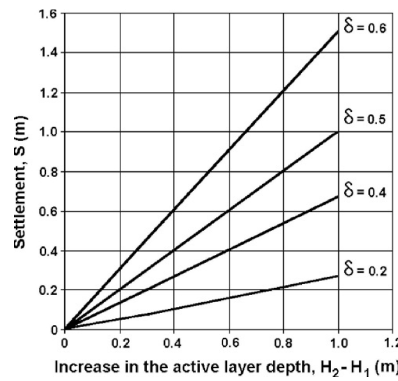

Figure 8. Thaw settlement (S) with increases in the active layer depths (H2-H1) for various thaw strains (δ).

Research questions:
1. How do roads and other infrastructure affect the process of thermokarst? Are the complex interactions between thermokarst formation, hydrology, patterned-ground landforms, and vegetation succession modified in infrastructure-modified environments?
2. *What will these landscapes look like in 50-100 years? In natural conditions, ice-wedge thermokarst often ceases under the negative feedback created by fast growing vegetation in warm shallow ponds above melting ice wedges (Fig. 7, blue arrows). Will ice-wedge thermokarst in infrastructure-modified environments also terminate or will the ice wedges and segregated ice in central parts of polygons continue to thaw forming large thaw lakes (Fig. 7, red arrows) and a continuously eroding landscape? Do the changes on the soil surface affecting local patterns of plant productivity promote thermokarst development? What are the implications of the changes for local biodiversity and carbon accumulation?*

Proposed work
We would build on earlier studies (Pullman et al., 2007; Jorgenson et al., 2006; Kanevskiy et al., 2012) with a project focused in areas of thermokarst associated with the road network. The history of infrastructure and the related landscape changes are well documented in high-resolution aerial photographs dating back to 1949. Thermokarst-affected areas adjacent to roads have steadily expanded

in extent over the 40-year history of the road network (Fig. 3). Our study will use this aerial-photo record, and focus in areas of road-related thermokarst in a variety of road types, road history and landscape settings. We would describe in detail the upper permafrost, vegetation and soils along transects, including the central parts of polygons and troughs above ice wedges. LIDAR imagery that shows details of topography associated with roadside thermokarst is available from the oil industry.

Different stages of degradation and recovery of ice wedges will be studied along transects extending away from the roads. We will use trenches and boreholes to describe the permafrost structure and properties to a depth of 2 m. The ice volume per unit area will be calculated as a sum of volume of wedge ice, segregated ice and pore ice. The active layer thickness at the end of warm seasons will be measured along transects to determine changes in area of indirect impact.

We will study the vegetation history at each borehole site by examining the live vegetation and surface organic layer to determine the history of dust accumulation (layers of dust in organic horizon), periods of enhanced impoundments (determined by moss species), and changes in the plant communities based mostly on macrofossil evidence. The vegetation studies will also include an analysis of plant-community succession in roadside environments with different dust and water regimes and comparison with vegetation/thaw transects placed across the Spine Road in the 1980s (Walker and Everett, 1987).

c. Local People's perceptions of change, responses to change and their implications to livelihoods.

Research questions:

1. How do local residents at Nuiqsut perceive cumulative effects related to the infrastructure at Prudhoe Bay, including the nearby Alpine field?
2. How are infrastructure changes affecting ecosystems services and important subsistence-cash economies at the community level?
3. How do Iñupiat evaluate their capacities to respond to change, given the projections for future industrial development and climate change?
4. Do landscape changes associated with infrastructure expansion and landscape change associated with thermokarst have relevance to the local people? How do these factors affect their use of the land (summer and winter travel, access to subsistence resources)? Do concerns outweigh the economic benefits of development for local residents?

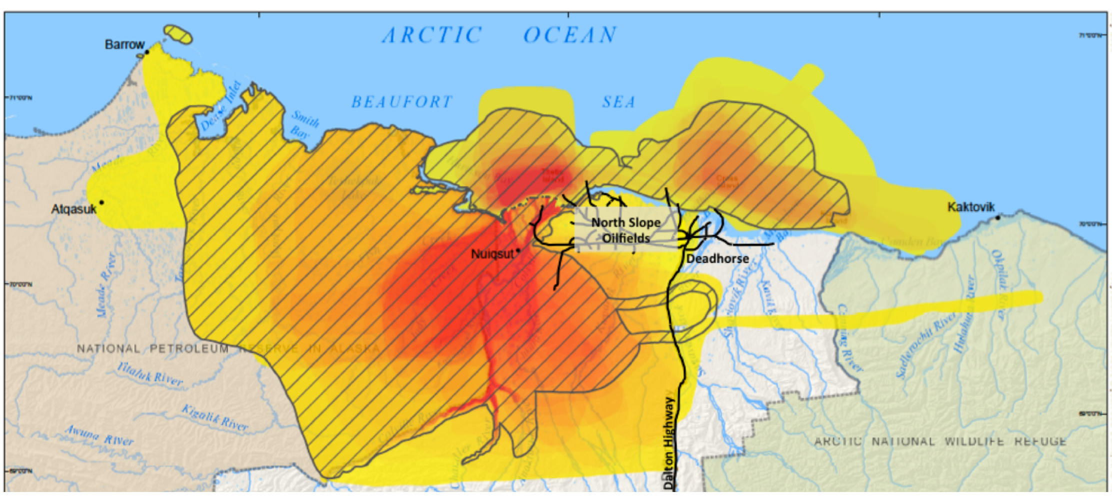

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Figure 9. Nuiqsut use area in relationship to the oil field complex. Shading portrays low (yellow) to high (red) village-use areas. Hatched areas show the use during last 12 months of the study. The figure is based on 756 use areas reported by 33 respondents, 1995-2006, illustrating very light to no use within the North Slope oilfields. (Based on Braund and Associates 2009.)

The first part of the human-dimension part of the Prudhoe Bay case study will be undertaken in conjunction with the newly funded University of Alaska EPSCOR project's northern test case, providing a value-added focus on cumulative effects to this study. This work is undertaken in partnership with the community of Nuiqsut using participatory mapping methods to document local knowledge - observations and understanding of land cover and land-use change and their implications on livelihoods. Our framework here examines 1) local perceptions of change resulting from infrastructure development, 2) community household and individuals' strategies for responding to those changes, 3) the implications to local livelihoods, and 4) an evaluation of the capacity to adapt in the face of future changes. This proposed study will complement the EPSCOR research with an analysis of time-series remote-sensing images and other data from the change analysis and thermokarst study for the traditional use area of Nuiqsut.

The integration of local knowledge and spatial analysis will be completed as iterative group interviews with residents of Nuiqsut, which is the Iñupiat Alaska community in closest proximity to oil infrastructure (Fig. 9). The focus is on the implications of landscape change to the community's mixed cash-subsistence economy, and also draws on census data, findings of the Survey of Living Conditions (SLICA), and the detailed socio-economic household data recently gathered through "The Study of Sharing Networks to Assess the Vulnerabilities of Oil and Gas Development Impacts in Arctic Alaska" (Kofinas, PI / MMS M07AC13028). Logistics funding for community research in this portion of the study will come primarily from the UA EPSCOR project.

Assessing use of adaptive management for infrastructure in Northern Alaska
The second part of the Human Dimension component of the study, funded entirely from this proposed project, will assess adaptive management (AM) as has been applied and could be potentially applied to Arctic infrastructure-related issues. ***Adaptive management*** (AM) is a structured, iterative process of decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring. The method is designed to learn about the system while simultaneously improving management of the system (Holling 1978). Academic analysts of land planning and resource management have long argued for the use of AM processes (Holling 1978; Walters 1986). In face of recent trends of directional rapid change, the concepts of adaptive co-management and adaptive governance have been developed and advocated as elements of sustainability science and resilience theory (Gunderson, Holling et al. 1995; Folke 2002; Gunderson and Holling 2002; Armitage, Berkes et al. 2007; Kofinas 2009). The development and use of decision-support systems (e.g., simulation models), adaptive or double-loop learning cycles, strong cross-scale linkages in governance, the inclusion of local knowledge in decision making, and view of policies as experiments have all been suggested. The realization of these ideas, however, has come with considerable challenges and in some cases failure (Walters 1997; Lee 1999).

In the context of the North Slope oil and gas development, the implementation of AM has been the espoused goal of specific agencies (e.g., AK Department of Natural Resources) as well as collaborative efforts (e.g., 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 2003 study of Alaska Department of Natural Resources/ Northern Regional Office found a number of organizational and informational constraints in the implementation of AM and CE assessment, including the problem of limited staff size, high turnover of agency personnel, limitations in handling the high number of applications received, a lack of standardized policies and guidelines for addressing applications, limited engagement with a greater community such as university researchers community and regional assessment teams, and inadequate GIS capacity (Wishnie 2003). In other cases problems have followed from the 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.

Proposed work: This study seeks to understand the organizational and informational conditions for achieving successful AM for oilfield planning and management in North Slope, Alaska, and in doing so, understand how theories of sustainability science relate to the real world challenges of implementation in the context of Alaska's North Slope. To meet this objective, we will document agency, community, and industry past experiences with the Alaska North Slope oil fields, with respect to the capacity of current management systems to use AM for predicting and mitigating cumulative effects.

Our analysis will be focused at three scales – the micro-scale of facility AM (operationally focused); the meso-scale of field-wide AM (decisions about roads and infrastructure planning and management); and the regional scale (through a focus on such initiatives as NSSI). We will also seek to understand if and how cross-scale linkages and polycentric structures (Kofinas 2009) have facilitated or constrained the implementation of AM ideas when addressing CE. To bound the research, we will focus on management issues related to the development of roads and other infrastructure as affected by climate change.

Method: We will start by reviewing publically available documents to identify past efforts to implement of AM on the North Slope oilfields. We will then interview approximately 50 agency and industry personnel and community leaders to document their first-hand experiences, social networks of information sharing, and evaluations of AM practices. Interviews will be partially structured so as to yield qualitative results and partially semi-structured, allowing for a grounded theory method (Glaser and Strauss 1967; Strauss and Corbin 1990) based on qualitative analysis that generates propositions about the conditions facilitating organizational and social learning in resource management. We will ask respondents to 1) describe past experiences with cumulative effects – cases in which interacting forces of change (e.g., climate warming, resultant hydrological changes, and infrastructure) have resulted in novel challenges to oilfield operations; 2) identify information sources used in responding to these problems and assess the extent to which available information was adequate or inadequate; 3) indicate if response time and other resources were sufficient for addressing emergent problems effectively; 4) provide examples in which CE produced unanticipated consequences, and 5) assess the strengths and weaknesses of multi-level decision making to support AM.

The findings from the literature reviews and interviews will be analyzed and then presented and discussed at a workshop for North Slope land managers and an International Action Group workshop (described below). Workshops will be structured to document transactions and the groups' evaluation AM methods for addressing CE in the northern oil and gas development.

Part 2. An International Arctic Infrastructure Action Group (AI-AG)

Our second major proposed activity is to initiate a circumpolar International Arctic Infrastructure Action Group (IAI-AG) to help predict future changes to Arctic industrial systems that result from a combination of infrastructure and climate change and to plan for a sustainable future using adaptive scientific, engineering, educational and management approaches.

The issues related to Arctic infrastructure are nationally and internationally important because mineral and hydrocarbon exploration is occurring across the circumpolar Arctic. For example, gas and oilfield development is occurring in similar wetland permafrost landscape in Alaska, the Mackenzie River Delta in Canada, and the Yamal Peninsula of Russia, but the economic, regulatory, political, and local social systems in each of these places are very different. A circumpolar initiative and forum for developing and sharing new ideas and methods will greatly facilitate the best practices for assessing and responding to CE of industrial infrastructure throughout the Arctic.

<u>Foci of the Action Group:</u>

Issues related to cumulative effects of industrial infrastructure.

The scope of the international AI-AG will be defined during an initial scoping meeting in Krakow, Poland, during the 2013 Arctic Science Summit Week. Initial activities will likely focus on site-specific case studies such as the one proposed here for Prudhoe Bay. Also, landscape- and regional-level models are needed that examine effects over larger watersheds and regions. The effects of climate change and other more or less natural disturbance factors (e.g. wildlife grazing, landslides, fires, thermokarst) also need to be considered, as well as other historical anthropogenic changes such as past grazing or forestry practices near treeline and synergistic feedback effects of multiple factors of change. Models and adaptive planning and management tools are needed to adapt to the changes. These tools need to embrace a "cradle to grave" approach from the planning and exploration phases of infrastructure to final abandonment. New methods are needed to inventory and track rapid changes in industrial extent at a global scale. Operationalizing the use of methods and tools in decision-making is a critical part of successfully implementing AM to address cumulative effects of oil development infrastructure. Comparative studies are needed between Arctic CE research and approaches in the U.S. (e.g., Walker et al. 1987a,b; Brueggmann et al. 1996; NRC, 2003; Streever et al. 2011), Canada (e.g., Durinker and Greng, 2005; Johnson et al., 2011; Gunn et al. 2011), and Russia (e.g., Forbes et al. 2009; Maynard et al. 2011; Kumpula et al. 2012; Walker et al. 2011).

Involvement of the local people and industry directly in the science of assessing and responding to change across the Arctic. Local community input is needed in all phases of development scenarios. Economic, political, demographic, land-use planning, and technology-change aspects need to be incorporated into CE analyses and models. The North Slope Science Initiative (NSSI) in Alaska is emerging as a possible model. The NSSI has a legislative mandate under the Energy Policy Act of 2005 (Section 348) to implement efforts to coordinate applied science needs relevant to resource managers on the North Slope. An oversight group consists of high-level agency executives and experienced agency personnel. An external advisory group called the Science Technical Advisory Panel (STAP) consists of Iñupiat elders and scientists from universities, nonprofit organizations, and industry. The scope of the NSSI was recently published in *Arctic* (Streever et al., 2011). The document emphasized the need to develop AM practices to address CE. The effectiveness of the NSSI and other models in other countries such as the Integrated Regional Impact Studies (IRIS) (Government of Nunavut, 2012) and the Arctic Development and Adaptation to Permafrost in Transition (ADAPT) project in Canada, and the procedures developed during the Finnish-sponsored Environmental and Social Impacts of Industrialization in Northern Russia (ENSINOR) project, would need to be evaluated to define the scope of the AI-AG (see letters of collaboration from Warwick Vincent, Bruce Forbes, Dmitri Drozdov and Marina Leibman).

Initial crosscutting focus of the AI-AG: ***Develop adaptive approaches to science, engineering, education, involvement of local people, and management methods that lead to sustainable infrastructure development in the Arctic.***

AI-AG workshops

A coordinated international action group would examine cumulative effects of infrastructure-driven changes. The initial workshop in Krakow, Poland will be done in collaboration with the Human and Social Working Group (HSWG), Cryosphere Working Group (CWG) and Terrestrial Working Group (TWG) of the International Arctic Science Committee (IASC), where the idea of the AI-AG was first suggested at the Montreal IPY 2012 meeting to the TWG and HSWG and received strong support.

Two additional workshops would follow focusing on regions of the Arctic where the most rapid development is currently occurring: one in Alaska that would examine issues related to the changing landscapes and social ecological implications of the Prudhoe Bay and North Slope region, and the other would be in Russia to address issues related to the rapidly expanding gas development in Bovanenkovo/Yamal region. Other studies that have examined changes in social-ecological systems (SESs) in major areas of development would be included where there are willing participants, including those related to the Canadian diamond fields, oil and gas development in the Mackenzie River delta, potential areas of development in far northern Canada, the North Sea and Barents Sea developments, and mining operations in the Russian Far East. We have made a modest funding request for these workshops ($45K each) because of the lack of detailed list of invitees and scope for the workshops at this time. We anticipate that a much larger group will be invited than can be supported with these funds including indigenous managers, herders and hunters, engineers, industry representatives, social scientists, permafrost, remote-sensing and other Arctic system scientists. The funds requested here ensure that a minimum of 2 indigenous users from Alaska and Russia will be included with efforts made to support additional participation.

Part 3. Education and outreach

<u>Arctic systems field course</u>

The large changes in industrial development coming in the Arctic will require a new generation of industrial and political leaders, engineers, and teachers knowledgeable about Arctic systems and the unique aspects of permafrost environments (Fig. 10). The first aspect of our outreach and education component is an 18-day field course along the Dalton Highway and the Prudhoe Bay oil field taught by D.A. Walker, M.K. Raynolds, A. Breen and Gary Kofinas. The course will have modules taught by experts in the fields of vegetation science, permafrost, hydrology, wildlife research, and social dimensions of Arctic systems. The course will introduce participants to the climate, terrain, vegetation, wildlife, permafrost, and methods used by road engineers and rehabilitation experts to address infrastructure issues related to the construction of the Dalton Highway and the oilfield at Prudhoe Bay. A special training session at Prudhoe Bay in conjunction with the planned field work and mapping in Part 1 will provide background and techniques in Arctic rehabilitation and restoration technology. A trip to Nuiqsut will provide students with first-hand knowledge of local residents' perceptions and adaptation to the ongoing climate change and industrial development occurring in their backyards. The course will camp at four sites along the road (Coldfoot, Galbraith Lake, Happy Valley, and near Deadhorse) and spend two days at the Toolik Field Station. A 17-ft dome tent (Fig. 11), generator, and stoves will provide a comfortable environment for evening slide shows, discussions and meals. The students will also have time to explore this exciting environment, develop their own research ideas for presentations at the end of the course. Field activities will include lectures and active training in vegetation sampling, collecting soil samples, measuring soil temperature. The course will be modeled after previous highly popular courses including Dr. Bill Gould's Arctic Field Ecology course (Gould et al. 2010). The International Arctic Research Center's 2010 Summer Field Course entitled "Arctic in a changing climate: Physical and biological linkages to Permafrost", and the UAF Biology Department's

Figure 10. The Arctic Systems field course will examine Arctic systems from the Brooks Range to the Arctic Ocean coast.

Figure 11. Playa® 17-foot dome tent to be used for the Arctic Systems field course.

summer course titled "Arctic Vegetation Ecology". We will offer the course through the UAF Summer Sessions program. We expect that the cost of the course will be paid for through course fees ($2000 per student plus tuition). We are requesting funds from NSF to support scholarships for 2 local North Slope students to increase the participation of locals in the project. We will also solicit scholarship funds through BP and local environmental consulting firms.

Post doc mentoring

Partial Post-doc support is requested for two candidates. 25% support is requested for a post-doc position that will focus on application of remote sensing and GIS to issues related to time-series analysis of Landsat data and use of very-high-resolution (VHR) imagery for classification and analysis of vegetation change at Prudhoe Bay. We have tentatively identified G.V. (JJ) Frost to fill this position. JJ has worked extensively with the Walker and Shur on previous projects. He will graduate from U. Virginia and is moving to Fairbanks to seek work. He has considerable experience in the Arctic and is excellently qualified to perform the post-doc duties. Funds are also requested for a post-doc who will act as data manager and researcher for the project. We have identified Marcel Buchhorn, from the Alfred Wegner Institute in Potsdam, for this position. Marcel has excellent qualifications and has worked with Walker on projects in Russia and northern Alaska. He will seek additional funding from the German government to work on this project. (See post-doc mentoring plan.)

Involvement of industry and contractors

Findings from this project, if appropriately communicated to local residents and industry representatives, may help both groups adapt more effectively to impending changes. They could also influence the way in which the oil industry and local populations interact. The indigenous people feel that they can adapt to the changes occurring if they are involved and can influence decisions that affect their ability to use the land and their resources (Forbes and Stammler, 2009). A major element of our human-dimension studies is adaptive co-management and active engagement of the local populations in the science. We also will actively engage industry. Dr. Bill Streever, environmental studies leader for BP Exploration (Alaska) Inc., will lead the Alaska industry and village outreach part of the project. He will aid in involving oil-industry employees and North Slope residents in Barrow, Alaska in the project and informing them about scientific results relevant to their interests while also showing appropriate follow-through to individuals interviewed in Nuiqsut. Industry employees will be reached through briefings in Anchorage and in the North Slope oilfields. Initially, Anchorage briefings will be managed through the Alaska Oil and Gas Association (the regional industry trade association) to capture representatives from all of the companies working in northern Alaska. Secondarily, follow-up briefings may be offered to individual companies as opportunities arise. On the North Slope, briefings will be offered to staff based in the oilfields during weekly safety and planning meetings. North Slope residents will be reached through public presentations in Barrow managed through Ilisagvik College (the two-year tribal college in Barrow) and the Barrow Arctic Science Consortium. The presentation and/or a question-and-answer session will be transmitted over the North Slope public radio station, KBRW, which is received by all of the North Slope villages. Also, one or more articles will be written in nontechnical language describing the project and its outcomes for publication in the North Slope's newspaper, *The Arctic Sounder*. Throughout the outreach, remote sensing products developed as part of the project and interview responses obtained, as part of the Nuiqsut studies will help nonspecialists understand both the methods and the relevance of this project.

APECS involvement

Because successful implementation of this project will stretch into the next decade and beyond, and the difficulty for senior investigators to make the commitments of time necessary for this Action Group to succeed, we will solicit involvement of the Arctic Polar Early Career Scientists (APECS) in the goals, hypotheses, workshops, and proposal development at the outset. It is envisioned that the project could be similar to the ART (Arctic in Rapid Transition) activity of APECS, which has a mainly marine focus.

Project coordination, data management, publication of results:

Coordination:

D.A. Walker will coordinate the research and data management activities. All the co-PI's are at UAF, so bi-monthly face-to-face meetings of the entire project will be held on the UAF campus to ensure that the components are well integrated. The subcomponents will meet more frequently as needed. A key element of the coordination will be a web-site that will contain all information related to the project including lists of project members, data information, publications, presentations at conferences and workshops, reports, and proposals.

Data management:

We will hire a data manager to handle the field data and GIS and remote sensing data from the Prudhoe Bay studies. Results and data from all the components will be centrally archived and accessible to project researchers via the project web site and the Arctic Geobotanical Atlas (Walker et al. 2008). We will also produce hard-copy annual data reports that will include the field and laboratory-analysis data. All data will also be made available in digital form with metadata according to protocols being developed within NSSI for North Slope data. All data and reports will be archived with metadata and submitted to the ARCSS CADIS Data Archive at NCAR/EOL. All datasets will also be archived in the international data archive PANGAEA (Data Publisher for Earth & Environmental Science), where they can be identified, shared, published and cited by the DOI number and freely downloaded from the portal. (See data management plan)

We include a request for a modernization of our GIS/ remote sensing and data management hardware. The request includes a new state-of-the-art workstation for our data and GIS manager and two other workstations for post docs and students who will be doing the GIS and remote sensing research required. The budget justification contains details of the request.

Publication of results:

Members of each component will present papers at planned workshops and a synthesis paper will be presented each year at the Fall AGU meeting. Final results from the project will be presented in papers that will be submitted to the journals *Permafrost and Periglacial Processes*, *Cold Regions Science and Technology, International J. of Remote Sensing, Remote Sensing of Environment, Sustainability Research, Journal of Geophysical Research,* and *Global Change Biology, Ecology and Society,* and *Frontiers of Ecology and the Environment*.

Results of prior research

(STARRED (*) PUBLICATIONS IN THE REFERENCES WERE PARTIALLY OR ENTIRELY FUNDED FROM THESE RESEARCH PROJECTS.)

Collaborative Research: Effects of the Aggradation and Degradation of Ground Ice on the Evolution of Permafrost-Dominated Landscapes Under a Changing Climate. ARC-0454939 ($260,934, March 31, 2005 to March 31, 2009), Y. Shur PI. Field study of soil stratigraphy and ground ice was conducted at six sites to assess factors affecting permafrost aggradation and degradation. High-resolution aerial photos were taken across Alaska to quantify permafrost degradation. The researchers published papers on: patterns of permafrost formation and degradation in relation to climate and 2 ecosystems (Shur and Jorgenson, 2007); evolution of lakes and lake basins in northern Alaska (Jorgenson and Shur, 2007; Shur et al. 2012), an encyclopedia on permafrost (Jorgenson and Shur 2008), an abrupt increase in permafrost degradation in Arctic Alaska (Jorgenson et al., 2006); thermokarst in Alaska (Jorgenson et al., 2008a); permafrost characteristics of Alaska (Jorgenson et al., 2010; Jorgenson et al., 2008b), the application of ground-penetrating radar for mapping near-surface structures in permafrost (Munroe et al. 2007); tomodensitometric analysis of basal ice (Dillon et al., 2008); formation of frost boils and earth hummocks (Shur et al., 2008); cryostratigraphy of Quaternary deposits (Kanevskiy et al., 2008, 2011a,b; Fortier et al., 2008, 2012, French and Shur, 2010); and chapters of encyclopedias (Jorgenson and Shur, 2008; Shur et al., 2011)..

Biocomplexity associated with biogeochemical cycles in frost boil ecosystems. OPP-0120736, $2,750,421, 10/1/01-9/30/06, D.A. Walker (PI), H.E. Epstein, W.A. Gould, W.B. Krantz, R. Peterson, C.-L. Ping, V.E. Romanovsky (Co-PIs). This project was the first integrated whole-system analysis of patterned ground ecosystems. It examined the complex interactions between vegetation, soils, permafrost and climate that are involved in the formation of small patterned-ground features along the Arctic bioclimate gradient in arctic Alaska and Canada (Walker et al., 2008b). The project focused on the hypothesis that as one moves from north to south along the gradient, changes in the thermal properties of the soils, as a result of organic accumulation in different parts of the patterned-ground system, result in gradients of soil moisture, active-layer thickness, and frost heave, and these in turn affect the size and shape of the features. The project culminated in a special section volume of the *Journal of Geophysical Research*: "Biocomplexity of Arctic Tundra" (Walker et al., 2008a) which contained 9 papers from the project

(Daanen et al., 2008; Epstein et al., 2008; Michaelson et al., 2008; Nicolsky et al., 2008; Peterson and Krantz, 2008; Ping et al., 2008; Raynolds et al., 2008; Walker et al., 2008b). At least 15 other published papers and 3 PhDs resulted from the project (Kade et al., 2006; Kade and Walker, 2008; Kade et al., 2005; Kelley et al., 2004; Kelley and Epstein, 2009; Nicolsky et al., 2007; Nicolsky et al., 2008; Peterson and Krantz, 2003; Ping et al., 2008; Romanovsky et al., 2008; Vonlanthen et al., 2008; Walker et al., 2004; Walker et al., 2011 (*Applied Vegetation Science* Editors Choice Award for best paper in 2011)). The project provided full or partial funds for 4 doctoral students (Kelley, Kade, Nikolsky, Raynolds), 2 Master's students (Borden, Munger) and 4 postdocs (Daanen, Kuss, Peterson, Vonlanthen). The project brought a total of 51 participants into the project through the research component and 60 participants through the educational component, including 5 scientists, 29 students in an *Arctic Field Ecology* course, 9 Inuit elders, 16 additional Inuit participants, and 8 technicians or administrative personnel. Participants came from nine countries (Gould et al., 2010).

Kofinas: Resilience and adaptation in the context of indigenous villages of Alaska's boreal in response to climate and economic change was assessed (Kofinas et al., 2010). The use of local ecological knowledge to model changes in ecosystem services through the lens of resource availability was studied (NSF 0732758) in villages of Interior and Arctic Alaska (Brinkman et al, submitted). The heterogeneity and resilience of Human-Rangifer (reindeer and caribou) systems across the high latitudes was studied (NSF/OPP: 0531200) as regional case studies with a focus on institutional, socio-economic and physical interactions, and is in review as a special issue of *Ecology and Society* (Kofinas et al, in review). The film, "Voices of Caribou People" (Bali and Kofinas) was produced based on 96 interviews with village residents from Alaska to Quebec, with all interviews archived and to be available via the WWW as part of Circumpolar Arctic Flora and Fauna (CAFF) portal (NSF/OPP: 0531200). IGERT and OPUS funding (NSF: 0654441;0640638) to UAF led to the publication of the graduate textbook *Principles of Ecosystem Stewardship: Resilience-Based Management in a Changing World*, with a trans-disciplinary framework for the study of SES (Chapin et al. 2009).

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