PROJECT SUMMARY

Overview:

We will study one of the most vulnerable elements of the rapidly changing Arctic -- ice-rich permafrost (IRP). IRP is at the center of a web of interacting ecosystem components that we call the IRP system (IRPS). Our key questions are: How are climate change and infrastructure affecting IRPS? What roles do ecosystems play in the development and degradation of IRP? and How can people and their infrastructure adapt to changing IRP systems? We are particularly interested in how differences in vegetation, water, and time influence the accumulation and degradation of ground ice in IRP landscapes, and how the loss of ground ice can radically change these landscapes, their components, and the infrastructure built on them. Our ultimate goal is to understand IRPS at local, regional and circumpolar scales.

Intellectual Merit:

Our initial focus is at Prudhoe Bay and Point Lay, Alaska, where permafrost temperatures are changing rapidly with large impacts to ecosystems and infrastructure. Both areas provide excellent examples of IRP-related issues relevant to many other areas of Alaska and the Arctic. We will develop three IRP observatories: 1) Roadside IRP Observatory in the Prudhoe Bay oilfield; 2) Natural IRP Observatory remote from infrastructure; and 3) Village IRP Observatory at Point Lay. The Prudhoe Bay region has the best historical record of geoecological change within the Arctic with key legacy datasets and good collaboration between industry and science. We will revisit permanent plots and remap Prudhoe Bay vegetation and landscapes first studied in the 1970s. We will characterize and compare the permafrost, hydrology, vegetation, and greenhouse gas (GHG) fluxes of IRPS in three main situations: 1) disturbance gradients adjacent to heavily traveled roads in the Prudhoe Bay oilfield; 2) undisturbed tundra first mapped in the 1970s in a relatively undisturbed landscape consisting of drained lake basins and residual surfaces unaffected by thaw lake processes; and 3) extremely-ice-rich yedoma soils in the village of Point Lay, which similar to several other coastal villages in northwest Alaska. We will use a multidimensional remote-sensing time-series to measure and monitor changes to microtopography, water, snow cover, vegetation, thermokarst, and thermo-erosional features. We will use the field observations, detailed geoecological maps, and remote-sensing products to provide input for improved permafrost and hydrology models to predict permafrost degradation over the next century under different GHG emission scenarios.

Broader Impacts:

The project offers a transformative view that places IRP at the center of change to social-ecological systems in many areas of the new Arctic. Much of the response to permafrost-related damage has been incremental actions driven by the necessity to repair and stabilize existing roads and structures. There is an immediate need to develop more strategic approaches to mitigation and adaptation informed by science and engineering in collaboration with local observations, knowledge, and preferences. Point Lay has received less research and agency attention than other climate-impacted communities, yet its thaw-related issues are among the most critical. Researchers from the UAF Institute of Northern Engineering, Geophysical Institute, Institute of Arctic Biology, and International Arctic Research Center will combine their expertise to address IRPS-related questions in collaboration with project partners. We will work with the Cold Climate Housing Research Center, Regional Housing Authority, Point Lay community, and North Slope Borough planners to collaboratively produce adaptive housing strategies and actionable knowledge regarding other infrastructure that is relevant to many arctic villages. We will leverage previous and current NSF research, oil-industry resources, and ongoing work by the Alaska Department of Transportation to advance knowledge on IRP-related impacts to roads and industrial infrastructure and contribute to best practice guidelines for road and airport construction. STEAM education and training components will reach K-12, undergraduate, graduate, and post-doctoral students. A permafrost and infrastructure symposium will bring together US-Canadian science and engineering expertise. We will communicate the results to other circumpolar communities through the Rapid Arctic Transitions due to Infrastructure and Climate (RATIC) action group and Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections (T-MOSAiC) project.

Overview

Ice-rich-permafrost systems

Ice-rich permafrost (IRP) is the most susceptible element of Arctic terrestrial landscapes to the warming climate (Fig. 1A to E). IRP underlies nearly 50% of the Arctic (Brown et al. 1997), creating dynamic ecosystems and extremely hazardous conditions for infrastructure. IRP is highly unstable upon thawing (Shur et al. 2011)—the average volumetric ice content of the upper 4–5 m of sediments along Alaska's northern coast is estimated to be 77% (Kanevskiy 2013). Many characteristic arctic periglacial landforms, including ice-wedge polygons (Fig. 1 F, G), non-sorted circles, thaw lakes, thaw-lake basins, palsas, and pingos are associated with IRP (Washburn 1980). Several large integrated research programs are modeling the consequences of climate change to permafrost (IRP) (e.g., McGuire et al. 2006; Hinzman et al. 2005, 2013; Wullschleger et al. 2014; Gross et al. 2016; Vincent et al. 2017; Parazoo et al. 2018). In order to better understand the intricate connections between IRP and arctic social ecological systems (Fig. 2), we will employ a new conceptual model of permafrost evolution that places ice-rich permafrost at the center of a web of changing factors that play key roles in IRP's evolution and degradation, including the climate, micro-topography, vegetation, hydrology, and soils

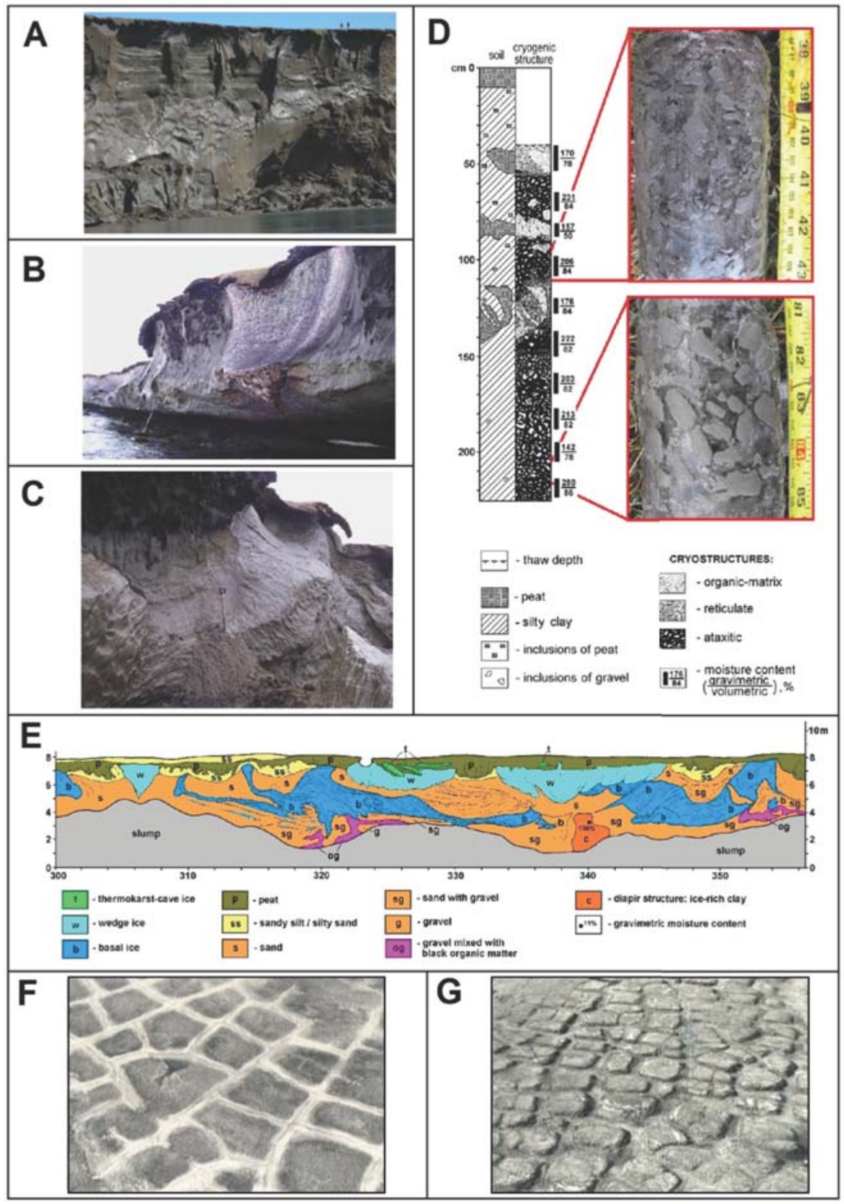

Figure 1. Common types of ground ice and periglacial landforms in northern Alaska. **A**. Very large syngenetic ice wedges along 35-m high yedoma bluff of the Itkillik River (Kaneveskiy et al. 2011). **B**. Epigenetic ice wedges exposed along the coast near McLeod Point. **C**. Folded massive ice body (presumably buried basal glacier ice, Barter Island (portion of this section is shown in E). **D**. Cryo-stratigraphy of the primary surface of the coastal plain. Photos show ataxitic (suspended) cryostructure. **E.** Fragment of a 600-m long cryostratigraphic map, showing the variety of massive ground ice and sediments. **F.** Networks of low centered ice-wedge polygons and **G** high-centered ice-wedge polygons are indicative of IRP. Ice wedges, such as those shown in **B** separate the polygons. (B–E from Kanevskiy et al. 2013; F–G, Walker et al. 1980)

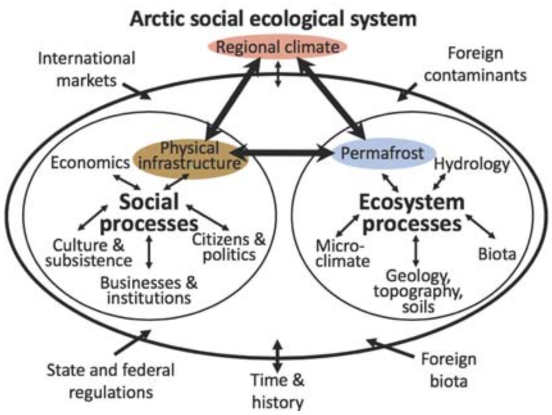

Figure 2. Position of permafrost within the context of the arctic social-ecological systems. The diagram emphasizes the interactions between permafrost (a component of the ecological subsystem), physical infrastructure (a component of the social subsystem), and the regional climate (a major external driver of change). Other external drivers, such as state and federal regulations, and international markets, play as strong or stronger influences on both subsystems. (Based on Whiteman et al. 2004; Chapin et al. 2006a, b; Warwick et al. 2017).

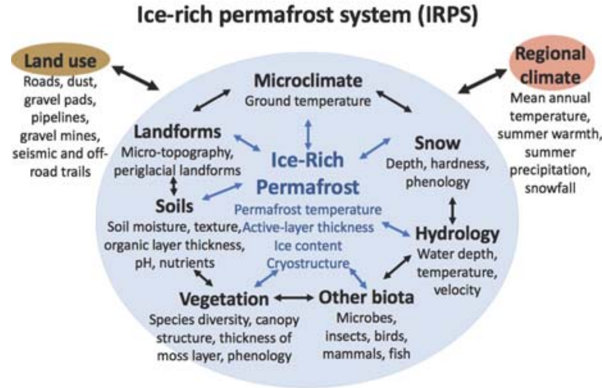

Figure 3. Conceptual diagram of IRPS in relationship to major drivers of change (land use and regional climate). Permafrost is placed at the center of the diagram to emphasize its prominent influence on many ecosystem properties, which are strongly affected by both climate change and land-use changes. Double arrows linking components of the system indicate ecosystem processes that affect other ecosystem components, such as water uptake, photosynthesis, decomposition, and respiration. Most of these involve feedbacks. Not all linkages between system components are shown.

(Fig. 3). Thus, IRP is conceived as having a role similar to that of a "keystone species" in ecology (Paine 1969), whereby if the keystone element is removed or drastically reduced, the system is radically transformed. Our research will also help develop better strategies for building villages and other infrastructure on IRP. The impacts and risks of climate change to arctic social-ecological systems are especially high in regions with IRP (IPCC 2018; Vincent et al. 2017; Hjort et al. 2018; AMAP 2017 a, b, 2018; Walker and Peirce 2015). A recent paper in *Nature Communications* (Hjort et al. 2018) reports: *"…nearly four million people and 70% of current infrastructure in the permafrost domain are in areas with high potential for thaw of near-surface permafrost… Alarmingly, these figures are not reduced substantially even if the climate change targets of the Paris Agreement are reached."*

Cumulative effects of climate change and infrastructure to IRPS

The discovery of oil at Prudhoe Bay (Fig. 4) in 1968 triggered a series of environmental studies that documented the terrain, soils, and vegetation in the early phases of oil development in the National Petroleum Reserve Alaska (Gryc 1988; Ebersole 1985; Lawson et al. 1978; Lawson1982, 1986) and the Prudhoe Bay oilfield (Brown 1975; Everett and Parkinson 1977; Everett et al. 1978; Walker et al. 1980; Walker 1985).

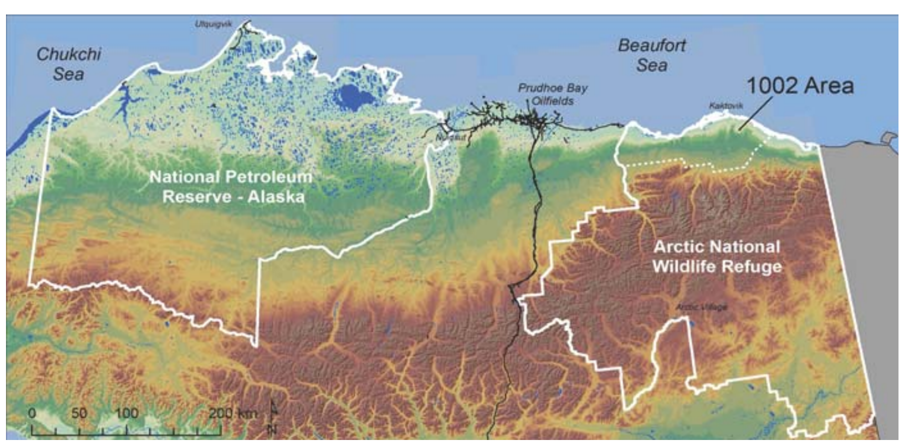

Figure 4. Northern Alaska, Prudhoe Bay oilfield, and other geographic locations mentioned in the text. Point Lay is on the west coast just west of the western boundary of this map.

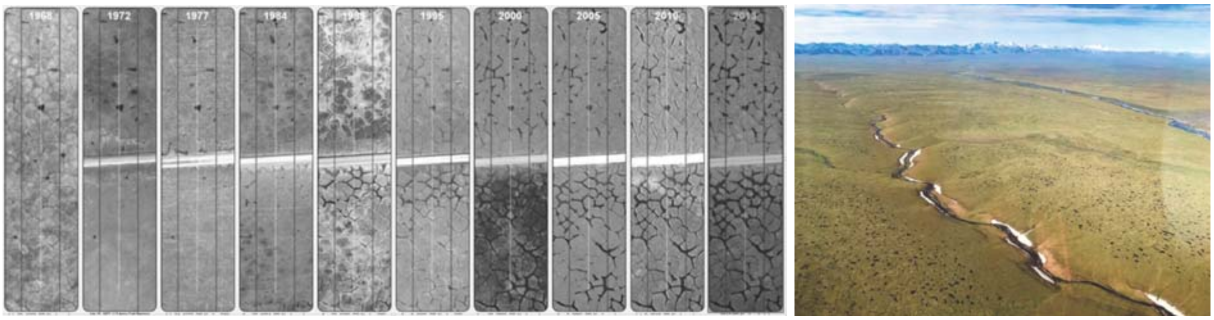

Figure 5, **Left**. Time series (1968–2013) of aerial photos showing thermokarst development along the Spine Road, the main gravel road through the Prudhoe Bay Oilfield. Thermokarst developed near the road between 1977 and 1995, and by 2010 thermokarst affected areas both near to and distant from the road. The thin white vertical line and black rectangle on all photos delineate transects and study areas on both sides of the road established in 2015 to study the long-term effects of the road (Walker et al. 2015, 2016, 2018). **Right:** Thermokarst pits in undisturbed IRP terrain of the 1002 Area of the Arctic National Wildlife Refuge (M. Nolan 2019). The numerous small thermokarst ponds are caused by melting of the upper surface of ice wedges that separate the ice-wedge polygons. Thermokarst such as this has recently become widespread across large areas of undisturbed tundra in northern Alaska and other Arctic regions (Liljedahl et al. 2016).

The cumulative effects of oilfield development were documented somewhat later (Walker et al. 1987; Orians et al. 2003; Raynolds et al. 2014). Regional abrupt increases in ice-wedge degradation and thermokarst were first noted west of the Prudhoe Bay Oilfield (Jorgenson et al. 2006) and have now been reported from areas around the circumpolar Arctic (Liljedahl 2016; Fraser et al. 2018; Frost et al. 2018; Farquharson et al. 2016; 2019 in review). Roadside ecosystem changes have become much more apparent in recent years (Fig. 5 left). A GIS-based update of cumulative effects of oil and gas development described a widespread steep increase in the abundance of thermokarst features both near and distant from roads (Raynolds et al. 2014; Walker et al. 2014a; Shur et al. 2016). The primary processes creating change in IRP systems are thermokarst and thermal erosion. *Thermokarst* is the process, whereby upon thawing, the ground surface settles, usually

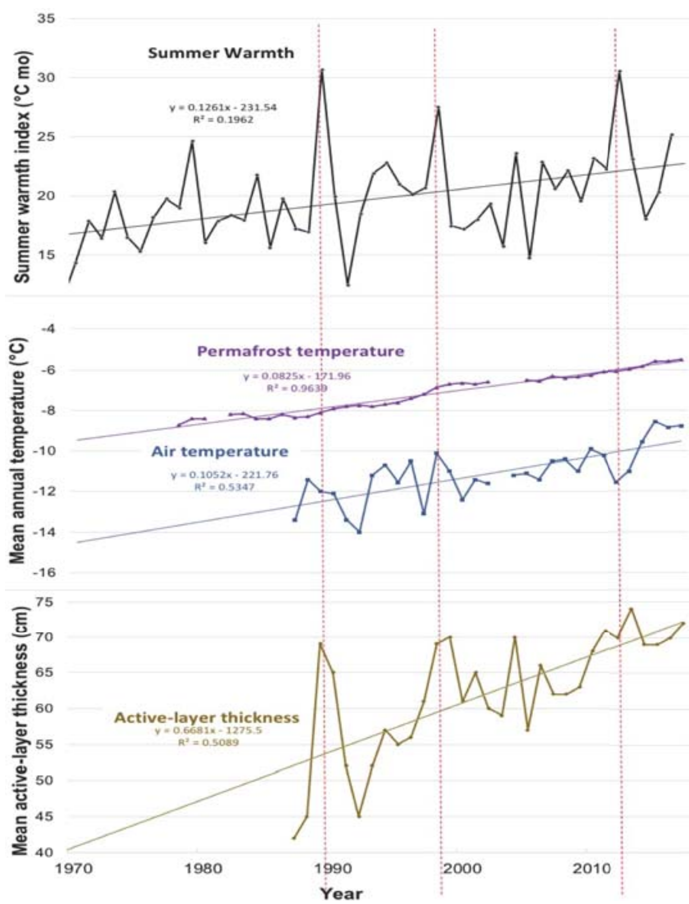

Figure 6. Trends in summer warmth, mean annual air temperature, mean annual permafrost temperature at 20-m depth, and the active-layer thickness at Deadhorse, AK (1970–2015) (Walker et. al. 2019, in review, data from V. Romanovsky's Deadhorse permafrost- borehole station.)

differentially, and develops characteristic landforms, such as thermokarst pits, thaw lakes, and irregular terrain consisting of depressions and mounds. *Thermal erosion* is the erosion of ice-rich permafrost by moving water (van Everdingen 2005). The recent abrupt increases in thermokarst are related to recent increases in air and permafrost temperature and active-layer thickness (Romanovsky et al. 2017) (Fig. 6).

The impacts of a combination of climate change and infrastructure placed on ice-rich permafrost are illustrated by two situations we focus on in this proposal. One is related to the extensive ecosystem changes that occur near roads in the Prudhoe Bay (Walker et al. 2014b, 2016, 2018) (Fig. 7A). An unprecedented 2015 flood of the Sagavanirktok River caused extensive thermal erosion of ice wedges and destruction of a portion of the Dalton Highway (Shur et al. 2016) (Fig. 7B). The second situation is the ongoing crisis at the village of Point Lay, which is experiencing multiple major threats to its housing, roads, freshwater supply, and sewage system caused by thermokarst and subsidence of the local terrain (UMIAQ 2014, Bjella 2015, Reynolds et al. 2016). Much of the severe subsidence at Point Lay is due to the presence of thick ice-rich deposits called *yedoma* that have enormous potential for thermokarst and thermal erosion (Lawson 1982, 1986; Kanevskiy et al. 2011, 2017). Figure 5 (right), shows yedoma with extensive thermokarst pits that have developed recently in undisturbed terrain of the Arctic National Wildlife Refuge, Alaska, and Figure 7C shows an example of the subsidence associated with housing at Point Lay.

A **B** **C**

Figure 7. **A.** Ecosystem changes related to roadside impoundment of water (Photo: D.A. Walker); **B.** Damage to the built environment. Northern end of the Dalton Highway looking south near the Deadhorse Airport during height of a flood May 19, 2105, showing an area of thermokarst collapse. (Photo: Alaska DOT & PF). **C.** New Point Lay house with foundation that is threatened by thermokarst. Note subsidence and ponding in a newly developed ice-wedge polygon trough around the pilings supporting the house; the bottom of the steps leading to the second story used be at the ground surface (Photo B. Grunau).

Adaptation strategies specific to changes in IRP related to climate change, oil development, and village infrastructure are of circumpolar concern (e.g., Walker et al. 1987; AMAP 2010, 2017a, 2017b, 2018; Stammler 2005; Forbes et al. 2009; Kumpula et al. 2010, 2011; Allard et al. 2013; Streletskiy et al. 2012; Raynolds et al. 2014a; NPC 2015; IASC 2016; Melvin et al. 2016; Vincent et al 2017; Berman and Schmidt 2019 in press). In Alaska, such research is needed because of the continued expansion of roads and infrastructure in existing and new oil fields, degrading infrastructure in villages, and future plans by the State of Alaska for extensive new road systems in areas with IRP (e.g., Roads to Resources, NPC 2015), and the recent decision by the U.S. Congress to open the 1002 Area of the Arctic National Wildlife Refuge to oil and gas development (H.R. 1, the Tax Cuts and Jobs Act, 2017). Adaptation strategies are discussed in the section devoted to Broader Impacts.

Intellectual Merit

Overarching questions

A great deal is already known regarding types of ground ice, how they form and are distributed (e.g. Dillon et al. 2008; Fortier et al. 2008, 2012; Kanevskiy et al. 2008, 2012, 2013; Shur et al. 2007, 2012; Fig. 1), and the pathways for degrading permafrost (Jorgenson et al. 2015; Kanevskiy et al. 2017, Fig. 9). Our principle questions are *How are IRP systems affected by climate change and infrastructure? What roles do ecosystems (namely vegetation, hydrology, and time) play in the development IRP?* and *How can people and their infrastructure adapt to the changing IRP system?* We address these questions with proposed research along two major themes: *Landscape evolution* and *Adaptations to change*.

Landscape evolution

Ice-rich permafrost observatories

We propose three IRP observatories to examine the spatial distribution and temporal changes of ground ice, and to examine how IRP systems evolve along environmental and disturbance gradients. We first describe the three observatories and then the proposed studies.

Road effects IRP observatory (RIRPO)

Roads are among the most sensitive engineered structures built on permafrost. Nidowicz and Shur (1998) studied the impacts of roads on permafrost in Alaska and showed that, based on Alaska climate data prior 1990, permafrost was degrading under roads in the discontinuous permafrost zone but remained stable in the continuous permafrost zone of Northern Alaska (AEIC 1989). However, recent climate warming now requires reexamination of that conclusion because roads in northern Alaska are also experiencing subsidence and degradation. For example, flooding of the Sagavanirktok River in spring 2015 caused catastrophic erosion of ice wedges near the Deadhorse Airport that resulted in closure of the Dalton Highway near Prudhoe Bay for long periods (Fig. 7B). The cost to repair the road and Trans-Alaska Pipeline corridor was estimated at $27 million. An additional $40-50 million was spent to elevate the highway to prevent a reoccurrence of flooding (Shur et al. 2016; Toniolo et al. 2017).

Ecosystems near roads are rapidly changing due to a combination of climate- and infrastructure-related effects. Soils near the roads are warming at a faster rate than soils distant from roads. What is happening to permafrost near the roads may be a precursor of what will happen more widely in the future. If the soils at depth do not refreeze during the winter, a destabilizing cycle of ever-deepening thaw develops (Parazoo et al. 2018; Kanevskiy et al. 2017). *One hypothesis is that as climate continues to warm and winter snow cover becomes thicker, areas near and distant from roads will become unstable leading to the development of taliks (year-round unfrozen layers in areas of permafrost) and general regional loss of near surface permafrost (Parazoo et al. 2018). An alternative hypothesis is that the areas near roads may become more unstable, but areas distant from roads will start to stabilize as the vegetation and moss layers become thicker, more insulative, and protective of the permafrost (Kanevskiy et al. 2017).*

We have been investigating changes to IRP systems along disturbance gradients near two heavily traveled roads (NSF ArcSEES award 1263854). Road transects were established perpendicular to the Prudhoe Bay Spine Road near Lake Colleen and the Dalton Highway near the Deadhorse Airport (Figs. 5 left and 8 left). A full history of annual changes at both study sites are recorded in high-resolution aerial photographs taken by the U.S. Navy in 1949 and the oil industry every year after the discovery of oil in 1968 (Fig. 4, left). Full descriptions of the transects, data collected, and early results are in AGC data reports (Walker et al. 2015, 2016, 2018), several papers (e.g., Kanevskiy et al. 2016, 2017; Buchhorn et al., 2016; Raynolds et al. 2014a, 2016; Shur et al. 2016; Walker et al. 2017), and a synthesis paper (Walker et al. 2019 in review). Some of the documented effects include:

(1) Large changes in the morphology of ice-wedge polygons and the distribution of water (e.g. Fig. 4 left). The original low-centered ice-wedge polygons with less than 0.5 m of micro-topographic relief were converted to high-centered polygons with microrelief exceeding 0.5 m. Extensive ice-wedge degradation and thermokarst on both sides of the road, with deeper degradation to polygon troughs on the wet side.

(2) Large changes to the vegetation. Lower species richness (alpha diversity) but increased landscape diversity (beta diversity). Greater primary productivity (higher LAI and Normalized Difference Vegetation Index) occurred on flooded sides of the roads. Similar changes in ecological heterogeneity due to sudden increases in thermokarst were recently reported in polar desert systems of Canada (Becker et al. 2016; Farquharson et al. 2016).

(3) Warmer soils near roads due to a combination of factors related to effects of road fill, road dust, snow drifts, and flooding.

(4) Changes to the structure of the upper permafrost. A surprising result of the study was that after partial degradation of ice-wedges, enhanced sedge and moss communities in many of the flooded polygon troughs tended to insulate the soils, resulting in an increase of the intermediate layer, which is a highly-organic and ice-rich layer on top of ice wedges that protect them from melting (Fig. 9). However, in some flooded areas immediately adjacent to roads, thaw was very deep (>150 cm at the Airport site), indicating that taliks (zones of permanently thawed soils) are forming beneath some ponds near roads, particularly at sites that are also covered by deep, insulating, road-related snow drifts. In other places, we observed well-protected ice wedges very close to the roads that were stabilized due to fast accumulation of road dust in the troughs.

We are completing the synthesis of the vegetation, environmental, and permafrost data collected at the Lake Colleen and Airport sites. We are proposing new studies to build on this data resource, including monitoring permafrost temperatures along the transects, hydrology observations and modeling, ground-ice studies and modeling, greenhouse-gas (GHG) flux measurements, and multi-dimensional remote-sensing analysis. The project will also collaborate with the Alaska Department of Transportation and Public Facilities (DOT&PF) on placement of permafrost temperature monitoring sites at the RIRPO and the production of a synthesis of best practices for design, construction, and maintenance of roadways and airports on permafrost. The synthesis will cover topics such as the types of permafrost and how they impact road design, best practices for geotechnical investigation, mitigation techniques, impact of changes in climate and impacts of infrastructure on the thermal regime.

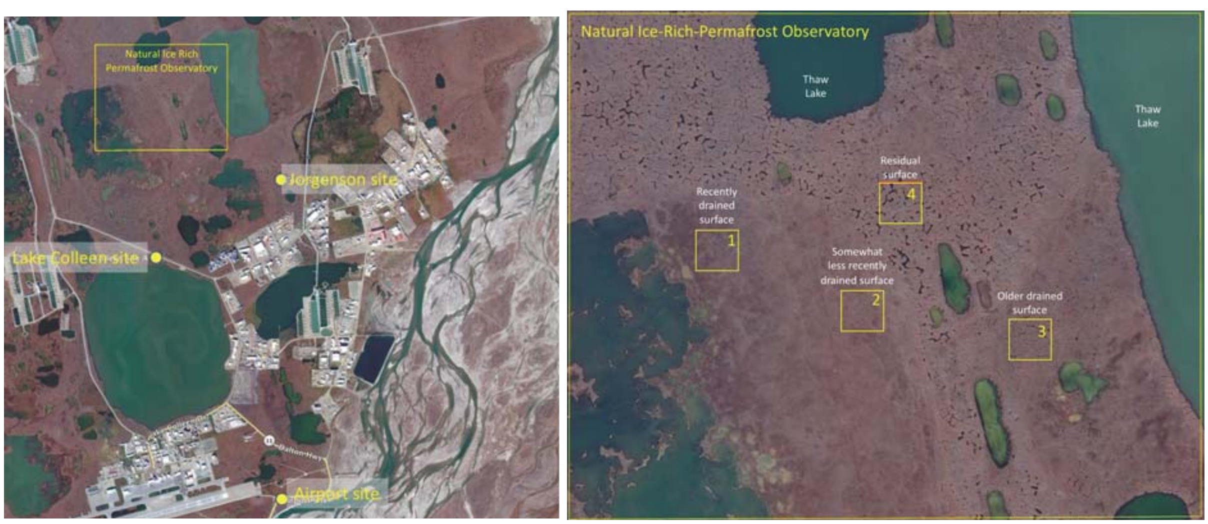

Figure 8. Prudhoe Bay oilfield IRP observatories. Left: The Roadside IRP Observatory (RIRPO) includes the Lake Colleen and Airport sites. Right: Four proposed 100-m x 100-m grids located on different-age IRP surfaces within thaw-lake basins and a residual surface in the Natural IRP Observatory (NIRPO). Imagery: Google Earth.

Natural ice-rich permafrost observatory (NIRPO)

Roadside areas in the road-effect observatory (RIRPO) have changed from their pre-oilfield status due to a combination of a warmer climate, altered drainage patterns ice-wedge degradation, road dust, and other roadside disturbances that resulted in ice-wedge degradation. Another observatory is needed to answer the question of what has happened in similar tundra areas mainly affected by climate change in the absence of infrastructure. We have selected a relatively natural remote site within the Prudhoe Bay oilfield that is on the same geologic surface as the RIRPO (Fig. 8, right). Within the NIRPO, we will survey four 100 m x 100 m grids in ice-wedge-polygons complexes with differing degrees of ice-wedge development and degradation. We will conduct vegetation studies, measure permafrost temperatures, characterize the permafrost and hydrologic conditions, measure GHGs, and conduct remote sensing analyses described below.

Village ice-rich permafrost observatory (VIRPO)

We chose Point Lay to establish a village IRP observatory because the village is situated on yedoma, which typically has extremely ice-rich permafrost with thick and deep ice wedges. The ice in yedoma formed during the late Pleistocene and occurs extensively on foothills of the Brooks Range and some coastal areas (Carter 1988; Kanevskiy et al. 2011). We will work with the village to understand the variables influencing IRP-related changes in the yedoma-rich environments that also occur in other villages in coastal northwestern Alaska. We will build on existing geophysics, remote-sensing, and mapped information available for Point Lay (Miller 1995; Bjella 2015; Reynolds et al. 2016) and work closely with the village to plan studies and adaptation strategies relevant to local planning needs; host a symposium of scientists, engineers and locals to share observations, identify knowledge gaps and propose new solutions and research priorities; and produce a manual of best practices for new and existing building foundations in areas of thawing IRP. We will also collect data matching the other IRP observatories, including boreholes to monitor permafrost temperatures and characterization of the permafrost, hydrology, and geoecology in areas of the village that are experiencing extreme thaw subsidence, as well as adjacent natural areas within thaw-lake basins with low-centered polygons, and residual yedoma surfaces with high-centered polygons. We will partner with the Kali School to involve students in research.

<u>Landscape characterization and evolution approaches</u>

Permafrost

Properties of IRP of Northern Alaska differ widely, which reflect the climate at the time of its formation, terrain and ecosystems succession (Fig. 1). The main types of terrain in the Prudhoe Bay area are drained-lake basins of different ages and primary (residual) surfaces unaffected by thaw-lake processes. Ice wedges are the most important landscape element in all terrains, but the amount of massive ice and ground-ice content of soils between ice wedges increase with the age of the terrain (Kanevekiy et al. 2013). The type and extent of ice defines the reaction of permafrost to changes in climate and disturbance and are important in predicting the behavior of permafrost and the impacts of changes in IRP on ecosystems and infrastructure. We will work closely with the rest of research team at the three IRP observatories to describe the properties and structures of the for main types of permafrost in the Prudhoe Bay area and Point Lay in relation to natural and developed areas. The permafrost structure will be described according to French and Shur (2007) and Kanevskiy et al. (2017) (examples in Fig. 1).

Data from the studies will be used to improve the conceptual models of IRP evolution and degradation (Fig. 9). The data will also be used to develop a thermal model to evaluate and predict the rate, extent, and mechanisms of permafrost degradation over the coming century specific to the Prudhoe Bay region. The thermal model of permafrost dynamics will be based on the GIPL2 model (Marchenko et al. 2008; Nicolsky et al. 2007, 2009). Input data for the model include air temperature, precipitation, and soils data from observations and, in the case of future projections, climate forcing from global or regional climate models. Soil data include heat capacity and thermal conductivity of thawed and frozen soils and soil moisture. These properties will be either derived from field measurements or based on Prudhoe Bay geoecological map information (Walker et al. 1980, 2014a). The model results will be validated against the active layer and permafrost temperature records from existing nearby permafrost monitoring sites (e.g. south of Deadhorse and at West Dock). Additionally, we will install new monitoring stations at key locations in natural and disturbed areas to collect continuous data on soil temperature dynamics. At each site we will characterize vegetation composition, peat composition and thickness, measure thermal soil properties (in-situ and in the laboratory). To quantify the potential for ground subsidence, we will use excessive ice-content measurements. To produce several scenarios of future changes in permafrost under

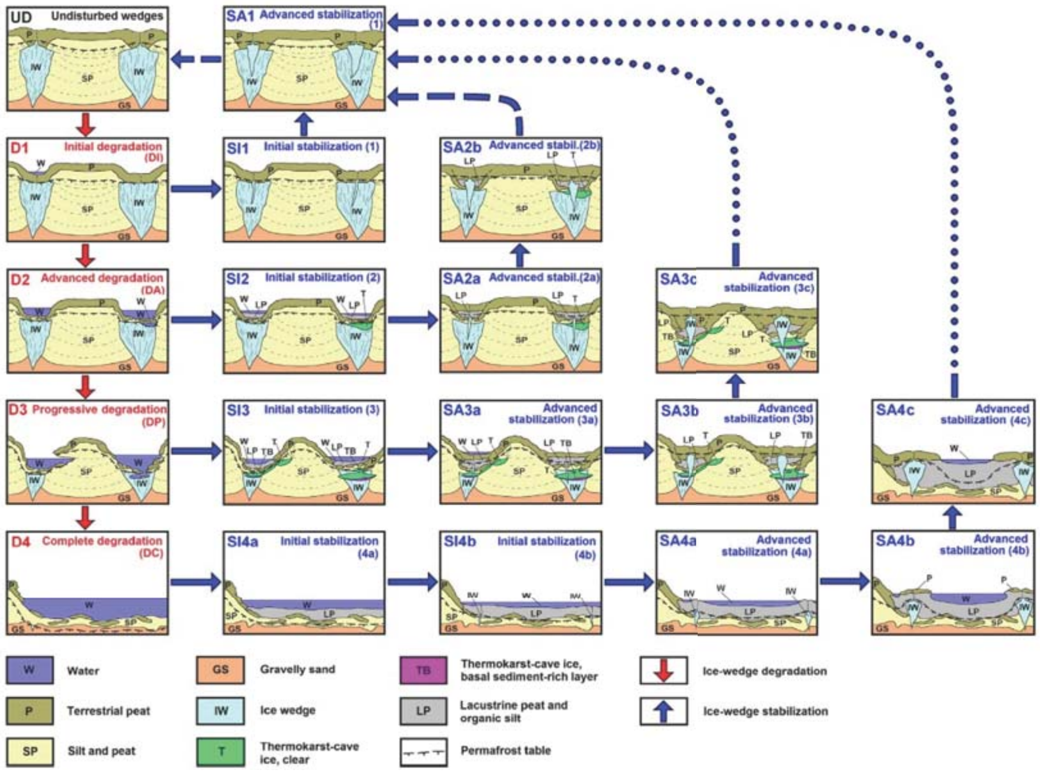

Figure 9. Conceptual scenarios of ice-wedge degradation (red arrows) and stabilization (blue arrows) (Kanevskiy et al. 2017). Ice-wedge degradation occurs when the protective organic- and ice-rich intermediate layer above the ice wedge is lost. The process can be reversed through ecosystem and/or hydrological processes leading to stabilization and regrowth of the intermediate layer.

natural conditions, we will use climate forcing (2010-2100) under two different greenhouse gas emission scenarios, representative concentration pathway (RCP) 4.5 and 8.5 (Moss et al. 2010). The high-resolution climate forcing under different emission scenarios are available from the Scenario Network for Alaska and Arctic Planning (SNAP) group (www.snap.uaf.edu). Using the optimized parameters and the improved GIPL2 model, we will produce local maps of active layer thickness, ground temperatures, and talik thickness. Site-specific information will be used to estimate the degree of ground surface subsidence as a result of permafrost degradation under natural conditions. This information will be combined with a Digital Elevation Model (DEM) of the study area to identify sites of potential thermokarst.

Hydrology

Changes in hydrology within IRP systems are linked to the dramatic changes in microrelief of periglacial landforms that occur during ice-wedge degradation. The hydrology-permafrost studies will include field measurements, remote sensing, and numerical modeling. The field measurement and remote sensing products will inform and test a permafrost hydrology model, which will be used to perform experiments to allow an assessment of the impacts of infrastructure and/or climate change on permafrost hydrology and landscape evolution. Field measurements will include existing team members' studies of vegetation, soils, active layer depth, air and soil temperatures, snow depth, and ground-ice content at the NIRPO and RIRPO sites (Fig. 8). Continuous precipitation data will be obtained from the Deadhorse NOAA site. Additional field measurements will include water levels (Hobo Onset dataloggers), and ~1m profiles of water and soil temperatures (at the sediment-water interface, 5 cm below the interface, at the bottom of the active layer, and 10 cm into the permafrost) using Hobo Onset dataloggers. End-of-winter snow accumulation will be measured using ground-based LiDAR (RIEGL Laser Measurement Systems), which will also be used for a detailed elevation and canopy structure survey. Occasional discharge measurements will be made during site visits. We will use maps of ice-wedge polygon cover together with ground-ice field measurements to parametrize ground-ice distribution within the model. We will utilize the Water balance and Simulation Model (WaSiM), which we will force with hourly field observations and downscaled climate projections (air temperature, precipitation, wind, relative humidity and solar radiation) (Cai et al. 2017). WaSiM has been extensively applied to temperate and alpine regions, resulting in >100 peer-reviewed publications. WaSiM can successfully represent permafrost hydrology at scales ranging from ice-wedge polygon troughs (sub-meter) to the watershed (Liljedahl et al. 2016; Kaiser 2015). WaSiM includes 1-D soil and snow heat conduction and advection, 1-D unsaturated zone representation (Richard's equation), variable or fixed groundwater flux boundary conditions, Penman-Monteith evapotranspiration, moss evaporation, and a topographic and wind-controlled snow distribution (Schulla 2017). Liljedahl and Daanen are linking vegetation, soil nitrogen, and topography (ground subsidence) dynamics in WaSiM under an active NSF award (#1722572). Liljedahl has been as user of NSF's Extreme Science and Engineering Discovery Environment (XSEDE) since 2015 and has previously received their support for code optimization. The modeling effort will include calibration, testing, and application. The calibration and testing will be made separately using field measurements of water levels, snow accumulation, and soil temperatures and sporadic discharge measurements. The application will include a series of model experiments aimed to assess the impacts of climate change and/or disturbance caused by infrastructure. For example, we will use our calibrated model to map the effects of the road system on hydrology and landscape evolution by simulating the last 50 years and digitally include or remove the road network.

Remote sensing

We will investigate the land-surface and land-cover changes occurring in permafrost regions using multidimensional remote sensing and data fusion techniques, which have emerged as primary tools for advancing the field of thermokarst research from local, to regional, to Pan-Arctic scales (Rowland et al. 2010; Kokelj and Jorgenson, 2013; Grosse et al. 2006; Grosse and Jones, 2018; Nitze et al. 2018). Although widespread instability in IRP regions has been documented with extensive ecosystem effects (see description of IRP systems above), no one remote sensing tool is particularly suited for detecting and observing the large variety of landscape change scenarios associated with transitioning permafrost landscapes (National Research Council, 2014). The spatial and temporal rate at which permafrost degradation manifests itself; the spectral response of the land surface to thaw-induced perturbations; and the observationally limiting conditions caused by cloud-cover, short northern latitude summers, and variable ecological conditions requires the use of multiple remote-sensing platforms to address the guiding research question: "How are ice-rich permafrost landscapes changing?" New remote-sensing and data-fusion techniques are emerging that can address previous limitations associated with the complex nature of environmental change and the need to incorporate various earth observational datasets. The remote-sensing data are diverse and multidimensional. The sensors range from ground-based, to airborne, to spaceborne; from optical to microwave; can be active or passive; and they collect data at various spatial, temporal, and spectral resolutions, capable of resolving both 2D and 3D land-surface changes. A radical shift from per-pixel based to computer vision-inspired approaches have revolutionized imagery-derived knowledge generation and can integrate observations across platforms using object-based identification (Nitze et al., 2018). In addition, regional- and even planetary-scale automated change detection at multiple spatial and temporal resolutions is becoming standard, with Google Earth Engine serving a major role (Gorelick et al. 2017). This project will conduct multidimensional remote-sensing observations at the three IRP observatories that capture the regional temporal and spatial differences in ecology and human development, including micro-topography, water and snow distribution, and variation in vegetation cover, The inherent differences in ecology, climate, and landscape history and their role in transitioning permafrost regions will be tested using common approaches across all sites as well as value-added products that are available in particular regions. Remote sensing datasets that will be used in this research include Landsat, Sentinel 1 and 2, SPOT, AVIRIS, ASTER, MODIS, DigitalGlobe Inc., Planet Cubesats, Radarsat 1 and 2, ERS 1 and 2, TerraSAR-X, ASCAT, Ice-Sat, InSAR, airborne LiDAR, as well as manned and unmanned aerial systems (UASs). A consistent, yet nested approach will provide valuable information on the most appropriate tools for detecting and understanding the multidimensional responses of permafrost region transitions. It will also foster the development of tools capable of scaling change detection techniques to the entire Arctic.

Vegetation

Several legacy plot vegetation datasets relevant for this study are archived in the Alaska Arctic Vegetation Archive (Walker et al. 2016), including Prudhoe Bay plot data from the 1970s (92 plots, Walker 1985); and 2000s (117 plots, Kade et al. 2005), and recent data from disturbed sites along the roads (50 plots, Walker et al. 2015, 2016). We are proposing two main new vegetation studies and an analysis of greenhouse gas fluxes:

(1) Comparison of present-day Prudhoe Bay vegetation and geoecological patterns with legacy datasets from the 1970s (Everett et al. 1978; Walker et al. 1980; Walker 1985). We will resample permanent vegetation plots, and remap the geoecological conditions that were first documented the 1970s during the IBP studies (Brown 1975; Brown et al. 1980). We will relocate and resample as many as possible of the permanent legacy plots that were sampled at Prudhoe Bay in the 1970s (approx. 50 plots of the 92 total plots). Detecting change using legacy vegetation data sets and estimates of vegetation cover presents numerous problems. Most serious are accurate relocation of plots, changes in plant nomenclature, unrecognized errors in plant identification, and consistency of cover estimations (Villareal et al. 2012; Daniëls et al. 2010; Chytrý et al. 2013). Several of these problems will be minimized in this study. We will only sample plots where the boundaries of the plots are marked with permanent stakes that are still in place. The PI established these plots, has worked in the region for over 50 years, is very familiar with the flora and will provide consistency for the vascular-plant, moss and lichen identification. Based on a preliminary comparison of data from the road-effects and the 1970s datasets, we should be able to demonstrate clear trends of change in several aspects of tundra vegetation near roads including vegetation height, shrub cover, lichen cover, moss cover, and species richness (alpha and beta diversity). We also expect to detect more subtle changes in vegetation types distant from roads, including increased shrub cover and shrub height, and a reduction in lichen cover. In areas distant from roads, we expect to see vegetation shifts due to climate change similar to those documented in other regions of the Arctic (Walker et al. 2006: Elmendorf et al. 2011, 2012; Meyers-Smith 2015), including decreased abundance of lichens in dry and moist sites, increased abundance of shrubs and sedges in moist sites, and overall greater productivity in wet sites. Comparison of the 1970s plot and map information with the current data from NIRPO will provide insights regarding the response of vegetation to climate warming for cold coastal nonacidic tundra, which is dominant at Prudhoe Bay and much of the eastern portion of the Arctic coastal plain and which is not well represented in the ITEX warming experiments and other circumpolar assessments of tundra vegetation change.

(2) Vegetation trends along an ice-wedge polygon chronosequence. We will sample vegetation in 2-m x 2-m permanent vegetation plots to document the existing vegetation in each of the four 100-m x 100-m grids in the natural IRP observatory (NIRPO) (Fig. 8). Each grid contains polygons in different stages of succession following thaw-lake drainage. We will sample three replicate permanent vegetation plots in the common dry, moist, wet, and aquatic tundra vegetation types in each grid (approximately 48 total plots). We will follow the Braun-Blanquet sampling and classification approach (Westhoff and van der Maarel 1978) and the data collection and data management approaches of the Circumpolar Arctic Vegetation Archive and Classification (Walker et al. 2016, 2017, 2018). We will use the software program JUICE (Tichý 2002) to determine the separability of the vegetation units and classify the vegetation types based on the fidelity of diagnostic species to each type. We will use a variety of ordination approaches (McCune et al. 2002) to examine vegetation composition and structure along the chronosequence and gradients of soil moisture. We will also compare the data from the dry, moist, wet, and aquatic types in the NIRPO with the same vegetation types sampled in the RIRPO and in the plots from the 1970s. Along the chronosequence of increasing age, we expect to see a trend of increased ice-wedge development, increased differences in microrelief, greater percentage of moist and dry vegetation types, and greater amounts of thermokarst and open water on the older surfaces. We predict that *vegetation, ground ice, and hydrology of the oldest (residual) surfaces will show the greatest degree of*

change since 1973 due to geomorphological changes caused by extensive thermokarst. Vegetation composition of the dominant vegetation types will show changes mainly related to altered hydrologic conditions. Such a trend is suggested by a negative trend between 1985 and 2011 of overall terrain greenness in the Prudhoe Bay region, as measured by the Landsat-derived normalized difference vegetation index (NDVI) (Raynolds and Walker 2016). A downward trend in NDVI would normally suggest a downward trend in vegetation productivity, but another possible explanation is the abrupt increase in unvegetated thermokarst ponds (Jorgenson et al. 2006; Raynolds et al. 2014), which have very low NDVI associated with unvegetated water. We will also map the vegetation, soils, surface geomorphology and distribution of water in each grid using the geoecological mapping approach developed for Prudhoe Bay in the 1970s. We will use the most recent high-resolution satellite imagery for the base maps and the LiDAR-based high-resolution digital elevation models of the IRP observatories (see above). Several sets of vegetation plot and map data will provide vegetation, soil, and site information needed for the GIPL and WaSiM, and conceptual models of ground-ice evolution and degradation and aid in the analysis of results from the GHG studies (discussed below).

(3) GHG fluxes. Few studies have examined microscale GHG variation within networks of periglacial landforms (e.g., Kade et al. 2012) and none with respect to disturbance gradients associated with roads or with respect to ice-wedge polygon microhabitats. Here we will investigate GHG fluxes in ice-wedge-polygon centers and troughs along Transects 1 (heavily dusted transect) & 2 (flooded transect) of the road-disturbance gradient at RIRPO, and in the natural chronosequences of ice-wedge polygon development at the NIRPO. At the RIRPO, we predict that CO_2 uptake by the vegetation (GPP) along with biomass production will decrease with increased dust effects from road disturbance. CO_2 loss due to respiration should be lower closer to the heavy dust-side of the road due to less biomass and soil organic matter, but it might be offset by the warmer and more deeply thawed soils. Along the flooded side of the road, CO_2 uptake should increase along with biomass production and CH_4 efflux should increase due to anaerobic conditions. At the NIRPO, we expect greater CO_2 uptake and CO_2 respiration loss to be linked to areas of higher biomass production. Greater differences in vegetation types tied to ice-wedge development on the older surfaces should also result in greater CO_2 differences. CH_4 efflux should increase where warmer temperatures have resulted in wetter soil conditions due to thermokarst. The two most abundant types of ice-wedge polygons in IRP tundra, low- and high-centered polygons, have not only different moisture regimes and plant communities, but also different functional potentials (Taş et al. 2018). Transect 1 has unflooded low-centered polygons and transect 2 has flooded high-centered polygons. We will sample GHG fluxes at 5, 25 and 200 m from the road (3 replicates at each distance). In each of the four grids of the NIRPO study area, we will select plots in high-centered polygons, low-centered polygons and troughs. All plots will have three replicates, for a total of 54 plots. Plant communities, soils, and site factors will be sampled in permanent plots as described above. To relate GHG fluxes to the different environmental factors and vegetation types associated with the IRP features, we will determine plot-level GHG fluxes using a translucent, portable chamber connected to an LGR Portable Greenhouse Gas Analyzer. We will measure CO_2 fluxes, including ecosystem respiration and the light response of net ecosystem exchange as described in Shaver et al. 2007 and Kade et al. 2012, and CH_4 fluxes as described in Vaughn et al. 2016 at all 54 plots during three measurement campaigns at the beginning, height and end of the growing season (approximately June through September). We will use repeated measures analysis to examine the effects of disturbance on ecosystem respiration, net ecosystem exchange and CH_4 fluxes over the course of the growing season and use ordination techniques, PERMANOVA, and ANCOVA to study the effects of the disturbance gradient GHG fluxes and their interaction with environmental parameters and vegetation.

Broader Impact

Adaptations to change

Changes to IRP systems are having major economic impacts in Alaska with the largest impacts predicted for roads and rural villages (Melvin, 2018; Berman and Schmidt, 2018). The impacts include shortened useful life of buildings, additional maintenance and repair costs, and early reconstruction and replacement (Larsen et al. 2008; Berman and Schmidt 2018). The cumulative cost of permafrost thaw-related damage to public infrastructure (buildings, roads, airports, railroads and pipelines) in Alaska through the end of the century has been estimated at \$1.6–\$2.1 billion, depending on climate change scenario (Melvin et al. 2016). This does not include damages from coastal erosion, flooding or other environmental stressors associated with warming, nor does it include the burden to owners of commercial and industrial infrastructure and private homes. Alaska's remote rural communities are especially susceptible to thaw-related impacts because many are located on rapidly eroding coastlines and river

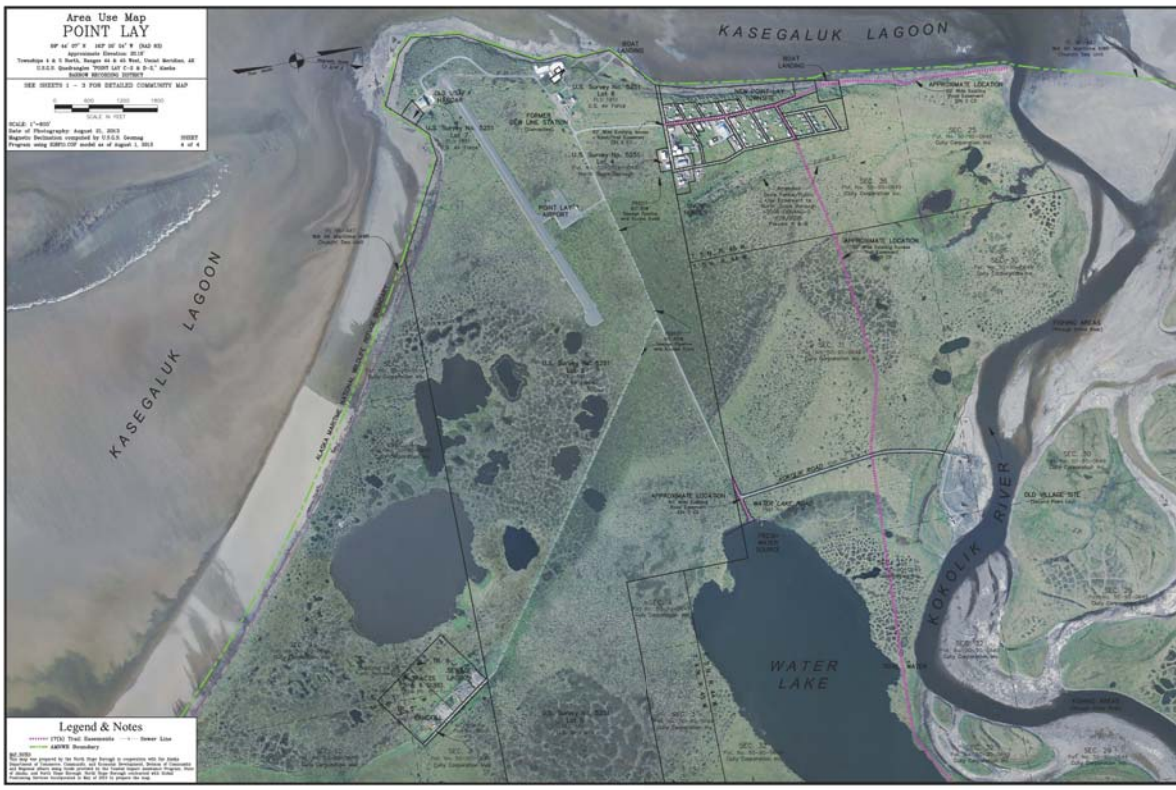

Figure 10. Village of Point Lay and vicinity. Ice-wedge polygons occur nearly everywhere in lake basins and remnant surfaces of various age. Roads passing through the lake basins block the natural drainage patterns causing local flooding. The village is on a yedoma deposit with large ices wedges that are degrading rapidly and threatening the foundations of many of the houses (Fig. 7C) and the village's buried utility system. The water lake near the bottom of the image was the village water supply and drained into the Kokolik River in 2016 due to thermal erosion of ice wedges in the lake shore.

banks. Some, like the Native Village of Point Lay (pop. 269, 90% Iñupiat) (Fig. 10), are built on ice-rich syngenetic permafrost (yedoma) with extreme risk of land subsidence due to permafrost degradation. Point Lay has received less research interest and agency attention than other climate-impacted communities, yet its thaw-related subsidence (up to 3 m) is among the most critical anywhere in the Arctic. The community is currently in its third location and is at risk from multiple permafrost-related impacts including coastal thermal erosion, flooding of the airport from storm surges, and thaw-related subsidence. The upper 10–15 feet of soils within the village are extremely ice rich (60–95% ice by volume). Ice wedges near the coastal bluffs are exposed and melting fast; surfaces around houses are settling, and some residents need ladders to reach their front doors (Figure 6, right). The community recently lost its fresh water source due to thermal erosion of the reservoir lake's shores. Parts of its piped water and wastewater system are damaged and roads and the runway are in unstable condition. Broken utility lines are creating health and safety risks and economic peril for residents (Reynolds et al. 2016). As severe as permafrost thaw is in Point Lay, the infrastructure issues created are typical of numerous arctic communities.

Arctic communities like Point Lay are actively working to mitigate and adapt to the impacts of thawing permafrost (Larsen et al. 2008; Melvin et al. 2016). Much of this is incremental adaptation driven by the necessity to repair and stabilize existing structures. Although Native Alaskans are highly resourceful and adaptive, there is a need for more strategic approaches to adaptation informed by science and engineering undertaken in collaboration with local residents' observations, knowledge, and preferences. Key to developing successful adaptation strategies is the active participation of local communities and regional governments in problem solving and planning. The Arctic Council (AMAP 2017a, 2017b, 2018), the IRIS program in Canada (Allard et al. 2013), and others (Armitage et al. 2011, Beier et al. 2017, Miller and Wyborn 2018) provide guidance for how to achieve meaningful coproduction to reach sustainability goals. We will work with the Point Lay Tribal Council and a project steering committee of local residents to determine methods for engaging the community in the study, including the development of a local IRP monitoring program, village housing study, and a permafrost and infrastructure symposium. As a part of this process, the project will identify the best method for documenting local / traditional knowledge (observations, understandings, preferences) related to thawing permafrost and its implications to the community. For example, several small-group interviews may be used to document local knowledge, with that information summarized and reported to researchers and others involved in the project. A project advisory group, including key members from the science and engineering teams and representatives from the tribe, school and borough will guide the overall direction of the project, review progress and work plans, identify collaborative and educational opportunities, and advise on products.

Village housing, Point Lay, Alaska

The community has identified safe, stable housing as its top planning goal. The region's Taġiuġmiullu Nunamiullu Housing Authority (TNHA) has been working to stabilize housing foundations in partnership with the Cold Climate Housing Research Center (CCHRC) and the University of Alaska. An industry-based nonprofit, CCHRC has been identified as a boundary organization which supports the knowledge-to-adaptation-action process by effectively communicating science knowledge to solve real-world problems (AMAP 2017). CCHRC will work with TNHA and local residents to evaluate the performance of adaptive foundations previously constructed by TNHA and co-produce strategies that address housing and other infrastructure issues created by thawing permafrost. Solutions may include thermal raft foundations, thermosiphons, and other techniques. Potential solutions will be evaluated in context of other social, economic and infrastructure needs and assets as part of a holistic approach to sustainable development recently piloted by CCHRC in Oscarville, Alaska (Schaeffer 2019). The project will generate recommendations applicable to new and existing building foundations in other northern communities in regions of ice-rich yedoma, such as Shishmaref and Kivalina. Research products will include: 1) retrofit strategies for existing foundations that can be implemented by a homeowner or contractor; 2) a suite of mitigation strategies formulated as guidelines for community-level mitigation efforts, including tools for inspecting existing foundations; and 3) peer-reviewed journal manuscripts in the areas of resource economics and resilience analysis focusing on the impact of permafrost damage on property tax revenues and urban-versus-rural resilience. Education and training products will include: 1) for K-12 students, real-world, place-based educational materials related to the project developed in partnership with Kali School as part of its A World Bridge® curriculum (AWorldBridge.com); 2) for homeowners and contractors, permafrost outreach materials including a short informational video on permafrost foundations; and 3) for TNHA staff and construction crews, training in adaptive strategies and best practices for thaw-stable foundations in new and existing foundations.

Permafrost and infrastructure symposium in Point Lay

To address the broader range of thaw-related impacts on roads, public facilities and utilities, the Point Lay community will host a two-day symposium of permafrost scientists and infrastructure engineers from Alaska and Canada. The NNA-IRPS team will work with the Tribal Council and North Slope Borough Planning and Community Services Department to plan and co-facilitate the symposium. We will adapt a convergence model (Transport Canada 2015) used in Canada to pair scientific and engineering research practices with local knowledge and priorities in order to develop better strategies for improving arctic infrastructure. Invited engineers will include those with experience with Point Lay issues, including Canadian engineers. The multidisciplinary science team will include members of the NNA-IRPS natural science team with expertise in permafrost, vegetation, hydrology, and scenarios modeling. The goals of the symposium will be to: 1) educate and foster dialog among participating scientists and engineers about permafrost and infrastructure issues faced by Point Lay and other arctic communities, especially those on ice-rich permafrost; 2) provide community members with a forum to voice their concerns and desires for their community; 3) provide local residents and planners with guidance on issues that can be addressed now and those that require additional research; and 4) assist in the development of overall strategies for improving arctic infrastructure and the lives of those who live and work in the Arctic. Outcomes will include: 1) proceedings volume summarizing notes from the listening session, presentations by local and regional planners, scientists, and engineers; 2) collection of short post-symposium reports by participants with their observations and recommendations; and 3) a synthesis of knowledge and identification of knowledge gaps and research priorities by symposium organizers based on the proceedings volume and post-symposium reports.

STEAM education and international outreach

STEAM (Science, Technology, Education, Art, and Mathematics) elements are included in all components of the project. A new graduate student and a post-doctoral fellow will examine interactions between climate and infrastructure at the IRP observatories. Secondary school students in Point Lay will participate in the VIRPO field study, integrating IRPS lessons and research methods into science and math curriculum through A World Bridge partnership. Regional housing staff and technicians will receive training in permafrost monitoring and science-based adaptive construction techniques. New knowledge and relationships developed through the project will be used to refine UAF's 3-week multi-disciplinary summer field course for undergraduate and graduate students conducted along the climate-geoecological gradient from Fairbanks to Prudhoe Bay. At the international level, we will promote the sharing of data, adaptive approaches, models, and other knowledge codeveloped with northern communities through participation in the Point Lay Permafrost and Infrastructure Symposium, the International Arctic Science Committee (IASC) Rapid Arctic Transitions due to Infrastructure and Climate (RATIC) action group and IASC's Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections (T-MOSAiC).

Conclusion: Relevance to NNA goals

We propose research that spans permafrost science, hydrology, vegetation science, remote sensing, northern engineering, social science, art, and education to aid in the development of adaptive land-use management approaches in ice-rich permafrost systems (IRPS). Our proposed landscape evolution research directly addresses Goal 6 of the U.S. Arctic Research Plan (NSTC, 2016) by advancing "understanding of processes controlling permafrost dynamics and the impacts on ecosystems, infrastructure, and climate feedbacks". The entire proposal and especially the strategies for *adaptation to change* address NNA Focus Area 3 "Enabling fundamental science and engineering research in forward-looking, *sustainable, adaptable, and resilient infrastructure* to meet current and future challenges of a changing Arctic"; and Focus Area 4. "*Convergence* of research approaches to help researchers to understand the complex relationship between Arctic residents and their natural and cultural landscape."

The multi-disciplinary research, the co-development of actionable knowledge with the community of Point Lay and regional stakeholders, and its application to broader infrastructure issues in the Arctic directly address the *convergence* element of NNA. We are working with STEAM educators, students, artists, and community members to develop direct collaborations at all project stages as appropriate. Our RATIC action group and collaboration with T-MOSAiC will engage us with the international community that is addressing sustainable approaches in the circumpolar Arctic.

Results of prior support

Cumulative effects of arctic oil development – planning and designing for sustainability. PLR-1263854, $1,402,992, 8/15/13–7/31/18, Walker (PI), Kofinas, Shur (Co-PIs).
Intellectual merit: This project assessed cumulative effects of climate change and infrastructure in the Prudhoe Bay oilfield (Raynolds et al. 2014, Walker et al. 2019 in review) and analyzes impacts of roads to roadside permafrost and ecosystems (Buchhorn et al. 2014, 2016; Shur et al. 2016; Kanevskiy et al. 2016, 2017; Walker et al. 2014, 2015, 2016, 2017; Romanovsky et al. 2017). Most data are published in data reports and national archives (Walker et al. 2015, 2016, 2018). We are completing synthesis of this material (e.g. Walker et al. 2019 in review). A new raster-based circumpolar arctic vegetation map has been created (Raynolds and Walker 2018, Raynolds et al. 2019 submitted). 20 journal articles and book chapters, 6 AGC publications, and 46 conference presentations were supported partially or in full by this grant to date. Broader impacts: The Rapid Arctic Transitions due to Infrastructure and Climate (RATIC) initiative is a major outcome (Walker and Peirce 2014), including 5 RATIC workshops, 2013–2017. This grant partially supported 2 PhD, 1 MS, and 1 post-doctoral student, 2 visiting scientists, as well as Arctic field summer courses in 2014, 2015, 2016 and 2018, which helped train 33 students in Arctic ecosystem ecology. **Resilience and adaptation of Arctic communities in response to climate, land use, and socio-economic change** were assessed through related NSF grants to Kofinas (NSF 0732758, NSF/OPP 0531200, NSF/OPP 0531200, NSF 0654441, NSF 0640638) resulting in multiple publications on resilience (Blair et al. 2014, Gerlach et al. 2017, Kofinas et al. 2016a), subsistence and sharing networks (Brinkman et al. 2016, BurnSilver et al. 2016, Forbes and Kofinas 2015, Kofinas et al. 2016b, Zhou et al. 2017), local knowledge sharing (Bali and Kofinas 2014, Padilla and Kofinas 2014), adaptive capacity and sustainability (Baggio et al. 2016, Berman et al. 2017, BurnSilver et al. 2017, Knapp et al. 2014) and a forthcoming synthesis in *Frontiers of Ecology and the Environment* (Kofinas et al. 2019 in review).
Collaborative Research: Regional impacts of increasing fire frequency on carbon dynamics and species composition in the boreal forest. OPP 1737166, $150,235, 01/01/2018–12/31/2020, Romanovsky (PI). Intellectual Merit: Unprecedented warming and the emergence of a new fire regime over the past 60 years threatens to disrupt existing dominance of black spruce and release significant amounts of C into the atmosphere. This research will improve understanding of how C cycling and species composition of boreal forests responds to climate change. Broader Impacts: Our activities have been designed to train graduate students, involve Native American high school students in research, and help K-12 students learn about climate change. We collaborate with Your World Rocks (YWR), a nonprofit organization dedicated to promoting education with a specialization in environmental science, geology, chemistry, and engineering. As it was recently awarded, no publications have yet been produced.
Collaborative research: Patterns, dynamics, and vulnerability of Arctic polygonal ecosystems: From ice-wedge polygon to pan-Arctic landscapes (ARCSS 1722572, 1720875, 1721030, $1,317,630, 2018-2021, Liljedahl (PI). Intellectual merit: We are investigating key mechanisms affecting the resilience of ice wedges to climate change and the effects of ice-wedge degradation on watershed hydrology, while also providing the first pan-Arctic map of ice-wedge polygons that is key to scaling to the pan-Arctic domain. One publication to date on the application of deep learning on permafrost science (Zhang et al. 2018). Broader impacts: Postdocs and students are supported and trained in field, laboratory and/or remote sensing science. Three ‘Earth as Art’ satellite image galleries have been hosted in public libraries. Data and products will be archived at the NSF Arctic Data Center.

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