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LANDSCAPE AND PERMAFROST CHANGES IN THE PRUDHOE BAY OILFIELD, ALASKA

DONALD A. WALKER, MARTHA K. RAYNOLDS, YURI L. SHUR, MIKHAIL KANEVSKIY, KENNETH J. AMBROSIUS, VLADIMIR E. ROMANOVSKY, GARY P. KOFINAS, JERRY BROWN, KAYE R. EVERETT, PATRICK J. WEBBER, MARCEL BUCHHORN, GEORGE V. MATYSHAK, LISA M. WIRTH

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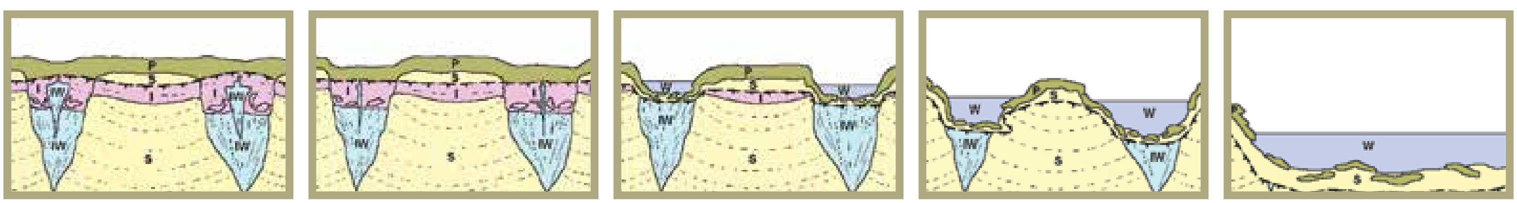

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UNIVERSITY OF ALASKA FAIRBANKS

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Pipelines, powerlines, and processing facility in the Prudhoe Bay Oilfield, June 2014. Photo by M.K. Raynolds. Thermokarst evolution graphic by Y.L. Shur and M.K. Kanevskiy.

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PREFACE

Alaska's North Slope oilfields are the most extensive and one of the oldest industrial complexes in the Arctic. A primary challenge for adaptive management of large Arctic oil and gas developments is documenting the changes that have already occurred. The first and most straightforward element is a catalog of incremental changes to the extent of oilfield infrastructure, followed by an assessment of the consequences to the environment.

After the discovery of oil at Prudhoe Bay in 1968, environmental studies periodically documented the changes resulting from the rapidly expanding network of roads and oilfield facilities. In 1949 the U.S. Navy obtained high-resolution aerial photographs of most of the North Slope, including the Prudhoe Bay region. The International Biological Program's (IBP) U.S. Tundra Biome study began documenting the effects of development at Prudhoe Bay in the 1970s (Brown, 1975; Walker *et al.*, 1980). The oil industry, starting in the 1980s, obtained nearly annual aerial photographs and kept an up-to-date geographic information system (GIS) database of infrastructure changes (Ambrosius, 2014). Assessments of the cumulative effects of Prudhoe Bay infrastructure have been published by government agencies (e.g., AMAP, 2010), nongovernmental agencies (e.g. Speer & Libenson, 1988), and scientific journals (Walker *et al.*, 1987; Raynolds *et al.*, 2014). The most comprehensive assessment of cumulative effects for North Slope oil development was done by the National Research Council (Orians, 2003).

The present document contains the most recent assessment, published in *Global Change Biology* (GCB) (Raynolds *et al.*, 2014), along with key supplementary information and recent field observations regarding the long-term effects of oilfield roads. The first chapter is the main *GCB* article, which describes the history of infrastructure across all of the North Slope region as well as a landscape-scale analysis of the spread of indirect effects such as road dust, infrastructure-related flooding, and thermokarst. The biggest surprise from this analysis was the rapid thawing of ice-wedges and abrupt increase of thermokarst that occurred between 1990 and 2010. The increase in thermokarst was most extensive in areas adjacent to infrastructure, but it also occurred widely in areas remote from infrastructure, a likely response to a series of recent exceptionally warm summers.

The next three chapters contain key information that supports the conclusions of the Raynolds et al. (2014) article. These were published as supplementary information and are reformatted here for easy access in a single document. Chapter 2 includes a description of the Prudhoe Bay permafrost environment and the potential effects of climate change and infrastructure on thermokarst (Shur *et al.*, 2014). Chapter 3 contains the methods used for the regional-scale analysis and a time-series tabular account of the variety of different types of infrastructure within the oilfield (Ambrosius, 2014). Chapter 4 provides the background and detailed methods, maps and legends used for the local-scale analyses (Walker *et al.*, 2014).

Chapters 1 through 4 thus describe the historical changes that have been documented mainly through the use of time-series analysis of aerial photographs and GIS databases. Chapter 5 provides an overview of a ground-based study that we began in August 2014 to examine the changes to the ice wedges, geomorphology, hydrology, soils, and plant communities. We conclude with a series of questions that were generated by the field studies, and a recommendation that echoes that of the National Research Council, which called for a total ecosystem approach to examine the consequences of rapid infrastructure expansion and climate change.

Forty-six years after the discovery of oil at Prudhoe Bay, we are still learning about the ecological consequences of large-scale infrastructure expansion and the impacts of climate change in ice-rich permafrost environments. The authors who were involved with the Tundra Biome studies in the 1970s could not foresee the changes that occurred, but the baseline studies provided a means to document the transitions up to the present. The results will provide a basis for new field studies and methods to monitor future changes to permafrost and regional social-ecological systems. We hope they will also aid in developing new methods for sustainable management of industrial development in the Arctic.

D.A. (Skip) Walker
October 21, 2014, Fairbanks

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CONTRIBUTORS

DONALD A. WALKER
Alaska Geobotany Center, Institute of Arctic Biology and Department of Biology and Wildlife, University of Alaska Fairbanks, Fairbanks, Alaska

MARTHA K. RAYNOLDS
Alaska Geobotany Center, Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska

YURI L. SHUR
Department of Civil and Environmental Engineering, University of Alaska Fairbanks, Fairbanks, Alaska

MIKHAIL KANEVSKIY
Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, Alaska

KENNETH J. AMBROSIUS
AeroMetric, Anchorage, Alaska

VLADIMIR E. ROMANOVSKY
Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska

GARY P. KOFINAS
Department of Natural Resources, University of Alaska Fairbanks, Fairbanks, Alaska

JERRY BROWN
International Permafrost Association, Woods Hole, Massachusetts

KAYE R. EVERETT (DECEASED)
Byrd Polar Research Center, Ohio State University, Columbus, Ohio

GEORGE V. MATYSHAK
Department of Soil Science, Lomonosov Moscow State University, Moscow, Russia

PATRICK J. WEBBER, EMERITUS
Department of Plant Biology, Michigan State University, East Lansing, Michigan

MARCEL BUCHHORN
Alaska Geobotany Center, Institute of Arctic Biology, and Hyperspectral Imaging Laboratory, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska

LISA M. WIRTH
Geographic Information Network of Alaska, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska

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

MARTHA K. RAYNOLDS[1], DONALD A. WALKER[1], KENNETH J. AMBROSIUS[2], JERRY BROWN[3], KAYE R. EVERETT[4]†, MIKHAIL KANEVSKIY[5], GARY P. KOFINAS[6], VLADIMIR E. ROMANOVSKY[7,8], YURI SHUR[5] and PATRICK J. WEBBER[9]

[1]*Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775, USA,* [2]*Aerometric Geospatial Solutions, Anchorage, AK 99501, USA,* [3]*P.O. Box 7, Woods Hole, MA 02543, USA,* [4]*Byrd Polar Research Center, Ohio State University, Columbus, OH 43210, USA,* [5]*Department of Civil & Environmental Engineering, University of Alaska Fairbanks, Fairbanks, AK 99775, USA,* [6]*School of Natural Resources and Agricultural Sciences, University of Alaska Fairbanks, Fairbanks, AK 99775, USA,* [7]*Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA,* [8]*Earth Cryosphere Institute SB RAS, Box 1230, Tyumen, 625000, Russia,* [9]*P.O. Box 1230, Ranchos de Taos, NM 87557, USA*

Abstract

Many areas of the Arctic are simultaneously affected by rapid climate change and rapid industrial development. These areas are likely to increase in number and size as sea ice melts and abundant Arctic natural resources become more accessible. Documenting the changes that have already occurred is essential to inform management approaches to minimize the impacts of future activities. Here, we determine the cumulative geoecological effects of 62 years (1949–2011) of infrastructure- and climate-related changes in the Prudhoe Bay Oilfield, the oldest and most extensive industrial complex in the Arctic, and an area with extensive ice-rich permafrost that is extraordinarily sensitive to climate change. We demonstrate that thermokarst has recently affected broad areas of the entire region, and that a sudden increase in the area affected began shortly after 1990 corresponding to a rapid rise in regional summer air temperatures and related permafrost temperatures. We also present a conceptual model that describes how infrastructure-related factors, including road dust and roadside flooding are contributing to more extensive thermokarst in areas adjacent to roads and gravel pads. We mapped the historical infrastructure changes for the Alaska North Slope oilfields for 10 dates from the initial oil discovery in 1968–2011. By 2010, over 34% of the intensively mapped area was affected by oil development. In addition, between 1990 and 2001, coincident with strong atmospheric warming during the 1990s, 19% of the remaining natural landscapes (excluding areas covered by infrastructure, lakes and river floodplains) exhibited expansion of thermokarst features resulting in more abundant small ponds, greater microrelief, more active lakeshore erosion and increased landscape and habitat heterogeneity. This transition to a new geoecological regime will have impacts to wildlife habitat, local residents and industry.

Keywords: Arctic, climate change, cumulative impacts, geoecological mapping, ice-rich permafrost, ice-wedge polygons, infrastructure, photo-interpretation, thermokarst, tundra

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Introduction

Oil and gas exploration and extraction are occurring in ice-rich permafrost (IRP) areas of Alaska, Canada, and Russia, and it is inevitable that more extensive networks of infrastructure than presently exist will be required to extract the resources of these areas (AMAP, 2010). These will be constructed against a backdrop of rapid climate change, rapid technological changes, and unpredictable social-ecological changes (Truett & Johnson, 2000; Orians *et al.*, 2003; ACIA, 2005; AMAP, 2010; Krupnik *et al.*, 2011; Kofinas *et al.*, 2013). Documenting the history of these developments as they occur will aid local communities, researchers, land managers, industry, and policy makers in developing adaptive approaches to plan for and respond to future changes (AMAP, 2010; Streever *et al.*, 2011).

Correspondence: Martha K. Raynolds, 311 Irving, Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775, USA, tel. + 907 474 6720, fax + 907 474 7666, e-mail: mkraynolds@alaska.edu
†Deceased.

The Prudhoe Bay Oilfield

The Prudhoe Bay Oilfield (PBO) in northern Alaska was the first developed oilfield in the Arctic, and is the largest in the United States. It is an extremely important asset to the United States and the state of Alaska, containing 16% of US proven reserves of oil and gas (Alaska Oil & Gas Association, 2012; USEIA, 2012). In 2012, taxes on the oil from the Northern Alaska oilfields accounted for over 90% of the Alaska state budget (Alaska Oil & Gas Association, 2012). The PBO is located on the Beaufort Sea coast, halfway between the Canadian border and Point Barrow, a region that was remote and roadless prior to the discovery of oil in March 1968. An extensive infrastructure network quickly grew following the oil discovery, resulting in development within an approximately 2600 km^2 area (Fig. 1a).

Oilfield engineering evolved rapidly in response to the IRP conditions encountered (Gilders & Cronin, 2000; Orians *et al.*, 2003). Gravel construction pads over 2-m thick were used to insulate the frozen tundra. Since 1995, new technologies, including much closer spacing of the well heads, directional drilling to reach deposits up to 6.4 km from the drilling sites, and reinjection of drilling fluids into the geological formations to eliminate the need for reserve pits, considerably reduced the size of gravel pads for drill sites in newer oilfields. The use of winter ice-roads and roadless access to drill sites have further reduced the footprint of modern oilfields (Gilders & Cronin, 2000; AMAP, 2010; Streever *et al.*, 2011).

The early phase of PBO development stimulated geoecological and permafrost research in the region by the Tundra Biome investigations of the International

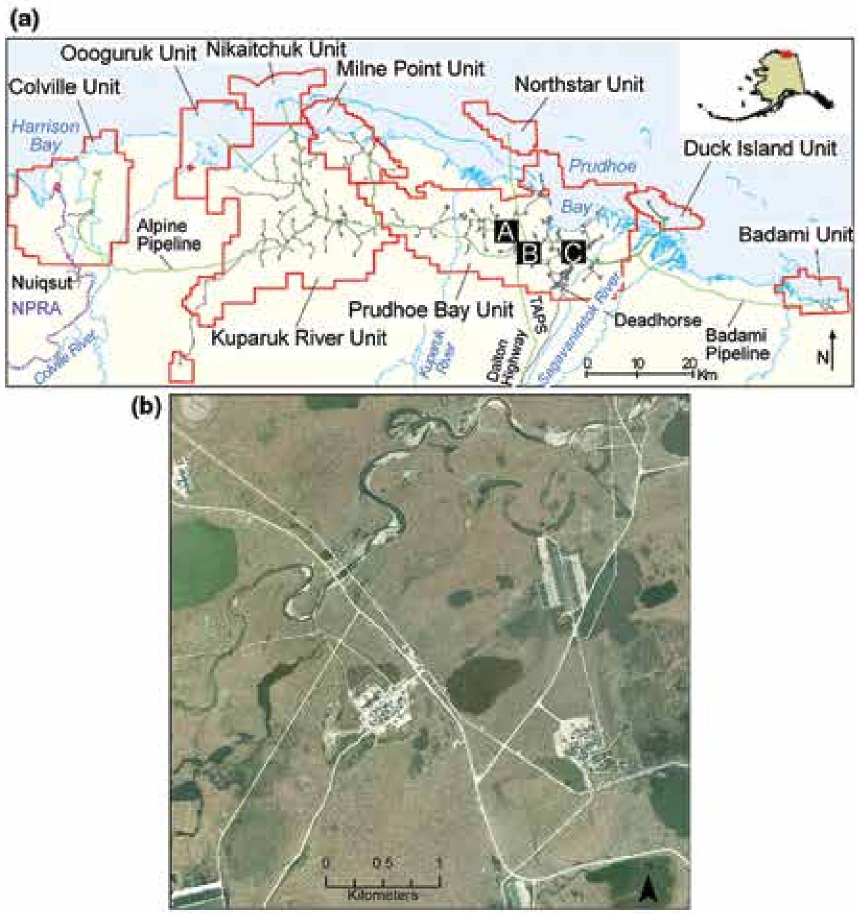

Fig. 1 Alaska North Slope production units that comprise the Prudhoe Bay Oilfield referred to in this article. (a) Major oil production units (red boundaries) and extent of infrastructure. Gray lines are gravel roads, airstrips, and construction pads. Green lines are major pipelines. Small black squares A, B, and C are locations of the detailed 20-km^2 map areas of this study. Note the Iñupiat village of Nuiqsut at left in the National Petroleum Reserve Alaska, the Trans-Alaska Pipeline System and Dalton Highway that link the oilfields to southern Alaska. *Inset*: Location within Alaska. Map courtesy of Aerometric, Inc. and BP Alaska, Inc. (b) Map B, showing the meandering Putuligayuk River and its floodplain, thaw lakes, drained lake basins, and primary surfaces between lakes. The infrastructure consists of a network of roads, drill sites, and processing facilities. The width of the area shown is 4.7 km. See Fig. 5 for geoecological and historical change maps of this area. Imagery courtesy BP Exploration (Alaska), Inc.

Biological Programme (Brown, 1975, 1980; Walker *et al.*, 1980); and the Circumpolar Active-Layer Monitoring Program (Brown *et al.*, 2000). Although the oil industry states that the density and extent of the infrastructure of the PBO will likely not be replicated in new oilfields, we focused our studies here because it has the longest history of development and scientific research, and is the only area with detailed time-series of geoecological and historical-change maps that span the complete history of the field. Many of the types of landscape change seen here, such as those associated with roads and climate change, will occur in other IRP areas.

IRP terrain and thermokarst

The PBO region is a showcase of periglacial landforms, including thaw lakes, pingos, meandering beaded streams, and many types of patterned ground such as nonsorted circles, and ice-wedge polygons indicative of IRP (Everett, 1980a). Within this landscape, ground-ice formation and thawing occurs in a hierarchy of time and space scales ranging from daily needle-ice formation to annual processes associated with frost-heave features (e.g., frost boils) to centuries and millennia involved with ice-wedge-polygon and thaw-lake formation (Walker, 2000). These processes create a mosaic of exceptionally dynamic landforms, soils, and vegetation that are susceptible to abrupt changes, especially if the features are disturbed by mechanical means or by rapid climate change (Lawson *et al.*, 1978; Lawson, 1982; Komárková & McKendrick, 1988; Walker, 1996, 1997; Callaghan *et al.*, 2005; Shur & Jorgenson, 2007; Shur & Osterkamp, 2007; Grosse *et al.*, 2011).

Permafrost is ground (soil or rock, in most cases including ice) in which a temperature below 0 °C exists for two or more years (Van Everdingen, 1998). At Prudhoe Bay, permafrost is continuous and extends to a depth of 660 m (Gold & Lachenbruch, 1973). The *active layer*, the layer of soil near the surface that thaws annually, varies in thickness from about 0.25 m in peaty soils near the coast to over 2 m on some south-facing gravelly slopes and averages about 0.5 m (Everett, 1980b). IRP has a high percentage of *excess ice*, where the ice in the ground exceeds the total pore volume that the ground would have under unfrozen conditions (Van Everdingen, 1998). Although IRP has high load-bearing capacity if its thermal stability is maintained, it has none if the excess ice melts. Nearly all of the developed and developing oil and gas fields in arctic Alaska, Canada, and Russia are in regions with extensive IRP.

Much of the excess ice in the Prudhoe Bay permafrost is in the form of ice-wedges, which occupy on average 11% of the total volume of the upper 2–3 m of permafrost for all sites studied along the Beaufort coast, but which can reach 30% in some areas of the Arctic Coastal Plain of Alaska (Everett, 1980b; Kanevskiy *et al.*, 2013). The average total volumetric ice content, including the wedge ice, segregated ice, and pore ice, exceeds 80% on all terrain units studied except in sand dunes and deltas (Kanevskiy *et al.*, 2013).

If the insulative vegetated mat over ice wedges is disturbed or if other causes introduce heat to the ice-wedges (e.g., standing or flowing water), thawing of the ice will result in settling of the surface and creation of *thermokarst terrain* (Fig. 2) (Van Everdingen, 1998). Although thermokarst is not a form of karst, the subsidence and collapse associated with thermokarst terrain has some analogies to karst topography (French, 1976). Considerable research has been devoted to defining the hazards of thermokarst to structures (Nelson *et al.*, 2002) and in the development of engineering solutions to avoid thermokarst formation (US Arctic Research Commission Permafrost Task Force, 2003).

Within the PBO, most of the extremely IRP occurs within approximately 2 m of the surface, in frozen, organic-rich silts that overlie more stable alluvial sands

Fig. 2 Flooding and thermokarst along roads at Prudhoe Bay, AK. (a) Typical roadside environment showing flooded troughs and resulting thermokarst terrain. Heavy road dust killed vegetation on the centers of ice-wedge polygons near the road. (b) Thermokarst with active erosion of resulting high-centered polygons and widening of polygon troughs, near a gravel road. (c) Aerial photograph of flooding of ice-wedge polygon troughs due to blocked drainage. Previous low-centered ice-wedge polygons were converted to high-centered polygons. *Photos*: D.A. Walker, 1 July 2013.

and gravels (Everett, 1980b; Rawlinson, 1993) (Fig. SA1). See Supporting Information, Appendix S1, for further explanation of IRP in the PBO with photographs of segregated ice and a cross–section of a 100-m trench illustrating the types and amount of ice in the substrate (Fig. SA5).

Scattered small *thermokarst pits* were mapped during the baseline geobotanical mapping in the PBO (Walker *et al.*, 1980). These small near-circular ponds commonly overlie the intersections of ice wedges, most commonly on *primary surfaces* (old landscapes unaltered by thaw-lake or river processes) (Sellmann *et al.*, 1975), wherever there has been time for large ice-wedges to form (Fig. SA6a). These pits have been identified in the Russian literature as the first step in thermokarst development (Shur & Osterkamp, 2007). Until recently, the thermokarst pits in natural landscapes at PBO appeared to be fairly stable because most of the pits noted in the 1970s were also visible on the 1949 aerial photographs and showed little change through 1990 (Fig. 3). Recent abrupt changes in thermokarst pit size and density were documented in the Fish Creek region, about 40 km west of the PBO. These changes were thought to be a response to a period of warm summer temperatures during the 1990s (Jorgenson *et al.*, 2006). As discussed below, our study documents a similar trend in thermokarst in the PBO.

Cumulative effects of oil development

The effects of oil and gas activities take different forms in different parts of the Arctic, where environmental and social conditions vary. Summaries of some of the cumulative effects have been addressed in Russia (Forbes *et al.*, 2009; Walker *et al.*, 2011; Kumpula *et al.*, 2012), Alaska (Walker *et al.*, 1987; Orians *et al.*, 2003), and globally (AMAP, 2010). The cumulative effects of oil development were first studied at Prudhoe Bay in the 1980s with mapping that quantified the extent of direct and indirect landscape effects of oilfield infrastructure (Walker *et al.*, 1986a,b, 1987). *Direct effects* were defined as physical changes that were planned in advance, such as roads, gravel pads, and gravel mines. The unplanned *indirect effects* were more difficult to anticipate (Walker *et al.*, 1987; Shur, 1988). They often occurred in areas adjacent to infrastructure and

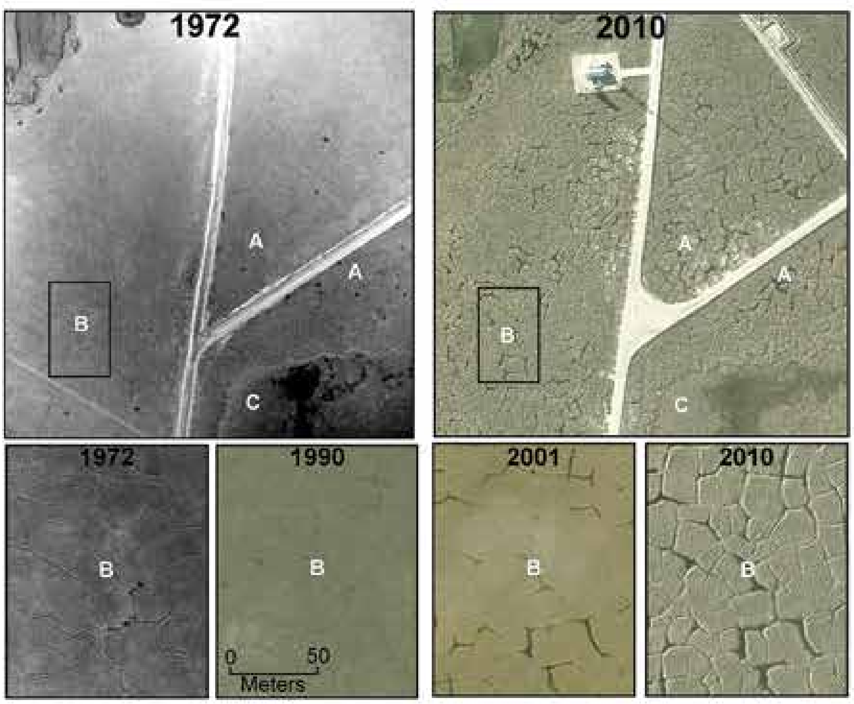

Fig. 3 Changes between 1972 and 2010 near the main road junction in map B. Note changes in infrastructure, including small new gravel pad and building near the top of the photo, a new pipeline and gravel road on the upper right side, and an expanded road intersection. Also note extensive changes in the character of the ice-wedge polygons with many more flooded ice-wedge troughs between polygons in 2010. Areas near A and B have extensive ice-wedge polygons. Numerous scattered small thermokarst pits (small dark ponds) are visible near A in 1972, with little change in 1990. Areas A and B and show marked increases in thermokarst in 2001 and even more by 2010. Area C is in a drained thaw lake basin with ice-poor soils and shows little evidence of new thermokarst. Changes in area A were mapped as infrastructure-related because of the proximity of the road and the pipeline that have significantly altered the hydrology of this area. Area B is not clearly affected by infrastructure.

included roadside dust, infrastructure-related flooding, off-road vehicle traffic, and thawing of near-surface permafrost (Walker *et al.*, 1987) (Appendix S3).

A 2003 US National Research Council (NRC) study of the cumulative effects of oil development on Alaska's North Slope (Orians *et al.*, 2003) included a time-series inventory of the total extent of infrastructure on the North Slope (Ambrosius, 2003). Although the NRC study recognized that climate change would likely have numerous effects to sea ice and Arctic ecosystems, the report concluded that climate change would not seriously affect oil and gas activities on the North Slope (Orians *et al.*, 2003). This was based largely on the assumption that cold, continuous permafrost, such as that found in the PBO, is robust and not likely to thaw even if the permafrost temperatures were raised several degrees. Since the NRC study, several regional studies have pointed to terrain and vegetation changes related to climate change (Sturm *et al.*, 2001; Jia *et al.*, 2003; Bhatt *et al.*, 2010; Myers-Smith *et al.*, 2011; Epstein *et al.*, 2012; Tape *et al.*, 2012), including recent thawing of the near-surface permafrost (Jorgenson *et al.*, 2006).

Here, we update both the regional assessment of total infrastructure extent from the NRC report (Orians *et al.*, 2003) and the analysis within three 20-km^2 areas previously analyzed in 1983 (Fig. 1) (Walker *et al.*, 1987). This article addresses the questions 'How have oilfield infrastructure and climate change affected the IRP landscapes of the PBO over 62-year of observations?' And 'How have the initial geoecological conditions in the region affected the changes?'

Materials and methods

Total North Slope oilfield infrastructure footprint

BP Exploration (Alaska) Inc. maintains a time series of aerial photographs and a set of topographic base maps (map scale 1 : 6000) of the PBO. Aerial photos taken in 1968 were used to define the areas prior to most development. Infrastructure changes were added from each successive analysis year (1973, 1977, 1983, 1988, 1994, 2001, 2006–2007, 2010, and 2011), creating CAD files for calculating incremental changes for the area shown in Fig. 1a. The files contained the areas covered by gravel facilities, roads, and mine excavations. Indirect effects, exploration facilities, riverbed gravel extraction, and other impacted areas not covered by gravel facilities were not included on these maps. Calculations were performed using ARC View software in an Alaska State Plane, zone 4, NAD27 projection (Appendix S2).

Integrated geoecological and historical change maps

A detailed mapping approach was used to examine both direct and indirect landscape changes within three 20-km^2 areas (A, B, C, example shown in Fig. 1b). The set of aerial photo missions used for the analysis included the years 1949, 1968, 1970, 1972, 1973, 1977, 1979, 1983, 1990, 2001, and 2010 (Table SC1). The methods used in the first analysis of cumulative effects of oil development (Walker *et al.*, 1986a,b) were modified for this update to take advantage of new advances such as heads-up digitizing, GIS database formatting and improved infrastructure maps of the region. The database contained polygons coded with nine geoecological attributes: dominant vegetation, secondary vegetation, tertiary vegetation; percentage open water; landform; dominant surface form, secondary surface form; dominant soil, and secondary soil (Table SC2). Secondary and tertiary variables were mapped if they covered more than 30% of a map polygon. Eighteen infrastructure-related change attributes, and six non-infrastructure-related change attributes were also mapped (Table SC2).

Results

North Slope oilfield infrastructure footprint

Results for the entire oilfield are presented by number of infrastructure items, length of linear infrastructure items, and area covered by facilities (Fig. 4a–c respectively). As of 2011, there were 127 production pads, 25 facility pads, 145 support pads (power stations, camps staging areas, etc.), 103 exploration sites, 13 offshore exploration islands, 7 offshore production islands, 9 airstrips, 4 exploration airstrips, 2037 culverts, 27 bridges, 50 caribou crossings, and one active landfill. The number of these infrastructure items increased rapidly between 1968 and 1983 and more slowly since then. The number of exploration pads decreased slightly after 2001, but increased again after 2007 (Fig. 4a and Table SB1).

The road network consisted of 669 km of gravel roads, 154 km of abandoned peat roads, 12 km of causeways, 96 km of abandoned tractor trails, and 54 km of exploration roads with thin gravel or tundra scars. Similar to the number of facilities, the total length of roads increased rapidly until 1988 and then leveled off at 931 km (Figs 1a and 4b). The 790-km pipeline network includes groups of parallel pipelines elevated 1–2 m above the tundra surface on vertical supports. Pipeline corridors included anywhere from 1 to 21 closely spaced parallel pipelines with diameters up to 60 cm. The length of major powerlines with towers totaled 541 km (Table SB1).

The total oilfield infrastructure covered 7429 ha of the North Slope by 2011, mainly consisting of 2345 ha of gravel pads, 2737 ha of gravel mines, and 1255 ha of gravel roads and causeways (Fig. 4c). Impacted areas also included airstrips (125 ha), offshore gravel pads and islands (82 ha), exploration sites (290 ha),

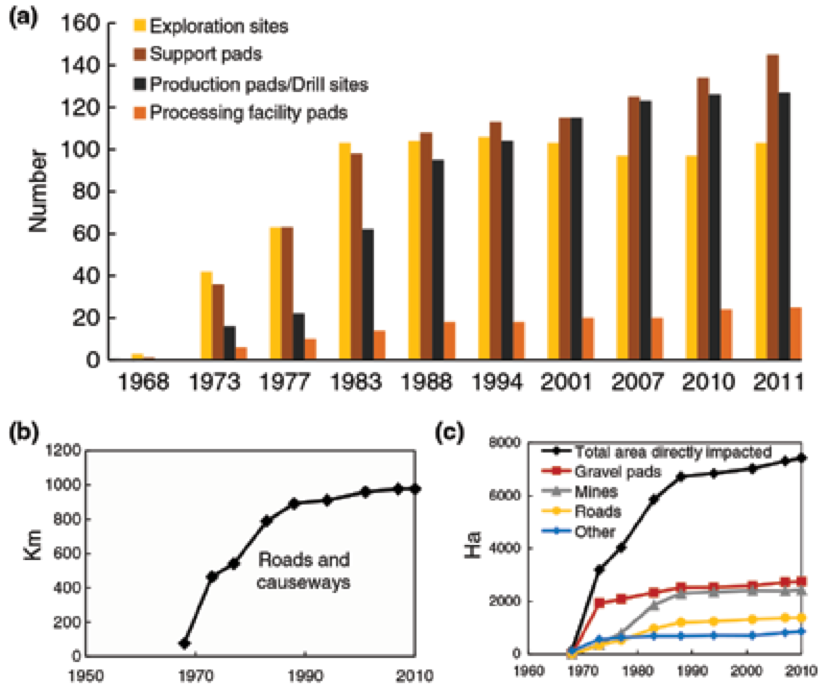

Fig. 4 History of infrastructure on the North Slope oilfields 1968–2011 (excluding the Dalton Highway and Trans-Alaska Pipeline System). (a) Number of infrastructure items, (b) total length of roads (km), (c) directly impacted area (ha). Data courtesy of Aerometric, Inc. and BP Exploration (Alaska), Inc.

exploration airstrips (20 ha), peat roads (209 ha), tractor trails/scars (104 ha), exploration roads (72 ha), and areas where pads have been removed and are in the process of recovery (190 ha). Most of the direct effects to the landscape occurred within 18 years of the initial discovery of oil, reaching 6722 ha by 1988 (Fig. 4c). Since 2001, the oil development has expanded westward, increasing the infrastructure area to 7429 ha (Table SB1).

Direct and indirect effects of infrastructure in maps A, B, and C

Thematic maps for area B show the dominant vegetation, landforms, and surface forms prior to development (Fig. 5). The landform map is overlaid with the major infrastructure-related changes (Fig. 5c). Area B is of special interest because it was the focus of the International Biological Programme Tundra Biome studies and several other scientific studies at Prudhoe Bay (Brown, 1975; Everett & Parkinson, 1977; McKendrick, 1987, 1991; Walker *et al.*, 1987; Walker & Everett, 1991) and contains Pump Station 1, the start of the Trans-Alaska Pipeline System. Thematic maps for all three map areas (A, B, and C) portray surface forms, landforms, dominant vegetation, soils, percent water, total infrastructure-related effects, and total noninfrastructure-related effects (Fig. SC4–SC6).

Time series of maps portraying infrastructure-related changes (Fig. SC7–SC9) showed that the progression of area impacted by direct effects on maps A, B, and C (Fig. 6a) was similar to that in the larger North Slope area (Fig. 4), except that this area was the first to be developed and construction leveled off within 15 years (by 1983 instead of by 1988 as was the case for the regional infrastructure) and declined some afterwards as a few sections of roads were removed and revegetated and some areas of gravel mining in rivers were no longer detectable. The total area of direct effects in 2010 on the three detailed maps was 919 ha (14.6%), ranging from 12.2% in map A to 19.3% in map C (Table SC5). Gravel pads covered the most area (438 ha), followed by excavations (257 ha), roads (136 ha), and pipelines (79 ha) (Fig. 6a and Table SC5).

The total area of indirect effects of oilfield development exceeded the direct effects by 1977, and showed an almost linear rate of increase of about 23 ha year^{-1} in the most recent twenty years (1990–2010), resulting in a total of 1794 ha (28.6% of the area of the three maps), about double the area of the direct effects (919 ha) (Fig. 6a and Table SC5). By 2010, indirect effects included 701 ha of flooding, 367 ha of infrastructure-related thermokarst, 332 ha of gravel and

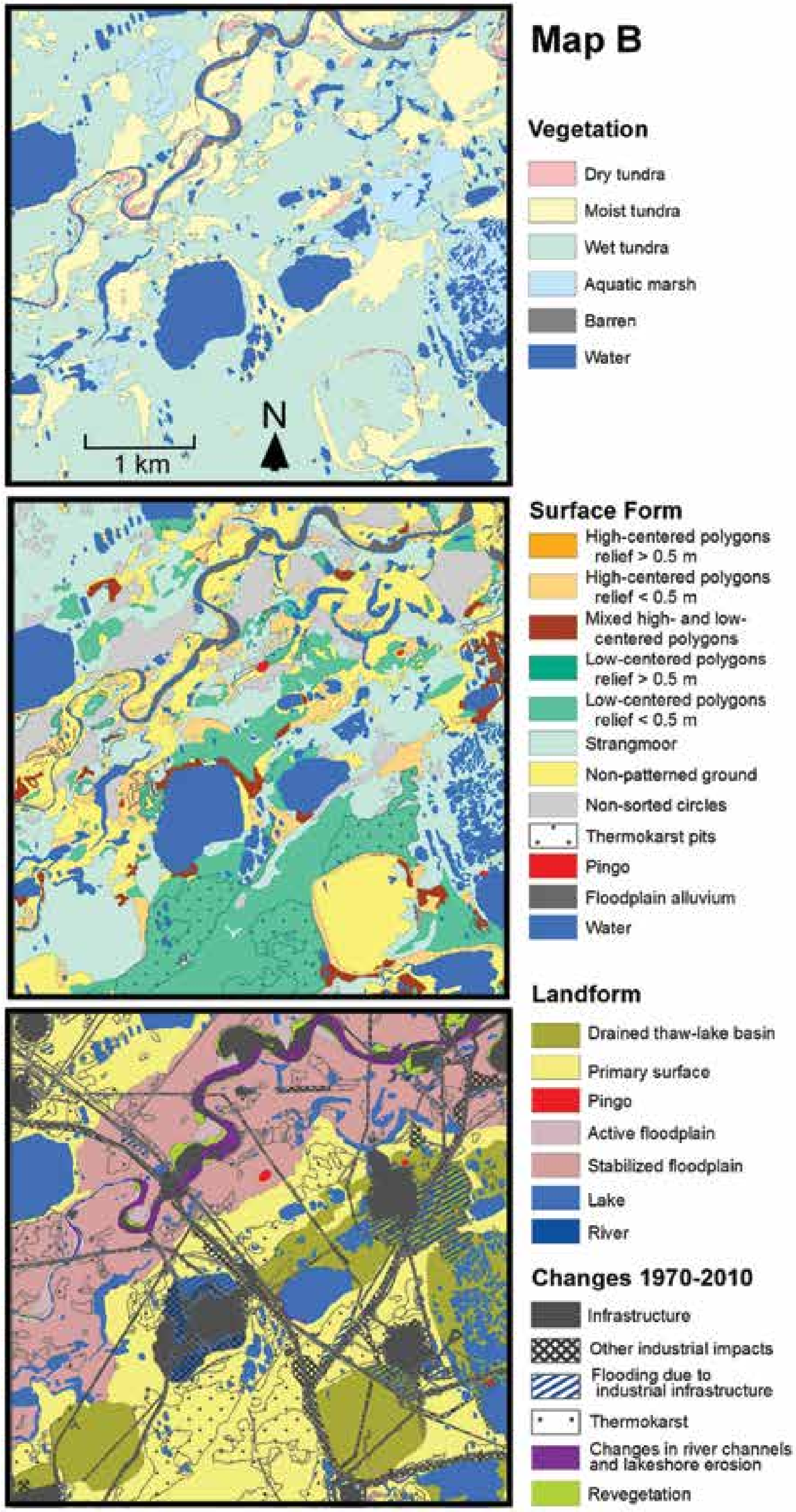

Fig. 5 Dominant vegetation types, surface forms, and landforms with mapped changes (1968–2010) for 20-km^2 area of the Prudhoe Bay oilfield (map B on Fig. 1). See Fig. SC4–S-C6 for full sets of thematic maps for maps A, B, and C.

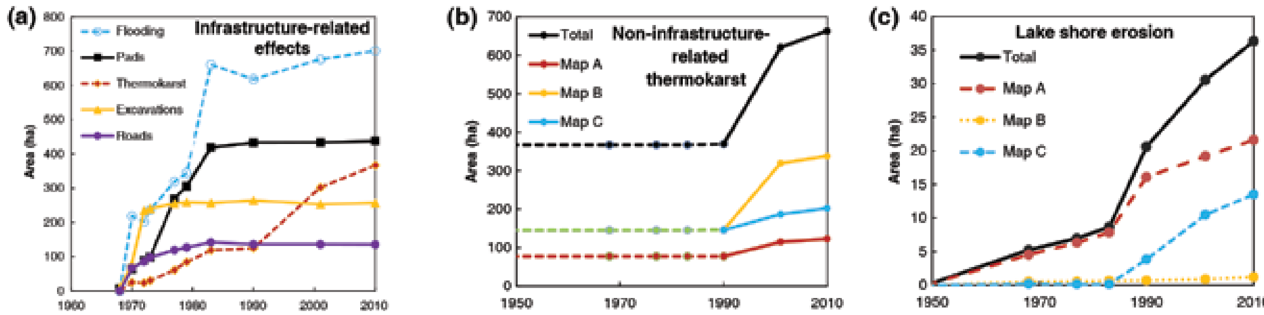

Fig. 6 History of changes (1949–2010) in three 20-km^2 mapped areas within Prudhoe Bay Oilfield, North Slope, Alaska: (a) history of most common infrastructure-related effects – direct effects (solid lines) and indirect effects (dashed lines); (b) history of noninfrastructure-related thermokarst and (c) history of lake-shore erosion for maps A, B, and C and for the total mapped area (60 km^2). See Fig. SC7–S-C9 for maps of these changes.

debris adjacent to roads and pads, 291 ha of off-road vehicle tracks, and 34 ha of road dust (Table SC5). The extent of road dust and vehicle trails is underrepresented in the data because they were difficult to detect at the scale of mapping. Furthermore, these factors were most often mapped as secondary or tertiary effects in areas where flooding and thermokarst occurred and thus do not show up as the dominant factors, which are summarized here.

Flooding developed quickly as roads and pipelines spread across the flat PBO landscape and dammed the flow of runoff waters during the spring melt season. The extent of flooding nearly leveled off after 1983 at over 650 ha of maps A, B, and C (Fig. 6a). By 2010, the area of infrastructure-related flooding ranged from 25.1% of map A (an extremely flat area with many thaw lakes) to 2.0% of map C (a relatively well-drained area close to the Sagavanirktok River).

Thermokarst, the second most extensive indirect effect, began developing in roadside areas soon after the roads were built (Fig. 2). Visible on the aerial photographs as increased standing water in polygon troughs and subsidence of polygon edges, thermokarst initially covered rather small areas, but expanded at a linear rate over the entire history of the field (9.2 ha year^{-1}, $r^2 = 0.96$). After 42 years, within maps A, B, and C, 367 ha of tundra near infrastructure had thermokarst (Fig. 6a). Road dust in high concentrations adjacent to the more heavily traveled roads kills much of the vegetation (Fig. 2a), especially the low-growing mosses and lichens, decreasing the insulative value of the vegetation, and greatly increasing the active-layer thickness (ALTs) and susceptibility of the tundra to thermokarst (Walker & Everett, 1987). In winter, snow drifts develop along both sides of the elevated road berms, resulting in warmer winter soil temperatures near the roads, which increases ALTs and thermokarst in areas adjacent to infrastructure. Road dust in the snow reduces its albedo and leads to early snow melt next to the roads (Benson *et al.*, 1975), increased roadside flooding, and deeper ALTs (Walker & Everett, 1987).

Changes not related to infrastructure

Numerous changes that cannot be attributed to oilfield development also occurred (Fig. 6b, c), including thermokarst far from facilities, erosion of lake shorelines, and erosion, deposition, and revegetation of river bars and banks along the Putuligayuk and Sagavanirktok Rivers. The total area affected by these changes by 2010 was 687 ha (11% of the three mapped areas, Table SC5). While erosional and depositional changes in the rivers mostly compensated for each other, trends for thermokarst (Fig. 6b) and lakeshore erosion (Fig. 6c) were unidirectional.

Lakeshore erosion totaled 36 ha, 0.6% of the mapped area by 2010 (Fig. 6c). Lakeshore erosion showed an abrupt increase in recent years, as was seen with noninfrastructure-related thermokarst. There was a slow, steady increase in lakeshore erosion between 1949 and 1983, reaching 8.6 ha on maps A, B, and C; then to 36 ha from 1983 to 2010, more than a fourfold increase in 27 years (Fig 6c).

The most extensive noninfrastructure-related change was thermokarst, visible as increased standing water in the troughs of ice-wedge polygons (Figs 2 and 3), which covered 503 ha by 2010, 8% of the three mapped areas (Table SC5 and Fig. SC7h–S-C9h). Thermokarst in areas distant from infrastructure increased from 367 ha in 1968 to 663 ha in 2010 (Fig. 6b). The area of thermokarst did not noticeably increase between the late 1960s and 1990 on any of the maps (e.g. Fig. 3), but increased 1.8-fold between 1990 and 2010.

By 2010, noninfrastructure-related thermokarst occurred on 19.1% of the areas unaffected by development where thermokarst potentially could occur (i.e., excluding lakes and active floodplains). The landforms most affected by noninfrastructure-related thermokarst were primary surfaces between thaw lakes (residual surfaces not affected by thaw-lake processes), and stabilized river floodplains (31.3% and 16.2%, respectively, Fig. 7, Table SC6). Drained thaw lakes showed little increase in thermokarst features. Surface forms showed a wide range of responses. Low-centered polygons with <0.5 m elevation contrast between the center and the rim, and areas with mixed high- and low-centered polygons were most affected by thermokarst (46.1% and 45.7%, respectively), whereas only 26.0% of high-centered polygons with <0.5 m center-trough contrast had enhanced thermokarst (Fig. 7). Of the area without industrial effects and mapped as having thermokarst pits in 1968, 54% showed increased thermokarst by 2010. Wet tundra and moist tundra were the vegetation types showing the most nonindustrial thermokarst (23.9% and 16.7%, respectively); no other vegetation type had over 5% affected by increased thermokarst. Wet, patterned-ground soil associations showed the most increase in thermokarst (37.6%, Fig. 7 and Table SC6). The total area where increased thermokarst was detected, including infrastructure-related and non-infrastructure-related thermokarst was 870 ha (13.9% of the mapped area).

Discussion

Relationship of thermokarst to air and soil temperatures, ALT, and precipitation

The documented regional increase in thermokarst is most likely due to a long-term upward trend in summer temperatures and to the exceptionally warm summers of 1989 and 1998 (Fig. 8). Summer air temperatures as indicated by the summer warmth index (SWI = sum of monthly mean air temperatures above 0 °C, or thawing degree months [°C mo]) increased about 5 °C mo over the 1970–2012 period of record at the Deadhorse airport (Fig. 8). Similar trends are seen in the long-term records from Barrow and Umiat (Jia *et al.*, 2003). The highest recorded SWI at Deadhorse occurred in 1989 and 2012 (30.7 °C mo, 30.5 °C mo), and the third highest was in 1998 (27.5 °C mo). The average SWI for the period 1970 to 1999 was 19 °C mo. The 1989 and 1998 SWI peaks at Deadhorse are similar to the magnitude of thawing-degree-day peaks at the Kuparuk Airport, 100 km west of the study area (Jorgenson *et al.*, 2006).

The mean annual air temperature (MAAT), mean annual permafrost temperature at the upper surface of the permafrost ($MAPT_S$), and at 20-m depth ($MAPT_{20}$),

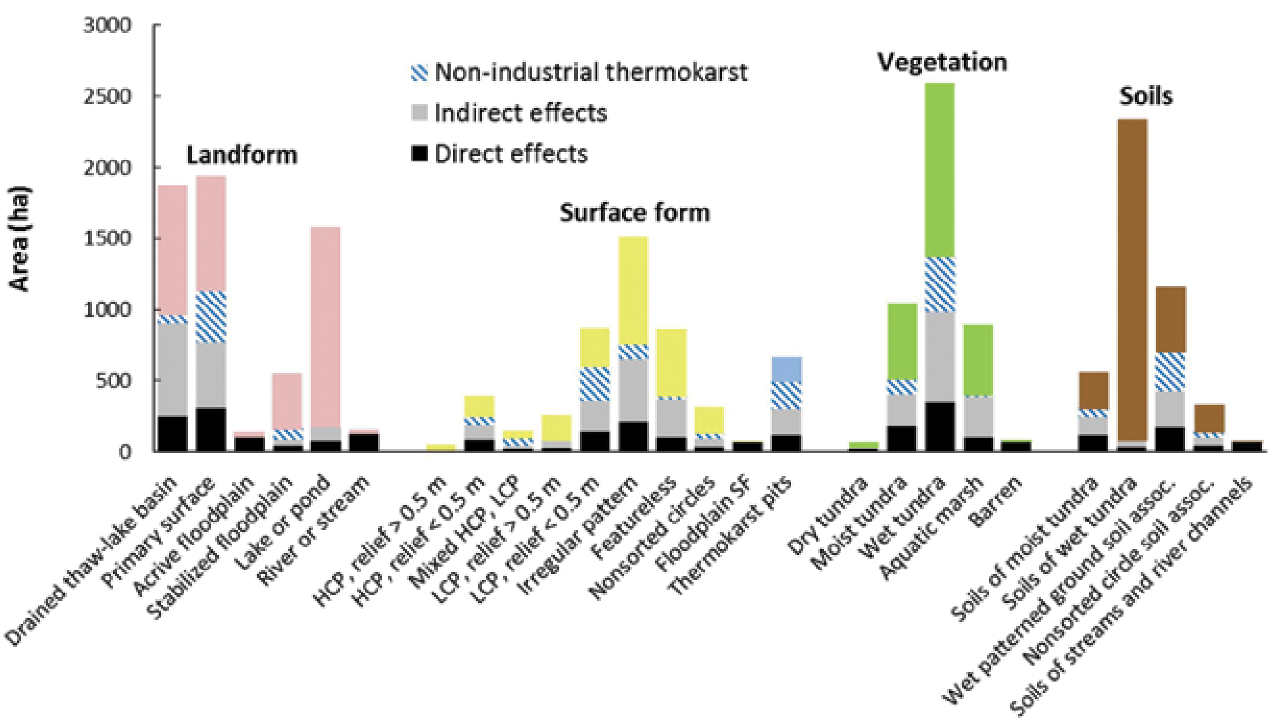

Fig. 7 Total areas of geoecological units >50 ha within maps A, B, and C, area of each unit with direct (black) and indirect (gray) industrial impacts, with nonindustrial thermokarst (blue diagonal stripes) and remaining unchanged portion (includes area of floodplain gravel erosion and deposition). Thermokarst pits include areas mapped with this code as dominant or secondary surface form. HCP, high-centered polygons; LCP, low-centered polygons; SF, surface form. See Supporting Information Table C6 for tabular summary.

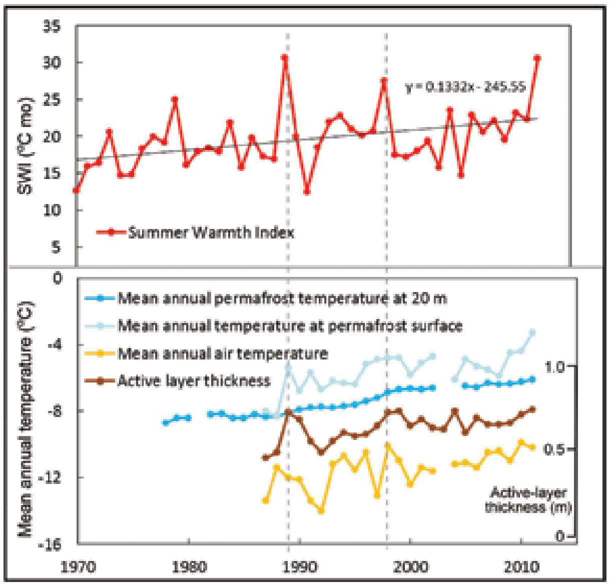

Fig. 8 *Top*: Trend of summer air temperature as indicated by the summer warmth index (SWI = Sum of the monthly mean temperatures above freezing, °C mo). Data are from the Western Regional Climate Center, Prudhoe (1970–1986) and Deadhorse (1987–2012). *Bottom:* Mean annual air temperature at 2 m height (MAAT, orange line), mean annual permafrost temperature at 20-m depth ($MAPT_{20}$, dark blue line), mean annual temperature at the upper surface of permafrost ($MAPT_s$, light blue line); and active layer thickness (ALT, brown line and scale on right). All data are from Osterkamp and Romanovsky Deadhorse station. The climate station and maps (A, B, and C) are within 15 km of each other. Active layer depth was measured by interpolation of soil temperature data from several depths for 1987–1996 and by using a metal probe for 1997–2011. Note the corresponding peaks in SWI, ALT, and $MAPT_s$ in the extreme warm summers of 1989 and 1998 (gray dashed lines). Trend lines are as follows: SWI = 0.1332 year − 245.55; $MAPT_{20}$ = 0.082 year − 170.9; MA PT_s = 0.1089 year − 223.37; MAAT = 0.0918 year − 194.92; AL T = 0.0665 year − 141.85.

and ALT all increased markedly (Fig. 8). The period of most rapid increase in all these variables was during the 1990s. The rate of increase declined from 2001 to 2010, corresponding to a period of moderate air temperatures. Records of ALT from CALM grids at West Dock and Deadhorse also showed maximum thaw depths in 1998, followed by less deep summer thaws in the following decade (Shiklomanov *et al.*, 2012).

Increases in ALT can trigger thawing of ground ice in the upper permafrost, including the top parts of the ice wedges, which can result in the formation of water-filled thermokarst troughs above ice wedges. However, the expansion of thermokarst pits into a network of flooded ice-wedge-polygon troughs as documented in this study may also be related to thermal feedbacks associated with flooding of the troughs. We find no indication that the increase in surface water visible in the ice-wedge polygon troughs in the recent aerial photographs from 1990, 2001, and 2010 was due to higher water tables or to exceptionally wet years. No change in lake levels was detected on the aerial photographs. Furthermore, precipitation records over the 1991–2000 and 2001–2010 period averaged 10.6 and 9.9 cm year^{-1}, respectively, with values for the years of the aerial photography at 7.4 cm in 1990, 7.4 cm in 2001, and 3.9 cm in 2010 (WRCC, 2012). Modeled Prudhoe Bay Region ALTs for 1992–2000 showed an exceptionally deep active layer in 1998, and a trend of subsidence of the ground surface caused by the melting of soil ice (Liu *et al.*, 2012). The similarity of thermokarst patterns in the PBO with those detected west of the oilfield (Jorgenson *et al.*, 2006) indicates that regional climate change is the most likely cause of thermokarst.

Relationship of thermokarst to mapped geoecological features

The occurrence of thermokarst is not uniformly distributed across the landscape and was to some extent predictable based on the earlier geoecological mapping. Areas mapped on the 1968 imagery as 'primary surfaces', 'low-centered ice-wedge polygons', 'wet sedge, moss tundra', 'wet patterned-ground soil association', and 'thermokarst pits' were the most susceptible to further thermokarst. Most of the thermokarst is occurring on surfaces that have not experienced recent lake drainage or reworking of riparian sediments, and are old enough to have accumulated large volumes of excess ice in the form of ice wedges and segregated ice. High-centered ice-wedge polygons experienced less change than low-centered polygons, most likely because these areas have experienced previous thawing and subsidence of ice wedges. Accumulation of organic and mineral matter in the troughs probably helped to protect these ice-wedges from additional thawing (Jorgenson *et al.*, 2006), making these areas less susceptible to the present-day climate change.

A planning process for siting new infrastructure that recognizes the susceptibility of different landforms, vegetation types, and soils to flooding and thermokarst would help to minimize these effects.

A conceptual model of infrastructure-related and climate-change-related thermokarst

Thermokarst development is a complex process that includes numerous positive and negative feedbacks. Thermokarst in areas of IRP with near-surface ice wedges can follow two distinctly different scenarios (Fig. 9). Both scenarios start with partial thawing of the upper ice wedges and formation of small shallow ponds (thermokarst pits) in the troughs over ice wedges and especially at ice-wedge intersections. This initial stage of thermokarst development is triggered by an increase in the ALTs caused by higher than normal air temperatures, flooding, or destruction of vegetation.

The first (stable or reversible) scenario (Fig. 9, blue arrows) is often observed in a natural environment and is described in part by Jorgenson *et al.* (2006). This scenario is possible when the ice wedges are affected by thermokarst, while the polygon centers remain relatively stable because of an undisturbed insulative mat of vegetation and soils. An increase in the ALTs in the polygon centers usually results only in moderate surface subsidence due to partial thawing. Over time, mineral and organic matter accumulate in the troughs from erosion of the trough margins and increased plant productivity due to a combination of deeper thaw,

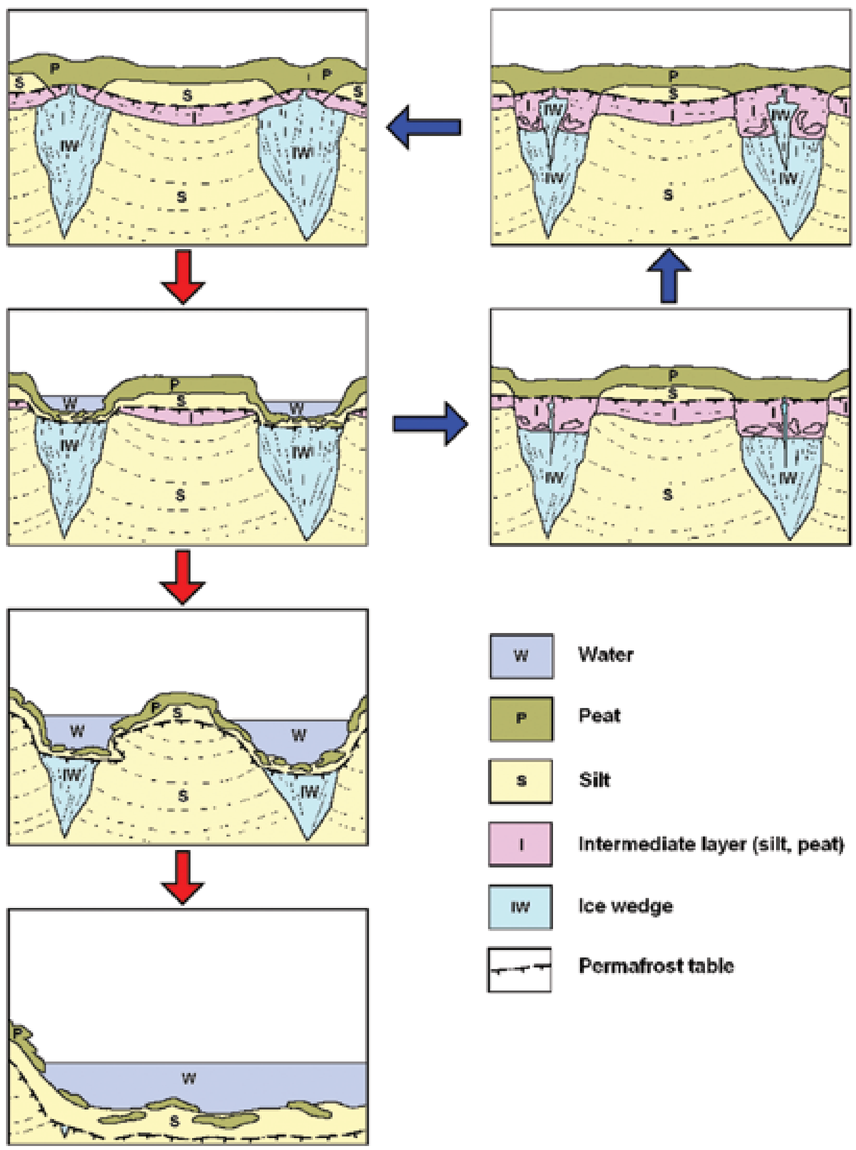

Fig. 9 Two possible thermokarst scenarios associated with ice-wedge polygon terrains. A stable or reversible process (blue arrows) is often observed in natural environments. The centers of the polygons remain stable because the protective insulative mat of vegetation and organic soils remains undisturbed.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

release of nutrients and wetter soils. The mineral and organic matter insulates the trough bottoms and slows the thawing of ice wedges, eventually stabilizing the landscape in a new configuration with higher centers and deeper troughs. In areas with cold climates, a new generation of ice wedges may start to form. These wedges penetrate into the previous generation of wedges that were truncated by thermokarst (Fig. 9, two right boxes with blue arrows). If the climate remains favorable for ice wedge growth, the melted wedge-ice eventually reforms and returns the landscape to its original condition.

The second (unstable or irreversible) scenario (Fig. 9, red arrows) usually occurs where there is disturbance to the central part of the polygons, as often occurs in areas in close proximity to infrastructure. This scenario is more severe because the reduction in the protective organic layer can lead to thawing of the upper permafrost in the polygon center, rapid erosion of the edges of the polygon, and subsidence of the entire polygon. Further thermokarst development results in continuing ground subsidence, and to the formation of a shallow thermokarst pond above the polygons. This leads to accelerated thermokarst and relatively fast degradation of ice-rich soils under the pond.

Consequences to ecological systems

The areas that have been affected by extensive thermokarst in the PBO exhibit major ecological changes. No detailed plot-based studies of vegetation changes related to the transformed landscapes were available for this report, but a photographic survey of the roadside areas in map B in summer 2013 showed that numerous areas that were previously low-centered polygons as late as 1983 have been converted to well-drained high-centered polygons. The redistribution of water on the tundra surface has changed the plant communities. The vegetation in the centers of the polygons has been converted from a wet sedge, moss tundra to either a moist sedge, prostrate dwarf-shrub, moss tundra or, in more extreme situations particularly near heavily traveled roads where there has been continuous input of dust for the past 40 years, to a dry prostrate dwarf-shrub, grass, forb tundra (Fig. 2) (Walker, 1985). Many low-centered polygon troughs that previously had wet sedge, moss tundra are now ponds with up to a meter of water with either no vegetation or with aquatic sedges.

The thermokarst terrain is more topographically complex than the initial condition. The changes in hydrology and vegetation undoubtedly affect the distribution and abundance of a wide variety of organisms including insects, shorebirds, waterfowl, small mammals such as voles and lemmings , and could in turn affect the patterns of use by prey species (Batzli & Jung, 1980; Brown *et al.*, 2007). Increases in surface water may increase the habitat of some waterfowl species harvested by village residents of the region (Ward *et al.*, 2005). The implications of thermokarst on the habitat and distribution of fish species, such as the three-spined stickleback (*Gasterosteus aculeatus*) and broad whitefish (*Coregonus nasus*), are not well-understood, nor are the overall effects on lakes and outputs to streams and rivers. Surface water distribution and extent, and connectivity among water bodies influence fish abundance by affecting their access to seasonally important overwintering, spawning, and rearing habitats (M. Wipfli, personal communications). The altered hydrology associated with widespread thermokarst formation also has implications for tundra CO_2 and methane exchanges (Schuur *et al.*, 2009; Sturtevant *et al.*, 2012).

Consequences to engineered and social systems

The negative consequences of thermokarst to infrastructure are well-known and extensively documented (US Arctic Research Commission Permafrost Task Force, 2003; Streletskiy *et al.*, 2012). The additional maintenance and replacement costs due to climate change on public infrastructure in Alaska is estimated at $3.6–6.1 billion through 2030, but it is difficult to isolate the projected costs of thermokarst from other climate change effects (Larsen *et al.*, 2008). Within the PBO, thermokarst affects rehabilitation efforts at sites where gravel has been removed (e.g. former gravel pad or road) and trenches where cables and pipelines are buried, resulting in subsidence that greatly exacerbates the cost of rehabilitation (Streever, 2012).

Situations similar to those in the PBO also occur in villages. High-resolution satellite images show that thermokarst has become extensive within the village road network at Nuiqsut, west of the PBO. Deeper thermokarst (up to 2 m) occurs in the sandy eolian deposits west of the Colville River (Lawson *et al.*, 1978), and much deeper thermokarst (up to 5.5 m) occurs in the thick, silty, organic-rich, and extremely ice-rich *yedoma* deposits of the northern Arctic Foothills (Lawson, 1983; Carter, 1988; Kanevskiy *et al.*, 2011; Shur *et al.*, 2012). Apart from current rough projections of costs related to relocation of Alaskan villages facing erosion problems, we are unaware of any cost estimates for private or industrial infrastructure on the North Slope related to thawing permafrost. Future effects are difficult to predict especially when combined with simultaneous rapid changes to climate, political, and socio-economic factors, and oil drilling technology.

Value of long-term studies of a rapidly changing ecosystem

When the PBO studies began in the 1970s, none of the now-senior authors who were involved foresaw the possibility of the rapid transitions that are occurring now. For over 20 years, the areas that were not affected by oilfield infrastructure showed little change. Based on the mapped information and current air and permafrost temperature trends, starting in 1990 we are witnessing landscape changes that will have major implications for much of the Arctic Coastal Plain. The conceptual model of thermokarst formation presented here and the description of the characteristics of areas most vulnerable to thermokarst will help in the development of predictive models of how thermokarst spreads in different climate-change and infrastructure scenarios.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Ice-rich permafrost at Prudhoe Bay. By Y. Shur, M. Kanevskiy, V.E. Romanovsky, K.R. Everett, J. Brown, and D.A. Walker.
Appendix S2. Calculation of impacts of oilfield development, North Slope Alaska, by K.J. Ambrosius.
Appendix S3. Integrated Geoecological and Historical Change Mapping: history, methods, maps, and summary information, by D.A. Walker, M.K. Raynolds, P.J. Webber and J. Brown.

2 Supporting information regarding ice-rich permafrost at Prudhoe Bay

YURI L. SHUR, MIKHAIL KANEVSKIY, VLADIMIR E. ROMANOVSKY, KAYE R. EVERETT, JERRY BROWN AND DONALD A. WALKER

The following information is specific to the Prudhoe Bay region. Much of the information is based on K.R. Everett's chapters—"Geology and Permafrost" (Everett, 1980a) and "Landforms" (Everett, 1980b)—in the Geobotanical Atlas of the Prudhoe Bay Region, Alaska (Walker et al., *1980). More recent material is from other permafrost scientists who have worked in the Prudhoe Bay region (Jorgenson* et al., *2006; Jorgenson & Shur, 2007; Kanevskiy* et al., *2011; 2013).*

Prudhoe Bay permafrost

Permafrost is a ground (soil or rock) in which a temperature below 0°C has existed for two or more years (van Everdingen, 1998). It is not implicit in this definition that ice be present although it commonly is. The amount of ice depends on topographic position, material type, its porosity and permeability, and the past climatic and geomorphic history. Within the Prudhoe Bay Oilfield (PBO) permafrost extends to a depth of at least 660 m (Gold & Lachenbruch, 1973). This is the greatest known thickness of permafrost in Alaska. In portions of northern Alaska not covered by Quaternary glaciers, permafrost formed and was modified perhaps several times during the glacial and interglacial ages of the Pleistocene. Increasing glacier ice during the last major glaciation (the Wisconsinan, from approximately 110,000 to 12,000 years ago) caused a lowering of sea level and its retreat many tens of kilometers north of the present coastline.

Most of the Prudhoe Bay region is a decidedly younger surface than areas to the east of the Sagavanirktok River and west of the Kuparuk River. A generalized stratigraphic section of the near-surface deposits in the PBO within the main area of geoecological mapping (Walker *et al.,* 1980) shows approximately 2 m of windblown and lacustrine silt overlying alluvial gravels and sands that were deposited by ancient channels of the Sagavanirktok and Putuligayuk rivers (Rawlinson, 1993). The source of the contemporary wind-blown silt is the Sagavanirktok River bars, whose silt has been retransported by wind over the broad area between the Sagavanirktok River and the Kuparuk River, south to the Arctic Foothills (Walker & Everett, 1991). A date obtained from the basin of the lake drained for Pump Station No. 1 indicates that the silts began accumulating on the alluvial surfaces about 9330 years ago (Fig. 2.1). A date obtained from organic inclusions in silty sands (depth 160 to 170 cm) in the Prudhoe Bay region was 8950 years BP (Kanevskiy *et al.,* 2013).

Permafrost that formed on the exposed continental shelf is today still found in the subsea environment where it has persisted since marine inundation began at the close of the last glaciation (Lachenbruch & Marshall, 1977; Sellmann & Chamberlain, 1979). At present the coastline in the Prudhoe Bay region is retreating at an average rate of 1.5 m/yr, largely as a result of thermal erosion (Jones *et al.,* 2009). As the newly eroded land-based permafrost is inundated it becomes part of the subsea permafrost.

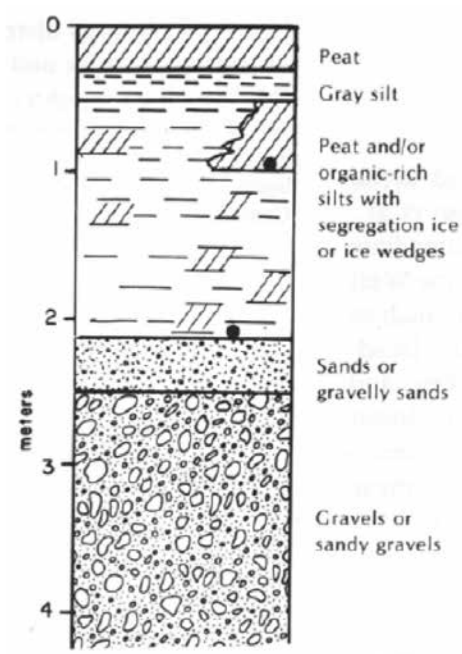


Figure 2.1. *Generalized stratigraphic section of the near-surface deposits in the Prudhoe Bay region. Radiocarbon dates are indicated by dots. The upper date (4700 years BP) was obtained from the basin of a low-centered polygon. The lower date (9330 years BP) came from the drained lake site of Pump Station No. 1 (Everett, 1980a).*

a b

Figure 2.2. *Typical cryostructures (patterns formed by inclusions and lenses of pore and segregated ice in the frozen soil) of the upper permafrost in the Prudhoe Bay area: (**a**) reticulate cryostructure, (**b**) ataxitic cryostructure (in soils with ataxitic cryostructure the volume of visible ice can exceed 80%). The scales are in inches and cm.*

Figure 2.3. *Ice wedge in peat and organic silt exposed along the coast at Prudhoe Bay. Similar ice wedges occur beneath polygon troughs (Fig. 2.5 and 2.6).*

Segregated ice, ice wedges, and ice-wedge polygons

The ground ice in the Prudhoe Bay area occurs mainly as segregated ice (Fig. 2.2) and massive ice (Fig 2.3). *Segregated ice* is ice in layers or lenses, formed by ice segregation as a result of pore water migration to the frozen fringe (the thin zone at which the ice-lens is forming in a frost-susceptible soil) and its subsequent freezing (van Everdingen, 1998). Large masses of ground ice (*massive ground ice*) include ice-wedges, pingo ice, buried ice, and large ice lenses (van Everdingen, 1998).

Ice wedges can be seen exposed in coastal bluffs (Fig. 2.3) and in the walls of pipeline trenches (Fig. 2.5b) and are associated with the formation of *ice-wedge polygons* that are so characteristic of the Arctic Coastal Plain (Fig.2.5a, 2.6, 2.7). The initial polygonal patterns develop in response to rapid, intense winter cooling and subsequent contraction of the fine grained coastal-plain sediments (Fig. 2.4) (Lachenbruch, 1962). The narrow thermal contraction cracks thus formed are subsequently filled by ice in the form of winter hoarfrost or water produced in spring from melting snow. The process of cracking and filling, repeated over many centuries, results in the growth of vertical wedge-shaped masses of ice that in favorable conditions penetrate many meters and may attain widths up to ten meters.

Ice-wedge polygons at the Beaufort Sea coast of Alaska vary in size from 10 to 25 m across with average of 15 m (Kanevskiy *et al.,* 2013). The maximum width of ice wedges at some sites is over 5 m, while their vertical extent usually does not exceed 4 m

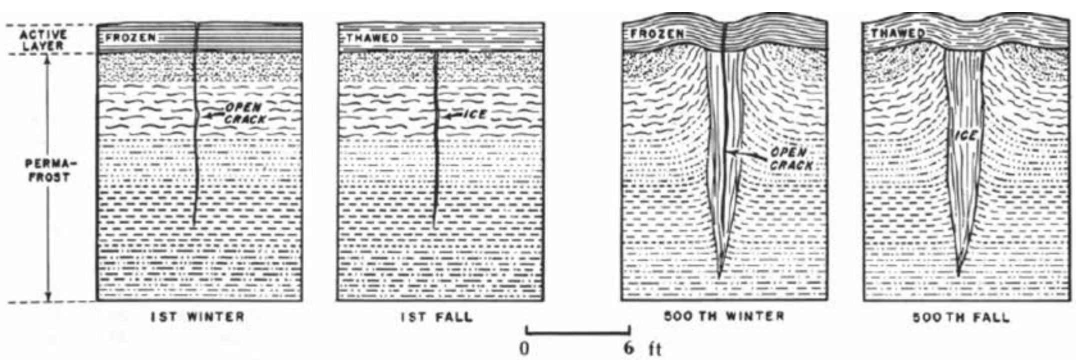


Figure 2.4. *The evolution of an ice wedge. Fine-grained mineral soils contract and crack in response to abrupt decrease in air temperature in the winter time. Hoarfrost and snow-melt water fill the crack in the spring, resulting in expansion of the ice mass. These processes, repeated over long periods of time, produce ice wedges (Fig. 2.3 and 2.5b) and the ice-wedge polygon landforms as seen in Figs. 2.5, 2.6 and 2.7. The cracks are often expressed at the surface within ice-wedge-polygon troughs (see figure A6). Surface expression of the crack may disappear during the summer (Lachenbruch, 1962).*

(Black, 1983; Kanevskiy *et al.,* 2013). The volumetric wedge-ice content varies widely between different terrain units, ranging from 3% to 50% with average of 11% (Fig. 2.5). The top surfaces of ice wedges are usually located no deeper than 10-20 cm beneath the permafrost table. The upper permafrost at the Beaufort Sea coast of Alaska is extremely ice rich with ice-wedge polygons existing practically everywhere (Brown & Sellmann, 1973; Kanevskiy *et al.,* 2013).

The soils between ice-wedges in the PBO are also extremely ice rich. Soils with ataxitic (suspended) and reticulate cryostructures (Fig. 2.2) prevail at depths of 1 to 2 m. These ice-rich soils have the highest volumetric ice content, reaching 90% and even 95%. The visible ice content of these sediments varies from 50% to more than 80%. Lower ice contents are typically observed in sands and gravels. The average total volumetric ice content at the Arctic Coastal Plain, which includes wedge ice, segregated ice, and pore ice is 77% (Kanevskiy *et al.,* 2013). As a result, this area is vulnerable to thermokarst and thermal erosion because an increase in the active layer thickness can trigger thawing of massive ice and development of thermokarst.

The borders of the ice-wedge polygon are defined by the axes of ice wedges. The standard form of an ice-wedge polygon at the stage of development of ice wedges is a *low-centered ice-wedge polygon* (Fig. 2.6), which has a low-lying polygon *basin* in the center of the polygon, a raised polygon *rim* that surrounds the basin, and a shallow *trough* that is situated above the growing ice wedge and between two adjacent rims. The increase in near-surface volume of frozen ground caused by the expanding ice wedges produces the buckling or mounding of the tundra on either side of the ice wedge, forming the somewhat elevated polygon rims (Fig. 2.4). With time, accumulation of wedge-ice may decrease and accumulation of sediment, organic material, and segregated ice inside polygons turns them into flat polygons. Subsidence of polygon troughs can occur when the upper surface of ice wedges thaw during warm summers or after flooding, resulting in *thermokarst pits* and the collection of water in polygon troughs (Fig. 2.6a and 2.8, left, second from top diagram).

In areas affected by thermokarst, as well as in areas with steeper hydrologic gradients, such as

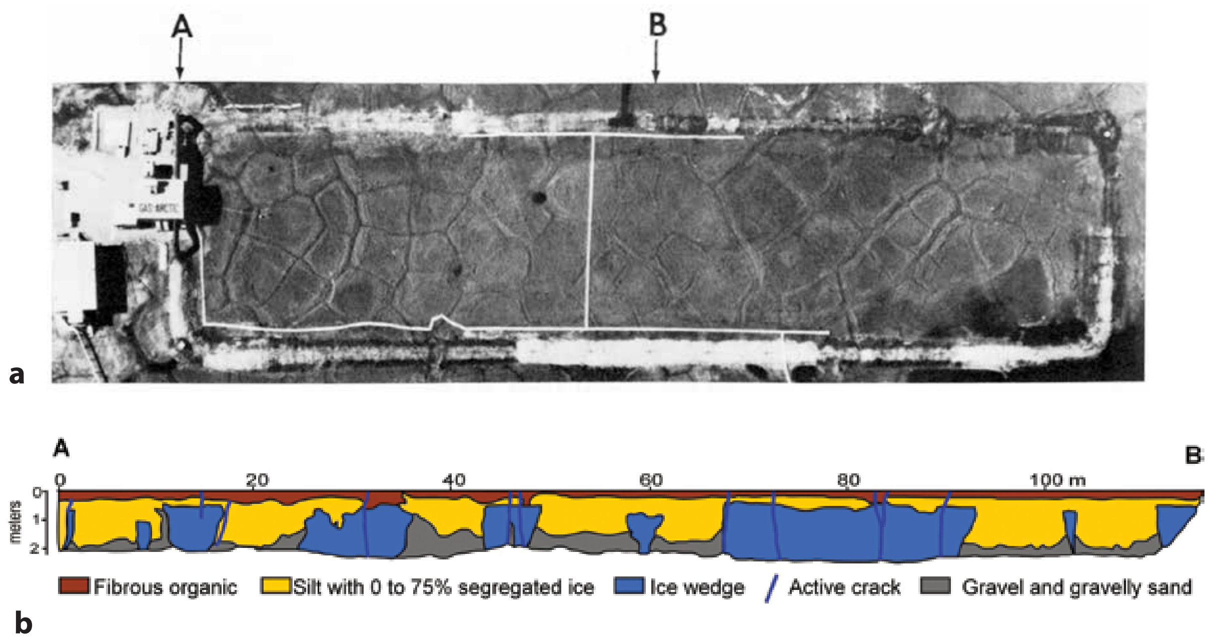
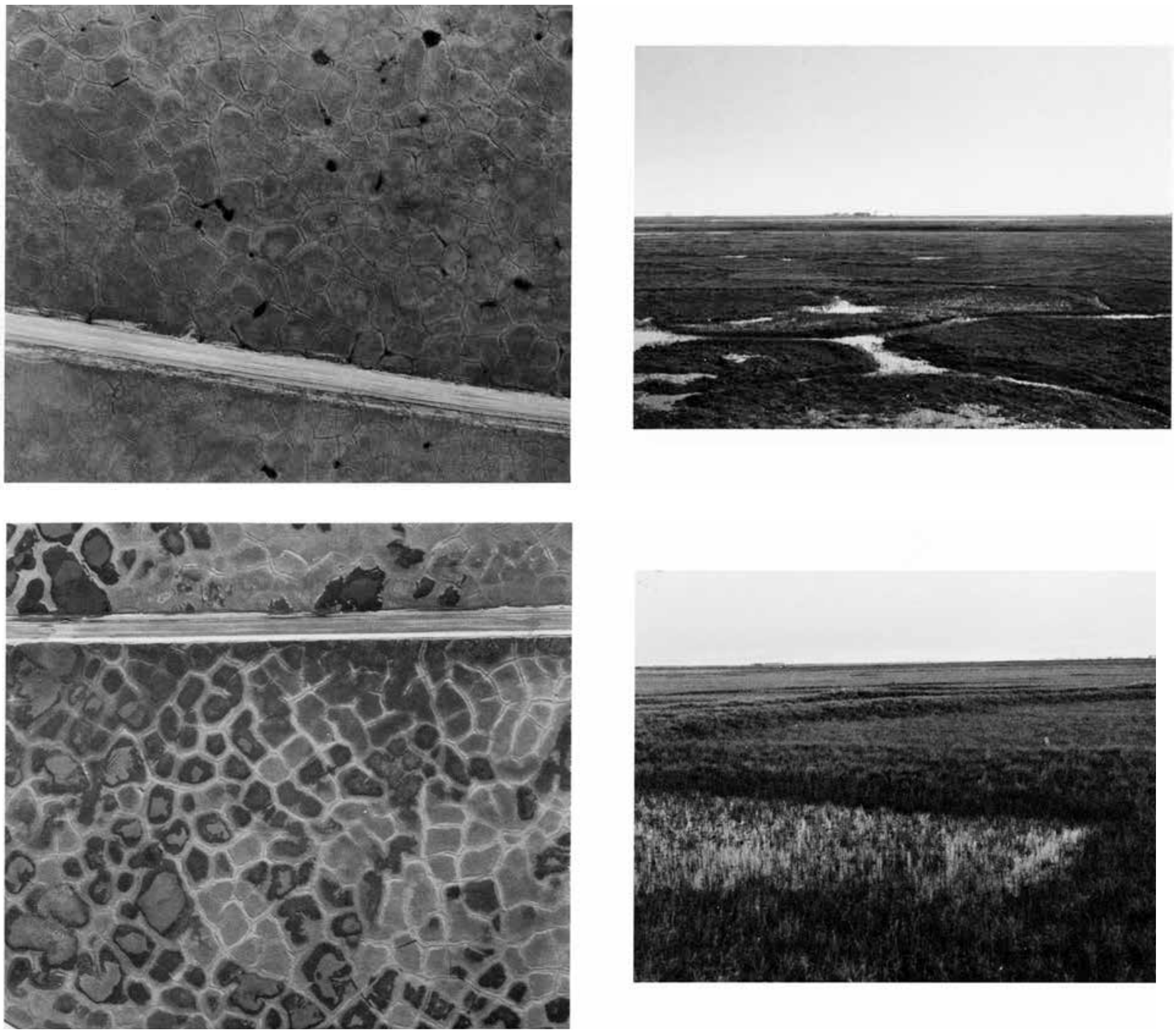


Figure 2.5. (a) *Detail of polygonal tundra surface at the experimental Gas Arctic test facility at Prudhoe Bay, where construction techniques for burial of a 122-cm (48-in.) pipeline were tested and the effects on the surface and permafrost environments were evaluated. The rectangular disturbance marks where the approximately 500-m long pipe was buried in a 2.5-m deep trench in April 1971. Cold gas was pumped through the pipeline from the facility in the upper left of the photo.* **A** *and* **B** *denote the portion of the trench shown in cross section in* **(b)**, *which shows the ice wedges exposed in the trench (highlighted in blue) that underlie the polygon troughs in* **(a)**. *A huge ice body at 68-90 m of the trench is an ice wedge oriented almost parallel to the trench, whose cross-sectional width probably does not exceed 3 or 4 m. 1.5-2 m of silt (tan) overlie alluvial gravel and gravelly sands (gray). Segregated ice (Fig. 2.2) occurs in the silts between ice wedges. Visual estimates of segregated ice volume in the areas between the ice wedges were noted on the original drawing by Kaye Everett and range from 0 to 75%, but it is not possible to display this detail at the scale of reproduction here (Everett, 1980a).*

along stream bluffs, drained lake margins, coastal bluffs and some pingos, ice wedges can degrade as a result of thawing or become actively eroded by flowing water that is channeled along the polygon troughs. As a result, the polygon troughs subside, and the polygon centers become relatively elevated, forming *high-centered ice-wedge polygons* (Fig. 2.7).

Thermokarst

The above-described process of high-centered-polygon formation is a form of *thermokarst*, whereby a variety of characteristic landforms can result from the thawing of ice-rich permafrost or the melting of massive ice (Shur, 1988). Thermokarst development is a complicated process which includes numerous positive feedbacks (*e.g.,* accumulation of

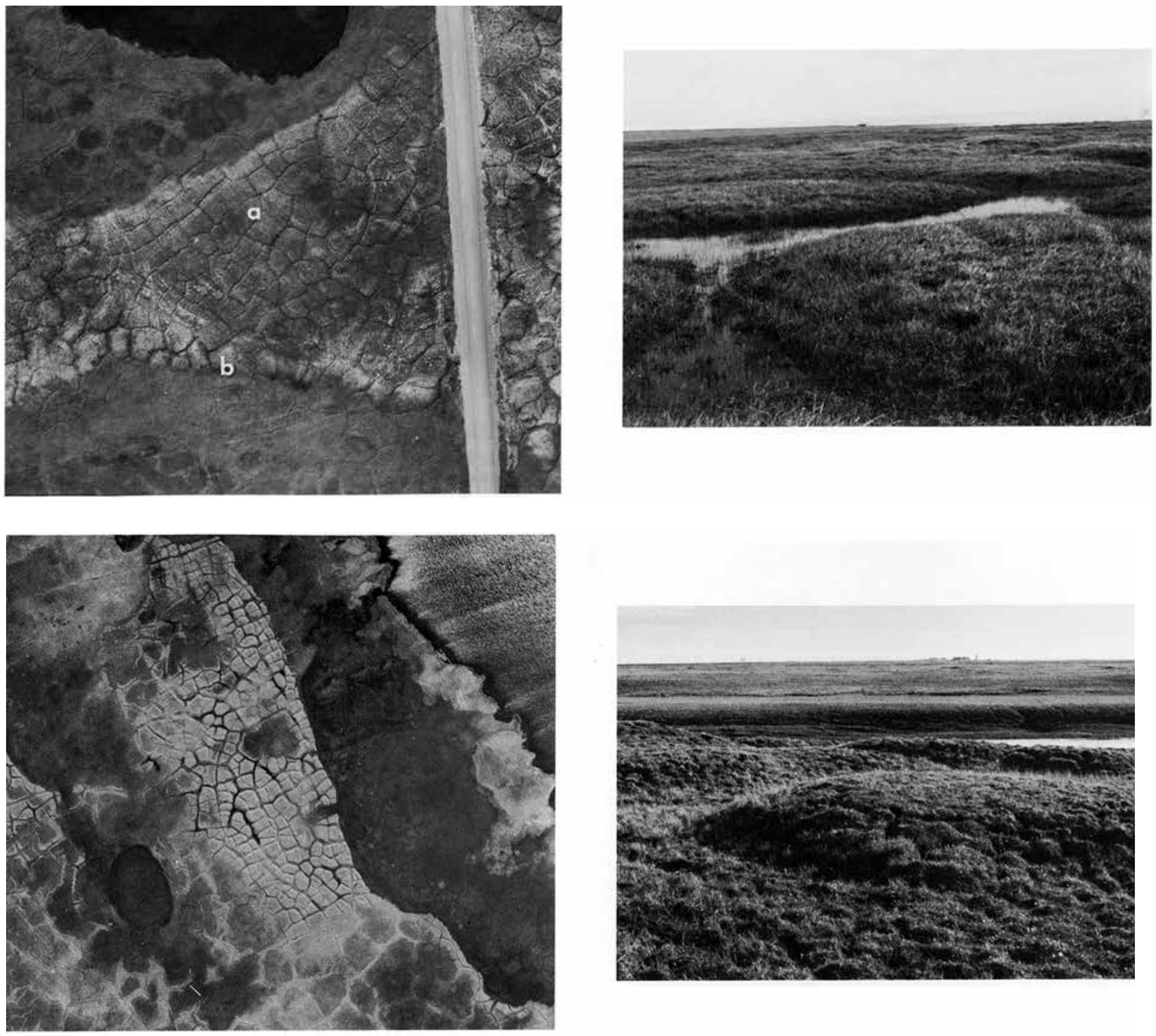


a

b

Figure 2.6. *Low-centered ice-wedge polygons.* **(a, left)** *Low-centered polygons with less than 0.5 m of relief between polygon centers and rims. In the aerial photo, the diameter of the polygons is about 10-15 m. Lighter tones correspond to relatively well-drained microsites, mainly along polygon rims. Darker gray tones are wetter, mostly in the low polygon centers. Dark linear features between the individual polygons are the troughs that denote the position of the ice wedges that lie just below the troughs. Note the scattered small dark ponds (thermokarst pits) that occur at the junctions of some ice-wedge-polygon troughs.* **(a, right)** *Ground-view of low-centered polygons with some transitioning to high-centered polygons. Some flooding extends along the length of the ice-wedge polygon troughs.* **(b, left)** *Low-centered polygons with greater than 0.5 m of relief between polygon centers and rims. Polygons of this type are common in sandier portions of the PBO and in the river deltas. Most of the polygon centers have standing water with aquatic vegetation. Note minor ponding adjacent to the road.* **(b, right)** *Ground view of similar terrain (Everett, 1980b). The vertical aerial photographs were taken by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in 1972, at a photo scale of 1:3000. The ground-views taken by K.R. Everett, show similar terrain, but not the same areas as in the aerial photographs.*

surface water and snow in the troughs) and negative feedbacks (*e.g.,* vegetation growth and accumulation of organic matter) (Jorgenson *et al.,* 2006). These feedbacks determine the response of ice-wedge polygonal systems to climate change and infrastructure-related effects. Natural thermokarst has shaped the variety of ice-wedge polygon forms in different parts of the PBO permafrost landscape (Fig. 2.6 and 2.7). Thermokarst can also lead to the natural formation of thermokarst lakes (Everett, 1980a), whereby subsidence and thermal erosion of the central parts of polygons causes the ponds to expand and coalesce to form larger ponds. Eventually larger lakes develop and other processes, such as wind driven currents and ice shove can cause more rapid lakeshore erosion. This thaw-lake expansion and drainage has shaped the majority of the PBO landscape (see maps in Chapter 4 showing drained thaw lake basins, Fig. 4.4b, 4.5b, and 4.6b). Natural thermokarst occurs most commonly



a

b

Figure 2.7. *High-centered ice-wedge polygons.* **(a, left)** *High-centered polygons, mostly with less than 0.5 m of relief between polygon centers and troughs. In the aerial photo the white 'a' denotes polygons with less than 0.5 m of relief; and 'b' a few polygons with greater than 0.5 m of relief.* **(a, right)** *Ground view of similar high-centered polygons with less than 0.5 of relief and thermokarst.* **(b, left)** *High-centered polygons with greater than 0.5 m of relief between centers and troughs. The aerial photo on the left shows water-filled thermokarst troughs.* **(b, right)** *ground view of similar polygons. Thermal erosion of ice wedges occurred causing subsidence of the troughs, but there is no ponding due to drainage to the stream in the background. The vertical aerial photographs were taken by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in 1972 at a photo scale of 1:3000. The ground-views taken by K.R. Everett, show similar terrain, but not the same areas as in the aerial photographs (Everett, 1980b).*

in ice-wedge polygon complexes on primary surfaces – surfaces that have not experienced recent lake drainage or re-working of riparian sediments (Hussey & Michelson, 1966). These surfaces are old enough to have accumulated significant volumes of wedge ice in the near-surface permafrost. When the upper parts of the ice wedges thaw, the polygon rims, which previously held water within the polygon basins, subside into the troughs and the centers become drained of water.

Thermokarst in the areas of ice-rich permafrost with near-surface ice wedges occurs in two distinctly different scenarios: reversible and irreversible (Fig. 2.8). Both scenarios start with partial thawing of the upper ice wedges and formation of small shallow ponds in the troughs over ice wedges and especially at their intersections. This initial stage of thermokarst development is triggered by an increase in the active layer thickness caused by higher than normal air temperatures, flooding, or destruction of vegetation.

Thawing of the top parts of ice wedges starts only after complete degradation of a thin zone of ice-rich layer of permafrost termed the "*intermediate layer.*" This layer forms below the base of the active layer (Fig. 2.8, pink horizon), and normally overlies the upper surfaces of ice wedges, preventing them from thawing (Shur *et al.,* 2005; French & Shur, 2010). An increase in depth of the summer thaw (the active layer) is required to thaw the intermediate layer and initiate melting of the upper parts of ice wedges. Thermokarst frequently starts at the intersection of ice wedges in the form of a small pond (thermokarst pit) and can expand along the length of the ice wedges due to warming of the standing water from absorption of sunlight (Jorgenson *et al.,* 2006). Warm and wet summers are especially favorable to a deeper thaw.

The first (reversible) scenario (blue arrows in Fig. 2.8) is often observed in a natural environment. This scenario is possible when only the ice wedges are affected by thermokarst, while the central parts of the polygons remain relatively stable because of an undisturbed protective insulative mat of vegetation and organic soils. Increases in the active layer thickness in the central parts of the polygons usually result only in moderate surface subsidence due to partial thawing of the intermediate layer, which can recover with time. In several years or decades, this early stage of ice-wedge thermokarst development can be interrupted by drainage of the initial ponds or by accumulation of organic matter in the troughs (Jorgenson *et al.,* 2006; Shur *et al.,* 2012). Rapid growth of aquatic vegetation and accumulation of organic material in the troughs can slow down the thawing of ice wedges and eventually lead to the formation of a new intermediate layer on top of the partly degraded ice wedges. In areas with a cold climate, a new generation of ice wedges may start forming after the termination of thermokarst (sometimes even below the residual thermokarst ponds). These new ice wedges penetrate through the intermediate layer into the previous generation of ice wedges that were truncated by thermokarst (Fig. 2.8, two right boxes with blue arrows). When these new ice wedges reach a significant size—usually after several centuries of development—they

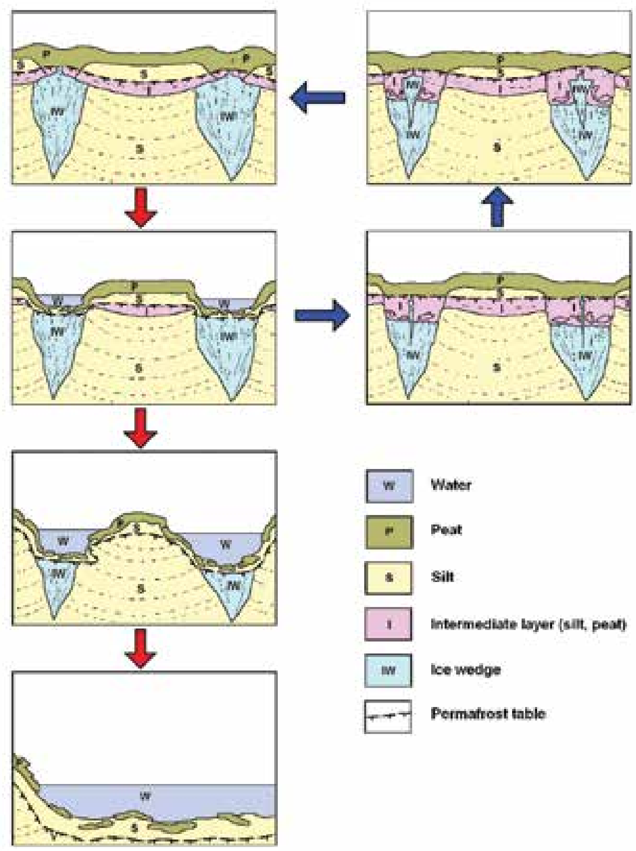


Figure 2.8. *Two possible pathways of thermokarst associated with terrains with common occurrence of ice wedges. A reversible process* **(blue arrows)** *is often observed in a natural environment when the central parts of polygons remain stable because of the protective insulative mat of vegetation and organic soils remains undisturbed. The process can take a different pathway leading to larger water bodies and lakes if the central parts of polygons experience thaw settlement* **(red arrows)**. *This progressive thermokarst can start abruptly with an increase in the thickness of the active layer as a result of a warming climate or a change in vegetation on the soil surface. It can be triggered by accumulation of road dust or infrastructure-related flooding which changes the thermal insulating properties of the soil in the polygon centers.*

can be affected by a new cycle of thermokarst, and the reversible scenario may repeat itself again.

The second (irreversible) scenario (red arrows in Fig. 2.8) usually occurs where there is simultaneous disturbance to the central part of the ice-wedge polygons. This can occur under a continuing warming climate or by disturbance of the polygon center as often occurs in areas in close proximity to infrastructure. Deep thawing of the central parts of polygons can be triggered by removal of surface vegetation and organic-rich soils, accumulation of road dust, infrastructure-related flooding, or other processes that destroy vegetation or change the thermal insulating properties at the soil surface. This scenario is more severe because the loss of the protective organic layer can lead to thawing of the upper permafrost and subsidence of the entire polygon. Further thermokarst development results in continuing ground subsidence, ponding of surface melt-water, and formation of shallow thermokarst ponds above the polygons. Eventually the deeper and larger thermokarst ponds accelerate the thermokarst, and can cause relatively fast degradation of ice-rich soils under the ponds.

Thermokarst within the PBO is generally not as severe as in areas with thick ice-rich loess deposits (*yedoma*), which occupy vast areas of northern Alaska (Kanevskiy *et al.*, 2011). For example, during the exploration in the East Oumalik, where the loess is estimated to be 30 m thick, the subsidence following drilling activities ranged from 3 to 5.5 m (Lawson, 1982). The concentration of ice-rich silt in the upper 2 m underlain by ice-poor alluvial gravels within the PBO limits the depth of thermokarst development. However, the areas affected by thermokarst in the PBO are very large and its influence on the environment and infrastructure should not be underestimated. In other areas of hydrocarbon resources in Northern Alaska, thick fine-grained ice-rich soil could greatly complicate placement of stable infrastructure.

Variation of permafrost temperatures within the PBO

The regional warming that is responsible for the thawing of the upper portion of ice-wedges in the natural landscapes within the PBO is evident in data taken from two permafrost-monitoring sites within the Prudhoe Bay region (Fig. 2.9) (Romanovsky *et al.*, 2012). Present day permafrost temperatures at 20 m depth vary from -6 °C at inland locations (Deadhorse permafrost research site, 70.16 °N 148.47 °W) (Fig. 2.9a) to -8 C near the Arctic coast, 23.6 km north-northwest of the Deadhorse site (West Dock site, 70.37 °N 148.55 °W) (Fig. 2.9b). Even though the mean annual air temperatures averaged over the 1990-2010 period at these two sites are very similar (-11.45 °C at Deadhorse and -11.25 °C at West Dock), the seasonal variations are very different. The Deadhorse site has a more continental type of climate with an average July temperature of 8.0 °C and an average January temperature of -28.1 °C (1990-2010 averages). The West Dock site climate is more maritime. The mean July temperature here is cooler, 5.7 °C and the mean January temperature is slightly warmer, –27.0 °C. These two sites also have very different winter snow accumulation on the ground. While the typical maximum winter snow depth at the Deadhorse site is between 0.4 and 0.6 m, the maximum snow depth at the West Dock site is typically between 0.15 and 0.25 m. The 1990-2010 average active-layer thickness measured at the Deadhorse site was 0.61 m, while at the West Dock site it was only 0.27 m. This is a function of the relatively

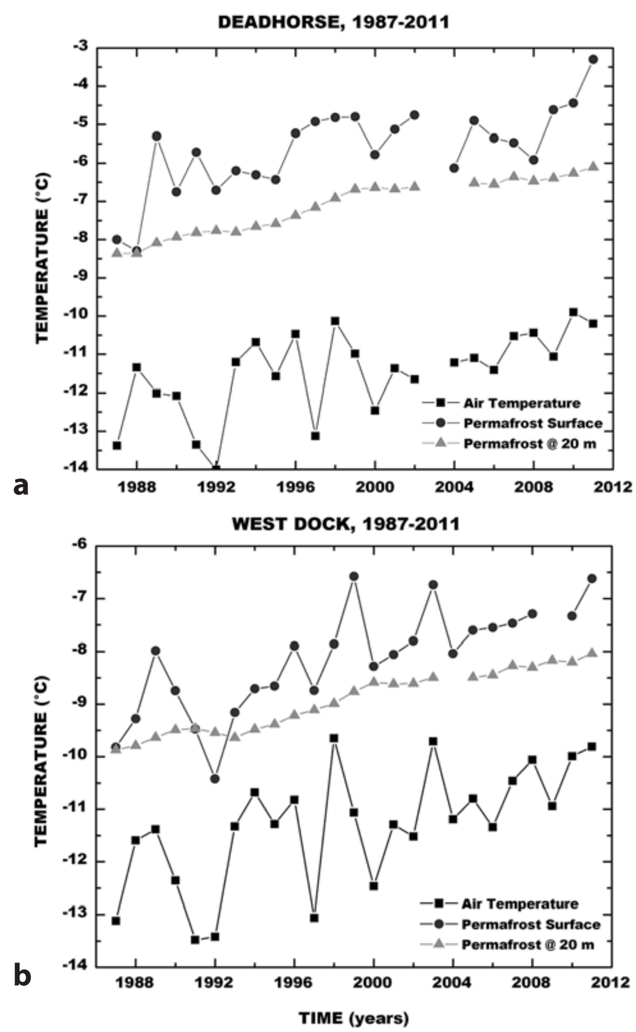


Figure 2.9. *Mean annual air and permafrost temperatures at* **(a)** *Deadhorse, and* **(b)** *West Dock (1987-2011) (Romanovsky* et al., *2012).*

warmer summer temperatures and the less insulative vegetation and soils at Deadhorse. At the same time, the temporal variability of the mean annual air, ground surface, and permafrost temperatures during the last 20 to 30 years are similar at these two sites. At both locations these temperatures increased by approximately 2 °C over the last 25 years (Romanovsky *et al.,* 2012).

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3 Supplementary information regarding calculation of impacts of oilfield development, North Slope, Alaska

KENNETH J. AMBROSIUS

This chapter provides a description of the calculations of the regional-scale impacts due to oil field development on the Alaskan North Slope and the summary table of the measurements of these impacts. This work was made possible thanks to BP Exploration (Alaska) Inc.

Methods

General

Original calculations for the impact area were calculated through the use of BP Exploration (Alaska) Inc. owned large-scale topographic base maps and historical aerial photography for the years 1968, 1973, 1977, 1983, 1988, 1994 and 2001. Updates were accomplished in 2007, 2010, and 2011. Some facility types were re-classified in 2011 to reflect current function.

The geographic area of this project was limited to north of 70° 5′ north latitude, and between 145° 55′ and 151° 20′ west longitude.

For the purpose of these calculations "impact" was defined as the footprint of a gravel facility, or the area used for gravel extraction and overburden piles, or any visible marks or scars on the tundra that persisted for a period of approximately 10 years or more.

All facilities related to the oil field development were included for the purpose of these calculations. No distinction was made between industry-owned facilities, contractor facilities, or State of Alaska facilities such as Deadhorse. Those portions of the Trans Alaska Pipeline System and the DOT's Dalton Highway that fell within the study limits were included. Only the Distant Early Warning (DEW Line) military sites and any native owned or other private property sites were excluded.

These calculations did not include the exploration work done by the U.S. Government in NPRA, exploration wells or seismic camps in the foothills of the Brooks Range, the DOT Dalton highway that fell outside the study area limit, nor any of the Trans Alaska Pipeline system that fell outside of the study area limit. The geographic area of the project was limited to the area for which detailed maps and photos were available for use.

Oil field facilities and roads are raised gravel structures that have well defined edges. Pit gravel mines in the tundra also have well defined edges. These items were mapped to 1″=500′ standards through photogrammetric methods.

Exploration activity before 1978 sometimes took place without raised gravel pads or roads. Prior to 1978 some gravel was extracted from riverbeds by grading material into a pile and then hauling it off. Some of these items were well defined in recent aerial photos while others were not. The area limits for those items that were not well defined were interpreted from historical photography.

Base maps

BP Exploration (Alaska) Inc. maintains a set of topographic base maps of the North Slope, Alaska producing oil fields. These maps were produced by photogrammetric methods from 1973 through 2011 aerial photography. The map scale was 1:6000; the horizontal datum was Alaska State Plane, NAD83, based on USC&GS monuments. The vertical datum was Mean Sea Level based on a limited number of tidal observations at East Dock in 1968. The survey of photogrammetric control points was done to third order class two standards. The planned map accuracy is:

- 90% of the planimetric features were plotted to within 1/40 inch of their true positions. *(At 1:6000 this is ± 12.5 feet.)*
- Independent ground surveys have shown the horizontal accuracy to be ± 2.0 feet for gravel facilities and pipelines.

The 2001 detailed mapping covered all production facilities with the exception of the ConocoPhillips operated oil fields: Alpine, Meltwater, and Tarn. Less detailed 1:63,360 maps were used for the calculations in these areas. The 2011 calculations were all done from 1:6000 scale topographic maps.

Area calculations

The procedure used for the area calculations involved the following steps:

- A 'footprint' polygon was extracted from the most recent topographic map CAD files (2001 vintage) available from BP Exploration (Alaska) Inc. This polygon was placed in a single CAD file and was used as a 'base' for construction of all prior years studied. The file contained only the areas currently covered by gravel facilities, roads, and mine excavations. Exploration facilities, riverbed gravel extraction, and other impacted areas (disturbed tundra not covered by gravel facilities) were not included.

- The 1968 aerial photos were examined to determine the impact area for that year. The 'base' reference file was used to help locate and define the areas as they appeared in 1968. Well-defined gravel facilities that were a match to what was observed in the 1968 photos were copied from the 'base' reference file into the 1968 CAD file. From an examination of the 1968 photos other impacted areas were then also digitized into the 1968 file with the aid of the current industry topographic maps as a backdrop.
- The 1968 CAD file was then copied and renamed 1973. The 1973 photos were examined, those polygons from the 'base' reference file that matched were copied into the 1973 CAD file, and other impacted areas were digitized as above. The procedure was repeated for the years 1977, 1983, 1988, 1994, and 2001. A CAD file that contained all impact areas up to that time was created for each year. Each year depicts a cumulative impact up to that time with no consideration for "rehabilitation". These CAD files were the source for the calculations in the accompanying excel tables. Calculations were done using ARC View software in an Alaska State Plane, zone 4, NAD27 projection.
- NOTE: In 2005 all base map data was converted to Arc Geo-database format and NAD83 Alaska State Plane coordinate system. Additional calculations were made using 2006-07, 2010, and 2011 photos and base mapping.

Exploration facilities

Access to exploration wells from 1963 through 1973 was achieved by three methods and each had a varying degree of impact on the tundra. These methods of access were only used prior to 1973. Later, permanent production facilities and gravel roads were constructed over some of these early access routes when possible.

1. Tractor Trails / Tundra Scars. For some early exploration wells the rig was simply parked on the frozen tundra and shimmed up on timbers to level. These were accessed by driving over the frozen tundra. Continued use of these routes after spring thaw produced ruts and tundra scars that persisted for many years. All of these rutted or scarred areas were included in the cumulative impact area calculations. Natural processes have since re-vegetated areas where the routes crossed well-drained high ground. Other low lying wet areas remained marked by well-defined water-filled depressions or ditches.

2. Peat Roads. For a few years peat roads were used for exploration-well access and rig movement. Peat roads were constructed by using a bulldozer to blade the native soil into a mound, one bulldozer on each side of a route centerline. The result was a pair of parallel shallow ditches on either side of a mound. The mound was graded and packed and when frozen provided a roadbed. Peat roads left a very well defined mark on the landscape still visible today. The peat roads have become re-vegetated through natural processes and most have shallow ponds on each side. However, the construction of peat roads altered the native vegetation patterns and the drainage patterns, creating a new habitat type different than was originally present.

3. Exploration Access Roads of Thin Gravel & Frozen Tundra. A third method of access was a combination of a) the placement of a thin layer of gravel over uneven ground and, b) driving over frozen tundra where the ground was already smooth and even. In the areas where no gravel was placed a visible scar on the tundra was observed that persisted for as many as ten to fifteen years, probably a die-off of vegetation through repeated passage. All of these areas of thin gravel or vegetation die-off were included in the cumulative impact area calculations.

Some of the tundra scars had disappeared by 1994 or 2001, re-vegetated through natural processes. Some of the low-lying wet areas where a thin layer of gravel was placed also appear to have become re-vegetated through natural processes. Other well-drained areas where gravel was placed have remained pretty much as they were when first constructed.

4. Exploration Drill Site – Disturbed Tundra

- **a. Site on Tundra.** Early exploration wells were drilled in winter when the tundra was frozen. For some wells the rig sat on the tundra and was leveled with timbers, and no gravel was used at all. Activity around the rig caused some vegetation die-off, other areas were rutted and scarred by vehicle activity, sometimes pits were dug in the tundra. After the rig was demobilized from the site some pits were filled in, material that was dug up was spread around, and some sites appear to have been graded. All of these disturbed areas were included in the impact area calculations, “Exploration Site – Disturbed Tundra”. Over time some of these disturbed areas have become re-vegetated through natural processes.

b. **Thin Gravel Site.** For some exploration wells a thin layer of gravel was used to level the site. Activity around the rig caused vegetation die-off, other areas were rutted by vehicle activity, and pits may have been dug in the tundra. After the rig was demobilized the thin gravel may have been left in place or it may have been spread around or used to fill in reserve pits. The material that was dug from the pits may have been spread around; some sites appear to have been graded. All of these disturbed areas were included in the impact area calculations, “Exploration Site – Disturbed Tundra”. Some sites were revisited by industry and rehabilitated. The area calculations for these sites or portions of these sites were reported in the ‘gravel pad removed, site in process of recovery’ category.

c. **Gravel Pad – Disturbance Area.** For some exploration wells a gravel pad was constructed, normally 3 to 5 feet thick with a pad and camp area and reserve pits constructed at grade by use of gravel dikes or berms. These sites generally had activity off the pad that impacted the tundra. These disturbed areas were included in the impact area calculations “Exploration Site - Disturbed Tundra”, the gravel area was not. Some of these gravel exploration pads were revisited by industry and ‘closed out’ to State of Alaska specifications. The close out procedure may have included re-grading some of the gravel found onsite to cover the reserve pits or it may have included breaching the dikes to prevent ponding of water. Sometimes these activities slightly increased the disturbed area.

5. Exploration Site – Gravel Pad. These are the footprint areas of the portions of the exploration sites that were raised gravel pads. The area calculation was cumulative and included some sites that were no longer visible on the aerial photography. Some of the sites were located on barrier islands and have since washed away. A few others have become thermokarsted or re-vegetated by natural processes. Some sites were removed and rehabilitated by industry. The area calculations for these sites or portions of these sites may now be reported in the ‘”Gravel Pad Removed, Site in Process of Recovery” category.

6. Exploration Airstrips Thin Gravel / Tundra Scar. Some of the early exploration wells were accompanied by airstrips created by a combination of the placement of a thin layer of gravel over uneven ground and a thin ice pad where the native ground was smooth and even. In the areas where no gravel was placed a visible scar on the tundra was observed that persisted for as many as ten to fifteen years, probably a die-off of vegetation through repeated passage. Areas where gravel was placed have remained mostly as they were when first constructed. All of these areas of thin gravel or vegetation die-off were included in the cumulative impact area calculations.

7. Exploration Islands. The area included in these calculations was only that portion of the islands that was above Mean Sea Level. The depth of the original seabed beneath the islands was up to approximately fifteen feet. No effort was made to interpolate the area of seabed actually covered. For the cumulative figures every island was included, even after an island may have been washed away or removed by mechanical means.

Production facilities

8. Roads. Gravel roads for general transportation were normally five feet thick and varied in width. Some gravel roads were constructed for pipeline inspection or maintenance and were not intended for general use; these may be less than five feet thick. All of these roads were included in these calculations. Area was calculated from the toe of the roads.

9. Causeways. The causeways were generally constructed to be about twelve feet above Mean Sea Level; side slopes were approximately 7 to 1. The depth of the seabed beneath any of the causeways varied from zero to approximately fifteen feet. The area included in these calculations was only that portion of the causeway that was above Mean Sea Level, no effort was made to interpolate the area of seabed actually covered. The area of the causeways was reduced from 1994 to 2001 due to the construction of a breach at West Dock and another at Endicott. Construction of erosion control features and reconstruction of washed out areas increased the calculated area for these structures since 2001.

10. Airstrips. Area calculations include both active usable airstrips and airstrips that were constructed for exploration activities that were no longer in use. All of these airstrips were constructed from gravel and were generally a minimum of five feet thick. Though some of the exploration airstrips had severe thermokarst and were no longer useable, the area remained under this 'airstrip' heading. The gravel from some airstrips was removed for use in construction of other facilities. In the tables the areas that was removed and reused was not included in the airstrip area calculation. The calculations for those removed areas were recorded under the "Gravel Removed From Tundra" heading. Some airstrips were closed and the surface area was put into use as storage or other support activities, these were reclassified to the "Support Pad" category.

11. Production Islands. Production islands area calculations included only those portions that were above sea level in the same manner as was done for "Causeways". One production island was incorporated into a causeway; that area was segregated out and reported as a production island. Production islands contain production wells but may also include process and support facilities.

12. Production Pads / Drill Sites. Some production drilling pads were constructed over exploration sites. In these cases the area calculations were reported as "Drill Sites" rather than under "Exploration sites". At the time of construction some facilities were built in such a way as to enclose areas of tundra that were not part of the facility. Other areas that were to be used as flare or reserve pits were completely enclosed, though some were never used and appear to be native tundra with no impact. The drill site area as calculated here included all of those parts of a facility that were intended for use as a pit, as well as the areas of tundra actually covered by gravel. The tundra areas that were not part of the facility but were surrounded by the facility were not included in the area calculations.

13. Processing Facilities. Processing facilities are generally large pads with large equipment. Since 1995 several small pads were built for automated valves, pipeline pigging (cleaning or assessment), and metering. The valve pads were at shore fall and at the bank of rivers, and contain automated valves and a helicopter-landing pad. Other pads were located along pipelines.

Some facilities were built in such a way as to enclose areas of tundra that were not part of the facility. Some of these areas were large and were not visibly impacted; others were small and have filled with storm runoff or snowmelt debris. Areas intended as flare or reserve pits were completely enclosed by gravel dikes. The production facility areas as calculated here included all of those parts of a facility that were intended for use as a pit, the small impacted enclosures, and the areas of tundra covered by gravel pad. The larger tundra areas with no visible impact but surrounded by the facility were not included in the area calculations.

14. Support Pads. Support pads included facilities under the control of the oil industry and State of Alaska owned and leased properties that were not under industry's control. In general these facility footprints were well defined, however on occasion they spread out onto the tundra and then contracted back to the gravel pad. All of these areas that were used for storage or that appear to have otherwise disturbed the tundra were included in the impact area calculations. Over time some of these storage areas were cleaned up and some disturbed areas have become re-vegetated through natural processes. In the 'current conditions' columns of the table those areas that were considered rehabilitated were left out.

15. Gravel Pad Removed – Site in Process of Recovery. By year 1973 the very first gravel pad constructed, the ARCO base camp, was reconfigured. A portion of the gravel pad was removed and reused elsewhere. In every subsequent year of photography examined additional areas of gravel pad or gravel road were found that had been picked up. Some areas have become re-vegetated through natural processes in a relatively short time. Others took as long as ten to fifteen years, while still others remained a visible scar. For the years 1973 through 1994 all gravel removed from tundra was placed in this category regardless of status of recovery. Note that this category was used only for those areas where a raised gravel pad or road was removed; it was not used for other 'disturbed areas' or thin gravel. Also note that a few of these areas of removed gravel were in riverbeds and the 'removal' may have been caused by erosion rather than by construction equipment.

16. Gravel Pad Removed – Site Recovered. After 1995, industry began to remove un-needed portions of gravel pads and some exploration site gravel pads. These areas were reported here, they appear to be recovered by natural means or rehabilitated by industry. After 2001 some of these sites were re-excavated to remove contaminated materials and this activity caused a change in this area calculation.

17. Gravel Mine in Riverbed. Gravel for facility construction was removed from the Sagavanirktok and Kuparuk Rivers (typical gravel-filled, meandering glacier riverbeds) by two different methods:

a. Up to 1978 gravel was removed from some portions of the riverbed by pushing portions of the gravel bars into large piles and then hauling them off with earth moving equipment. The equipment used for this surface mining left some well-defined and some not so well-defined tracks, pits and piles in the riverbeds. Subsequent spring flooding erased much of the evidence. Some areas the river channels changed due to the removal of gravel and this further erased evidence of the gravel removal. All of these disturbed areas were included in the cumulative impact area calculations. Over time evidence of gravel removal for some of these areas disappeared due to spring floods and the action of the river.

b. From 1973 through 2001 a side channel of the Kuparuk River was the site of deep pit mining. This side channel floods during spring break-up but is otherwise a series of oxbow lakes. From year to year, depending on the results of the spring floods, these oxbows are connected by streams. A series of pits was dug from the Spine Road to the river delta. Some surface mining and surface grading was also done in some of these areas. All of the pits are currently full of water. Those that had no surface mining at the edges appeared to be natural oxbows and were indiscernible from the natural environment. Some of the pits are currently used as reservoirs and have a flat graded area for vehicle traffic next to them. All of the areas used for mining were included in the cumulative impact area calculations.

18. Gravel Mine in Tundra. Some gravel mines were situated in tundra areas near rivers or streams; these have a very well-defined footprint. Typically an overburden layer of mixed organics and gravel was removed and placed to the side of the mine area. The area calculations here included the footprint of the excavation as well as the overburden pile.

Other facilities

1. Pipelines. The length and number of pipelines data set was taken from the industry topographic maps. On these maps individual pipelines were not shown, pipeline bundles were mapped with an annotation to denote the estimated number of pipelines in each bundle. This was only calculated from the 2001 and 2011 maps.

2. Transmission Lines. The transmission lines were extracted from the most recent industry topographic maps. These included all known power lines that were located above ground on poles. No effort was made to research and define the many buried power lines nor those located on pipe racks. This was only done from the 2001 and 2011 maps.

3. Number of Culverts. Culvert locations were extracted from the most recent topographic map where available and from spill contingency maps for areas not yet covered by topographic maps. The numbers here were for culvert locations rather than for individual culverts. Many culvert locations contained more than one culvert. Large culverts (some as much as eight feet in diameter) were included here and not under 'bridges'.

4. Number of Bridges. The bridge count included causeway breaches as well as road bridges. These were from the most recent topographic map where available.

5. Number of Caribou Crossings. Caribou crossing numbers were from the industry topographic maps. Some caribou crossings had pipelines built across rather than under them in recent years. For the purposes of this count these were not included.

Table 3.1. *Summary of North Slope infrastructure impacts. Data from K. Ambrosius (2002) in NRC Report (Orians* et al., *2003), revised April 24, 2012.*

North Slope - all areas

YEAR	1968	1973	1977	1983	1988	1994	2001	2007	2010	2011
YEARS SINCE DISCOVERY	0	5	9	15	20	26	32	38	42	43
Facility Type (Number of gravel pads)										
Production pads/ drill sites	0	16	22	62	95	104	115	123	126	127
Processing facility pads	0	6	10	14	18	18	20	20	24	25
Support pads (power stations, camps, staging pads, etc.)	1	36	63	98	108	113	115	125	134	145
Exploration sites	3	42	63	103	104	106	103	97	97	103
Exploration islands offshore	0	0	2	12	13	13	13	13	13	13
Production islands offshore	0	0	0	0	2	3	4	6	6	7
Airstrips	1	11	15	16	16	16	16	15	9	9
Exploration airstrip - thin gravel / tundra scar	0	4	4	4	4	4	4	4	1	4
Number of culverts	N/A	N/A	N/A	N/A	N/A	N/A	1395	N/A	2067	2037
Number of bridges	N/A	N/A	N/A	N/A	N/A	N/A	17	N/A	25	27

LENGTH MEASUREMENTS

Travel ways (km)										
Road	0.0	158.7	223.7	472.8	575.7	595.3	644.1	662.6	663.4	668.5
Peat road	47.6	161.9	161.7	161.7	155.0	154.2	154.2	154.2	153.7	154.0
Causeway	0.0	0.0	3.1	4.3	12.1	12.1	12.4	12.2	12.2	12.2
Tractor trail / tundra scar	30.6	86.4	94.1	91.9	90.9	90.9	90.8	90.8	90.8	95.9
Exploration road - thin gravel / tundra scar	0.0	57.8	58.7	58.1	58.1	58.1	57.9	56.8	56.8	54.2
TOTALS (km)	**78.2**	**464.8**	**541.4**	**788.9**	**891.7**	**910.6**	**959.3**	**976.5**	**976.9**	**984.9**

Table 3.1 (cont.) *Summary of North Slope infrastructure impacts. Data from K. Ambrosius (2002) in NRC Report (Orians et al. 2003), revised April 24, 2012.*

North Slope - all areas

YEAR	1968	1973	1977	1983	1988	1994	2001	2007	2010	2011
YEARS SINCE DISCOVERY	0	5	9	15	20	26	32	38	42	43
Pipeline corridors (km)										
1 pipe	N/A	N/A	N/A	N/A	N/A	N/A	117.8	N/A	N/A	100.1
2 pipes	N/A	N/A	N/A	N/A	N/A	N/A	180.1	N/A	N/A	176.4
3 pipes	N/A	N/A	N/A	N/A	N/A	N/A	91.6	N/A	N/A	149.8
4 pipes	N/A	N/A	N/A	N/A	N/A	N/A	153.5	N/A	N/A	150.5
5 pipes	N/A	N/A	N/A	N/A	N/A	N/A	46.7	N/A	N/A	77.1
6 pipe	N/A	N/A	N/A	N/A	N/A	N/A	50.7	N/A	N/A	45.9
7 pipes	N/A	N/A	N/A	N/A	N/A	N/A	27.0	N/A	N/A	35.7
8 pipes	N/A	N/A	N/A	N/A	N/A	N/A	13.5	N/A	N/A	12.2
9 pipes	N/A	N/A	N/A	N/A	N/A	N/A	15.6	N/A	N/A	14.0
10 pipes	N/A	N/A	N/A	N/A	N/A	N/A	4.7	N/A	N/A	8.4
11 pipes	N/A	N/A	N/A	N/A	N/A	N/A	6.6	N/A	N/A	6.6
12 pipes	N/A	N/A	N/A	N/A	N/A	N/A	3.2	N/A	N/A	3.7
13 pipes	N/A	N/A	N/A	N/A	N/A	N/A	1.3	N/A	N/A	1.0
14 pipes	N/A	N/A	N/A	N/A	N/A	N/A	1.1	N/A	N/A	2.6
15 pipes	N/A	N/A	N/A	N/A	N/A	N/A	1.9	N/A	N/A	1.0
17 pipes	N/A	N/A	N/A	N/A	N/A	N/A	1.6	N/A	N/A	2.3
18 pipes	N/A	N/A	N/A	N/A	N/A	N/A	3.4	N/A	N/A	1.4
19 pipes	N/A	N/A	N/A	N/A	N/A	N/A	1.9	N/A	N/A	0.8
20 pipes	N/A	N/A	N/A	N/A	N/A	N/A	0.3	N/A	N/A	0.0
21 pipes	N/A	N/A	N/A	N/A	N/A	N/A	0.6	N/A	N/A	0.6
26 pipes	N/A	N/A	N/A	N/A	N/A	N/A	0.5	N/A	N/A	0.0
TOTALS (km)							**723.7**			**790.0**

Table 3.1 (cont.). *Summary of North Slope infrastructure impacts. Data from K. Ambrosius (2002) in NRC Report (Orians* et al., *2003), revised April 24, 2012.*

North Slope - all areas

YEAR	1968	1973	1977	1983	1988	1994	2001	2007	2010	2011
YEARS SINCE DISCOVERY	0	5	9	15	20	26	32	38	42	43
Transmission lines (km)										
Major transmission lines with towers (km)	N/A	N/A	N/A	N/A	N/A	N/A	351.8	N/A	N/A	540.7
AREA MEASUREMENTS										
Gravel roads (ha)										
8. Roads	0.0	278.7	405.9	821.0	988.5	1025.6	1111.3	1164.4	1164.8	1162.6
9. Causeways	0.0	0.0	19.3	33.0	94.9	92.7	91.7	87.5	88.0	92.0
SUBTOTALS (ha)	**0.0**	**278.7**	**425.2**	**854.0**	**1083.4**	**1118.3**	**1203.1**	**1251.9**	**1252.8**	**1254.6**
Gravel or paved airstrips (ha)										
10. Airstrip	2.5	54.9	101.9	116.3	126.8	126.7	116.0	124.1	124.9	124.8
Off-shore gravel pads / islands (ha)										
7. Exploration Islands	0.0	0.0	2.2	22.4	23.2	23.2	21.6	21.8	21.8	21.2
11. Production Islands (drillsite, process, support)	0.0	0.0	0.0	0.0	30.9	37.4	40.9	45.3	59.8	60.5
SUBTOTALS (ha)	0.0	0.0	2.2	22.4	54.1	60.6	62.5	67.1	81.6	81.7
Gravel pads (ha)										
12. Production pads/ drill sites (not islands)	0.0	111.9	262.0	889.7	1180.0	1221.3	1264.7	1179.2	1170.0	1164.1
13. Processing facility pads (not islands)	0.0	30.1	157.7	280.1	353.6	360.0	371.3	342.9	348.6	345.3
14. Support pads (camps, power station, storage, etc. but not islands)	5.7	178.3	308.3	539.6	582.4	592.9	592.2	680.5	716.2	728.6
15. Exploration site - tundra covered by gravel pad	0.0	44.1	70.8	136.8	126.5	125.2	119.5	128.1	116.9	106.5
SUBTOTALS (ha)	**5.7**	**364.4**	**798.8**	**1846.3**	**2242.5**	**2299.4**	**2347.7**	**2330.7**	**2351.8**	**2344.5**
Gravel footprint (ha) **TOTALS (ha)**	**8.1**	**698.0**	**1328.1**	**2839.0**	**3506.9**	**3605.1**	**3729.3**	**3773.8**	**3811.0**	**3805.6**

Table 3.1 (cont.). *Summary of North Slope infrastructure impacts. Data from K. Ambrosius (2002) in NRC Report (Orians* et al., *2003), revised April 24, 2012.*

North Slope - all areas

YEAR	1968	1973	1977	1983	1988	1994	2001	2007	2010	2011
YEARS SINCE DISCOVERY	0	5	9	15	20	26	32	38	42	43
Other impacted areas and gravel removed from tundra										
4. Exploration site - disturbed tundra	22.4	139.9	188.8	248.0	253.1	262.7	253.9	237.4	267.6	289.6
6. Exploration airstrip - thin gravel / tundra scar	0.0	27.7	27.7	27.7	27.7	27.7	27.3	26.3	26.3	20.4
2. Peat roads	58.0	221.2	220.8	220.5	210.5	209.4	209.4	209.4	208.9	209.3
1. Tractor trail / tundra scar	44.4	101.1	110.2	105.6	104.4	104.4	104.4	104.4	104.4	104.5
3. Exploration road - thin gravel / tundra scar	0.0	71.4	72.3	71.8	72.2	72.2	71.6	70.3	70.6	71.6
15. Gravel pad removed, site in process of recovery	0.0	5.8	8.5	16.6	21.7	34.2	41.2	131.2	155.5	166.3
16. Gravel pad removed, site is recovered	N/A	N/A	N/A	N/A	N/A	N/A	33.2	33.2	33.2	24.4
OTHER IMPACT AREA TOTALS (ha)	**124.7**	**567.2**	**628.3**	**690.2**	**689.5**	**710.6**	**740.9**	**812.2**	**866.5**	**886.1**
Gravel mines										
17. Mine in rivers	10.0	1915.0	2021.6	2027.9	2048.7	2048.0	2056.5	2178.7	2178.9	2179.3
18. Mine in tundra	0.0	13.7	61.0	301.5	477.0	479.8	529.2	546.1	574.0	557.8
GRAVEL MINE TOTALS (ha)	**10.0**	**1928.7**	**2082.6**	**2329.5**	**2525.7**	**2527.7**	**2585.7**	**2724.8**	**2752.9**	**2737.1**
TOTAL IMPACT (ha)	**142.8**	**3193.9**	**4039.0**	**5858.6**	**6722.2**	**6843.4**	**7055.9**	**7310.8**	**7430.5**	**7428.8**

4 Supplementary information regarding the Geoecological and Historical Change Mapping (IGHCM) method

DONALD A. WALKER, MARTHA K RAYNOLDS, PATRICK J. WEBBER AND JERRY BROWN

This chapter describes the method, legends, and maps used for the long-term, landscape-level change analysis within three 22 km² areas at Prudhoe Bay.

History

The long-term ecological assessment of cumulative effects of the United States' first Arctic oilfield would not have occurred without the simultaneous occurrence of two major events in the late 1960s: first the actual discovery and development of the Prudhoe Bay oil field and secondly, the design and subsequent implementation of the U.S. Tundra Biome Program of the International Biological Program (IBP) (Brown 1980). The Tundra Biome research project was based at Barrow, Alaska, with objectives to develop a predictive understanding of how tundra ecosystems operate and to bring basic environmental knowledge to bear on problems of degradation, maintenance and restoration of temperature-sensitive ecosystems. Activities in the Prudhoe Bay region provided an opportunity to undertake exploratory ecological research by many of the same scientists and their students who were conducting the intensive studies at Barrow. Since there was essentially no independent logistical support available in the Prudhoe Bay region, collaboration with industry was critical. The Prudhoe Bay Environmental Subcommittee and its member companies provided funding and logistical support for these early studies, which were reported in *Ecological Investigations of the Tundra Biome in the Prud-*

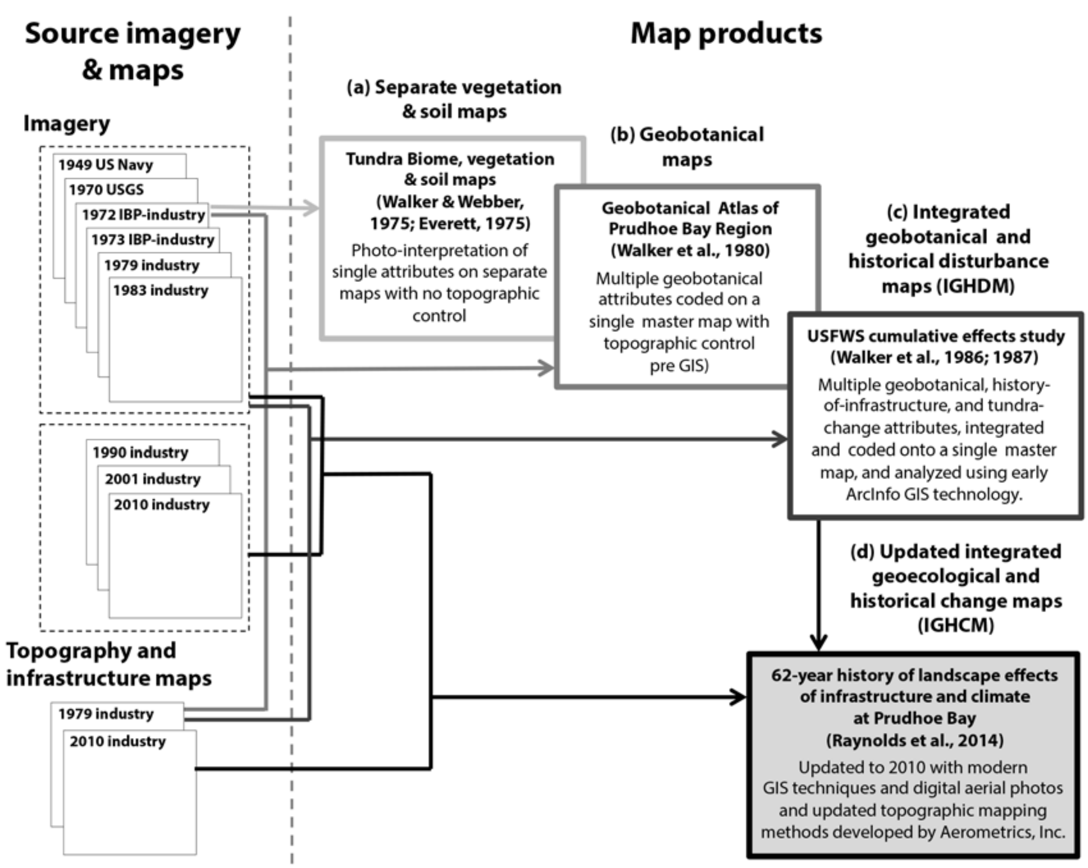

Figure 4.1. *Steps in the evolution of the Integrated Geoecological and Historical Change Mapping (IGHCM) mapping approach. The methods used for the most recent update basically follow those of Walker* et al., *1986a; 1986b.*

hoe Bay Region, Alaska (Brown, 1975) with twelve chapters devoted to climate, soils, plants and animals. Included were the first vegetation, soils and landscape analyses and maps that ultimately lead to the preparation of the *Geobotanical Atlas of the Prudhoe Bay Region, Alaska* (Walker *et al.,* 1980), which later proved to be an invaluable baseline for assessments of the cumulative effects of oil-field development (Walker, Webber e*t al.,* 1986b; Walker *et al.,* 1987; Orians *et al.,* 2003).

Collaborative efforts between universities, the oil industry, government agencies, native organizations and local communities are necessary for optimizing these assessments (AMAP, 2010; Streever *et al.,* 2011). The recent Arctic Research Committee Report to the President emphasized the need for an integrated, science-based approach to arctic management (White House, 2013; Clement *et al.,* 2013). The arctic science community, recognizing the rapid rate of social and environmental change in the Arctic, is leading the effort to actively improve observation networks and assessments, including the Sustained Arctic Observing Networks (SAON) (www.arcticobserving.org), the Arctic Climate Impact Assessment (ACIA, 2005) and the Snow, Water, Ice, Permafrost in the Arctic (SWIPA) (Dicks, 2012). These efforts are sponsored by the partnership of the intergovernmental Arctic Council (www.arctic-council.org) and the non-governmental International Arctic Science Committee (www. iasc.info).

Evolution of the IGHCM method

The Integrated Geoecological and Historical Change Mapping (IGHCM) methods used in this volume evolved in four distinct stages during 40 years of research in the Prudhoe Bay region (Fig. 4.1 and 4.2). The earliest soil and vegetation maps produced during the Tundra Biome studies were all separate maps developed independently, using classical vegetation and soil mapping methods at 1:3000 scale (Webber & Walker, 1975; Brown, 1975; Everett *et al.* 1978; Walker *et al.* 1980) (Step a in Fig. 4.1). The focus area of these mapping efforts was the area of Tundra Biome intensive research along the portion of the road network shown in red in Fig. 4.2. It was quickly recognized that vegetation and soil map boundaries in most cases followed nearly the same landform boundaries, and that it would be possible to integrate all the information onto a single "geobotanical map" (Step b in Fig. 4.1) (Everett *et al.,* 1978). The geoecological approach is based on the principle that landforms and parent material are the key

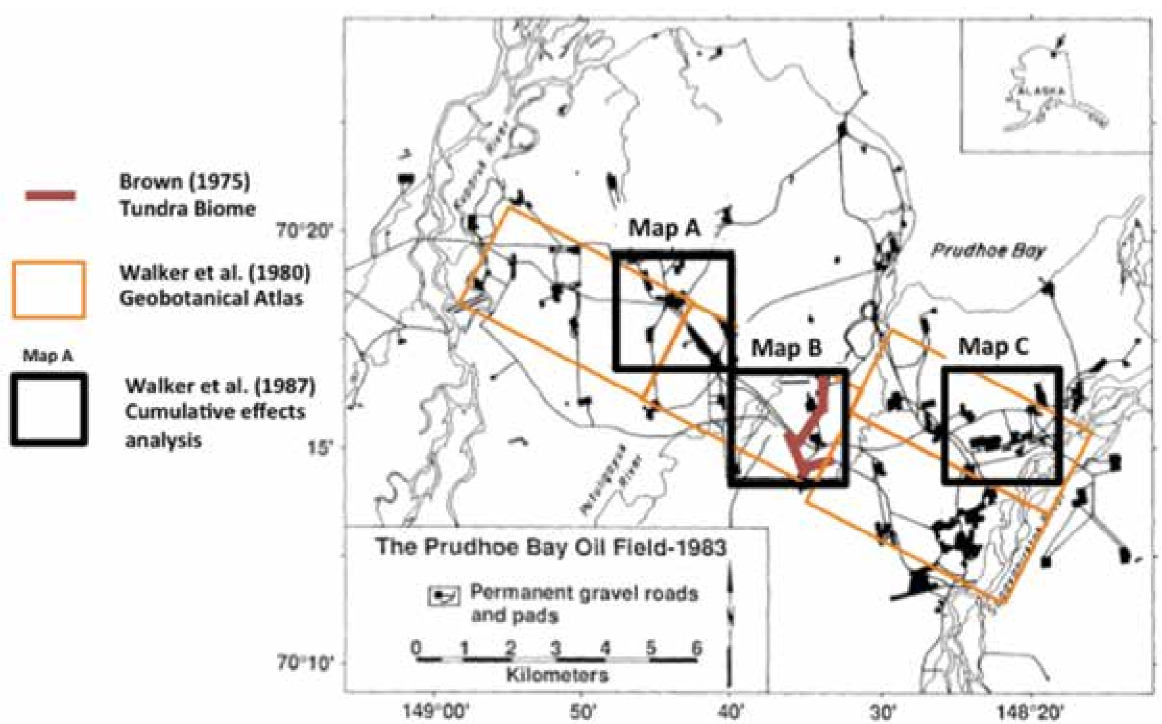

Figure 4.2. *Area of published vegetation, soils and geoecological maps discussed in the text. The history (1968-1983) of infrastructure changes and roadside flooding were mapped for the entire area in Walker* et al. *(1987) and updated in Orians* et al. *(2003). The areas within the three bold squares were mapped in detail using the IGHDM approach described in the text to document infrastructure and associated indirect landscape effects.*

variables controlling the distribution of arctic soils and plant communities. These controls are especially strong in the Prudhoe Bay region because of the ubiquitous patterned ground, where similar assemblages of periglacial landforms, soils, and plant communities are repeated over and over in the landscape. The method is similar to landscape-guided mapping approaches developed independently elsewhere (Christian & Stewart, 1964; Colwell, 1977; Rutter, 1977; Zonneveld, 1988; Dangermond & Harnden, 1990). This integrated mapping approach was used to make the maps in the *Geobotanical Atlas of the Prudhoe Bay Region, Alaska* (orange outlines in Fig. 4.2) (Walker *et al.,* 1980).

The next step in the evolution of the mapping method was the incorporation of the time dimension to map the progression of natural and infrastructure-related changes (Step c in Fig. 4.1). The early geobotanical mapping at Prudhoe Bay occurred prior to the widespread use of geographic information systems (GIS) for scientific applications. The Integrated Geobotanical and Historical Disturbance Mapping (IGHDM) method was a GIS-based approach that produced maps showing predevelopment landscapes as well as 'historical' changes (Walker, Webber e*t al.,* 1986b). The geobotanical maps and the time-series maps of changes lent themselves well to the Integrated Terrain Unit Mapping (ITUM) method and map data standardization approach used in the 1980s and 1990s by the Environmental System Research Institute (ESRI) (Dangermond & Harnden 1990). In brief, the IGHDM approach combined all the terrain, soil, vegetation, and time-series of changes onto a single integrated map and GIS database called the IGHDM Master Map. A wide variety of thematic maps and maps of historical changes could then be derived from the Master Map (for example, Figs. 4.3 to 4.5 and 4.6 to 4.9). The process of map integration is more thoroughly explained in Dangermond & Harnden (1990) and the specific application to the IGHDM method is explained in Walker, Webber e*t al.* (1986b).

The IGHDM approach was used to examine the cumulative effects of oil development to landscapes (Walker, Binnian e*t al.,* 1986a; Walker *et al.,* 1987) and breeding bird populations (Meehan, 1986b) within three 20 km^2 areas of intensive development at Prudhoe Bay (black boundaries, Maps A, B and C in Fig. 4.2). The areas chosen for the analysis overlapped with earlier mapping efforts. They are some of the earliest and most intensively impacted, and most extensively studied areas within the oilfield.

Methods used for this update

The last step in the evolution of the current method (Fig. 4.1, Step d) took advantage of new advances in photogrammetry and GIS technology used during the last two decades by the oil industry and Aerometrics, Inc. for mapping the North Slope oilfields. The full methods are summarized here.

Aerial photographs and topographic base maps

The set of aerial photo missions used for the analysis included the years 1949, 1968, 1970, 1972, 1973, 1977, 1979, 1983, 1990, 2001, and 2010 (Table 4.1). We used film and digital true color aerial photographs obtained by BP Exploration (Alaska) Inc. in 1990, 2001 and 2010 to update the GIS database that was created during earlier cumulative effects analyses (Walker *et al.,* 1987).

Table 4.1. *History of aerial photography in the Prudhoe Bay region. Imagery was obtained by several agencies including the U.S. Navy (USN), U.S Army (USA), U.S. Geological Survey (USGS), National Atmospheric and Space Administration (NASA), International Biological Programme U.S. Tundra Biome (TB), the oil industry (BP Prudhoe Bay Unit (PBU), BP Exploration (Alaska), Inc. (BP), Air Photo Tech, Inc. (APT), and ARCO. Types of imagery include black-and-white (B&W), color, and color-infrared (CIR) film; and color digital photography (D-color). (Meehan, 1984; 1986a)*

DATE	AGENCY	SCALE	TYPE
1949	USN	1:50,000	B&W
1955	USA	1:50,000	B&W
1968	ARCO	1:12,000	Color
1970	USGS	1:68,000	B&W
1972	APT, TB	1:3000	B&W
1972	APT, TB	1:24,000	B&W
1973	Sohio	1:6,000	B&W
1974	NASA	1:120,000	CIR
1977	NASA	1:60,000	CIR
1982	NASA	1:60,000	CIR
1983	PBU	1:18,000	Color
1977-2012[1]	PBU	1:18,000	Color, D-color
1990, July 1-2	BP	1:6000	Color
2001, July 3	BP	1-ft resolution	D-color
2010, July 9 & 25	BP	1-ft resolution	D-color

[1]*Color photographs at 1:18,000 scale and maps of infrastructure and topography by the oil industry for most years.*

Prior to 1990, all the photo-interpreted information was mapped onto mylar overlays that were registered to the 1:6000-scale topographic maps of the region. The three study areas (A, B and C in Fig. 4.2) correspond to sheets 22, 32 and 34 from a series of 49 1:6000-scale topographic map sheets of the Prudhoe Bay Unit Area prepared by Air Photo Tech, Inc., Anchorage, AK, in 1984. The topographic base is now a single continuous CAD topographic database covering the entire region of the study (see Chapter 3).

Baseline geoecological maps

Predevelopment geoecological conditions were photo-interpreted on 1:6000-scale enlargements of 1:24,000-scale photographs taken by the U.S. Navy in 1949, supplemented with extensive ground-based surveys conducted during the Tundra Biome studies in the 1970s (Everett & Parkinson, 1977; Everett, 1980a; Walker *et al.,* 1980; Walker, 1985). The method of making the integrated geoecological map is described in Walker, Webber e*t al.* (1986b). The final integrated geoecological maps contained polygons coded with nine geoecological attributes (dominant vegetation, secondary vegetation, tertiary vegetation; percentage open water; landform; dominant surface form, secondary surface form; dominant soil, and secondary soil), using the GIS attribute codes in Table 4.2. Secondary and tertiary variables were mapped if they were visually estimated to cover more than 30% of a map polygon.

Table 4.2. *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Landforms

MAP UNIT CODES	MAP UNIT COLOR	MAP UNIT NAME	GIS CODES[1]	DESCRIPTION
1	Olive green	Drained thaw-lake basin	1, 25	Distinct drained thaw-lake basin, includes islands within lakes and partially drained lake basins **(GIS code 25)**.
2	Sandy yellow	Primary surface	4	Residual surfaces unaffected by thaw-lake or river processes; may include some very old indistinct thaw-lake basins.
3	Red	Pingo	11	Small hills usually in drained thaw-lake basins. All the pingos in the mapped areas are closed system pingos, which are formed by hydrostatic forces that occur as the unfrozen sediments beneath the previous lake are refrozen after lake drainage. Within the mapped area, pingo dimensions are usually several tens of meters in diameter and up to 15 m high.
4	Light sandy rose	Active floodplain	12	Very active areas of floodplains with little vegetation.
5	Dark sandy rose	Stabilized floodplain	13, 15, 20	Areas adjacent to the very active floodplain that are vegetated but regularly flooded by spring and/or summer flood events. Also includes ancient floodplains with well-defined terraces, oxbow lakes and cut off stream channels , and drainages of smaller streams **(GIS code 15)**. The map unit also includes small areas of bluffs **(GIS code 20)** along the Putuligayuk River on Map B.
6	Dark yellow	Sand dunes (active and stabilized dunes)	16	Sand dunes (both active and stabilized dunes)
7	Bright blue	Lake or pond	51	Lake or pond
8	Dark blue	River or stream	52	River or stream

[1]*Walker, Webber* et al., *1986b.*

Table 4.2 (cont.). *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Dominant surface forms

NEW MAP CODES	MAP UNIT COLOR	MAP UNIT NAME	GIS CODES[1]	DESCRIPTION
1	Orange	High-centered polygons, center-trough relief > 0.5 m	1	High-centered ice-wedge polygons have an elevated central portion to the polygon (usually < 10 m in diameter) and troughs that are relatively low and a few meters wide because of thawing of the ice wedges and subsidence of the trough surface. High-centered polygons with > 0.5 m (often exceeding 1 m) of relief occur in areas with relatively steep hydrological gradients such as along lake margins and stream terraces and some pingos. The unit usually forms a narrow band a few meters wide along the margins of streams and shoreline of former thaw lakes. See Chapter 2, Fig. 2.7b.
2	Yellow or-ange	High-centered polygons, center-trough relief < 0.5 m	2, 11	High-centered polygons with <0.5 m relief occur in flatter, usually well-drained terrain, where there has been some subsidence of the ice-wedge polygon troughs. The centers may be nearly flat, and in some situations, particularly in well-drained situations near streams and drained thaw-lake margins, a secondary pattern of small nonsorted polygons (**GIS code 11**, reticulate pattern, and/or **GIS code 8**, nonsorted circles) is common. See Chapter 2, Fig. 2.7a.
3	Dark brown	Mixed high- and low-centered polygons	5	Complex patterns consisting of both high- and low-centered polygons. Usually this unit occupies relatively small areas and represents incomplete topographic adjustment to a recently decreased base level, for example the drainage of a thaw lake or the relatively recent headward extension of a tributary drainage.
4	Blue green	Low-centered polygons, center-rim relief > 0.5 m	3	Low-centered ice-wedge polygons have a low central *basin*, an elevated *rim* around the basin, and low *troughs* that overlie the ice wedges and separate a polygon from adjacent polygons. Low-centered polygons with greater than 0.5 m of relief between polygon centers and rims are common in sandier portions of the oilfield and in the river deltas. Most of the polygon centers have standing water with aquatic vegetation. See Chapter 2, Fig. 2.6b.
5	Light blue green	Low-centered polygons, center-rim relief < 0.5 m	4	Low-centered polygons with less than 0.5 m of relief between polygon centers and rims with polygon diameters of approximately 10-15 m. See Chapter 2, Fig. 2.6a.
6	Light blue	Irregular pattern	7	Irregular or weakly developed patterned-ground features occur mostly in wet drained lake basins. The raised features may consist of weakly developed strangmoor, aligned hummocks, and/or disjunct polygon rims that are visible on aerial photographs at 1:6,000-scale.
7	Medium yellow	Featureless	10	Featureless or with patterned-ground occupying less than 20% of surface.

[1]*Walker, Webber* et al., *1986b.*

Table 4.2 (cont.). *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Dominant surface forms

NEW MAP CODES	MAP UNIT COLOR	MAP UNIT NAME	GIS CODES[1]	DESCRIPTION
8	Light gray	Non-sorted circles	6	A patterned-ground form that is usually circular or elliptical in form, characteristically barren or partially vegetated in the central portion of the circle and surrounded by vegetation in the margins. Most nonsorted circles in the Prudhoe Bay region are 1-2 m in diameter, flat to slightly domed in the center, with center-center spacing of 2.5 to 4 meters. They are formed by differential frost heave that occurs in the winter (Walker *et al.,* 2008). Other terms include frost scars (Everett, 1980b), frost boils, mud boils, mud circles, and spotted tundra.
9	Blue dots over other pattern	Thermokarst pits	14	Small ponds, generally circular in form, a few meters in diameter and often over 70 cm deep. Thermokarst pits form at the junction of ice-wedges, where there has been thawing and subsidence of the ice wedge. With further thawing of the ice-wedge, the ponds can deepen and enlarge and extend along the length of the ice wedge. These features were mapped on the 1973 1:6000 black and white aerial photographs wherever the density of pits was greater than 4 pits per 1-cm circle. Most of the pits were also visible on the 1949 1:24,000-scale BAR photographs. The features were most often mapped as secondary surface forms in conjunction with other patterned-ground features.
10	Red	Pingo	9	Small ice-cored mound (see Landform legend for description)
11	Dark gray	Floodplain surface forms Water	13, 8, 16	Active floodplain features including channels, river bar and river bank deposits and erosion features. The map unit also includes small areas of hummock terrain **(GIS code 8)**, and actively eroding banks **(GIS code 16)** along the Putuligayuk River on Map B.
21	Dark blue		21	Water

[1] *Walker, Webber* et al., *1986b*

Table 4.2 (cont.). *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Dominant vegetation

NEW MAP CODES	MAP UNIT COLOR	MAP UNIT NAME[1]	GIS CODES[2]	DESCRIPTION (Bolded codes are those used in Walker *et al.*, 1980)
1	Pink	Dry tundra	62, 63, 64	Vegetation occurring on drier (xeric and xeromesic) tundra habitats, including: **B1**, Dry *Dryas integrifolia, Carex rupestris, Oxytropis nigrescens, Lecanora epibryon* prostrate dwarf-shrub, crustose-lichen tundra (well-drained sites, nonacidic gravelly soils, pingos, ridges, high-centered polygons); **B2**, Dry *Dryas integrifolia, Saxifraga oppositifolia, Lecanora epibryon* prostrate dwarf-shrub, crustose-lichen tundra (similar to B1, but on finer-grained soil with cryoturbation); **B6**, Dry *Dryas integrifolia, Astragalus alpinus* prostrate dwarf-shrub, forb tundra (river banks); **B14**, Dry *Dryas integrifolia, Salix reticulata, Cetraria richardsonii* prostrate dwarf-shrub, fruticose-lichen tundra (dry, nonacidic, early-thawing snowbanks with hummocky surface forms); **U6**, Dry *Dryas integrifolia, Cassiope tetragona, Cetraria nivalis* dwarf-shrub, fruticose-lichen tundra (well-drained nonacidic snowbeds); **U7**, Moist *Salix rotundifolia, Equisetum scirpoides* prostrate dwarf-shrub tundra (late-thawing, well-drained, nonacidic snowbeds).
2	Light yellow	Moist tundra	41, 42, 48	Vegetation occurring in moist (mesic to hygromesic) tundra habitats, including: **U3**, Moist *Eriophorum angustifolium* ssp. *triste, Dryas integrifolia, Tomentypnum nitens, Thamnolia subuliformis* sedge, prostrate dwarf-shrub, moss tundra [moderately-drained, zonal upland sites especially near streams and drained thaw-lake margins; also well-drained low-centered polygon rims, aligned hummocks. [This unit is equivalent to the northern variant of the zonal association *Dryado integrifoliae-Caricetum bigelowii* (Walker *et al.*, 1994) *Eriophorum angustifolium* ssp. *subarctium* variant (Kade *et al.*, 2005). Most of these areas contain high cover of non-sorted circles with a variety of vegetation types that have been grouped as **B3**, Dry *Saxifraga oppositifolia, Juncus biglumis* forb barren and described more thoroughly as the association *Junco biglumis-Dryadetum integrifoliae* (Kade *et al.*, 2005). Other moist tundra types that cover relatively small areas of the maps include: **U1**, Moist *Carex aquatilis, Dryas integrifolia, Ochrolechia frigida* sedge, prostrate dwarf-shrub, fruticose-lichen tundra (moderately drained, polygon rims and aligned hummocks in acidic portions of the western part of the Prudhoe Bay Oilfield, some areas on Map A); **U2**, Moist *Eriophorum vaginatum, Dryas integrifolia, Tomentypnum nitens, Thamnolia subuliformis* tussock-sedge, prostrate dwarf-shrub, moss tundra (nonacidic tussock tundra on moderately-drained nonacidic upland sites); **U4**, Moist *Carex aquatilis, Dryas integrifolia, Salix arctica, Tomentypnum nitens* sedge, prostrate dwarf-shrub, moss tundra (moister upland sites, centers of drier low polygon centers, polygon rims, aligned hummocks, without lichens); **U8**, Moist *Salix lanata, Carex aquatilis* erect dwarf-shrub, sedge tundra (stream banks with dwarf shrublands); and **U9**, Moist *Dryas integrifolia, Eriophorum angustifolium, Tomentypnum nitens, Didymodon asperifolius* prostrate dwarf-shrub, sedge, moss tundra (moist tundra along stream floodplains that are swept by the spring flood).

[1] *Walker & Acevedo, 1987.* [2] *Walker, Webber* et al., *1986b.*

Table 4.2 (cont.). *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Dominant vegetation

NEW MAP CODES	MAP UNIT COLOR	MAP UNIT NAME[1]	GIS CODES[2]	DESCRIPTION (Bolded codes are those used in Walker *et al.*, 1980)
3	Light blue	Wet tundra	21	Vegetation occurring in wet (hygric) tundra habitats generally without standing water or with shallow (<10 cm) water, including: **M2**, Wet *Carex aquatilis, Drepanocladus brevifolius* sedge tundra (wet nonacidic tundra, low-centered polygon basins and troughs, and lake margins); **M4**, Wet *Carex aquatilis, Scorpidium scorpioides* sedge tundra (wet nonacidic sites with summer-long shallow standing water, polygon centers, drained thaw-lake basins, lake margins); **M1**, Wet *Carex aquatilis, Carex rariflora, Saxifraga foliolosa, Drepanocladus brevifolius* sedge, forb, moss tundra (wet microsites in weakly acidic tundra areas primarily associated with aligned hummocks, mainly in the western part of the Prudhoe Bay Oilfield); **M3**, Wet *Carex aquatilis, Dupontia fisheri, Calliergon richardsonii* sedge, moss tundra (wet polygon centers and meadows in sandy nonacidic soils near the dunes of the Sagavanirktok and Kuparuk Rivers).
4	Light bluish green	Aquatic marsh	2, 3, 5	Emergent vegetation occurring in aquatic habitats with standing water, including: **E1**, Aquatic *Carex aquatilis* sedge marsh (water to about 30 cm); **E2**, Aquatic *Arctophila fulva* grass marsh (water to about 100 cm); **E3**, Aquatic *Scorpidium scorpioides* moss marsh (water to about 100 cm in sand dunes region near the Sagavanirktok River in sandy low-centered polygons with deep water in the polygon basins).
5	Gray	Barren	64, 81, 83, 99	Vegetation on predominantly barren habitats with sparse vascular-plant cover, including: **B4**, Dry *Epilobium latifolium, Artemisia arctica* forb barren (sparsely vegetated river gravel bars); **B5**, Dry *Dryas integrifolia, Salix ovalifolia, Artemisia borealis* prostrate dwarf-shrub, forb barren (sandy river terraces, stabilized sand dunes); **B9**, Dry *Elymus arenarius, Poa hartzii* grass barren (active sand dunes, sandy creek banks); **B13**, Dry *Salix ovalifolia, Artemisia borealis* prostrate dwarf-shrub, forb barren (stabilized sand dunes).
6	Dark blue	Water	1	Unvegetated water, including: **W1**, unvegetated water (lakes and ponds); **W2**, unvegetated water (streams and rivers).

[1]*Walker & Acevedo, 1987.* [2]*Walker, Webber* et al.*, 1986b.*

Table 4.2 (cont.). *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Soils

NEW MAP CODES	MAP UNIT COLOR	MAP UNIT NAME	GIS CODES[1]	DESCRIPTION: BRIEF DESCRIPTION	EVERETT UNITS[2]	EQUIVALENT IN GELISOL SOIL GREAT GROUP[3]
1	Red	Soils of dry tundra	1	Cold, well-drained, base-rich mineral soil with a dark, humus-rich surface horizon (mollic epipedon); calcium carbonate deposits occur on the underside of gravel fragments and free carbonate precipitates throughout the mollic epipedon; little evidence of cryoturbation; a deep active layer exceeding 1 m; mainly on pingos, but also some well-drained sites on terraces along streams and rivers.	Pergelic Cryoborolls	Typic Mollorthols or Calcic Mollorthols
2	Orange	Soils of moist tundra	2	Cold, moderately-drained soil complex, with a dark, base-rich, humus-rich mineral surface horizon (mollic epipedon) or a thick well-decomposed organic surface horizon (histic epipedon); the mineral horizon usually shows some mottling; underlain by permafrost within 1 m of the surface; usually associated with moderately well-drained areas between thaw lakes, river terraces, and stabilized dune features. Considerable cryoturbation may be present due to the presence of either non-sorted circles and/or small non-sorted polygons.	Complex of Pergelic Cryaquolls, Ruptic-Histic Pergelic Cryaquolls, Histic Pergelic Cryaquepts, or Pergelic Cryosaprists	Complex of Aquic Mollorthels; Ruptic, Aquic Molliturbels; Histic Aquorthels, and Typic Sapristels
3	Brown	Soils of wet tundra	3, 8	Cold, wet soil complex. Most soils have thick organic surface horizons of varying degrees of decomposition that overlie wet, silty to loamy, base-rich, gleyed mineral horizons; the depth of summer thaw is generally < 50 cm; occurs in drained lake basins with either featureless or irregular patterned ground.	Complex of Pergelic Cryohemists, Pergelic Cryofibrists, Histic Pergelic Cryaquepts and Pergelic Cryaquepts	Typic Hemistels, Typic Fibristels, Histic Aquorthels, and Typic Aquorthels

[1]*Walker, Webber* et al., *1986b.* [2]*Everett, 1980a, using the U.S. Soil Taxonomy (Soil Survey Staff, 1975) as mapped in Walker, Binnian* et al., *1986a.* [3]*Soil Survey Staff, 1999.*

Table 4.2 (cont.). *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Soils

NEW MAP CODES	MAP UNIT COLOR	MAP UNIT NAME	GIS CODES[1]	DESCRIPTION: BRIEF DESCRIPTION	DESCRIPTION: EVERETT UNITS[2]	DESCRIPTION: EQUIVALENT IN GELISOL SOIL GREAT GROUP[3]
4	Tan	Wet patterned-ground soil association	4	Cold, wet association of soils occurring in areas of wet patterned-ground, mainly low-centered polygon complexes: **a) Polygon basins:** similar to Unit 3 with a thick organic horizon that may penetrate into the permafrost and overlie a wet gleyed mineral horizon. The thickness and degree of decomposition of the organic layer varies and may be sufficient to qualify as an organic soil; depth of summer thaw is generally < 50 cm. **b) Polygon rims:** Soil on the rims and elevated microsites are better drained and in varying states of decomposition, and the active layer is somewhat deeper than in the polygon basin. The soils in vicinity of the rim and ice wedge often exhibits considerable cryoturbation with irregular and distorted soil horizons. **c) Polygon troughs:** Wet soils with thin organic horizons that overlie a thin frozen organic-rich mineral horizon above an ice wedge.	Association of soils: **a) polygon basins:** Pergelic Cryohemists, Pergelic Cryofibrists, Histic Pergelic Cryaquepts, **b) polygon rims:** Pergelic Cryosaprists, Histic Pergelic Craquepts, Pergelic Cryaquolls, **c) polygon troughs:** Pergelic Cryaquepts. (Ref. Fig 43 in Everett, 1980a.)	Association of **a) Polygon basins:** Typic Hemistels, Typic Fibristels, Histic Aquorthels, **b) polygon rims:** Typic Aquiturbels, Histic Aquiturbels, Typic Sapristels, Histic Aquorthels, Aquic Mollorthels, **c) polygon troughs:** Typic Aquorthells
5	Light gray	Non-sorted circle soil association	5	Cold, wet association of soils occurring in areas of non-sorted circles consisting of: **a) Inter-circle areas:** As in Unit 2, with a dark humus-rich mineral surface horizon (mollic epipedon) or a thick well-decomposed organic surface horizon (histic epipedon); the mineral horizon usually shows some mottling; active-layer thickness is generally less than 50 cm. **b) Nonsorted circles:** Mineral soils, that interrupt and underlie the vegetated area surrounding the circles; silts and silt loams, with platy structure due to ice-lens formation in winter; little horizon development, and deep active layers, often exceeding 70 cm. A widespread association, but is shown on the maps only where the non-sorted circles are the dominant element, covering more than 50% of a mapped polygon. In the new Gelisol Great Group, this association is considered a single soil (Turbel) that exhibits evidence of cryoturbation in the form of irregular, broken or distorted horizon boundaries, involutions and accumulation of organic matter	Association of **a) inter-circle areas:** Pergelic Cryaquolls or Histic Pergelic Cryaquepts, **b) nonsorted circles:** Pergelic Cryaquepts (Ref. Fig. 46 in Everett, 1980a.)	Ruptic-Aquic Molliturbels or Ruptic-Histic Aquiturbels

[1]*Walker, Webber* et al., *1986b.* [2]*Everett, 1980a, using the U.S. Soil Taxonomy (Soil Survey Staff, 1975) as mapped in Walker, Binnian* et al., *1986a.* [3]*Soil Survey Staff, 1999.*

Table 4.2 (cont.). *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Soils

NEW MAP CODES	MAP UNIT COLOR	MAP UNIT NAME	GIS CODES[1]	DESCRIPTION: BRIEF DESCRIPTION	DESCRIPTION: EVERETT UNITS[2]	DESCRIPTION: EQUIVALENT IN GELISOL SOIL GREAT GROUP[3]
6	Dark grey	Soils along stream and rivers channels	10, 6	Well-drained, gravelly or sandy alluvial soil with little horizon development. The unit includes the gravel channels with no soils in the active floodplains of the rivers and streams and more stable river bars that may have some soil development.	Pergelic Cryorthents or no soil (in active floodplains)	Typic Haplorthels
7	Yellow	Sand dune soils or other soil covered by layer of aeolian sand	7, 9	Well-drained sand-dune soil, underlain by permafrost at considerable depth. Includes soils covered by a thin layer of wind-blown sand [**9**]	Pergelic Cryopsamments	Typic Psammorthels
8	Blue	Water	21	Water	Water	Water

[1]*Walker, Webber* et al., *1986b.* [2]*Everett, 1980a, using the U.S. Soil Taxonomy (Soil Survey Staff, 1975) as mapped in Walker, Binnian* et al., *1986a.* [3]*Soil Survey Staff, 1999.*

Table 4.2 (cont.). *Geoecological map units on Maps A, B, and C, Prudhoe Bay Oilfield, AK.*

Percent cover of water

1	Gray-blue	0-5 %
2	Light blue	5-30 %
3	Turquoise	30-60 %
4	Med blue	60-90 %
5	Blue	90- 100 %

Maps of historical infrastructure-related changes

Infrastructure-related changes (Table 4.3) were mapped previously for the years 1968, 1970, 1972, 1973, 1977, 1979 and 1983 (Walker *et al.,* 1987). The years 1990, 2001, and 2010 were added using the aerial imagery obtained by the oil industry. Fig. 4.3 shows some of the types of infrastructure-related change that were mapped.

Prior to 1990, the aerial images were enlarged to the 1:6000 mapping scale of the base maps, and areas of direct and indirect anthropogenic effects were delineated on frosted mylar overlays. For each map polygon thus drawn, direct effects, such as gravel roads and pads, and indirect effects, such as flooding from blocked drainage and thermokarst, were coded. For this latest update (1990, 2001, 2010), we used direct on-screen delineation and editing to map the changes. This eliminated the need to make hard copy map layers and hand digitization of the maps.

Historical non-infrastructure-related changes

Natural changes related to riverbank and lake-shore erosion, and stream-channel changes were mapped for the years 1968, 1977 1983, 1990, 2001, and 2010 using a similar approach to that used for the infrastructure-related changes. Up to 1983 there were not noticeable changes in thermokarst occurrence except in roadside areas, where this was mapped as part of the historical indirect infrastructure-related changes. Starting in 2001, a new code was added to the natural changes to designated areas of new thermokarst formation not related to infrastructure.

Map analysis

The geoecological boundaries, historical anthropogenic changes, and historical natural changes were integrated into a single map database (the Master Map) that contained all the information for each of the three map areas (A, B and C, in Fig. 4.2). The IGHCM master maps include geoecological, historical natural change, and historical an-

Figure 4.3. *Examples of direct infrastructure-related effects:* **(a)** *road,* **(b)** *pad,* **(c)** *pipelines; and indirect effects:* **(d)** *flooding due to impeded drainage,* **(e)** *permafrost degradation due to altered drainage patterns—in a 1-km² area of the Prudhoe Bay Oilfield, Alaska, as seen on 2010 aerial photography. Other indirect effects are visible at full resolution, including: powerlines (one crosses from upper left to lower right, passing near* **(d)**, *trails in lower left corner, and gravel and dust adjacent to the road in upper left. This site is located in Map B (Fig. 4.2), near letter* **(n)** *in Figure 4.8.*

thropogenic change boundaries in GIS shapefiles (Walker, Binnian e*t al.,* 1986a; Walker, Webber e*t al.,* 1986b). Each map polygon on the master maps is coded with geoecological, infrastructure-related, and non-infrastructure-related attributes. The total number of attributes assigned to each polygon varied from 34 attributes on Maps A and B to 36 attributes for Map C, because of an extra year (1968) of mapping of dominant and secondary infrastructure-related effects. Attributes included 10 geoecological attributes, 18 infrastructure-related change attributes, and 6 non-infrastructure-related change attributes. ArcMap GIS software was used for digitizing and analyzing the updated maps. The name of the method was modified to Integrated Geoecological and Historical Change Mapping (IGHCM) to incorporate the older 'geoecological' term introduced by (Everett *et al.,* 1978) and the more neutral 'effects' to replace 'disturbance'.

Maps

Thematic maps

The full set of geoecological and historical change maps for areas A, B, and C are in Figs. 4.4, 4.5 and

Table 4.3. *GIS codes for infrastructure-related effects (Walker, Webber* et al., *1986b).*

GIS CODE	DESCRIPTION OF INFRASTRUCTURE-RELATED EFFECT
1	Gravel road or pipeline construction road
2	Peat road
3	Gravel pad
4	Continuous flooding, >75% open water
5	Discontinuous flooding, <75% open water
6	Infrastructure-related thermokarst
7	Vehicle tracks – deeply rutted and/or with thermokarst
8	Vehicle tracks – not deeply rutted
9	Winter road
10	Gravel and construction debris > 75% cover
11	Gravel and construction debris, < 75% cover
12	Heavy dust or dust-killed tundra
13	Excavations of river gravels or other gravel sources, or construction-related excavations
14	Barren tundra caused by oil spills, burns, blading, etc.
15	Barren tundra caused by previous flooding or draining of lakes
16	Construction-induced eolian deposits
17	Pipeline
18	Powerline and associated trails
19	Fence and associated trails
20	Canal

Table 4.4. *GIS codes for non-infrastructure-related changes (Walker, Webber* et al., *1986b).*

NEW MAP CODE	GIS CODE	DESCRIPTION OF NON-INFRASTRUCTURE-RELATED CHANGES
1	2	New vegetation in lake
2	4	Partial revegetation of gravel
3	6, 64	Increase in thermokarst pits (and thermokarst of pingos)
4	61	Widening of thermokarst troughs
5	99	Deposition of river gravel
6	51	Erosion of lake shore
7	28, 52	Erosion of river shore (to gravel or water)
8	63	Erosion from surface flow, gullying
9	21	Decrease in vegetation in lake

4.6. Each set includes a Master Map, which shows all the GIS boundaries for the given area, and separate thematic maps for vegetation, surface forms, landforms, soils, percent cover of water, the total infrastructure-related changes, and total non-infrastructure-related changes.

Time series of infrastructure changes

Time-series maps of historical infrastructure-related changes display changes for nine dates for each of the maps areas (Figs. 4.7 to 4.9). For Maps A and B the time series starts with 1970, the first year of available photography in these areas after the discovery of oil, and continues with 1972, 1973, 1977, 1979, 1983, 1990, 2001, and 2010. For Map C there is an additional year, with the time series starting in 1968.

In Fig. 4.8 we trace the time series of anthropogenic changes on Map B in more detail to give a better impression of the historical record contained in the maps. In 1970, the most extensive changes were related to gravel mining in the Putuligayuk River floodplain (**a**). The gravel mined in the Putuligayuk River was used to construct roads and gravel pads for oil wells, some pipelines and other facilities. Other infrastructure included the main Spine Road (**b1**), a road to the gravel mines (**b2**) with gravel debris, dust and some flooding along the road margins, an aircraft runway that was used prior to construction of the roads (**c**), an early gravel construction pad (**d**), and some roadside flooding (**e**). In some areas, such as drained thaw-lake basins (**e**), the elevated roads and gravel pads acted as barriers to the natural drainage pattern, creating impoundments. During 1972 and 1973, a major oil-field pipeline was constructed (**f** and **g**). By 1977, a thaw lake had been drained (**h**) and Pump Station 1 (**i**) at the beginning of the Trans-Alaska Pipeline System was constructed on the relatively ice-free sediments in the lake basin. Several new gravel pads for oil wells were also constructed (**j**). In 1979, new pipelines (**k**) and a pad expansion (**l**) resulted in additional impoundments (**m**). Additional pad expansion occurred by 1983 (**n**) and 1990 (**o**). In 1990, a new pipeline (**p**) was also added, and in 2001 and 2010 additional off-road vehicle trails (**q**) and areas of dust (**r**) are evident.

Summary tables of changes

The area of infrastructure-related and non-infrastructure-related changes as of 2010 are summarized for Maps A, B, and C, and the total area mapped (Table 4.5). Infrastructure-related changes are further broken down by direct and indirect effects. Discussion of these results is in Chapter 1 (Raynolds *et al.,* 2014).

The distribution of thermokarst in each geoecological category (vegetation, surface forms, landforms, and soils), and for the total natural landscape outside of lakes and floodplains, is presented in Table 4.6. Discussion of these results is found in Chapter 1.

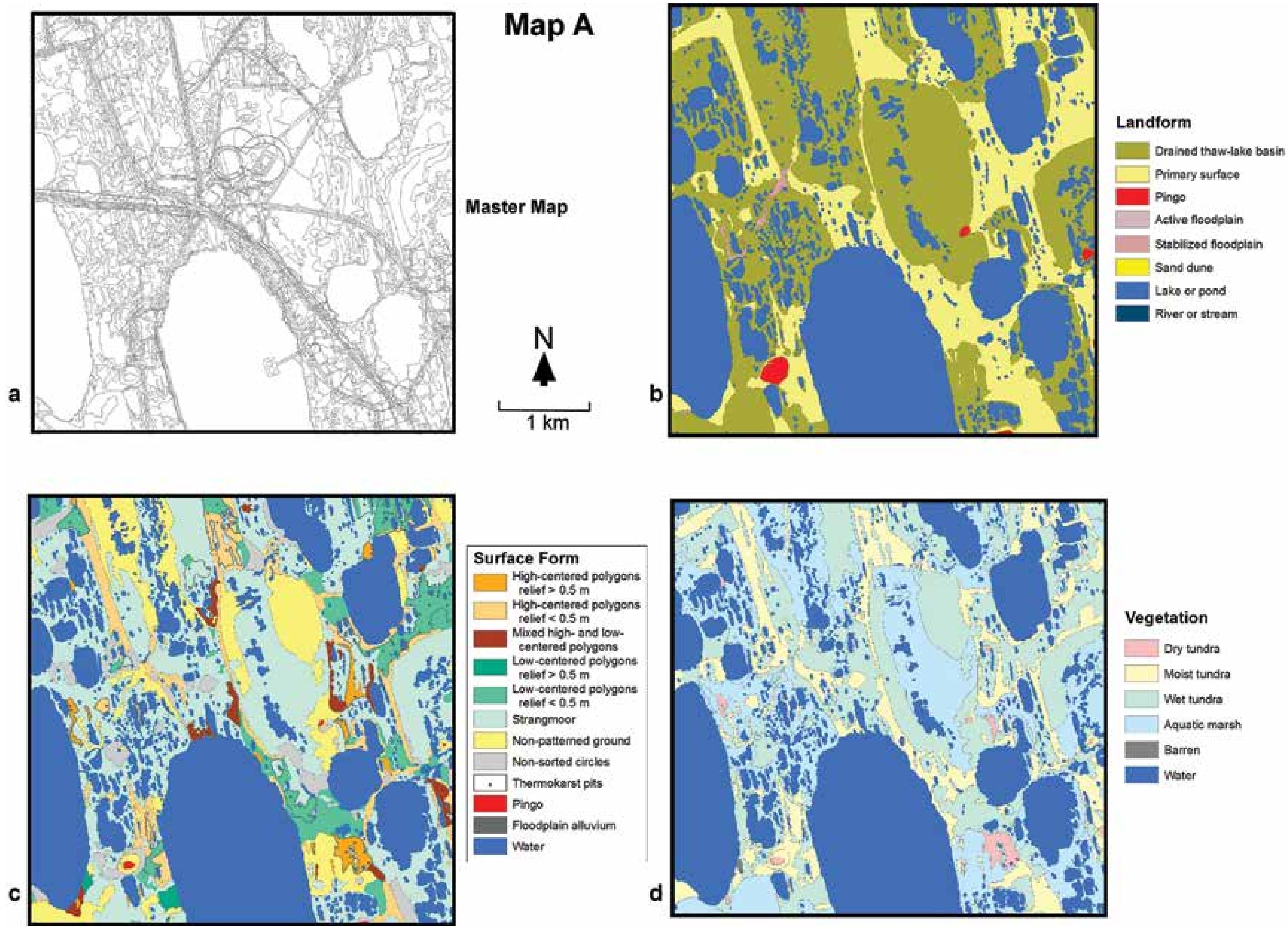

Figure 4.4 (a to d). *Thematic maps of Map Area A, Prudhoe Bay, Alaska (see location map in Fig. 4.2).* **(a)** *Master map showing all polygons in the GIS file;* **(b)** *Dominant vegetation;* **(c)** *Dominant surface form;* **(d)** *Landforms. Geoecological data are from Everett & Parkinson, 1977; Everett* et al.*, 1978; Walker* et al.*, 1980; Walker, 1985; Walker & Everett, 1991.*

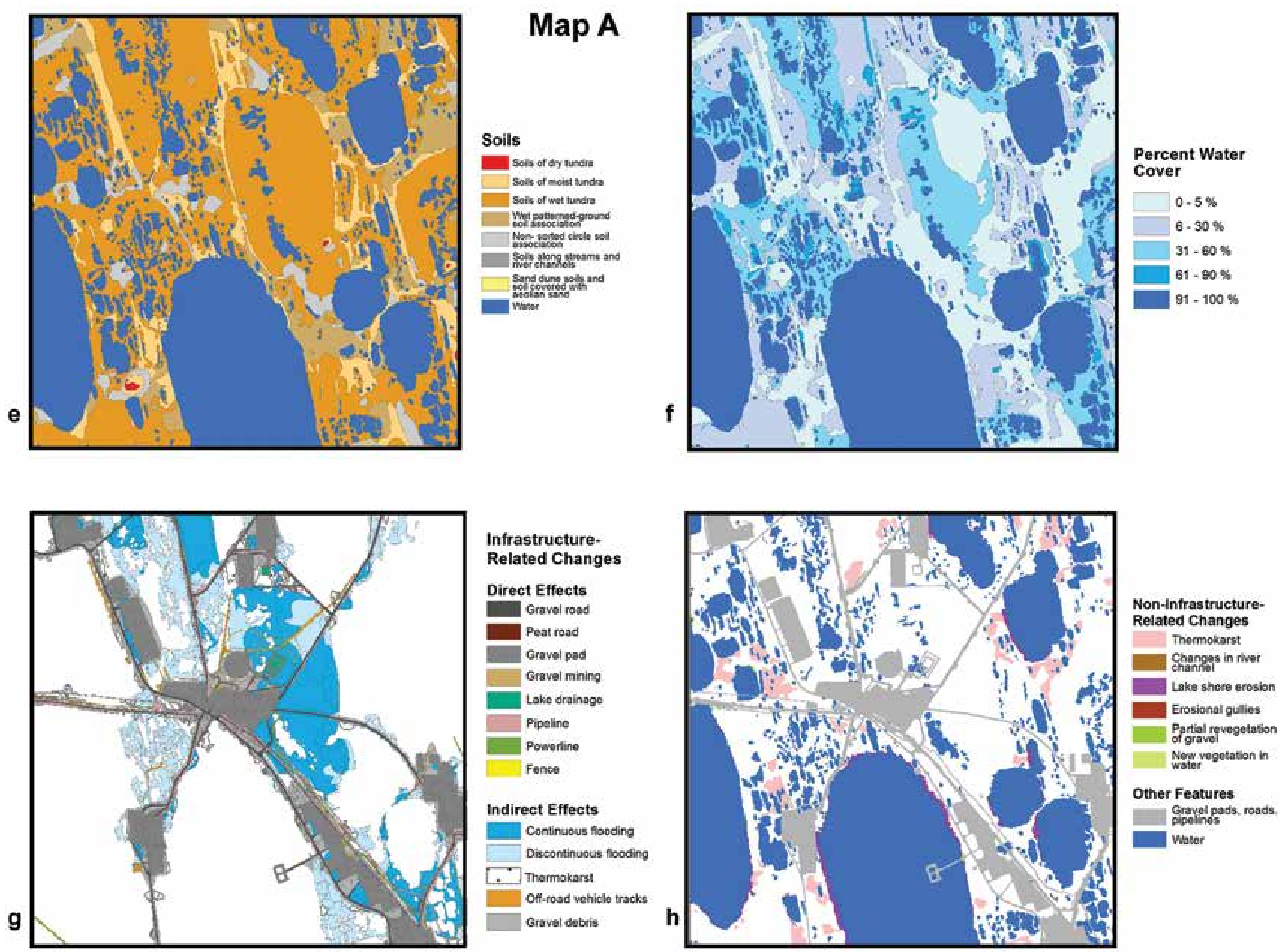

Figure 4.4 (e to h). *Thematic maps of Map Area A, Prudhoe Bay, Alaska (see location map in Fig. 4.2).* **(e)** *Soil;* **(f)** *Percent water cover;* **(g)** *Infrastructure-related changes;* **(h)** *Non-infrastructure-related changes. Geoecological data are from Everett & Parkinson, 1977; Everett* et al.*, 1978; Walker* et al.*, 1980; Walker, 1985; Walker & Everett, 1991.*

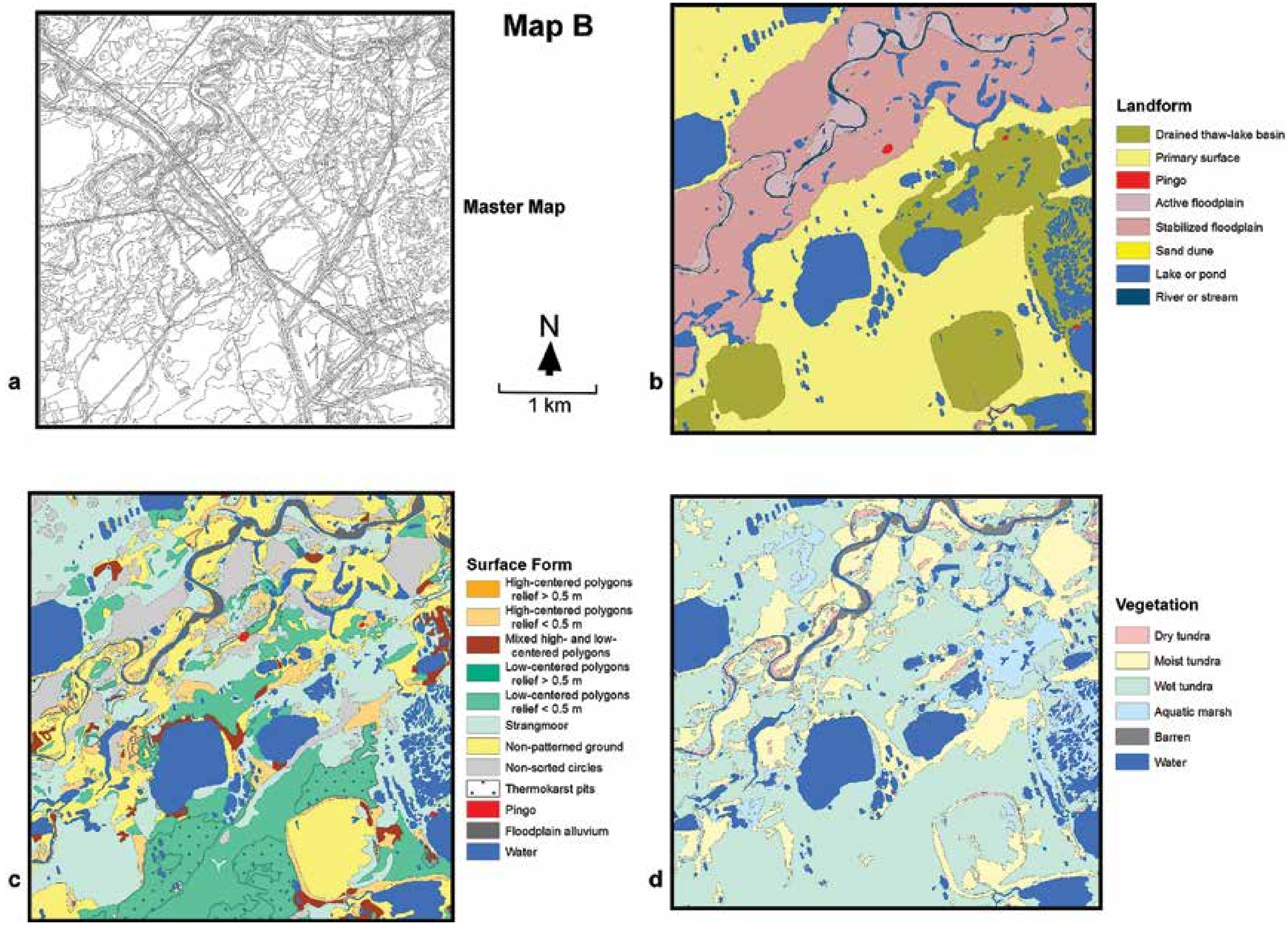

Figure 4.5 (a to d). *Thematic maps of Map Area B, Prudhoe Bay, Alaska (see location map in Fig. 4.2).* **(a)** *Master map showing all polygons in the GIS file;* **(b)** *Dominant vegetation;* **(c)** *Dominant surface form;* **(d)** *Landforms. Geoecological data are from Everett & Parkinson, 1977; Everett* et al.*, 1978; Walker* et al.*, 1980; Walker, 1985; Walker & Everett, 1991.*

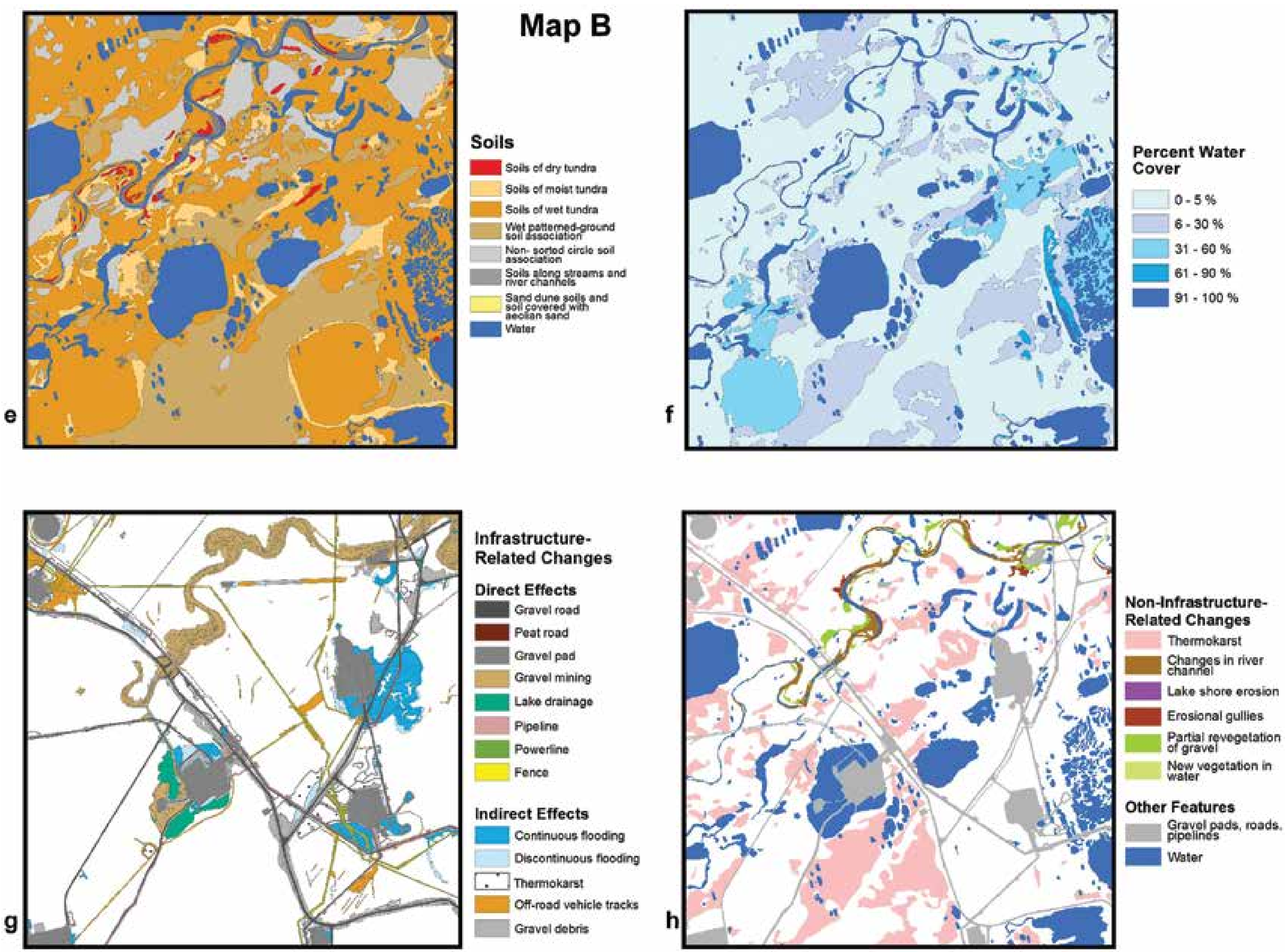

Figure 4.5 (e to h). *Thematic maps of Map Area B, Prudhoe Bay, Alaska (see location map in Fig. 4.2).* **(e)** *Soil;* **(f)** *Percent water cover;* **(g)** *Infrastructure-related changes;* **(h)** *Non-infrastructure-related changes. Geoecological data are from Everett & Parkinson, 1977; Everett* et al.*, 1978; Walker* et al.*, 1980; Walker, 1985; Walker & Everett, 1991.*

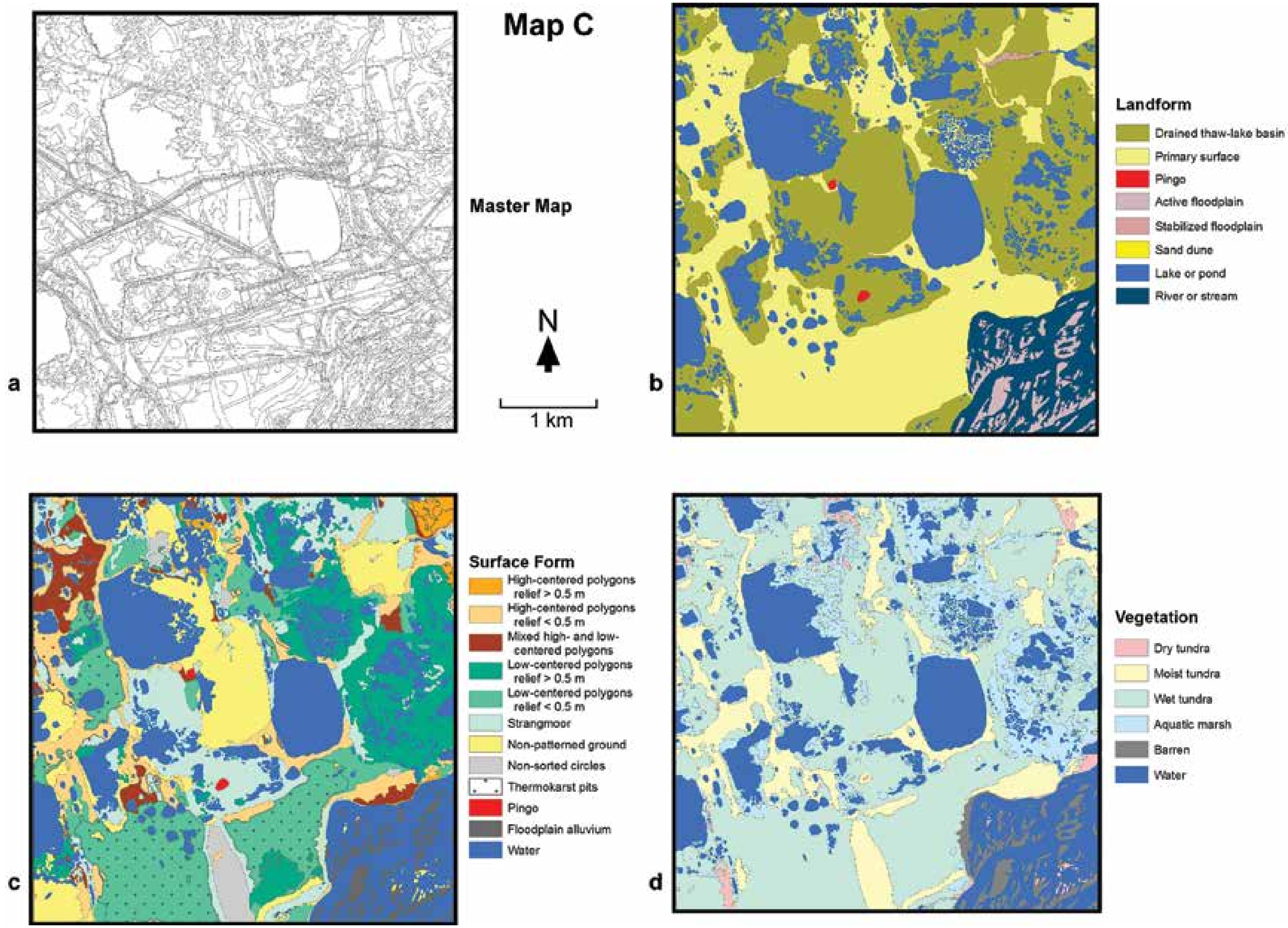

Figure 4.6 (a to d). *Thematic maps of Map Area C, Prudhoe Bay, Alaska (see location map in Fig. 4.2).* **(a)** *Master map showing all polygons in the GIS file;* **(b)** *Dominant vegetation;* **(c)** *Dominant surface form;* **(d)** *Landforms. Geoecological data are from Everett & Parkinson, 1977; Everett* et al.*, 1978; Walker* et al.*, 1980; Walker, 1985; Walker & Everett, 1991.*

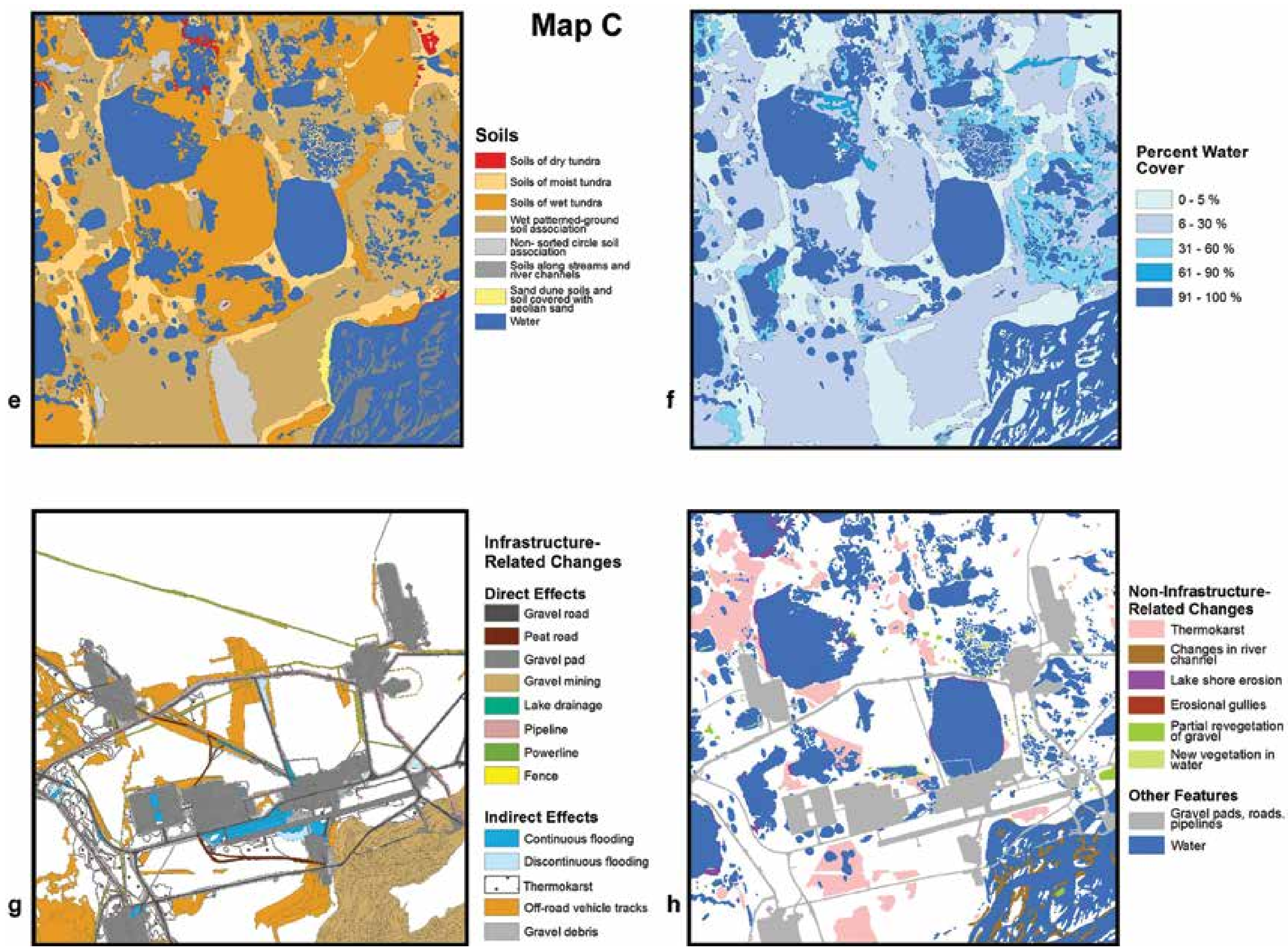

Figure 4.6 (e to h). *Thematic maps of Map Area C, Prudhoe Bay, Alaska (see location map in Fig. 4.2).* **(e)** *Soil;* **(f)** *Percent water cover;* **(g)** *Infrastructure-related changes;* **(h)** *Non-infrastructure-related changes. Geoecological data are from: Geoecological data are from Everett & Parkinson, 1977; Everett* et al., *1978; Walker* et al., *1980; Walker, 1985; Walker & Everett, 1991.*

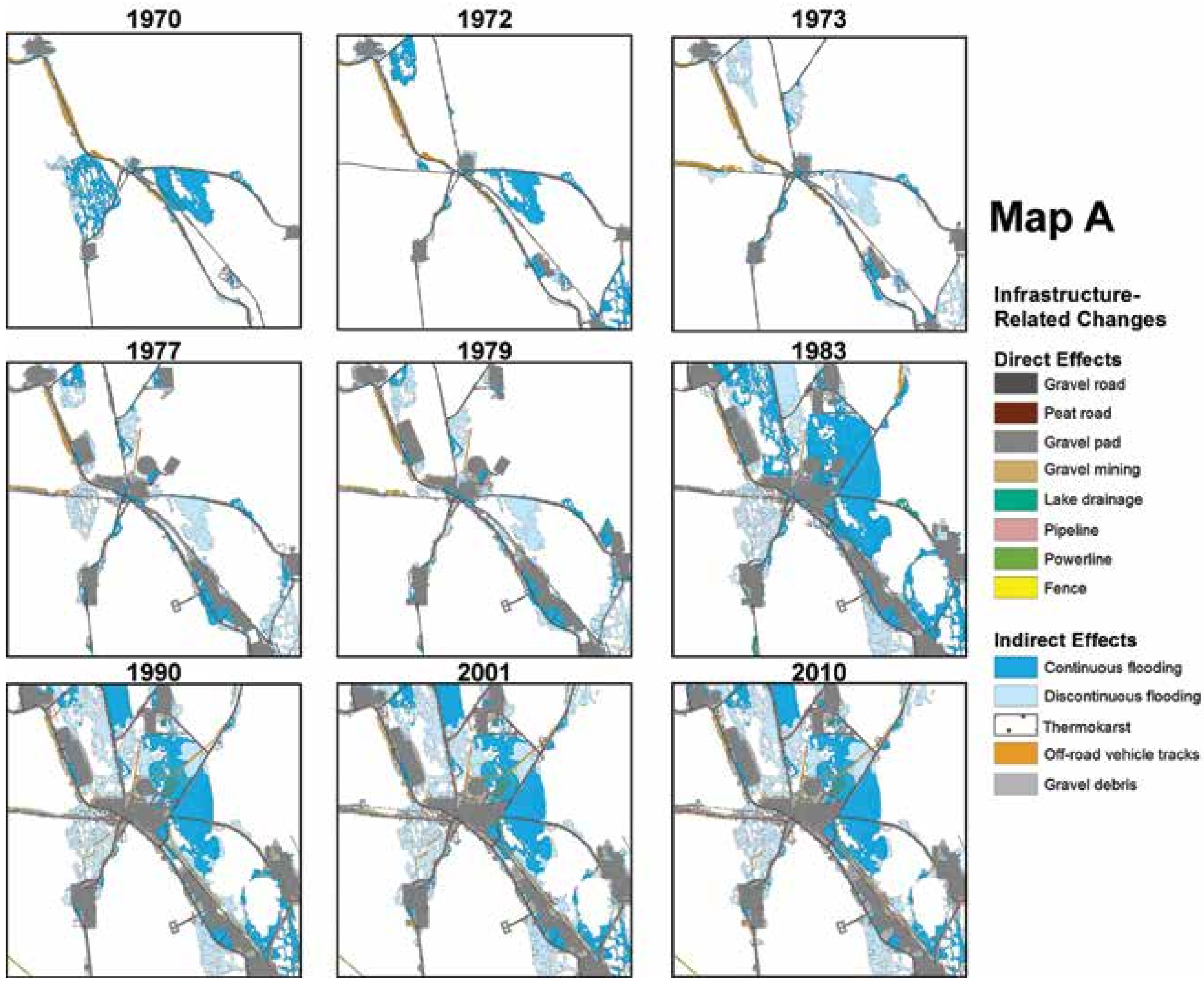

Figure 4.7. *Infrastructure-related changes in Map Area A, 1970-2010, Prudhoe Bay, Alaska (see location map in Fig. 4.2)*

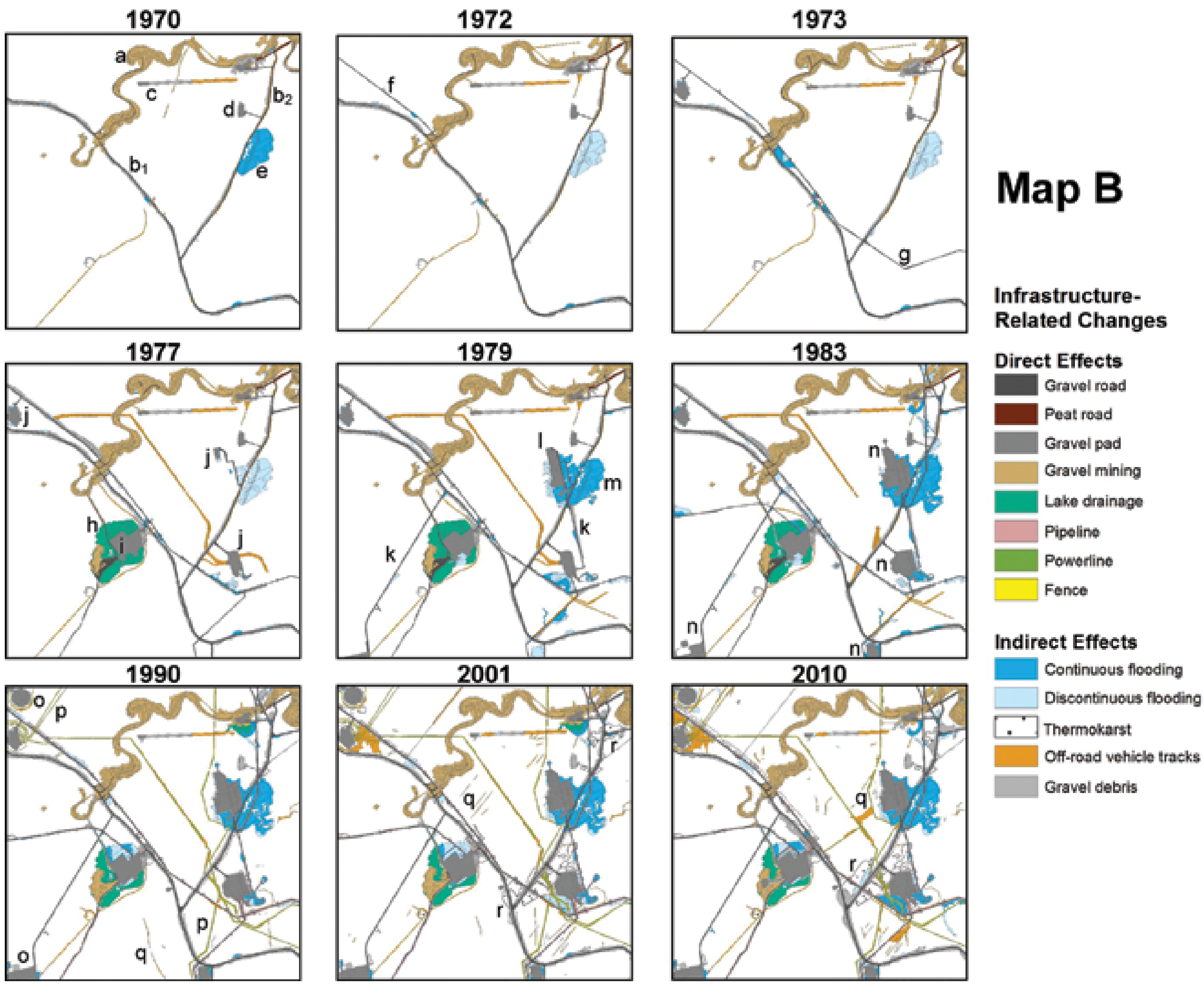

Figure 4.8. *Infrastructure-related changes in Map Area B, 1970-2010, Prudhoe Bay, Alaska (see location map in Fig. 4. 2). See page 45 for an explanation of map references* **(a)** *to* **(r)**.

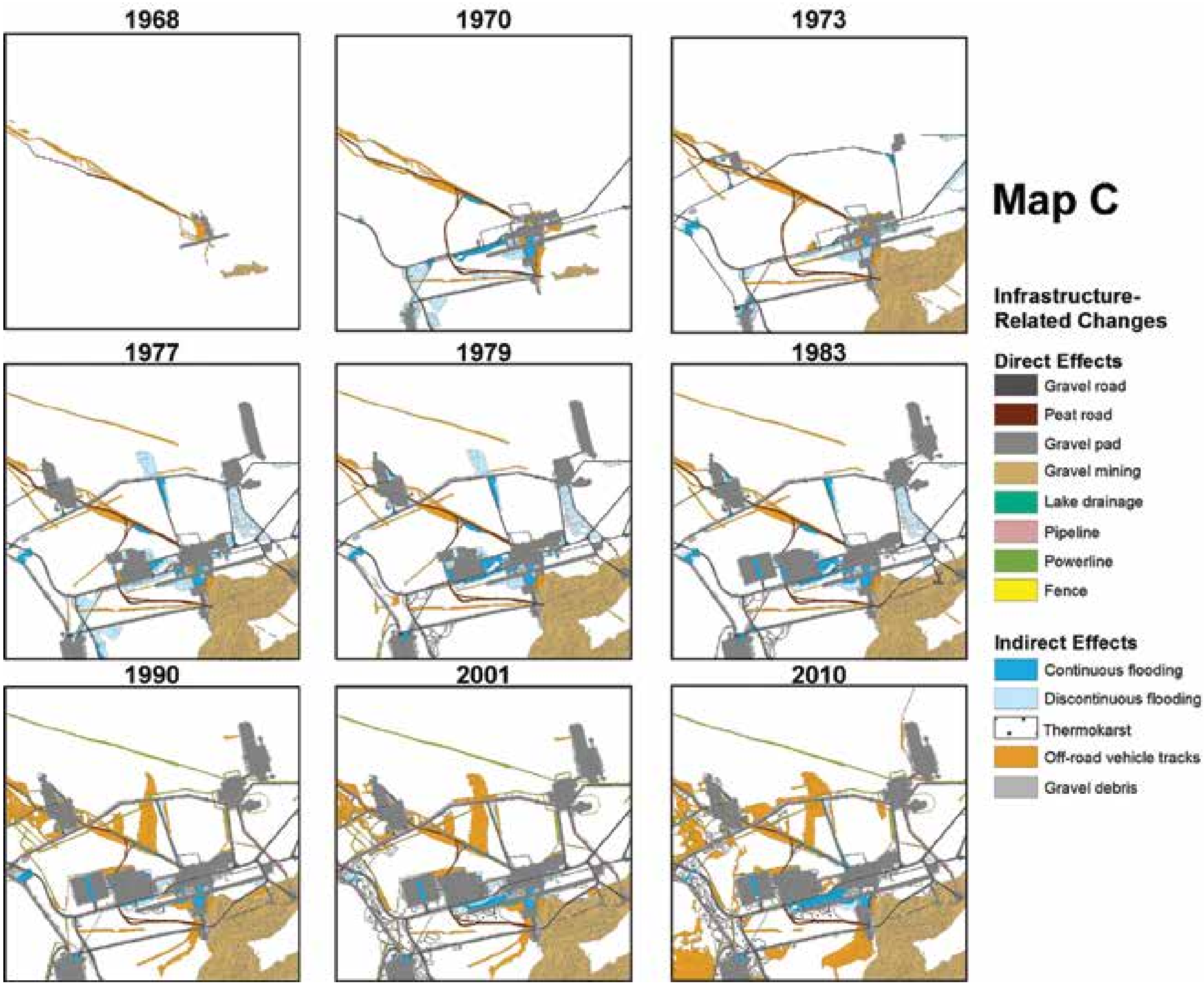

Figure 4.9. *Infrastructure-related changes in Map Area C, 1968-2010, Prudhoe Bay, Alaska (see location map in Fig. 4. 2)*

Table 4.5. *Total historical infrastructure-related and non-infrastructure-related changes on Maps A, B, and C and the total mapped area.*

TYPE OF IMPACT	GIS CODES[1]	MAP A AREA , HA (%)	MAP B AREA , HA (%)	MAP C AREA , HA (%)	TOTAL AREA , HA (%)
Direct infrastructure-related effects					
Gravel pads	3	170 (8.1)	89 (4.2)	179 (8.6)	438 (7.0)
Gravel roads	1	47 (2.3)	47 (2.2)	41 (2.0)	136 (2.2)
Pipelines	17	37 (1.7)	23 (1.1)	19 (0.9)	79 (1.3)
Peat roads	2	0	0	9 (0.5)	9 (0.2)
Excavations	13, 20	0	102 (4.9)	155 (7.4)	257 (4.1)
Total area with direct impacts		**254 (12.2)**	**260 (12.4)**	**404 (19.3)**	**919 (14.6)**
Indirect infrastructure-related effects					
Flooding	4, 5	524 (25.1)	136 (6.5)	41 (2.0)	701 (11.2)
Gravel and debris	9, 10, 11	140 (6.7)	84 (4.0)	108 (5.2)	332 (5.3)
Infrastructure-related thermokarst	6	85 (4.1)	99 (4.7)	184 (8.8)	367 (5.9)
Vehicle tracks	7, 8	16 (0.8)	57 (2.7)	217 (10.4)	291 (4.6)
Powerlines	18	9 (0.4)	26 (1.2)	29 (1.4)	64 (1.0)
Dust, barren tundra	12, 14, 15, 16, 20	7 (0.3)	27 (1.3)	0	34 (0.5)
Fences	19	2 (0.1)	2 (0.1)	1 (0.0)	5 (0.1)
Total area with indirect impacts		**783 (37.5)**	**431 (20.6)**	**581 (27.8)**	**1794 (28.6)**
Total area impacted by industrial development		**1037 (49.6)**	**691 (33.0)**	**985 (47.1)**	**2713 (43.3)**
Non-infrastructure-related changes					
Ice-wedge degradation	3, 4	67 (3.2)	299 (14.3)	137 (6.6)	503 (8.0)
River erosion	7, 8	0	12 (0.6)	99 (4.7)	112 (1.8)
Lake erosion	6	22 (1.0)	1 (0.1)	13 (0.6)	36 (0.6)
Revegetation	1, 2	1 (0.1)	14 (0.7)	11 (0.5)	26 (0.4)
River deposition	5	0	9 (0.5)	0	9 (0.2)
Total area impacted by non-industrial changes		**90 (4.3)**	**336 (16.1)**	**261 (12.5)**	**687 (11.0)**

[1] *Walker, Webber e*t al., *1986b.*

Table 4.6. *Total area of direct and indirect infrastructure-related effects and non-infrastructure-related thermokarst within each geoecological unit within Maps A, B and C in 2010.*

Map A

GEOECOLOGICAL MAP UNIT	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Landforms								
Drained thaw-lake basin	791.3	37.9	114.9	14.5	390.5	49.3	21.9	7.7
Primary surface	454.9	21.8	113	24.9	109	23.9	44	19.0
Pingo	11.0	0.5	1	9.9	3	24.6	1	14.8
Active floodplain	0.0	0.0	0	0.0	0	0.0	0	0.0
Stabilized floodplain	7.1	0.3	0.3	4.1	3.3	45.8	0.1	1.7
Sand dunes (active and stabilized)	0.0	0.0	0	0.0	0	0.0	0	0.0
Lake or pond	824.8	39.5	24	3.0	49	6.0	0	0.0
River or stream	0.2	0.0	0	0.0	0	0.0	0	0.0
Surface Form								
High-centered polygons, center-trough relief > 0.5 m	24.5	1.2	7	28.1	4	14.9	0	0.0
High-centered polygons, center-trough relief < 0.5 m	119.3	5.7	34.7	29.1	27.9	23.4	10.2	18.0
Mixed high-centered and low-centered polygons	27.3	1.3	9	32.8	6	22.3	0	2.4
Low-centered polygons, center-rim relief > 0.5 m	5.9	0.3	0	0.0	0	0.0	0	5.7
Low-centered polygons, center-rim relief < 0.5 m	128.5	6.2	28	21.4	32	24.6	22	32.2
Irregular pattern	658.5	31.5	104	15.8	283	43.0	22	8.3
Featureless	220.7	10.6	28	12.6	129	58.2	3	4.9
Non-sorted circles	76.5	3.7	19	25.1	24	31.7	8	24.4
Thermokarst pits (dominant code)	0.0	0.0	0	0.0	0	0.0	0	0.0
Pingo	2.3	0.1	0	0.0	0	0.0	1	23.4
Floodplain surface forms	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thermokarst pits (secondary code)	134.1	6.4	28	20.9	29	21.3	21	27.3

Table 4.6 (cont.). *Total area of direct and indirect infrastructure-related effects and non-infrastructure-related thermokarst within each geoecological unit within Maps A, B and C in 2010.*

Map A

GEOECOLOGICAL MAP UNIT	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Vegetation								
Dry tundra	15.8	0.8	6.4	40.5	2.6	16.3	0.0	0.0
Moist tundra	286.2	13.7	74.6	26.1	74.7	26.1	26.4	19.3
Wet tundra	497.3	23.8	102	20.4	187	37.6	33	15.9
Aquatic marsh	494.9	23.7	48.3	9.8	241.6	48.8	7.9	3.8
Barren	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	794.4	38.0	23	2.9	49	6.1	0	0.0
Soils								
Soils of dry tundra	2.5	0.1	0	0.0	0	0.0	0	1.8
Soils of moist tundra	175.8	8.4	50	28.2	39	22.3	11	13.2
Soils of wet tundra	871.2	41.7	130.3	15.0	408.4	46.9	24.5	7.4
Wet patterned ground soil association	137.1	6.6	28	20.1	34	25.1	23	30.1
Non-sorted circle soil association	77.1	3.7	22	28.5	23	30.0	9	27.3
Soils along streams and river channels	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sand dune soils and soils covered by layer of sand	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	825.7	39.5	24	3.0	49	6.0	0	0.0

Map B

GEOECOLOGICAL MAP UNIT	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Landforms								
Drained thaw-lake basin	346.2	16.6	41.1	11.9	70.9	20.5	9.0	3.8
Primary surface	782.5	37.4	70.6	9.0	127.7	16.3	211.8	36.3
Pingo	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Active floodplain	84.9	4.1	52.0	61.3	1.2	1.4	0.3	1.0
Stabilized floodplain	548.5	26.2	41.8	7.6	41.0	7.5	76.4	16.4
Sand dunes (active and stabilized)	0.6	0.0	0.0	5.7	0.0	0.0	0.0	0.0
Lake or pond	309.6	14.8	37.1	12.0	32.3	10.4	1.4	0.6

Table 4.6 (cont.). *Total area of direct and indirect infrastructure-related effects and non-infrastructure-related thermokarst within each geoecological unit within Maps A, B and C in 2010.*

Map B	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
GEOECOLOGICAL MAP UNIT	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
River or stream	18.1	0.9	14.5	80.2	0.0	0.1	0.0	0.0
Surface form								
High-centered polygons, center-trough relief > 0.5 m	0.7	0.0	0.1	9.2	0.1	20.0	0.4	86.6
High-centered polygons, center-trough relief < 0.5 m	122.0	5.8	20.0	16.4	15.0	12.3	27.0	31.1
Mixed high-centered and low-centered polygons	50.4	2.4	3.5	7.0	7.3	14.5	12.4	31.4
Low-centered polygons, center-rim relief > 0.5 m	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Low-centered polygons, center-rim relief < 0.5 m	398.9	19.1	28.5	7.2	63.9	16.0	162.2	52.9
Irregular pattern	563.5	26.9	65.8	11.7	85.7	15.2	64.6	15.7
Featureless	397.9	19.0	51.0	12.8	39.9	10.0	9.0	2.9
Non-sorted circles	200.8	9.6	12.3	6.1	28.8	14.4	20.9	13.1
Thermokarst pits (dominant code)	1.9	0.1	0.2	12.3	0.0	0.0	0.5	32.0
Pingo	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Floodplain surface forms	26.4	1.3	24.1	91.5	0.1	0.2	0.3	15.0
Thermokarst pits (secondary code)	182.3	8.7	15.0	8.2	24.6	13.5	93.7	65.6
Vegetation								
Dry tundra	25.9	1.2	10.9	42.3	1.7	6.6	0.7	5.0
Moist tundra	470.1	22.5	52.2	11.1	60.0	12.8	52.5	14.7
Wet tundra	1122.7	53.7	101.3	9.0	156.1	13.9	243.5	28.1
Aquatic marsh	159.4	7.6	22.3	14.0	24.3	15.2	1.1	0.9
Barren	23.1	1.1	22.0	95.0	0.1	0.6	0.3	31.6
Water	290.5	13.9	48.4	16.7	30.8	10.6	0.8	0.4
Soils								
Soils of dry tundra	16.7	0.8	5.0	29.9	0.5	3.2	0.3	2.3
Soils of moist tundra	164.3	7.9	24.0	14.6	17.1	10.4	30.9	25.1
Soils of wet tundra	954.4	45.6	110.8	11.6	130.0	13.6	81.6	11.4
Wet patterned ground soil association	398.8	19.1	28.8	7.2	63.9	16.0	162.5	53.1
Non-sorted circle soil association	202.9	9.7	12.4	6.1	28.9	14.2	21.8	13.5

Table 4.6 (cont.). *Total area of direct and indirect infrastructure-related effects and non-infrastructure-related thermokarst within each geoecological unit within Maps A, B and C in 2010.*

Map B	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
GEOECOLOGICAL MAP UNIT	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Soils along streams and river channels	26.5	1.3	24.5	92.6	0.3	1.3	0.3	20.2
Sand dune soils and soils covered by layer of sand	0.5	0.0	0.1	13.2	0.0	0.0	0.2	39.7
Water	327.7	15.7	51.6	15.7	32.3	9.9	1.4	0.6

Map C	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
GEOECOLOGICAL MAP UNIT	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Landforms								
Drained thaw-lake basin	734.3	35.1	96.6	13.1	189.6	25.8	25.2	5.6
Primary surface	700.6	33.5	125.4	17.9	218.4	31.2	111.6	31.3
Pingo	1.9	0.1	1.5	75.5	0.1	5.3	0.0	0.0
Active floodplain	55.4	2.6	46.4	83.7	0.4	0.8	0.0	0.0
Stabilized floodplain	3.8	0.2	0.0	1.1	0.1	2.5	0.0	0.0
Sand dunes (active and stabilized)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lake or pond	450.2	21.5	17.1	3.8	10.4	2.3	0.2	0.1
River or stream	144.9	6.9	115.6	79.8	0.4	0.2	0.0	0.0
Surface form								
High-centered polygons, center-trough relief > 0.5 m	30.1	1.4	0.3	1.0	0.2	0.6	0.6	2.1
High-centered polygons, center-trough relief < 0.5 m	181.3	8.7	35.6	19.7	66.7	36.8	20.6	26.2
Mixed high-centered and low-centered polygons	69.1	3.3	7.6	11.0	10.7	15.5	34.2	67.4
Low-centered polygons, center-rim relief > 0.5 m	255.7	12.2	32.5	12.7	42.4	16.6	2.9	1.6
Low-centered polygons, center-rim relief < 0.5 m	342.5	16.4	80.4	23.5	120.1	35.1	54.1	38.1
Irregular pattern	281.4	13.5	44.3	15.8	63.3	22.5	18.7	10.8
Featureless	243.4	11.6	20.0	8.2	102.1	42.0	1.4	1.1
Non-sorted circles	38.2	1.8	1.7	4.4	2.5	6.6	4.2	12.4

Table 4.6 (cont.). *Total area of direct and indirect infrastructure-related effects and non-infrastructure-related thermokarst within each geoecological unit within Maps A, B and C in 2010.*

Map C	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
GEOECOLOGICAL MAP UNIT	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Thermokarst pits (dominant code)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pingo	1.9	0.1	1.5	75.5	0.1	5.3	0.0	0.0
Floodplain surface forms	52.5	2.5	45.9		0.4		0.0	0.0
Thermokarst pits (secondary code)	348.4	16.7	76.0	21.8	126.9	36.4	81.4	56.0
Vegetation								
Dry tundra	27.5	1.3	1.2	4.5	5.3	19.1	1.1	5.1
Moist tundra	289.3	13.8	54.6	18.9	85.2	29.5	28.7	19.2
Wet tundra	967.1	46.2	143.4	14.8	292.5	30.2	106.5	20.0
Aquatic marsh	242.8	11.6	26.2	10.8	25.6	10.5	0.6	0.3
Barren	60.0	2.9	48.3	80.5	4.0	6.6	0.0	0.0
Water	504.3	24.1	128.8	25.5	6.7	1.3	0.2	0.1
Soils								
Soils of dry tundra	11.2	0.5	0.4	3.7	0.0	0.3	0.3	2.8
Soils of moist tundra	224.0	10.7	39.9	17.8	71.8	32.1	20.4	18.2
Soils of wet tundra	517.9	24.8	62.2	12.0	163.1	31.5	20.8	7.1
Wet patterned ground soil association	622.5	29.8	112.3	18.0	161.6	26.0	89.6	25.7
Non-sorted circle soil association	57.9	2.8	6.6	11.3	8.0	13.8	5.7	13.2
Soils along streams and river channels	55.4	2.6	46.4	83.7	0.4	0.8	0.0	0.0
Sand dune soils and soils covered by layer of sand	7.1	0.3	2.1	29.8	3.5	49.8	0.0	0.0
Water	595.1	28.5	132.7	22.3	10.7	1.8	0.2	0.1

Total of 3 Maps	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
GEOECOLOGICAL MAP UNIT	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Landforms								
Drained thaw-lake basin	1871.8	29.8	252.6	13.5	651.0	34.8	56.0	5.8
Primary surface	1937.9	30.9	309.0	15.9	454.7	23.5	367.7	31.3
Pingo	14.3	0.2	2.5	17.7	2.8	19.5	1.1	11.9

Table 4.6 (cont.). *Total area of direct and indirect infrastructure-related effects and non-infrastructure-related thermokarst within each geoecological unit within Maps A, B and C in 2010.*

Total of 3 Maps	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
GEOECOLOGICAL MAP UNIT	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Active floodplain	140.4	2.2	98.4	70.1	1.6	1.1	0.3	0.8
Stabilized floodplain	559.4	8.9	42.1	7.5	44.3	7.9	76.5	16.2
Sand dunes (active and stabilized)	0.6	0.0	0.0	5.7	0.0	0.0	0.0	0.0
Lake or pond	1584.6	25.3	78.6	5.0	92.1	5.8	1.7	0.1
River or stream	163.2	2.6	130.1	79.7	0.4	0.2	0.0	0.0
Surface form								
High-centered polygons, center-trough relief > 0.5 m	55.2	0.9	7.2	13.1	4.0	7.2	1.0	2.4
High-centered polygons, center-trough relief < 0.5 m	422.5	6.7	90.3	21.4	109.6	25.9	57.9	26.0
Mixed high-centered and low-centered polygons	146.8	2.3	20.1	13.7	24.2	16.5	46.9	45.7
Low-centered polygons, center-rim relief > 0.5 m	261.6	4.2	32.5	12.4	42.4	16.2	3.3	1.7
Low-centered polygons, center-rim relief < 0.5 m	869.9	13.9	136.5	15.7	215.7	24.8	238.6	46.1
Irregular pattern	1503.5	24.0	214.4	14.3	431.9	28.7	105.7	12.3
Featureless	862.1	13.7	98.7	11.5	270.6	31.4	13.5	2.7
Non-sorted circles	315.5	5.0	33.2	10.5	55.6	17.6	33.2	14.6
Thermokarst pits (dominant code)	1.9	0.0	0.2	12.3	0.0	0.0	0.5	32.0
Pingo	5.7	0.1	1.5	25.6	0.1	1.8	0.5	13.3
Floodplain surface forms	79.2	1.3	70.1	88.5	0.5	0.6	0.3	3.8
Thermokarst pits (secondary code)	664.8	10.6	119.0	17.9	180.1	27.1	196.2	53.7
Vegetation								
Dry tundra	69.2	1.1	18.6	26.9	9.5	13.8	1.7	4.2
Moist tundra	1045.6	16.7	181.4	17.3	220.0	21.0	107.6	16.7
Wet tundra	2587.0	41.2	346.3	13.4	635.5	24.6	383.1	23.9
Aquatic marsh	897.2	14.3	96.8	10.8	291.5	32.5	9.5	1.9
Barren	83.9	1.3	70.3	83.8	4.1	4.9	0.3	3.4
Water	1589.3	25.3	200.1	12.6	86.4	5.4	1.1	0.1
Soils								
Soils of dry tundra	30.4	0.5	5.4	17.8	0.6	1.9	0.6	2.4

Table 4.6 (cont.). *Total area of direct and indirect infrastructure-related effects and non-infrastructure-related thermokarst within each geoecological unit within Maps A, B and C in 2010.*

Total of 3 Maps

GEOECOLOGICAL MAP UNIT	TOTAL		DIRECT EFFECTS		INDIRECT EFFECTS		NON-INFRASTRUCTURE THERMOKARST	
	AREA (HA)	% OF MAP	AREA (HA)	% OF UNIT	AREA (HA)	% OF UNIT	AREA (HA)	% OF REMAINING UN-DISTURBED TUNDRA
Soils of moist tundra	564.0	9.0	113.5	20.1	128.2	22.7	62.7	19.5
Soils of wet tundra	2343.5	37.4	303.2	12.9	701.5	29.9	126.9	9.5
Wet patterned ground soil association	1158.4	18.5	168.6	14.6	259.9	22.4	274.6	37.6
Non-sorted circle soil association	337.9	5.4	40.9	12.1	60.0	17.8	36.3	15.3
Soils along streams and river channels	81.9	1.3	70.9	86.6	0.8	0.9	0.3	3.2
Sand dune soils and soils covered by layer of sand	7.5	0.1	2.2	28.8	3.5	46.8	0.2	8.5
Water	1748.5	27.9	208.7	11.9	92.5	5.3	1.7	0.1

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5 Ground-based studies of the effects of roads on landscapes and permafrost in the Prudhoe Bay Oilfield, Alaska

DONALD A. WALKER, MIKHAIL KANEVSKIY, YURI L. SHUR, MARCEL BUCHHORN, MARTHA K. RAYNOLDS, GEORGE V. MATYSHAK AND LISA M. WIRTH

This chapter describes research that began in summer 2014 to examine the long-term effects of oilfield infrastructure to the landscapes and permafrost in the Prudhoe Bay Oilfield.

Introduction

The main objective of our 2014 field campaign was to learn how the process of ice-wedge thermokarst near roads is initiated and how it progresses over time. Ice-wedge thermokarst has shown abrupt increases in recent years (Jorgenson *et al.*, 2006; Raynolds et al., 2014). Field studies of thermokarst within the Prudhoe Bay Oilfield are currently being conducted at Torre Jorgenson's site and our Colleen Site A study area, which are located in close proximity to each other in the vicinity of Deadhorse near Lake Colleen (Fig. 5.1).

The 2014 field study was conducted along a section of the Spine Road at 70˚13'23"N, 148˚28'15"W on the north side of Lake Colleen, 2.9 km north of the main Deadhorse airport. The Colleen Site A study area is a 420-m x 60 m swath of tundra that contains two transects: Transect T1 is on the northeast side of the road, and T2 is on the southwest side (Fig. 5.2). The principle tasks described here are to: 1) document the change at Colleen Site A using a time series of aerial photographs and remote sensing; 2) examine the effects and extent of dust and flooding on the landforms, soils and soil temperatures, and vegetation; and 3) examine the ice content of the soils and determine the current status of the protective layer of frozen mineral and organic soils above the ice wedges.

Here we provide a history and description of Colleen Site A, an overview of the methods used to examine permafrost and ecosystem change, and some of the key observations from the 2014 field campaign.

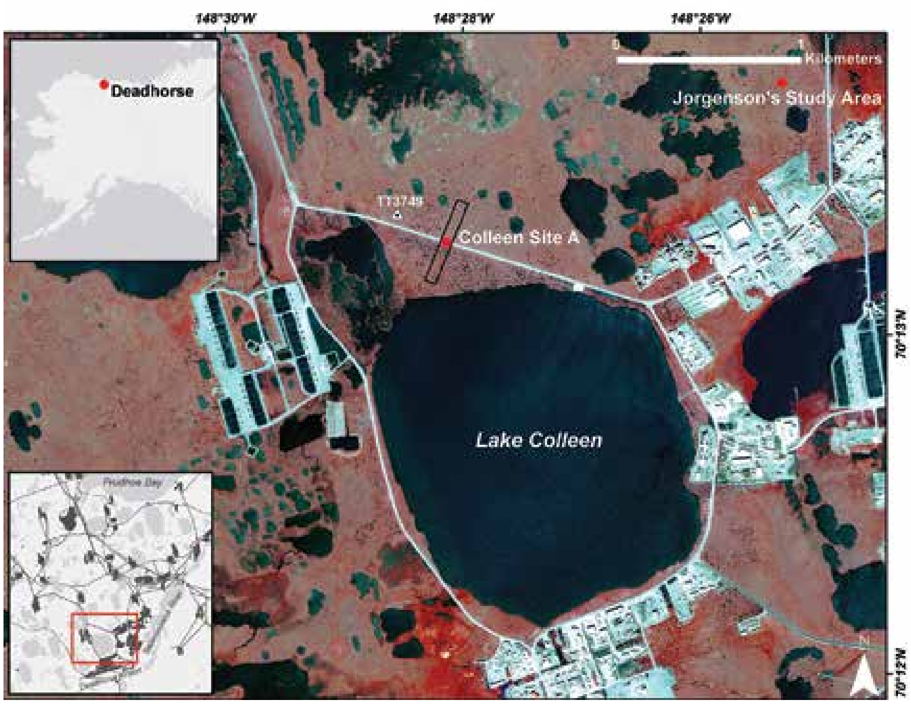

Figure 5.1. *The Lake Colleen region. The Colleen Site A study area is located along a straight section of the Spine Road on the north side of Lake Colleen, 2.9 km north of the main Deadhorse airport, which is just south of the area shown. Several partially drained thaw lakes are on the east, north, and west sides of the lake. Colleen Site A and Jorgenson's study area are both on a residual surface that shows no apparent history of thaw lake processes. Note that Lake Colleen is surrounded by roads and other infrastructure. TT3749 is a bench mark that provided reference for a 2014 topographic survey. The main study area, Colleen Site A, is shown enlarged in Fig. 5.2. The base image is derived from a false-color-infrared World View image (July 9, 2010). The red tones show areas of highly productive vegetation, mainly in drained lake basins and in areas of altered drainage near roads and gravel pads.*

History and description of Colleen Site A

Aerial photographs obtained by the U.S. Navy in 1949 prior to discovery of the oilfield (Fig. 5.3a) and a 1973 geobotanical map

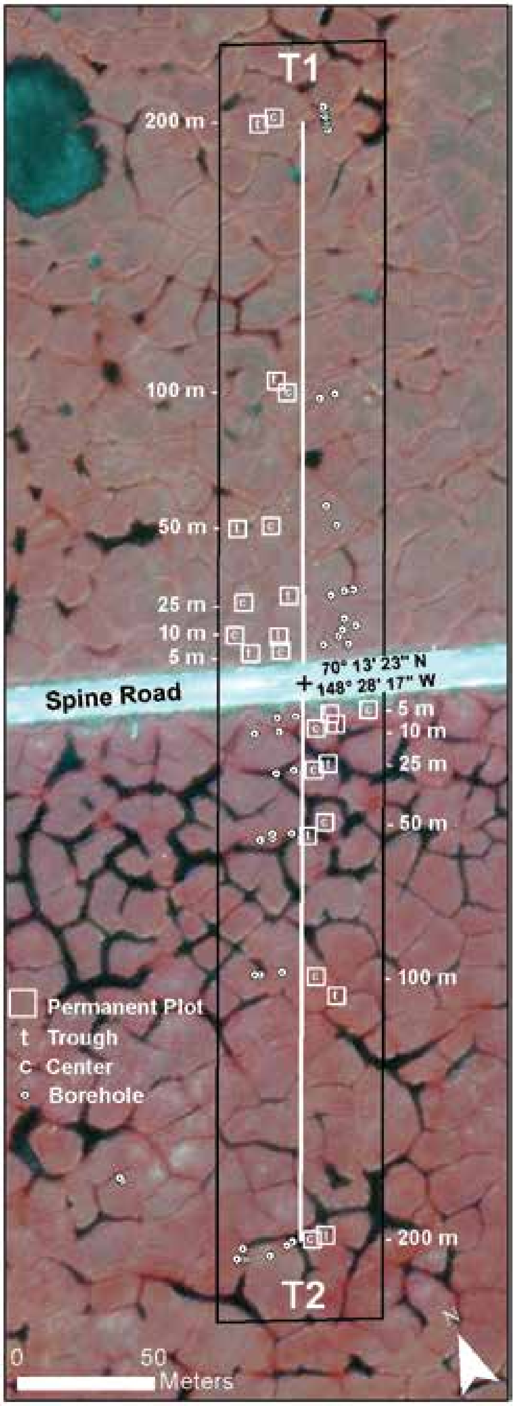

Figure 5.2. *The Colleen Site A study area. Transects T1 and T2 are each 200 m long. Permanent plots (white squares) are located in centers* **(c)** *and troughs* **(t)** *of ice-wedge polygons at 5, 10, 25, 50, 100, and 200 m from the road. Boreholes (white circles) are located at the same distances from the road in centers and troughs. Base image is the same as in Fig. 5.1. Transect T1 traverses mainly low-centered ice-wedge polygons. Transect T2 is periodically flooded. In late summer at the time of the image, flooding has resided exposing the mainly high-centered ice-wedge polygons with interconnected flooding in the polygon troughs.*

made shortly after development began (Fig. 5.4) (Walker *et al.,* 1980) provide a baseline against which changes to the landscape can be compared. A satellite image of the same area in 2010 shows the extensive network of infrastructure that now covers much of the original surface (Fig. 5.3b).

The flat landscape in the vicinity of Lake Colleen and Deadhorse is typical of much of the Arctic Coastal Plain. Numerous oriented thaw lakes, partially drained thaw-lake basins, and broad braided river floodplains cover most of the surface. The 1949 aerial photograph (Fig 5.3a) shows that Colleen Site A and Jorgenson's study site are both on a residual surface with few signs of previous thaw-lake processes. The extremely ice-rich nature of this surface was revealed in a 2-m deep trench that was dug at the Gas Arctic facility to bury a test gas pipeline (location in Fig. 5.4; also see a diagram and description of this trench in Chapter 3, Fig. 3.5). This residual surface is composed of a network of ice-wedge polygons with thermokarst troughs above ice wedges and thermokarst pits that lie at the intersection of many of the ice-wedges (see photos and explanation of thermokarst pits in Chapter 2). The thermokarst troughs and pits are indicative of large ice wedges that have undergone some thawing. The geobotanical map (Fig. 5.4) indicates that prior to and immediately after construction of the Spine Road, Colleen Site A was a rather homogeneous network of low-centered polygons with less than 50 cm of trough-rim elevation contrast. The vegetation was dominated by wet sedge, moss tundra in most of the polygon centers and troughs (vegetation map unit W2 of Walker *et al.,* 1980) and moist sedge, dwarf-shrub, moss tundra (vegetation map units U4 and U3) on the polygon rims. Details of the species composition of these vegetation units are in Walker & Everett (1991). Jorgenson's study site is in an area that is relatively uninfluenced by infrastructure; whereas Colleen Site A has been strongly affected by road-related impacts since the beginning of the oilfield.

Aerial photos of Colleen Site A taken in 1949, 1972, 1979, 2010 and 2013 reveal major changes in the extent of thermokarst (Fig. 5.5). The 1949 image reveals the extent of thermokarst at the site prior to construction. Although partially obscured by thin clouds in the 1949 image, the small lake in the upper left corner of the site and numerous thermokarst pits are visible. Nearly all of these features are also visible in the 1972 image, when the road had been present for three years. Some gravel left over from construction is visible near the road in the 1972 image, but otherwise the tundra shows

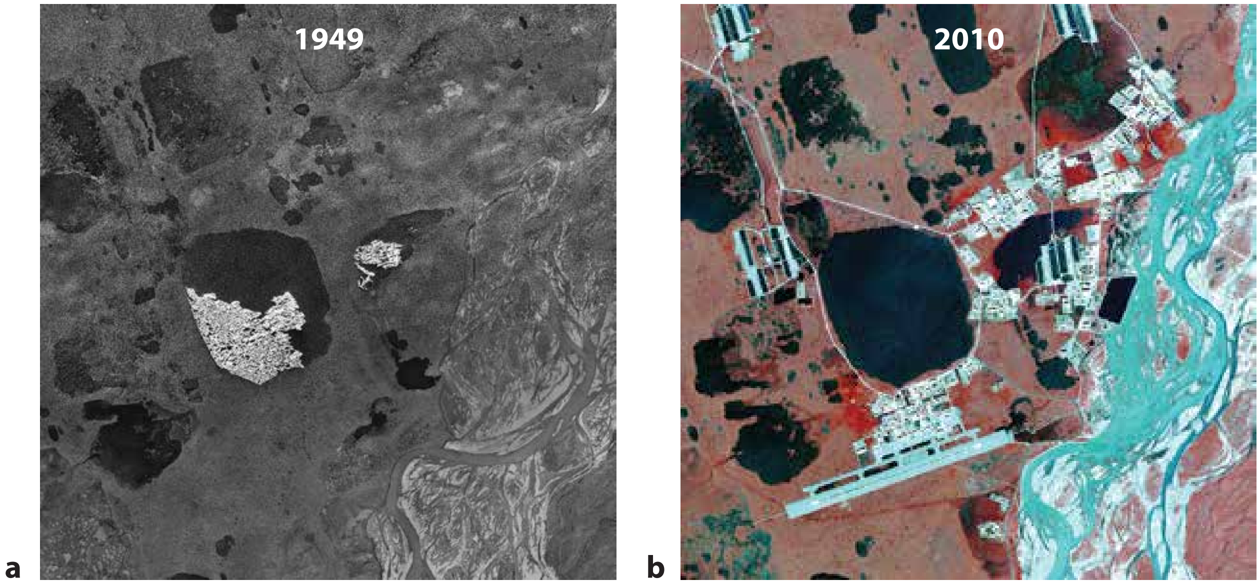

Figure 5.3. *Deadhorse region 1949* **(a)** *and 2010* **(b)**. *Images are from U.S. Navy, July 6, 1949, 1:20,000-scale BAR photography and World View false color-infrared (CIR) composite, July 9, 2010. Prominent features in both images include Lake Colleen, which is partially ice covered in 1949, and the braided Sagavanirktok River on the right side of the image. Also visible are several partially drained thaw lakes. Thermokarst pits are visible on residual surfaces that are unaffected by thaw-lake processes in both images. Prominent features in the 2010 image include the Deadhorse Airport south of Lake Colleen, numerous gravel pads that support service and contractor facilities for the oil field, two drill sites (Drill Site 13, center left, and Drill Site 12, center right), and the network of roads and pipelines that connect the various facilities. The 2010 World View image displays green photosynthetic vegetation as shades of red. The bright red areas have highly productive vegetation caused by altered drainage, warmer soils, and enhanced nutrient regimes mostly related to changes induced by infrastructure.*

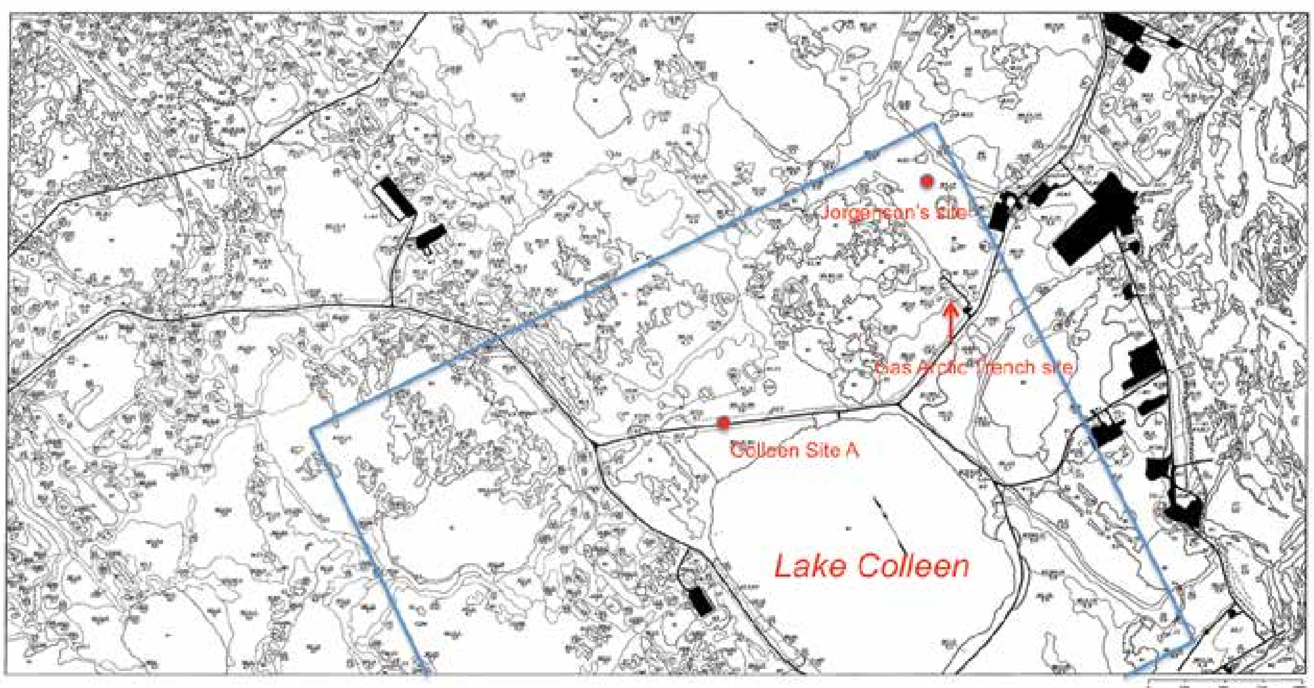

Figure 5.4. *Map of the geobotany as of 1973 in the vicinity of Lake Colleen. The map is coded with vegetation, soils and landforms codes that are described in Walker* et al., *1980. The blue rectangle is the area shown in Fig. 5.1, which includes the Colleen Site A study area (see also Fig. 5.2), Jorgenson's study area, and the Gas Arctic trench site, where Kaye Everett conducted dust studies and described permafrost characteristics in a 117 x 2.5 m trench. From Map 2 of the Geobotanical Atlas of the Prudhoe Bay Region, Alaska (Walker* et al., *1980).*

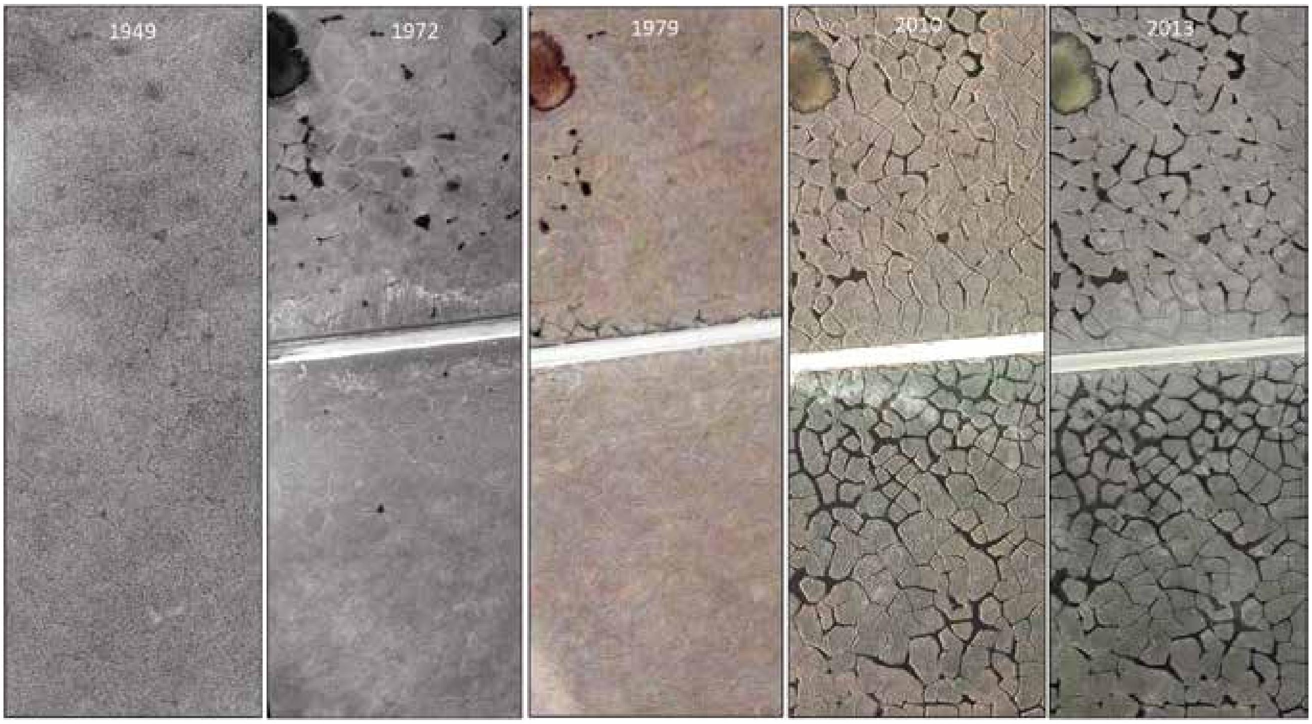

Figure 5.5. *Colleen Site A study area (as in Figure 5.2) time series 1949-2013, showing progression of change. Imagery and original scales: Jul 1, 1949, U.S. Navy, BAR, black & white, 1:20,000; July 15, 1972, U.S Army Cold Regions Research and Engineering Laboratory (CRREL), black & white, 1:6000; July 13, 1979, Prudhoe Bay Unit, color,1:18,000; 2010 BP Alaska, digital, color, 1-foot resolutions; 2013 BP Alaska, digital, color, 0.75-foot resolution. Notes: The Spine Road was constructed in 1969 so does not appear on the 1949 image. Thin cloud cover obscures the small lake in the upper left in 1949, but most of the thermokarst pits that are present in 1972 are also visible on the 1949 image.*

little change compared to 1949. The 1979 image shows some thermokarst starting to form on the north side of the road. Most of this thermokarst is not visible in the 2010 and 2013 because extremely heavy dustfall and gravel spray from road maintenance has buried the thermokarst features. Some thermokarst ponds present in 1972 are clearly reduced in extent in the 1979 image, possibly due to generally lower water levels or to colonization of the polygon troughs by dense vegetation. By 2010, extensive thermokarst had developed on both sides of the road, but most extensively on the southwest side. There is more water on the tundra in the 2013 image compared to 2010.

The 2014 sampling program

Transects

Ground-based studies are necessary to examine changes to the vegetation soils and permafrost that are not visible on the aerial photographs. Transects T1 and T2 were established to quantify changes to the vegetation, soils, active layer, and permafrost in relationship to distance from the road (Fig. 5.6). Pin flags were placed at one-meter intervals within 100 m of the road and then at 5-m intervals to 200 m from the road. Vertical 150-cm PVC posts with red stripes at 100 and 150 cm height were placed at 50, 100, and 200 m in order to locate the transects in winter. At each pin flag, we measured thaw depth, terrain elevation, plant-canopy height, water depth, thickness of the dust horizon, vegetation type, and leaf-area index (LAI).

Permanent vegetation plots

Permanent vegetation plots and photo points were established in ice-wedge-polygon centers and troughs at 5, 10, 25, 50, 100, and 200 m from the road on the left side of each transect as viewed from the road (Fig. 5.2 and 5.7). Three additional plots (relevés 14-1, 14-2, and 14-3, not shown in Fig. 5.2) were sampled in vegetation types with very heavy dust loads immediately adjacent to the road, and two other vegetation plots (relevés 14-4 and 14-5, also not shown in Fig. 5.2) were placed in relatively undisturbed mesic tundra at a distance of approximately 450 m from the road along Transect T1. Environmental data were collected including GPS location, elevation, slope, aspect, landform, site and soil moisture, disturbance, microsite relief and thaw depth. Lists and voucher collections of all vascular plants, mosses and lichens were collected

a

b

Figure 5.6. **(a)** *Transect T1 looking NE from the Spine Road. Note the low-centered polygons with the distinct rims and less than 0.5 m of trough-center relief.* **(b)** *Degraded ice-wedge polygon troughs along Transect T2 on the SW side of the road. Note the lack of rims on the ice-wedge polygon centers, greater than 0.5 m of trough-center relief, and lush sedge vegetation in the troughs and on the polygon centers. The brighter green sedge in the troughs is Carex aquatilis, and the duller sedge on the polygon centers is Eriophorum angustifolium.*

from each plot. Leaf-area index (LAI) was measured using an AccuPAR LP-80 PAR/LAI Ceptometer (Fig. 5.7). Species cover was estimated for all species and life forms using a 7-category Braun-Blanquet scale (Westhoff & Van der Maarel, 1973). Percentage cover of species at the top of the plant canopy was measured using a 100-point 1 x 1-m point-quadrat (Fig. 5.8) (Walker et al., 2010). Soil cores were extracted with a Sharpshooter shovel from tundra adjacent to each plot (Fig. 5.9). Soil samples were taken from the surface dust horizons and top organic horizons for laboratory analysis to determine dust content, percentage gravel, soil moisture, soil bulk density, soil organic matter, and soil pH. Maxim iButton® temperature loggers were installed at 0, -10, and -20 cm soil depths at vegetation plots on both sides of the road to monitor soil temperatures and at 10, 20, 50, 100, and 150 cm above the soil at Transect T1 to record the formation and melting of the roadside snowdrift.

Permafrost cores

We drilled 57 shallow boreholes using a motorized SIPRE corer to study soil stratigraphy, different types

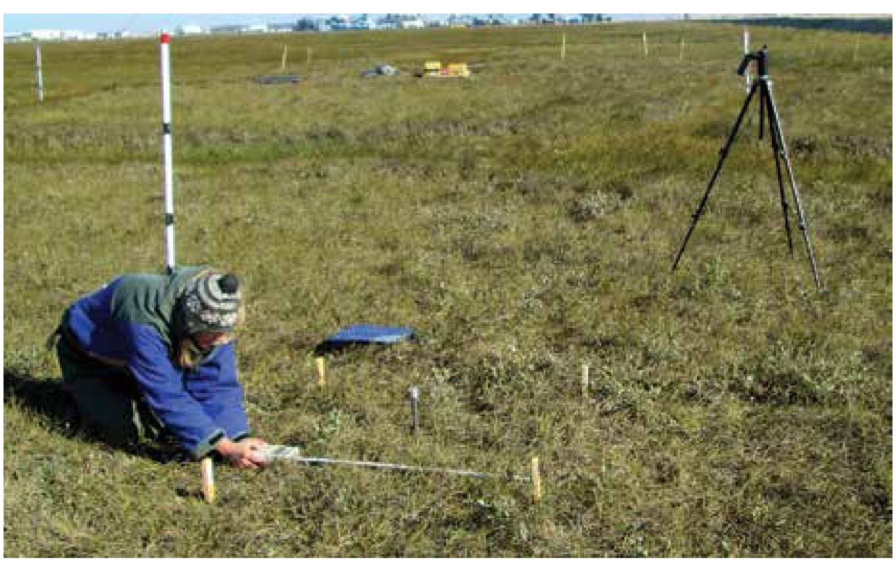

Figure 5.7. *Measuring leaf area index (LAI) with the AccuPAR LP-80, PAR/LAI Ceptometer within a 1 x 1-m permanent plot. The white horizontal sensor on the ground measures photosynthetically active radiation (PAR) that penetrates the plant canopy. The above canopy PAR sensor is mounted on the tripod to the right. LAI is calculated as the ratio of the below-canopy PAR to the above-canopy PAR. The marker in the center of the plot is the photo point marker, a circular survey marker stamped with the plot number mounted on an 18-inch piece of rebar.*

Figure 5.8. *Plot T2 025 C with point quadrat in place. The grid defines the 100 points of the point sampling. The point quadrat is mounted on legs that are inserted in metal washers that are nailed into the tundra to allow the frame to be re-positioned at the same point for resampling. Plant species are recorded at each of the intersections of two layers of monofilament lines, minimizing parallax error. The central metal disk is the photo-point marker.*

of ground ice, and dimensions of ice wedges (Fig. 5.10) (locations of boreholes are shown in Fig. 5.2). The boreholes were drilled in polygon centers and troughs at 5, 10, 25, 50, 100, and 200 m from the road along both transects. A soil plug was first extracted from above the permafrost table and described to note the depth of the organic horizons, and soil texture. Soil samples were collected to determine density and moisture content of the active layer. The cores were examined to study cryostratigraphy of the upper permafrost and to determine the ground-ice volume of the surface deposits (Fig. 5.11).

Topographic surveys

The location and elevation of all boreholes, transects, vegetation plots and other reference points were surveyed using a combination of a GPS real time kinematic (RTK) system and a robotic imaging system. In order to acquire the exact location and orthoheight of each surveyed point, all measurements where connected to the stable NOAA (National Oceanic and Atmospheric Administration) National Geodetic Survey (NGS) benchmark point TT3749 (lo-

Figure 5.9. **(a)** *Soil plug from center of an ice-wedge polygon at 5 m from the road along transect T2. Note the 13-cm thick mineral surface horizon, which is the dust layer above the original organic surface horizon.* **(b)** *Soil plug from trough of an ice-wedge polygon at 200 m from the road along transect T2. Note the gray color at the top of the organic soil horizon underlying the surface layer of moss, indicating leaching of dust into the organic layer. The blade of the Sharpshooter shovel used to extract the soil plugs is shown in both photos.*

cation shown in Fig. 5.1 at 70˚ 13′ 28.75176″ N, 148˚ 28′ 40.42570″ W). In addition, a transect linking Jorgenson's research site to Colleen Site A was surveyed on August 13, 2014. A total of 1038 points were surveyed. The coordinates, elevations and notes of all points at Colleen Site A are included in a forthcoming data report (Walker *et al.,* 2014).

Effects of flooding

Extensive tundra flooding in the flat landscapes of the Prudhoe Bay region is caused by blocked drainage of waters by roads and other infrastructure. Most roads are elevated about one meter above tundra by thick gravel roadbeds that protect the underlying permafrost from thawing. Lake Colleen is completely surrounded by roads that have few culverts. The 1.9 km straight section of road that runs along the north side of Lake Colleen (Fig. 5.1) has no culverts, and the terrain between the lake and the road experiences extensive flooding during the spring snowmelt season and early summer.

The water level in the flooded area fluctuates considerably during the summer. At the time of our visit, the water level was 75 cm below a wave-cut strand

Figure 5.10. **(a)** *Coring a polygon center on the southwest side of the road. Before drilling the vegetation was described and a soil plug was extracted as in the foreground. Sheets of plywood and wooden pallets were used to protect the tundra.* **(b)** *Extracting the drill and core from a borehole in a polygon trough ice wedge.*

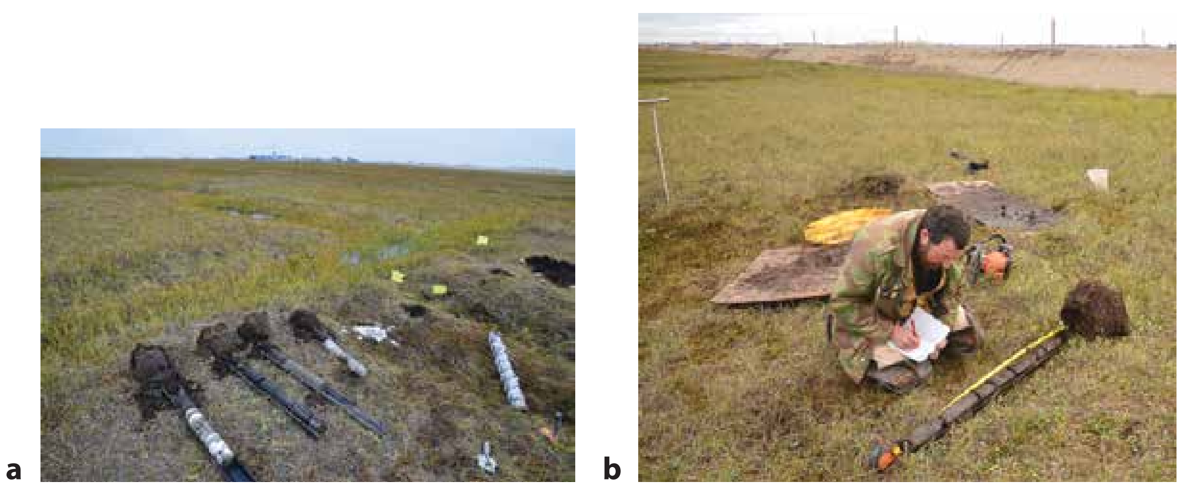

Figure 5.11. **(a)** *Cores taken from boreholes along a transect across an ice wedge.* **(b)** *Misha Kanevskiy describing a core from the center of an ice-wedge polygon.*

line along the edge of the road. The remains of grasses and sedges in the strand line were relatively fresh so this strand line likely represents a high water level for 2014. At this level, water would have covered the polygon centers on the southwest side of the road with approximately 45 cm of water. During our fieldwork in early August, water up to about 70 cm deep was still present in thermokarst pits and in most troughs on the southwest side of the road, requiring hip waders to work in these areas.

Lush aquatic sedge (*Carex aquatilis*) plant communities occupied most ice-wedge polygon troughs (Fig. 5.6b). Other common species in the troughs include common mare's tail (*Hippuris vulgaris*), small yellow water buttercup (*Ranunculus gmelinii*), and abundant aquatic mosses such as *Scorpidium scorpioides* and *Calliergon giganteum*. The relatively well-drained polygon centers had plant communities dominated by common cottongrass (*Eriophorum angustifolium*), some prostrate dwarf willows (*Salix arctica*, *S. lanata*), and mosses (mostly *Distichium capillaceum*).

Thaw depths were greater along the T2 flooded side of the road compared to thaw along the T1 transect (T2 thaw = 58 ± 0.3 (s.e.) cm, n = 200; T1 thaw = 49 ± 0.01 cm, n = 200). The sedges on the southwest side of the road were much taller and greener, resulting in 36% higher LAI compared to the northeast side (T2 LAI = 0.61 ± 0.027, T1 LAI = 0.45 ± 0.014). The enhanced productivity on the flooded southwest side of the road is likely caused by a combination of wetter soils, deeper thaw, higher rates of organic matter decomposition, increased nutrients from the dust, and high inputs of feces and decayed organic matter from grazing waterfowl. There were extensive tracks, feathers, feces, and signs of grazing by waterfowl throughout the study area on the southwest side of the road. Several flocks of Greater White-fronted Geese, and Canada Geese and two pairs of Tundra Swans persistently grazed on the southwest side of the road during the field visit.

Road-related flooding and thermokarst are much less prevalent on northeast side of the road (Fig. 5.1). Most of the present-day thermokarst at distances greater than 100 m from the road on the northeast side does not appear to be directly related to the road and is similar in appearance to the thermokarst at the Jorgenson study site. The more extensive thermokarst in areas distant from the roads is likely a response to a series of very warm years in 1989, 1998, and 2012 that are documented at the Deadhorse permafrost study site of Vladimir Romanovsky (Fig. 5.12).

Effects of dust and snow

Soils within approximately 50 m of the road, on both sides, have mineral soil surface horizons composed largely of road dust and gravel that overlie the original organic soil horizons (Fig. 5.9). Near the road on the southwest side, the dust horizons were up to 18 cm thick and up to 10 cm thick on the northeast side. In nearly all moderately well-drained areas within about 25-50 m of the road, the original thick moss carpets, which were composed of such large branched mosses as *Aulacomnium turgidum, Drepanocladus uncinatus, Hypnum bambergeri, Orthothecium chryseum,* and *Tomentypnum nitens*, have been replaced by bare soils or sparse moss carpets composed of a few small dust-tolerant species such *Bryum* sp., *Catascopium nigritum, Distichium capillaceum, Ditrichum flexicaule, Encalypta* spp., and *Pohlia* spp. Lichens that were previously common on mesic tundra, such as *Cetraria islandica, Flavocetraria*

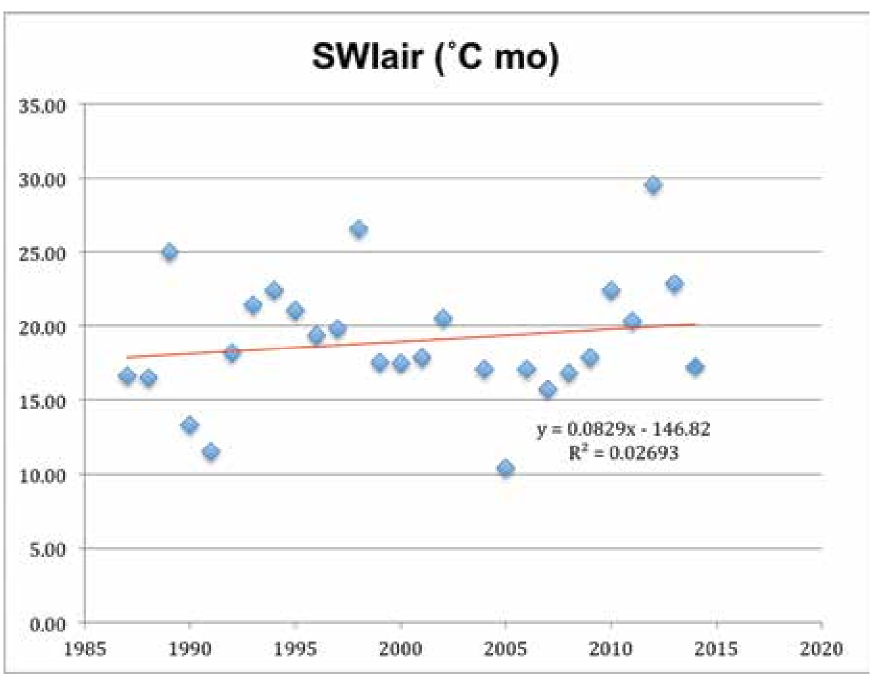

Figure 5.12. *Deadhorse summer warmth index (SWIair = sum of monthly mean air temperatures above freezing) for 1986-2014. (Data courtesy of Vladimir Romanovsky.)*

a

b

Figure 5.13. *Roadside areas along the Spine Road.* **(a)** *Heavy dust area adjacent to the southwest side of the road. Up to 18 cm of dust and gravel were measured in areas 5 m from the road. This photo shows deeper accumulations within 5 m have elevated the surface creating a relatively well drained gentle slope from the foot of the road that is colonized mainly by a few coastal and dune species, such as* Alopecurus alpinus, Dupontia fisheri, Elymus arenarius, Puccinellia phryganodes, P. andersonii*, and* Salix ovalifolia*.* **(b)** *Strip of erect dwarf willow (*Salix lanata*) growing on northeast side of the road.*

cucullata, F. nivalis, and *Dactylina arctica*, are now relatively uncommon along both transects, particularly within 50 m of the road. In some especially heavily dusted areas immediately adjacent to the road, the original tundra has been replaced by sparse plant communities composed of plant species that are more commonly found in salt marshes, beaches, and sand dunes near the Arctic coast (*e.g., Alopecurus alpinus, Dupontia fisheri, Elymus arenarius, Puccinellia phryganodes, P. andersonii,* and *Salix ovalifolia*) (Fig. 5.13b).

The dust strongly affects the timing of snowmelt along the road margins, and this is directly related to the orientation of the road and the amount of road traffic. We presently have no snow or dust deposition data from this section of road. Evidence from previous studies in the Prudhoe Bay region (Benson *et al.*, 1975; Everett, 1980; Walker & Everett, 1987) and from soil pits at the Lake Colleen site indicate that the northeast side of the road receives less dust than the southwest side due to the prevailing summer winds from the east-northeast. Carl Benson studied the effect of dust on snowmelt patterns early in the history of the oilfield and explained the effect of the prevailing winds:

> *The movement of dust and coarser sediments by the wind is related to snow drifting but there is an interesting difference. The most effective winds in moving…sediments are clearly from the east. The east winds move several times more dust than do the west winds: (a) There is a noticeable change in the direction of the strongest winds with the seasons….The strongest most frequent winds of winter are from the west. They yield progressively from April through July to winds that are predominantly from the northeast. (b) During the time when the strong west winds are most active there is little exposed sediment, so they move snow. When the northeast winds become more active the spring thaw exposes sediments in the dune area and along the river channels. Also, the roads become sources of dust when they become snow free during spring in direct proportion to the amount of traffic on them* (Benson *et al.,* 1975).

Benson *et al.* (1975) found that the largest snowdrifts form on the northeast sides of the roads that are oriented perpendicular to the winter storm winds, which are mainly from the west-southwest. Sequential aerial photographs taken during the melt period, May 24-June 30, 1972, showed that the tundra adjacent to the southwest sides of roads with heavy traffic were snow free by 24 May, whereas most tundra areas in areas distant from the roads were not snow free until 13 June. Snowdrifts persisted on the northeast side of the roads until 5 June and on both sides of infrequently travelled roads until at least 15 June (Benson *et al.*, 1975). The altered snow distribution patterns near roads have major implications for ground temperatures, the phenology of vegetation and use of the roadside areas by wildlife (Walker & Everett, 1987). The warmer soils and enhanced winter snow cover along the roads also provides protection for dwarf

Table 5.1. *Estimation of thickness of ice wedge melting (cm) based on the Stefan equation. Highlighted values are those where degradation of the ice wedge was expected by the end of the summer.*

BOREHOLE NO.	2011	2012	2013	2014
Transect 1				
T1-5T-1	0	2.4	0	0
T1-10T-1	4.3	8	5	3
T1-10T-2	1.7	5	2.5	0.5
T1-25T-1	3.5	7	4.5	2
T1-25T-2	1.5	3.5	2	0.7
T1-25T-4	3	6	3.8	2
T1-50-T1	0	0	0	0
T1-50-T2	0	0	0	0
T1-50-T4	0	0	0	0
T1-50-T5	0	0	0	0
T1-50-T7	3	6	3.7	2.5
T1-50-T8	1.5	6	2.2	0.7
T1-50-T9	1.3	4.5	2	0.3
T1-100-T1	3	5.5	3.5	2
T1-200T-1	0	1.3	0	0
T1-200T-2	0	0.1	0	0
T1-200T-3	0	0.5	0	0
Transect 2				
T2-5T-1	0	0	0	0
T2-10T-1	0	0.6	0	0
T2-25T-1	0	0	0	0
T2-50T-1	0	2	0	0
T2-50T-3	0	2.2	0	0
T2-100T-1	0	0	0	0
T2-100T-2	0	1.2	0	0
T2-200T-1	0	0	0	0
T2-200T-3	2.5	7	3.5	0.6
T2-200T-4	1.5	5	2.5	0.5
T2-200T-5	0.5	4	1.3	0
T2-200T-6	0.3	4	1.2	0
T2-200T-8	0.8	3.5	1.5	0

shrubs that are becoming more common particularly along the northeast side of the road. A zone of noticeably high cover of taller erect dwarf willows (*Salix lanata*) occurs on the northeast side of the road in response to the protective winter snowdrift and the warmer soils in a gravelly berm that apparently covers a buried cable or pipeline (Fig. 5.13b). Large flocks of waterfowl graze the roadside areas during the melt period until other areas become snow free. Other animals including ground squirrels and caribou also utilize the snow-free areas near the roads during this period.

Preliminary observations regarding changes to permafrost

Summer 2014 was relatively cold at Prudhoe Bay (Fig 5.12). Analysis of cryostructures in the permafrost cores showed the thaw depth measured from August 7 to 12 was commonly 7 to 12 cm less than the total thickness of the active layer and transient layer, which represent potential seasonal thawing in years with high summer temperatures and high moisture.

We calculated the projected maximum thaw depth for past years and for the end of summer 2014 using an approximation following from the Stefan equation and climate data for Deadhorse. We evaluated a thickness (h_{ice}) of ice melted in summers 2011 to 2014 using the following equation (Shur, 1988):

$$h_{ice} = \frac{k\Omega_{th}}{HL_{ice}} - \frac{L_s H}{2L_{ice}}$$

where k = thermal conductivity of thawed soil; Ω_{th} = thawing index; H = thickness of soil above an ice wedge; L_{ice} = latent heat of ice; L_s = latent heat of soil. This evaluation shows that the maximum thaw depth above ice-wedges at the end of summer 2014 will be about 1.1 times greater than it was at the time of our measurement and that about 1 to 3 cm of ice in the ice-wedges could melt in some ice wedges, but most of them will not be affected (Table 5.1).

We compared potential ice-wedge melt in 2014 with that of 2011, 2012, and 2013 (Table 5.1). The relatively cool summer of 2014 resulted in relatively small amounts of melting ice especially compared to the hot summer of 2012 (Fig. 5.12). Furthermore, the large amounts of organic productivity on the flooded southwest side of the road appear to be adding a layer of organic material to the bottom of the troughs protecting them from deeper thawing.

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6 Conclusions

Recent documented changes in the extent of regional thermokarst in northern Alaska (Jorgenson *et al*., 2006, Raynolds *et al*., 2014) prompted this analysis of the landscape and permafrost changes in the Prudhoe Bay Oilfield. We focused on infrastructure-related thermokarst, but this had to be done within the context of regional climate change. The first chapter, reprinted from *Global Change Biology*, documented the changes in the regional extent of North Slope oilfield infrastructure and the landscape-level changes that occurred within three intensively studied areas of the Prudhoe Bay Oilfield between 1949 and 2011 (Raynolds *et al*., 2014).

These changes must be examined with regard to the region's unique landscapes, ecosystems, and permafrost environments. Early studies in the Prudhoe Bay region by the U.S. Tundra Biome of the International Biological Program (IBP) (Brown, 1975; Walker *et al*., 1980) proved to be an invaluable baseline for the studies reported here. The relevant background information and history were summarized in Chapters 2, 3 and 4. Chapter 2 provided an in-depth picture of the permafrost environment; Chapter 3 documented the history of regional infrastructure expansion; and Chapter 4 described the integrated geoecological and historical change mapping procedures used in the landscape-level analyses. Chapter 5 gave a ground-level view of the changes currently occurring to ecosystems and permafrost along one of the oldest roads in the region. The total document provides a summary of the history and current situation of response of ecosystems and permafrost to infrastructure and climate change.

The most common form of thermokarst on the flat Arctic Coastal Plain occurs in networks of ice-wedge polygons where the tops of ice wedges melt, forming small ponds called thermokarst pits. During the early period of oilfield development in the 1970s, the extent of thermokarst pits was fairly stable. At the Colleen Site A study area, thermokarst extent changed very little between 1949 and 1972, and remained fairly stable through 1980s. Starting in about 1990, non-infrastructure-related thermokarst and, more prominently, infrastructure-related thermokarst, showed abrupt increases, paralleling the observations of Jorgenson *et al.* (2006). Most likely, a series of exceptionally warm summers in 1989, 1998, and 2012 caused active layers to penetrate to the tops of ice wedges. In areas near and far away from infrastructure, many new thermokarst ponds developed, and ponds that were initially confined to small areas at the junctions of ice wedges, expanded along the length of polygon troughs, and many became linked to each other by continuous water channels. A new conceptual model of thermokarst development, described in Chapter 1, illustrated two main pathways of thermokarst evolution. The first, a reversible process often observed in natural environments, leads to subsidence and ponding that are confined mostly to ice-wedge polygon troughs. The second is an irreversible process where the subsidence and ponding extends to the polygon centers.

The Prudhoe Bay Oilfield is, unfortunately for development, an extremely flat region with many drained thaw-lake basins and extensive networks of low-centered, ice-wedge polygons. These are prone to flooding due to the restricted drainage caused by the networks of elevated roads and gravel pads. At Colleen Site A, differences in the thermokarst activity on opposite sides of the road are related primarily to differences in the extent of flooding. Thermokarst altered the microtopography and increased the heterogeneity of roadside environments on both sides of the road, but most prominently on the flooded side. One consequence was the subsidence of the polygon troughs leading to the transformation of low-centered polygons into flat and high-centered polygons with more micro-topographic relief. Another interesting outcome was greatly increased productivity on the southwest side of the road, which attracted waterfowl. Also, dust and organic matter accumulation on the southwest side of the road now appear to be slowing the development of thermokarst by thermally protecting the tops of the ice wedges. Whether or not this leads to stabilization of thermokarst will require followup studies.

The Prudhoe Bay region is a naturally dusty region due to glacial silts that blow off the floodplain of the Sagavanirktok River (Walker, 1985). Although dust loads generated from the many roads strongly affect the local vegetation and soil temperatures, the ecosystems are well adapted to high dust fall and would recover quickly if the road-generated dust were to subside. Dust strongly affects the thermal properties of the tundra surface. High dust loads cause deeper active layers, and increased thawing of ice wedges. In extreme situations, such as immediately adjacent to the Spine Road, dust can accumulate faster than the ice wedges subside, leading to a narrow thermokarst-pond-free strip along some road margins. At the Colleen Site A study area, dust is heaviest on the southwest side of the road due to the prevailing summer winds from the northeast, but the effects are most noticeable on the northeast side because of the less extensive flooding. Thick dust fall has nearly eliminated vegetation from within 5 m of the southwest side of the road, where some plant communities now resemble those in unstable sand-dune environments and coastal areas. Within 50-100 meters of the road, dust has changed the fundamental structure of the soils, creating new mineral soil surface horizons, up to 18 cm thick, and added much mineral material to the underlying organic horizons. The thick dust layers also reduced lichen diversity and changed the moss floras near the roads.

The full extent and consequences of these soil and vegetation changes are not presently known. A full roadside plant-community analysis is in process. This will likely reveal complex patterns that show, for example, reduced diversity of forbs, lichens and mosses in mesic sites near the roads but also greater shrub and sedge productivity due to warmer soils. A combination of heavy dust loads, flooding, and snow banks causes deeper summer thaw near the road, but some of the soil-temperature changes are likely due to regional climate warming. The 129 data loggers placed at Colleen Site A will document the existing air, subnivian, and soil temperatures, and help lead to predictive models of infrastructure-related changes to tundra soil temperatures.

Of course, the chief factor contributing to the high thermokarst activity in the region is the extremely high volumetric ice contents, which exceed 80% on most regional terrain units (Kanevskiy *et al.*, 2013). The heterogeneous distribution of ice, organic carbon, and other soil properties within tundra sediments requires a statistical approach to determine the volume of ice in the soils. The borehole information from the transects at Colleen Site A and the Jorgenson site will be helpful in developing thermokarst sensitivity maps for the areas with ice-rich upper permafrost within the Prudhoe Bay region.

The field studies at Lake Colleen Site A triggered a variety of questions that will require an integrated whole-system approach to answer, including:

(1) Is it possible to develop models that link hydrological processes to ice-wedge melting to better predict pathways of thermokarst in networks of ice-wedge polygons?

(2) How are the diversity and distribution of tundra organisms including plants, invertebrates, small mammals, shorebirds, waterfowl, fish, caribou, and predators affected by the more diverse landscapes that are the result of thermokarst?

(3) How do the warmer soils associated with most forms of infrastructure affect a suite of key ecosystem processes, such as plant water uptake, plant productivity, decomposition rates, and trace-gas fluxes?

(4) How do heavy dust loads affect mosses, lichens, biological soil crusts, and the diversity of soil microorganisms that help stabilize and insulate the permafrost?

(5) What is the cause of the presence of numerous salt-tolerant species and plant communities in roadside areas?

Other questions related to the social effects of these changes include:

(6) Do landscape changes associated with infrastructure expansion and landscape change have relevance to the local people, including local oil-field workers?

(7) Do these factors affect local use of the land including summer and winter travel, and access to subsistence resources?

(8) How are infrastructure changes affecting ecosystems services and important subsistence-cash economies at the community level?

(9) How do local people evaluate their capacities to respond to change, given the projections for future industrial development and climate change?

(10) Can the knowledge gained from such studies improve the process of restoration of the tundra following the removal of gravel roads and pads?

(11) Can increased knowledge and documentation of the historical changes and the processes lead to improved adaptive management and planning for future oilfields?

In summary, it is worth reflecting on the conclusion of the National Research Council's Committee on *Cumulative Environmental Effects of Oil and Gas Activities* on Alaska's North Slope made over a decade ago:

> *Most ecological research in the Prudhoe Bay region has focused on local studies of the behavior and population dynamics of animal species.*

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

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GLOSSARY

Most terms are from the Multi-language glossary of permafrost and related ground-ice terms *(van Everdingen, ed. 1998, revised 2005).*

ACTIVE LAYER
The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.

ACTIVE LAYER THICKNESS
The thickness of the layer of the ground that is subject to annual thawing and freezing in areas underlain by permafrost.

CONTRACTION CRACK (THERMAL CONTRACTION CRACK)
A tensile fracture resulting from thermal stresses in frozen ground.

CRYOSOL
Soil formed in either mineral or organic materials having permafrost either within 1 m below the surface or, if the soil is strongly cryoturbated, within 2 m below the surface, and having a mean annual ground temperature below 0°C.

CRYOSTRUCTURE
The structural characteristics of frozen earth materials.

CRYOTURBATION
A collective term used to describe all soil movements due to frost action.

DEPTH OF THAW
The distance between the ground surface and frozen ground at the time of measurement.

EPIGENETIC PERMAFROST
Permafrost that formed through lowering of the permafrost base in previously deposited sediment or other earth material.

FROST HUMMOCK (FROST MOUND)
Any mound-shaped landform produced by ground freezing combined with accumulation of ground ice due to groundwater movement or the migration of soil moisture.

GROUND ICE
A general term referring to all types of ice contained in freezing and frozen ground.

ICE LENS
A dominantly horizontal, lens-shaped body of ice of any dimension.

ICE-RICH PERMAFROST
Permafrost containing excess ice.

ICE WEDGE
A massive, generally wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice.

ICE-WEDGE POLYGON
A polygon outlined by ice wedges underlying its boundaries.

INTERSTITIAL ICE (PORE ICE)
Ice occurring in the pores of soils and rocks.

LENS ICE
Ground ice occurring as ice lenses.

LOW-CENTER POLYGON
An ice-wedge polygon in which thawing of ice-rich permafrost has left the central area in a relatively depressed position.

MASSIVE ICE
A comprehensive term used to describe large masses of ground ice, including ice wedges, pingo ice, buried ice and large ice lenses.

MOISTURE CONTENT (TOTAL WATER CONTENT)
The total amount of water (unfrozen water plus ice) contained in soil or rock.

NONSORTED CIRCLE
A patterned ground form that is equidimensional in several directions, with a dominantly circular outline which lacks a border of stones.

NONSORTED POLYGON
A patterned ground form that is equidimensional in several directions, with a dominantly polygonal outline which lacks a border of stones.

PATTERNED GROUND
A general term for any ground surface exhibiting a discernibly ordered, more or less symmetrical, morphological pattern of ground and, where present, vegetation.

PEAT
A deposit consisting of decayed or partially decayed humified plant remains.

PERMAFROST
Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years.

PINGO
A perennial frost mound consisting of a core of massive ice, produced primarily by injection of water, and covered with soil and vegetation.

POLYGON

Polygons are closed, multi-sided, roughly equi-dimensional patterned-ground features, bounded by more or less straight sides; some of the sides may be irregular.

POLYGON TROUGH

The narrow depression surrounding a polygon.

RETICULATE CRYOSTRUCTURE

The cryostructure in which horizontal and vertical ice veins form a three-dimensional, rectangular or square lattice.

SUMMER WARMTH INDEX

An index of the total warmth available for plant growth or thawing of ice. Calculated as the sum of the monthly mean temperatures above freezing.

SYNGENETIC ICE

Ground ice developed during the formation of syngenetic permafrost.

SYNGENETIC PERMAFROST

Permafrost that formed through a rise of the permafrost table during the deposition of additional sediment or other earth material on the ground surface.

THAW LAKE (THERMOKARST LAKE)

A lake occupying a closed depression formed by settlement of the ground following thawing of ice-rich permafrost or the melting of massive ice.

THERMAL-CONTRACTION CRACK

A tensile fracture resulting from thermal stresses in frozen ground.

THERMOKARST

The process by which characteristic landforms result from the thawing of ice-rich permafrost or the melting of massive ice.

TUNDRA

Treeless terrain, with a continuous cover of vegetation, found at both high latitudes and high altitudes.

WEDGE ICE

Ice occurring in an ice wedge.

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ALASKA GEOBOTANY CENTER

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Alaska Geobotany Center
Institute of Arctic Biology
University of Alaska Fairbanks

P.O. Box 757000, Fairbanks, AK 99775-7000
Phone 1.907.474.2459
Fax 1.907.474.7666

www.geobotany.uaf.edu