Environmental changes in the lower Peel River watershed, Northwest Territories, Canada: Scientific and Gwich'in perspectives

by

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B.Sc., Laurentian University, 2011

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Abstract

The circumpolar Arctic is experiencing dramatic environmental changes that are already impacting tundra ecosystems and northern communities that are intimately linked to the land. Increasing permafrost degradation, shrub encroachment, larger and more frequent fires, and increasing human development have significant effects on biotic and abiotic conditions in the lower Peel River watershed, NT. To understand and respond to rapid environmental changes, diverse knowledge perspectives are needed, so my M.Sc. research uses scientific and social scientific approaches to investigate environmental change in the lower Peel River watershed. I investigated the impacts of the Dempster highway on plants, soils and permafrost in the Peel Plateau by conducting field surveys at sites dominated either by tall alder (*Alnus crispa*) shrubs or by dwarf shrubs, at 30 m and 500 m from the highway. At each site I measured vegetation composition, alder growth, soil nutrients, litter and organic layer thickness, active layer thickness, and snow depth. We found that alder growth and recruitment were enhanced adjacent to the Dempster Highway, and dramatic alterations to plant community composition, soil properties and ground temperatures were observed where alder shrubs had formed closed canopies. Tall shrub sites adjacent to the road exhibited lower abundance of understory vegetation including mosses, greater litter and organic soil thickness, higher nutrient availability, and deeper snowpack. Biotic and abiotic changes associated with road effects feedback with

alder canopy development, and have important implications for permafrost conditions adjacent to the roadbed, and potentially on road bed performance. This research contributes to our understanding of environmental changes caused by the highway and their consequences for infrastructure stability and pan-Arctic changes in vegetation cover.

In a separate but complementary effort, I worked with Teetl'it Gwich'in land users and youth from Fort McPherson, NT to map observations of environmental conditions and changes. In the pilot year of a community-based environmental monitoring program, we employed participatory multimedia mapping with Teetl'it Gwich'in land users and youth from Fort McPherson, NT. I accompanied Gwich'in monitors on trips on the land to document environmental conditions and changes. Observations made by land users were documented using photos, videos and audio taken by youth, and land users provided detailed information about each observation in follow-up interviews. I compiled observations (photo/video, GPS location, and interview audio and transcript) into a web-based map where the public will be able to see changes on the land in the images and words of Gwich'in land users. The online map will provide a medium for local residents to communicate their knowledge and concerns about the environment, and will be useful for land management and planning, environmental monitoring, and adaptation.

Table of Contents

List of Tables

List of Figures

Acknowledgments

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Chapter 1

Introduction

Northern ecosystems are experiencing a host of environmental changes due to rising global air temperatures and human development (ACIA, 2005; Stefansson Arctic Institute, 2004). The cumulative impacts of these ecosystem alterations have profound implications for northern infrastructure, and for indigenous communities whose livelihoods and cultural practices depend on the accessibility, availability, and health of their land and resources (Parlee et al., 2005). Changes such as melting permafrost, riverbank erosion, altered vegetation structure, exotic species introduction, altered distribution of wildlife populations, and changes to water quality and weather patterns (Chapin et al., 2005; Huntington et al., 2007; Krupnik & Jolly, 2002; Tape et al., 2006) require ongoing monitoring so that communities can respond and adapt appropriately. There is a need for detailed studies of the mechanisms of change, and for a thorough overview of where changes are happening and their possible causes and consequences.

The Peel River watershed (Figure 1.1), which drains into the Mackenzie River at the southern edge of the Mackenzie Delta, encompasses a diverse range of the ecoregions present in the Yukon and Northwest Territories, including the southern Arctic taiga plain (in which Fort McPherson is located), taiga cordillera, boreal cordillera and Pacific maritime ecozones (Yukon Ecoregions Working Group, 2004). The Peel watershed also falls within the traditional territory of several indigenous groups, including the Teetl'it Gwich'in and Nacho Nyak Dun in the lower (eastern) watershed and the Tr'on dëk Hwëch'in and Vuntut Gwitchin in the upper (western) watershed. The area is rich in plant and animal life, including woodland and barren ground caribou, Dolly Varden char, whitefish and small game, which support harvesting lifestyles and communities that are closely tied to the land (Andre, 2006; Sherry & Vuntut Gwitchin Nation, 1999; Vuntut Gwitchin Nation & Smith, 2010).

Much of the watershed remains intact and pristine because of a lack of access, but in areas affected by resource exploitation, historical and ongoing disturbances have the potential to fragment and alter ecosystems (CPAWS, 2004b). New impacts from resource extraction are also anticipated, since the Yukon territorial government has issued a call for nominations from the oil and gas industry since 1999, and is reviewing proposals for developments that could include the construction of all-weather roads, coal and iron ore mines, generating stations, power lines, and pipelines (CPAWS, 2004c). Plans to expand oil and gas extraction and associated infrastructure in the more northern Mackenzie Delta would also impact the Peel River watershed (National Energy Board, 2009). Northern First Nations have been vocal in advocating for conservation of the Peel River watershed, and the Canadian Parks and Wilderness Society has helped generate a national campaign to “Protect the Peel” (CPAWS, 2012). Still, as development in the Arctic intensifies and air temperatures continue to rise, uncertainty associated with how these ecosystems will respond, and how this will affect northern peoples, is expected to rise (Stefansson Arctic Institute, 2004).

Figure 1.1 The Peel River watershed (outlined in black) encompassing parts of the Yukon and Northwest Territories and draining into the Mackenzie River.

The northeastern, lower portion of the Peel River watershed is used extensively by Teetl’it Gwich’in families, who maintain hunting, trapping and fishing camps, traplines, and travel routes (Loovers, 2010; Slobodin, 1962). Teetl’it Gwich’in land users are concerned about environmental changes and play an active role in environmental monitoring and co-management in their territory (Kofinas, 1997; Scott, 2011).

The northern portion of the Peel watershed was an area of intense oil and gas exploration in the 1960s and ‘70s, and it is easily accessible from southern Canada via the Dempster Highway. The completion of the Dempster Highway in the late 1970s facilitated impacts from the road itself and associated human activity. In addition, increased temperatures and altered precipitation over the past 40 years have promoted accelerated permafrost degradation, changes to wildlife, and tall shrub expansion in this area (Gordon et al., 2008; Kokelj et al., 2013; Tunnicliffe et al., 2009). Collectively these environmental stressors have led Teetl'it Gwich'in land users to call for increased monitoring and the combination of scientific and traditional knowledge-based research to understand and address changing conditions (Scott, 2011).

The overarching objective of my MSc research is to improve our understanding of environmental changes in the lower Peel River watershed. To accomplish this I used scientific and social scientific research methods. Understanding changes in social-ecological systems ultimately requires both of these approaches. There is a need for specific, empirical and quantifiable descriptions of changes, best served by a scientific research design. There is also a need for comprehensive, culturally coherent and context-rich descriptions of changes, best served by a participatory, community-based and traditional knowledge-focused research design. For the first component of this M.Sc. project, I explored a specific research question by conducting a scientific observational study of tundra ecosystems affected by the Dempster highway. In the second component of this project, I worked collaboratively with the Gwich'in Social and Cultural Institute to pilot a participatory multimedia mapping protocol in Fort McPherson [1]. A similar protocol was developed and piloted in Inuvialuit communities beginning in 2009 (Bennett, 2012). Although these projects overlap in dealing with the effects of environmental changes due to anthropogenic and natural ecosystem alterations, I carried them out separately in order to avoid potential pitfalls associated with integrating science and traditional knowledge, such as the distortion and removal of context and the perpetuation of power imbalances (Gagnon & Berteaux, 2009; Huntington, 2000; Nadasdy, 1999). Both

[1] Several licenses were required in order to conduct this research in the Northwest Territories: they included Northwest Territories Scientific Research Licenses (15123 and 15109), a Gwich'in Social and Cultural Institute Traditional Knowledge Research Agreement (signed March 12, 2012), and a UVIC Human Research Ethics Board Certificate of Approval (12-064; see Chapter 3, Appendix 3).

perspectives are vitally important in order to understand what is happening and why, and using both sources of knowledge generated using both perspectives will undoubtedly lead to a more nuanced understanding of environmental change and its consequences (discussed in Chapters 3 and 4).

My research was organised around two questions, each addressing one of the two projects described above. Each of these questions is addressed in a stand-alone research paper. The first paper is presented in Chapter 2 of this thesis, and addresses the question: What are the impacts of the Dempster Highway on vegetation and microenvironment on tundra ecosystems in the lower Peel River watershed? To answer this question, I carried out an observational study comparing tundra ecosystems affected by the highway with undisturbed tundra in the Peel Plateau. Road effects are often greater than assumed (Forman & Alexander, 1998), and remain an important gap in our understanding of cumulative impacts in the region.

The second paper is presented in Chapter 3, and explores the question: What types of knowledge are elicited through participatory multimedia mapping of Gwich'in observations of the environment? In order to explore this question, I implemented a community-based monitoring program based entirely on local and traditional Gwich'in knowledge, intended to complement existing monitoring programs and build local capacity to monitor and respond to changes. Existing research such as the Arctic Borderlands Ecological Knowledge Cooperative and caribou and char monitoring programs already incorporate Gwich'in knowledge and observations of the environment. However, observations made by these programs are typically described in a generalized, non-systematic way that usually relies on recalled knowledge obtained in interviews. The participatory multimedia mapping protocol presented in this chapter ties knowledge to place and uses several forms of media to preserve its context.

In the final chapter of this thesis (Chapter 4), I explore possible avenues for using diverse forms of knowledge to inform environmental monitoring, decision making and education. In this chapter I also present directions for future research, and draw conclusions about the project as a whole.

The remaining sections of Chapter 1 provides critical context and background information that is necessary to understand the ecological, social and political context in which this research was conducted. I also elaborate on the need for both scientific and community-based monitoring strategies in the region.

Overview of the lower Peel River watershed

The Peel River flows northeast into the Mackenzie River, passing through taiga in the Yukon Territory and taiga and tundra in the Northwest Territories. The lower Peel River watershed includes the lower Peel River (which refers to the terminal 75 km) and its tributaries. The main tributaries between the Yukon border and the Peel are the Vittrekwa River south of the Dempster highway, and Stony Creek north of the highway (Kokelj, 2001). Western tributaries originate in the Richardson Mountains (Taiga Cordillera ecozone), and the entire watershed has high topographic relief compared to the Mackenzie Delta (Kokelj, 2001).

The lower Peel River watershed is an area of continuous permafrost, except under lakes and rivers, with an active layer rarely deeper than 1 m (Hughes et al., 1981). The climate is subarctic and is influenced by weather patterns from the Arctic Ocean (Hughes et al., 1981). The watershed includes the Peel Plateau, a large ecoregion bounded by the Richardson Mountains to the west, the Wernecke Mountains to the south, and by a scarp leading to the Mackenzie Delta to the north and east (Yukon Ecoregions Working Group, 2004). By the late Wisconsinan (approx 38,000 BP), the Laurentide ice sheet would have covered the region, and on two occasions the Peel River was blocked by ice and diverted to the Yukon River system, draining into the Bering Sea (Hughes et al., 1981). Glacial till deposited during the last glaciation is now overlain by ice-rich glaciolacustrine silt and clay. The NWT portion of the Peel Plateau is underlain by Cretaceous sandstone and mudstone (Hadlari, 2006). Throughout the lower Peel River watershed, the ground surface is marked by naturally occurring thermokarst lakes and ponds, and retrogressive thaw slumps along river banks (Hughes et al., 1981). Due to its location at the western glacial limit, some parts of the Peel Plateau were not covered by the Laurentide ice sheet.

The primary terrestrial ecozone of the lower Peel area is the Taiga Plains, featuring broad taiga lowlands and tundra plateaus (Kokelj, 2001). This area includes the northernmost portion of the Peel Plateau, bordered by the Richardson mountains to the west and transitioning eastward to the Peel Plains (Pyle & Jones, 2009). Vegetation in the valley bottoms of the Peel River and its tributaries consists of successional stands of *Salix, Populus, Alnus, Larix* and *Picea* (Hughes et al., 1981). In the eastern Richardson Mountains and Peel Plateau, vegetation ranges from tundra at higher elevations, to dense spruce forest and woodland in valley bottoms. The treeline occurs at approximate altitude of 305-457 m (Hughes et al., 1981).

Teetl'it Gwich'in History and Territory

The Gwich'in (meaning "one who dwells") are an indigenous people whose territory extends from northeastern Alaska (AK) to the Mackenzie Delta of the Northwest Territories (Vuntut Gwitchin Nation & Smith, 2010). The Gwich'in language is in the Athapaskan language family, and Gwich'in have historically been referred to as Dene, Loucheux, Kutchin, Tukudh and Athapaskan (Osgood, 1934). There are eight Gwich'in bands, including the Teetl'it Gwich'in (meaning "people of the headwaters" of the Peel River) (Vuntut Gwitchin Nation & Smith, 2010). Today, there are approximately 9000 members of the Gwich'in Nation associated with 11 communities in Alaska, Yukon Territory and the Northwest Territories, as well as settlements outside traditional territories where people have migrated. Teetl'it Gwich'in territory lies within both the Yukon and Northwest Territories, and includes the Peel River watershed (Figure 1.1) (Vuntut Gwitchin Nation & Smith, 2010). Today, the majority of Teetl'it Gwich'in reside in Fort McPherson, NT (in Gwich'in, *Teetl'it Zheh*, meaning "Peel River House") although some Teetl'it Gwich'in people live on the land or in other communities (Scott, 2011). Members of other bands such as the Gwichya Gwich'in have also settled in Fort McPherson, and many Teetl'it Gwich'in band members also have ancestry from other Gwich'in cultural groups as well as Inuvialuit, Sahtu and Métis cultural groups (Loovers, 2010). Fort McPherson was established in 1852, when the Old Fort trading post was moved 6 km up the Peel River to the present location. Fort McPherson is the largest Gwich'in community in the Northwest Territories, with a population around 800 people, more than 80 % of which is Gwich'in. The modern economy is based on hunting, fishing, trapping, wage labour and tourism (Scott, 2011).

The Teetl'it Gwich'in have occupied the Peel River watershed for thousands of years, travelling seasonally by dog-sled, canoe, snowshoe and on foot to hunt, trap, fish, and harvest foods, medicines and materials (Vuntut Gwitchin Nation & Smith, 2010). Over generations, they developed an extensive network of trails, camps, and temporary settlements that continue to be used, with most families maintaining camps along the Peel River and its tributaries from the Mackenzie Delta to far up the Peel in the Yukon (Loovers, 2010). An annual boat trip is organised by the Teetl'it Gwich'in Renewable Resource Council to the Wind, Snake or Bonnetplume River to reassert Gwich'in occupation and connection in these areas now threatened by development interess (CPAWS, 2012), and an annual snowmobile trip follows the dog-sled route between Fort McPherson and Old Crow (Loovers, 2010). Learning and teaching through experience, observation and story-telling over generations, the Teetl'it Gwich'in band has accumulated an intimate understanding of the land and how to live on it, including geography, wildlife and plants, water systems, and climate (Vuntut Gwitchin Nation & Smith, 2010: 2-4).

Figure 1.2 Gwich'in boaters up the Peel River, on an annual trip organised by the Teetl'it Gwich'in Renewable Resource Council to Snake River. Photo by Christine Firth.

Overview of Environmental Disturbances and Changes in the Lower Peel River Watershed

In the 1960s and 1970s, the construction of the Dempster Highway facilitated oil and gas exploration in the lower Peel River watershed, particularly in the Peel Plateau (CPAWS, 2004a). A network of trails, seismic cut lines, sumps and quarries was created on the landscape (CPAWS, 2004a; Kanigan & Kokelj, 2008). Seismic lines, created by cutting down all trees and shrubs in straight 10-30m wide swaths, were used as travel corridors for heavy equipment (CPAWS, 2004a). Seismic lines are known to cause lasting changes in soil conditions, plant community composition and vegetation structure (Kemper, 2005; Kemper & Macdonald, 2009). Drilling mud sumps are disturbances created when a pit is dug to hold drilling wastes. This feature alters vegetation, soil and permafrost (Johnstone & Kokelj, 2008; Kanigan & Kokelj, 2008). Tall shrubs have been observed to dominate successional vegetation on top of closed sumps, which causes snow accumulation and active layer deepening. Combined with rising air temperatures, this threatens the stability of sumps (Kanigan & Kokelj, 2008; Kokelj et al., 2010). Additionally, there are several historic and active gravel quarries along the Dempster Highway between the Richardson Mountains and Fort McPherson. Quarries cause mechanical disturbance to tundra vegetation, and successional vegetation and soil conditions are different from undisturbed terrain (Forbes, 1995; Koronatova & Milyaeva, 2011).

Recent temperature increases are also affecting the regional environment. Since the 1960s, the trend of increasing summer air temperatures in the western Arctic has accelerated, from 0.15-0.17 °C per decade to 0.3-0.4 °C per decade increase, accompanied by greater variability in weather and altered timing of freeze and thaw cycles (Chapin et al., 2005; Hinzman et al., 2005). In the Mackenzie Delta Region, mean annual air temperature has increased by more than 2.5°C since 1970 (Burn & Kokelj, 2009). This has contributed to increased permafrost degradation and shrub encroachment (Jorgenson et al., 2001; Lantz et al., 2013; Myers-Smith et al., 2011). Lantz et al. (2009) found that successional vegetation in permafrost thaw slumps features altered community composition and increased shrub growth, as well as increased soil nutrient availability, soil pH, snowpack, ground temperature and active layer thickness. Alterations to vegetation, soils and permafrost can influence how disturbed terrain responds to increasing air temperatures (Lantz et al., 2009), and can cause feedbacks with global change processes such as carbon cycling (Chapin et al., 2005; Lawrence & Slater, 2005).

Figure 1.3 Thaw slump due to permafrost degradation on the Peel Plateau, included as an observation on a participatory multimedia mapping trip along the Dempster Highway in August 2012. Photo by Ashley Kay.

Effects of Roads on Ecosystems

Roads are highly visible landscape disturbances, and studies of their ecological effects in various terrain types are numerous. Roads are negatively associated with biotic integrity in both terrestrial and aquatic ecosystems, contributing to animal mortality and altered behaviour, spread of exotic species, alteration of the physical and chemical environment, and intensification of human land use and impacts (Trombulak & Frissell, 2000). The effects of roads on soil chemistry are most pronounced immediately adjacent to roads (Trombulak & Frissell, 2000), but roads can also alter hydrological drainage patterns, and sediment and chemicals in runoff are carried away from the source in streams (Forman & Alexander, 1998). The tendency for roads to act as physical barriers that bisect and fragment the landscape leads to impacts on animal populations and increases the scale of disturbance (Forman & Alexander, 1998).

Roads are often accompanied by a managed strip of vegetation, where abundant sunlight and moisture from runoff promote quick growth. Typically, management consists of cutting this vegetation or planting native species, which can positively affect diversity (Forman & Alexander, 1998). In temperate regions, roadside plant communities often have relatively high species richness (Forman & Alexander, 1998; Cousins, 2006). However, the physical disturbance during road construction and maintenance promotes the establishment of non-native species (Hansen & Clevenger, 2005). The effects of roads on soil chemistry vary with road surface and the construction materials used. Precipitation runoff and chemical weathering deposit road salt, calcium, sand, other material applied to the road surface, pollutants and trash in adjacent soil, streams and water tables (Mason et al., 1999). Chemical deposition can alter nutrient cycles, ecosystem productivity, soil biota, plant nutrient composition, and soil and water pH (Forman & Alexander, 1998; Mason et al., 1999; Trombulak & Frissell, 2000).

In the Arctic, roads facilitate human development and impacts such as oil and gas exploration by increasing access to remote landscapes (Forman & Alexander, 1998). Increased access to remote regions via existing and planned roads permits greater intensity of resource extraction in the Arctic, which will drive more infrastructure construction, altered land use, and shifts in the movement of resources and people (Huntington et al., 2007).

The Dempster Highway

The Dempster Highway (Highway 8 in the Northwest Territories) is a two-lane all-weather road that extends 740 km from just south of Dawson City, YT to Inuvik, NT. The highway sits atop a 1.2-2.4 m thick raised gravel bed (GNWT, 2007), which reduces heat transfer to underlying permafrost and prevents road surface cracking as the ground heaves seasonally (Auerbach et al., 1997). The Dempster traverses a variety of ecosystems, from boreal forest, to tundra plateaus, to the Mackenzie Delta wetlands (GNWT, 2007). Moving eastward from the Northwest Territories-Yukon border in the Richardson Mountains, the highway descends 850 m in elevation into the Peel Plateau, and descends further into spruce-tamarack forest as it approaches the Peel River and the Mackenzie Delta (GNWT, 2007). The Dempster highway passes through the habitat of the Porcupine caribou herd, Dall's sheep, mountain goats, moose, wolves, wolverine, lynx, fox, grizzly and black bears, and hundreds of bird species (GNWT, 2012).

The highway was envisaged by the federal government in 1958, and became a top construction priority because it would be the first all-weather road linking the Mackenzie Delta to the south, and would play a crucial role in the proposed Mackenzie Valley and Alaska Highway pipelines (MacLeod, 1979: 1). In 1963, the road was named the Dempster Highway, after an RCMP corporal famous for travelling by dog-sled from Dawson City to Fort McPherson, following a centuries-old Gwich'in trail, which became the highway route (MacLeod, 1979: 1). However, when oil and gas drilling efforts in the Eagle Plains area in northern Yukon failed to find commercial deposits, the government grew reluctant to invest in road construction costs, and construction slowed and then halted between 1960 and 1968 (MacLeod, 1979: 9). Following the discovery of large oil and gas reserves at Prudhoe Bay, Alaska in 1968, the road regained priority as a supply route for pipeline materials and a way to assert Canadian sovereignty over Arctic resources (MacLeod, 1979: 13). Construction resumed in 1969, and the highway was officially opened in 1979 (GNWT, 2007). The total cost for the highway was much higher than anticipated, but money that had been allocated to the proposed Mackenzie Highway was reallocated to the Dempster (and other roads) as that project became less feasible due to rising costs.

Because the Dempster crosses mostly continuous permafrost terrain, pre-thawing of the underlying ground by stripping overlying vegetation and soil was not a viable strategy for preventing road bed subsidence. Instead, most highway exploration and construction occurred during the winter months and only tall trees and shrubs were removed. Highway engineers endeavoured to preserve permafrost under the road by constructing a thick embankment that would minimize heat transfer. Some thawing and subsidence was expected to occur in the first few summers following construction (Lingnau, 1985). Local shale and siltstone deposits were often of poor quality and sandstone construction materials had to be quarried from bedrock and hauled long distances (Hayley, 2005). Although few data are available on hydrological drainage patterns, culverts were used widely to preserve water flow and minimize runoff in the toe of the embankment, which would contribute to thermal disturbance and roadbed instability. Road surfacing occurred 2-3 years after embankment construction, after the expected subsidence and warping of the embankment would have halted (Lingnau, 1985). In the Northwest Territories, the road was surfaced with quarried limestone. In the first few years after construction, the highway performed well and settlement was limited between 10 and 100 cm (Lingnau, 1985), but below ground warming resulted in a subgrade collapse near the YT-NT border shortly after construction, and another subgrade collapse in 1985 caused a fatal collision (Hayley, 2005;

McGregor et al., 2008). With warming atmospheric temperatures and land use changes, additional mitigation measures will likely be required along the Dempster to prevent thawing.

The Federal Department of Public Works was initially responsible for supervising road construction, aided by territorial government engineering departments. The federal government of the day also created an explicit policy to employ local people as much as possible for construction and maintenance of northern roads. Today, the highway is managed by the GNWT Department of Transportation and Yukon Highways and Public Works, and contracts are auctioned for road maintenance; Gwich'in construction outfits are responsible for a majority of maintenance between the Yukon border and Fort McPherson.

Environmental and social impact studies were not conducted before highway construction was planned and built. It was not until 1972 that the Department of Public Works commissioned the first environmental study of the highway (MacLeod, 1979: 15). This short study based on literature, aerial images and field measurements concluded that the ecosystems affected by the highway were sensitive to environmental degradation due to their particular wildlife species, short growing season, limited plant diversity, and the presence of permafrost (MacLeod, 1979: 27). The study did not consider the effects of highway use after completion, and a systematic and thorough environmental impact assessment is still lacking. However, extensive research has been conducted on the effects of the road on caribou behaviour and population dynamics, a major concern expressed by local communities because the road bisects the winter range of the Porcupine caribou herd (Bergerud et al., 1984; Horejsi, 1981; Russell et al., 1993; Wolfe et al., 2000). A Dempster Highway Management Plan was approved in 1978, which recommended a 10-mile-wide hunting restriction corridor, but hunting controls were difficult to enforce while land claims were under negotiation (MacLeod, 1979: 38).

Figure 1.4 Christine Firth, a Gwich'in woman from Fort McPherson, walking along the Dempster Highway in the Peel Plateau. In the background several important features are visible: (a) Midway Lake, a community gathering place, (b) a gravel quarry, (c) a seismic cut line, and (d) shrub proliferation near the road. Photo credit: Emily Cameron.

Proposed Pipelines and the Berger Inquiry

In 1974 and 1975, the Canadian and U.S. governments received two applications for a proposed Mackenzie Valley natural gas pipeline (MacLeod, 1979). The proposed pipeline crossed from Prudhoe Bay, Alaska to the Mackenzie Delta, then south along the Mackenzie Valley into Alberta, where it would either branch into Canadian and U.S. markets, or Canadian markets only. Justice Thomas Berger, appointed Commissioner of the Mackenzie Valley Pipeline Inquiry by Indian Affairs and Northern Development Canada in 1974, held hearings in northern communities (Old Crow, Fort McPherson, Tsiigehtchic, Aklavik and Inuvik) to assess the environmental, social and economic impacts of the Mackenzie Valley Pipeline. Berger made his first report in 1977, and he eventually recommended a ten-year moratorium during which land claims could be settled and environmental and social issues addressed. An alternative proposal favoured by Berger was the Alaska highway pipeline, which would avoid sensitive areas and follow the Alaska Highway through Yukon, British Columbia and Alberta, then continue to U.S. markets. A pipeline along the Dempster highway corridor was considered as a connector to the Mackenzie Delta, but there was insufficient evidence to assess the environmental impact of a Dempster lateral route (MacLeod, 1979).

Gwich'in Comprehensive Land Claim Agreement

The history of treaty negotiations varies between Gwich'in bands. In 1921, Chief Julius Salu signed Treaty 11 on behalf of the Teetl'it Gwich'in band (Branch, 2009). However, some bands never entered into treaty agreements with the federal government, which initially favoured the preservation of northern peoples' traditional lifestyles because assimilation promised little economic gain (Branch, 2009). However, increasing hydrocarbon and mining pressures during the 1960s led to disputes about indigenous rights and land entitlement (Branch, 2009). In order to clarify land rights and ownership, the Gwich'in Nation began modern treaty negotiations with the federal and territorial governments in the 1970s, and the Gwich'in Comprehensive Land Claim Agreement (GCLCA) was signed in 1992 between the Gwich'in Tribal Council, the Government of Canada, and the Government of the Northwest Territories (AANDC, 1992). The land claim delineates the Gwich'in Settlement Area (GSA) (Figure 1.5), including 56,935 km^2 of land in the Northwest Territories. The Gwich'in Tribal Council was granted surface land ownership of 16,264 km^2, surface and subsurface land ownership of 6,065 km^2, and subsurface land ownership of 93 km^2 (AANDC, 1992). In the Yukon, the Vuntut Gwitchin First Nation signed a separate land claim agreement in 1995, the Vuntut Gwitchin First Nation Final Agreement, which includes Vuntut Gwitchin traditional territory outside the Northwest Territories. The GCLCA requires the territorial and federal governments to implement land use planning, environmental impact assessment and review, and regulation of land and water use. It also requires industry and government to consult with Gwich'in communities and representatives for any oil and gas development activities on Crown and Gwich'in lands in the Gwich'in Settlement Area. The agreement also makes provisions for the co-management of resources and stipulates the creation of co-management boards (AANDC, 1992). The Gwich'in Renewable

Resources Board was formed in 1996 to be the main management body for wildlife, fish and forest in the Gwich'in Settlement Area (GRRB, 1999). It is supported by a Renewable Resource Council in each community, which is also responsible for reviewing environmental research proposals. More recently, the Gwich'in Nation has been in negotiations with the federal and territorial governments to establish a Final Agreement that will implement the right to self-government provided for in the GCLCA, and has been involved in negotiations for devolution and transfer of responsibilities from the federal to the territorial governments (Aboriginal and Territorial Relations, 2008).

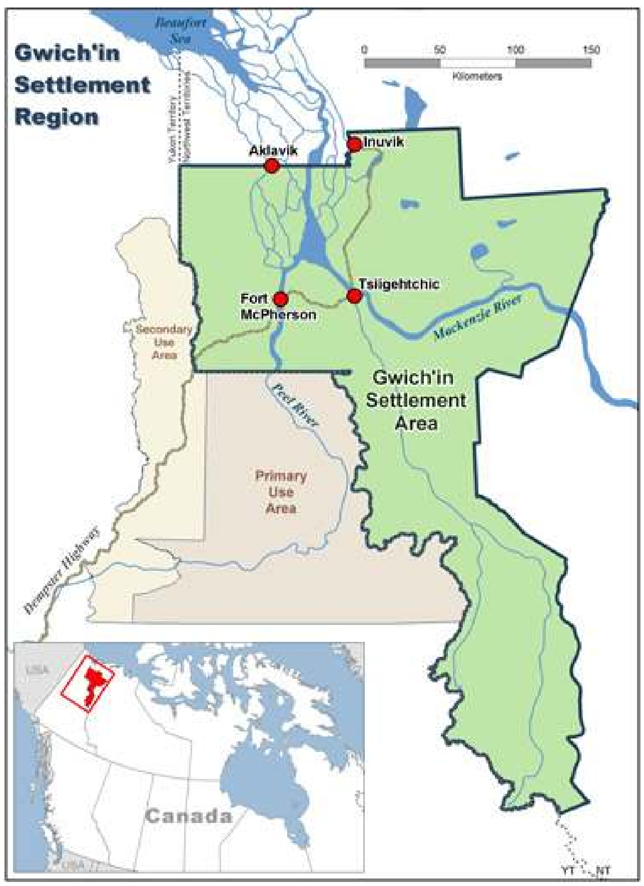

Figure 1.5 Gwich'in Settlement Area, established through the Gwich'in Comprehensive Land Claim Agreement in 1992. Map obtained from the Gwich'in Renewable Resources Board, http://www.grrb.nt.ca/settlementarea.htm.

Traditional Ecological Knowledge in Research, Monitoring and Management

Traditional ecological knowledge consists of the cumulative body of knowledge, beliefs and practices held by members of a culture that is developed through adaptive processes and transmitted through generations (Berkes 2000). Traditional ecological knowledge reflects a place-specific way of knowing and living, making it difficult and often problematic to apply in scientific and western research contexts (Berkes, 2009; Nadasdy, 1999). Often, traditional ecological knowledge is removed from its cultural context and made to fit into the established scientific framework, which invalidates its meaning and reinforces assumptions and power balances that favour dominant scientific agendas (Riedlinger & Berkes, 2001). However, traditional and scientific knowledge systems have some intellectual processes (eg. knowledge acquisition and verification) in common, and can complement each other in some domains (Huntington et al., 2004; King et al., 2008; Duerden & Kuhn, 1998; Riedlinger & Berkes, 2001). Using local expertise to guide the selection of study parameters and contextualize findings can produce research that is more relevant and useful at the regional scale (Riedlinger & Berkes, 2001; Kokelj et al., 2012). TEK has been to shown to have powerful applications in informing research on environmental change, including adaptation to climate change (Berkes & Jolly, 2002). Aspects of TEK relevant to environmental change include an intimate understanding of and ability to record and forecast weather and climate, environmental indicators, and oral records of trends and events (King et al., 2008).

Community-based monitoring is an important component of cooperative resource management in the north because it engages all stakeholders and responds to local understandings and priorities with respect to resources (Berkes et al., 2007). Collaboration between local experts and monitoring scientists and administrators can broaden the range of knowledge available for understand environmental systems. Observations of environmental change are one area where local and traditional knowledge and scientific knowledge converge, since the types of indicators used in traditional knowledge-based monitoring are often similar to those used in science, even if the objectives for monitoring are dissimilar (Berkes et al., 2007). For example, the frequency of sighting and trends in group size of bowhead whales are interesting to both Inuit hunters and biologists, but for different reasons (Inuit/bowhead relationships and access to resources, and conservation of species and populations, respectively) (Hart & Amos, 2004). Local indicators used for monitoring environmental change have the advantage of flexibility; unlike scientific indicators, local indicators are not formalized and can be modified with changing conditions or knowledge, reflecting the inherent complexity of the environment, and the climate change impacts already being felt by Arctic communities (Berkes et al., 2007).

Participatory Mapping as a Tool for Monitoring and Management

Participatory mapping is a method used to gather information about the regional environment and present it in a cartographic form (Chambers et al., 2004). Examples of information that might be mapped, depending on the goal of the research, include territorial boundaries, natural resources, habitats, places of economic or cultural significance, and the perceptions, activities and values of the people inhabiting that environment, all of which is part of a people's local and traditional ecological knowledge (TEK; defined in Chapter 3) (Chambers et al., 2004). The resulting map can serve as a valuable tool for negotiations about land claims and resource management, as well as communicating the community's perceptions and concerns about land-related issues. GIS mapping, which uses computer-based, georeferenced maps, is very accurate and provides rich spatial data, but is also technologically demanding and expensive, and likely depends on outside expertise and funds until capacity is built within the community. Multimedia and internet-based mapping also makes use of GIS, and embeds additional knowledge through various media, including words, photos, videos, and audio. This type of map is engaging and may be better at keeping local and traditional knowledge in its original context. However it also demands training and access to costly technologies, and there can be a disconnect between the media captured and how it relates to the spatial map data (Chambers, 2006). A common requirement for all participatory maps is ground truthing, which is done most accurately by recording the GPS location of map features, but is a step that can be logistically and financially difficult (Puri, 2011). In land-based mapping approaches, such as the participatory multimedia mapping protocol presented in Chapter 3, ground truthing is completed automatically as locations are recorded from true locations by tracking research trips using a handheld GPS.

Participatory mapping can be a powerful way to incorporate local and traditional ecological knowledge in environmental monitoring and management. It has become widely popular and in some cases mandatory to include TEK in resource management and land-use planning decisions in the North (Armitage et al., 2011; Berkes et al., 2007; Dowsley, 2009), and a common approach is to include indigenous people on management boards. However, land-use plans created by co-management boards can also fail to represent local interests, and collaboration is often hindered by cultural and language barriers (Duerden & Kuhn, 1998; Nadasdy, 2005). In participatory mapping, TEK is given precedence, and knowledge holders have more control over how their knowledge is communicated. However, mapping knowledge using an inappropriate scale or context can severely impairs the validity and integrity of TEK (Duerden & Kuhn, 1998). If TEK is transmuted in the mapping process, say from oral communication to written words or drawn features, the original meaning can be lost. TEK also loses validity if it is applied to a larger or smaller scale from which it was first communicated (Duerden & Kuhn, 1998). Maps have the potential to retain the spatial and cultural context of TEK, but care must be taken to collect and present information in a way that is compatible with the original format and scale of knowledge.

Participatory photo mapping (also known as participatory multimedia mapping) is an approach that employs digital tools and narrative interviewing to generate knowledge (Bennett, 2012; Dennis et al., 2009). Maps generated in this process can incorporate several perspectives, presentation media and types of information, making them effective tools for sharing knowledge and guiding community-based strategies for research and action. The participatory photo mapping approach is applicable across disciplines, and has been used to investigate the relationship between the built environment and health outcomes (Dennis et al., 2009), identify resource management practices and values (Sherren et al., 2010), development challenges and opportunities (Levison et al., 2012), and in collaborative ethnography (Clark, 2011). PPM has been used to engage youth throughout the process of research design and execution, and visual participatory research approaches in general are popular ways to engage youth (Jacquez et al., 2013).

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Chapter 2

Cumulative impacts of a gravel road on tundra ecosystems in the Peel Plateau, Northwest Territories, Canada

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Abstract

Vegetation and soils adjacent to the Dempster Highway in the Peel Plateau, NT were examined for effects of road dust deposition and drainage alteration since the highway was completed in the late 1970s. The relationship between roadside disturbance and tall shrub (*Alnus crispa*) abundance was examined by selecting road-disturbed and undisturbed tall shrub and dwarf shrub tundra sites. We found that alder growth and recruitment were significantly enhanced adjacent to the Dempster Highway, and dramatic alterations to plant community composition, soil properties and ground temperatures were observed where alder shrubs had formed closed canopies. Tall shrub sites adjacent to the road exhibited less understory vegetation, greater litter and organic layer thickness, higher nutrient availability, and deeper snowpack. Our results show that conditions generated by the maintenance and use of the road over time can interact with local ecosystem processes in a way that creates unexpected effects and possibly magnifies changes to vegetation communities and soil qualities. In this study, we found that where the road facilitated shrub dominance, feedbacks were initiated that enhanced snow accumulation and altered ground temperatures and soil chemistry. In turn, these changes likely promote shrub recruitment and growth. Shrub proliferation adjacent to the highway is part of a wider trend of shrub proliferation in Arctic tundra driven by increasing temperatures and disturbance, and will be an important consideration for the planning and maintenance of northern infrastructure. To improve our understanding of the spatial heterogeneity of shrub proliferation, research exploring the relationships between biophysical landscape features and shrub development is also needed.

Introduction

Gravel roads are common in regions underlain by continuous permafrost because they are less costly to construct and easier to maintain than paved surfaces (GNWT, 2012; Walker et al., 1987). Gravel roads provide critical transportation links between northern communities and the South, but they are increasingly vulnerable to environmental changes including changing precipitation regimes and permafrost degradation (Burn and Kokelj, 2009; Moritz et al., 2002; Lawrence and Slater, 2005; Tape et al., 2006). Gravel roads affect tundra ecosystems both directly and indirectly (Myers-Smith et al., 2006). Gravel roads alter the thermal properties of the ground surface, which has implications for the surface energy balance and ground thermal regime of underlying and adjacent permafrost, modify local hydrology, and create a physical barrier that fragments the landscape. During initial construction, the removal of vegetation and establishment of culverts for stream and river crossings alters local hydrology and increases soil erosion (Claridge and Mirza, 1981; Myers-Smith et al., 2006). In permafrost terrain a thaw bulb can develop to several meters depth below the toe of the road embankment within a few decades of construction, leading to subsidence of the embankment and adjacent land (Hayley, 2005; Lingnau, 1985). Development and maintenance of gravel roads requires significant amounts of borrow materials, which can lead to challenges in the development and management of quarries sometimes constructed in ice-rich permafrost terrain. Roads can also indirectly affect adjacent terrain by increasing dust deposition and runoff, altering soil properties, impacting plant physiology, and introducing invasive species (Auerbach et al., 1997; Eller, 1977). Roadside gravel deposition from ploughed snow, trash and vehicular pollution are other factors that may affect adjacent vegetation (Walker et al., 1987). Anecdotal evidence suggests that changes in vegetation structure adjacent to many northern roads have been extensive. These changes have the potential to alter ground temperatures adjacent to roadbeds (Myers-Smith et al., 2011). Additional research is needed to examine the feedbacks between gravel roads, vegetation change, snow accumulation and near-surface ground thermal regime in the Arctic since maintenance of permafrost in the roadbed and embankment are critical to long-term stability.

The Dempster Highway is a 740 km gravel highway between Dawson City, YT and Inuvik, NT. This highway is a critical transportation link between the Canadian western Arctic and southern Canada. The Dempster Highway begins at 64°N, and traverses boreal spruce forest, woodlands, alpine tundra and a variety of wetlands before terminating about 60 km south of the treeline at 68°N (Western Arctic Handbook Society, 2007). In the Peel Plateau region of the Northwest Territories, the Dempster Highway descends 850 m from the Richardson Mountains across a fluvially incised plateau consisting of ice-rich hummocky morainal deposits. This area is characterized by spruce forest at lower elevations and dwarf shrub tundra at higher elevations (GNWT, 2007). Residents in nearby communities have expressed concerns about the impacts of the road on vegetation and terrain stability (Kershner, 2010; Scott, 2011). The Peel Plateau is also an important area for harvesting country foods including wild berries, and development impacts on the abundance and distribution of berry patches are a concern to Teetl'it Gwich'in harvesters (Parlee et al., 2005).

Several studies in the western Arctic have investigated the impacts of gravel roads on moist sedge tussock and dwarf shrub tundra (Auerbach et al., 1997; Myers-Smith et al., 2006; Walker and Everett, 1987). However, to date no studies have explored the impact of gravel roads on upright shrub tundra, such as is found along parts of the northern portion of the Dempster Highway. The Dalton Highway and the Prudhoe Bay Road in Alaska have been shown to alter acidic and nonacidic tundra plant community composition, decrease species richness and soil moisture, and increase soil pH, bulk density, snow accumulation and the rate of snowpack melt (Auerbach et al., 1997; Myers-Smith et al., 2006; Walker and Everett, 1987; Walker et al., 1987). The Dalton Highway has also contributed to altered vegetation structure, deeper snowpack and increased active layer thickness adjacent to the road (Auerbach et al., 1997; Myers-Smith et al., 2006). In the Peel Plateau, the Dempster Highway has likely facilitated similar ecological changes, but the long-term impacts of this road have not been quantitatively investigated (Smith, 2009). This portion of the highway is constructed over ice-rich terrain, and the outcomes of disturbance are likely unique to the ecosystem processes and feedbacks in this zone of upright shrub tundra. A clear understanding of ecological feedbacks associated with the Dempster Highway in the Peel Plateau will contribute to a more thorough understanding of regional impacts. This study can provide insight into the feedbacks between roads and vegetation change, and the long-term consequences on permafrost conditions, which is of particular relevance to the Inuvik-Tuktoyatuk Highway currently being constructed across the latitudinal treeline between Inuvik and the Beaufort Sea coast.

In this study we used space for time substitution to examine the impact of gravel road construction and 35 years of use on shrub-tundra vegetation, soils and permafrost conditions in the Peel Plateau section of the Dempster Highway. Specifically, our primary objective was to examine if the physical disturbance associated with road construction and maintenance, including dust and altered drainage, have affected vegetation composition and structure, and whether this has resulted in positive feedbacks and impacts on permafrost. To examine how the effects of the road may be mediated by vegetation type, we compared biotic and abiotic conditions at sites adjacent to the road with undisturbed tundra, and we sampled in areas characterized as tall shrub tundra as well as dwarf shrub tundra. We hypothesized that the effects of the road would be greatest in tall shrub tundra, where feedbacks between tall shrubs and road inputs amplify effects on vegetation, soils and ground temperature underneath tall shrubs.

Methods

Study area

This study was conducted in the Peel Plateau region of the Northwest Territories, in a 70 km^2 study area approximately halfway between Fort McPherson and the Yukon border (Figure 2.1). This section of the highway corridor was selected because it has homogeneous soils and relatively uniform climate at similar elevations. This area is characterized by hummocky moraine ranging in elevation from 150 to 600 m above sea level. Deeply incised creek valleys drain to the Peel River via the Vittrekwa River south of the highway and Stony Creek north of the highway (Kokelj et al., 2013). The region is underlain by continuous permafrost (Smith and Burgess, 2000). Active layer development varies with soil conditions and vegetation type, and thicknesses range from about 50 to 100 cm (Hughes et al., 1981). Cretaceous sandstone and mudstone comprise bedrock which is overlain by ice-rich moraine and glaciolacustrine silt and clay deposits (Hadlari, 2006). In this area, the Dempster Highway is a two-lane all-weather road that sits atop a 1.2-2.4 m-thick raised gravel bed constructed of glaciofluvial bedrock and surfaced with quarried limestone or glaciofluvial bedrock (Hayley, 2005; Lingnau, 1985; MacLeod, 1979). The large gravel berm is designed to reduce heat transfer to underlying permafrost so a frozen foundation is maintained, which prevents settlement of the embankment and road surface cracking as the ground heaves seasonally (Hayley, 2005; McGregor et al., 2008; GNWT, 2007).

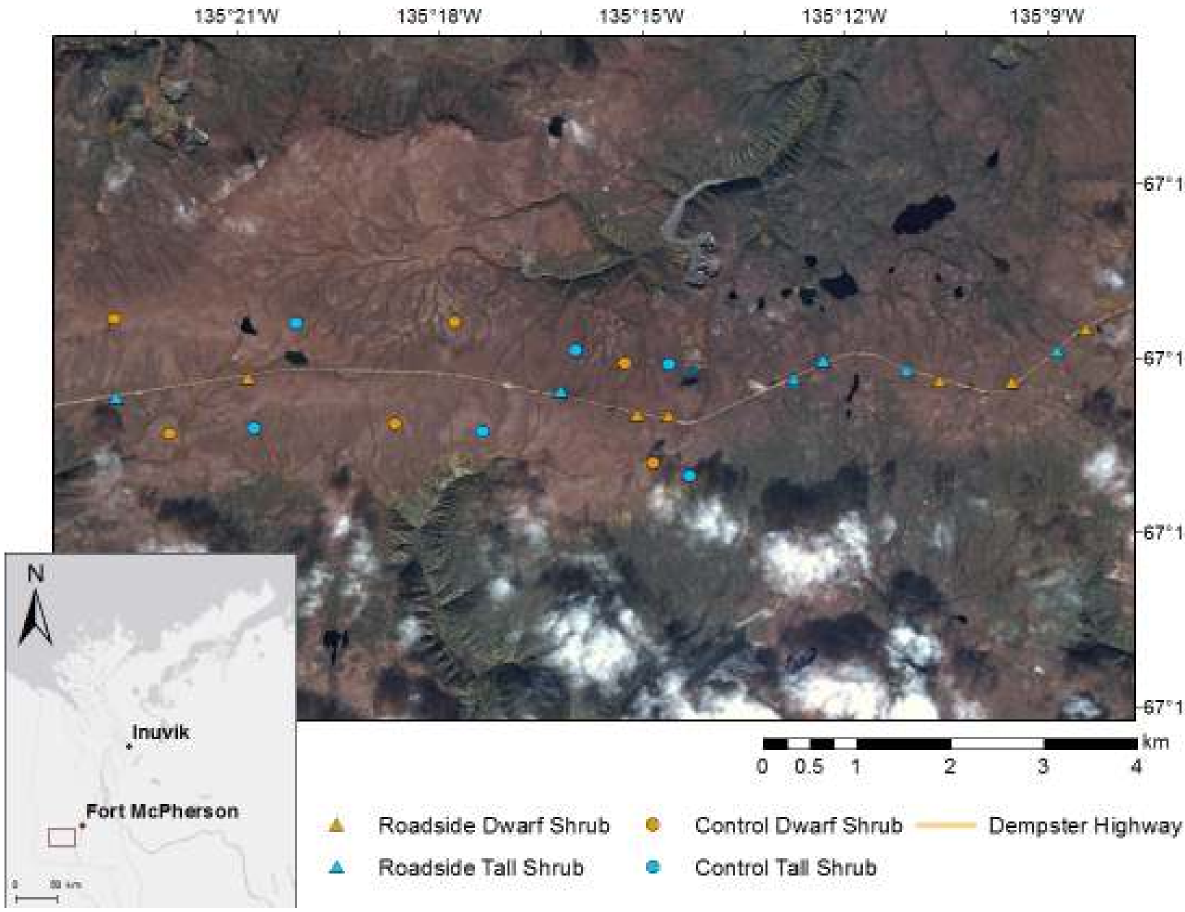

Figure 2.1 Quickbird (2004) satellite image of the study area showing sites along the Dempster Highway classified by disturbance and vegetation type. Inset map at bottom left shows the position of the study area in northwestern Canada (red box).

The study area lies at the northern edge of the Boreal forest, and is a heterogeneous landscape with spruce forest at lower elevations, transitioning to patchy tundra dominated by tall shrubs (*Salix, Alnus, Betula*) and ericaceous shrubs (*Ledum, Vaccinium, Arctostaphylos*) at medium elevations, and dwarf shrubs (*Ledum, Vaccinium, Empetrum, Rubus, Arctostaphylos*) and sedges (*Eriophorum* and *Carex*) at higher elevations (Meikle and Waterreus, 2008). The regional climate is characterized by long cold winters with average air temperatures below 0^{o}C from October through April. The mean annual air temperature at Fort McPherson is -7.3^{o}C and mean annual precipitation is 310 mm (Burn and Kokelj, 2009). Convective rainfall events can deposit tens of millimetres of precipitation over periods of a few hours. The presence of a shallow permafrost table can rapidly transfer surface water to streams, causing roadside washouts. Rapid saturation of the active layer can also result in the loss of shear strength resulting in active layer detachment slides, which may develop into retrogressive thaw slumps (Kokelj et al., 2013). Human disturbances in this region include seismic cut lines created in the 1970s, off-road vehicle tracks, and gravel quarries and pull-outs along the road. In the study area, old borrow pits are not actively quarried, but are used to store and distribute gravel excavated from active pits further west along the highway. The closest active quarries are at Midway Lake, 1 km West of the study area, and at Frog Creek, 70 km East of the study area. Traffic on the highway includes large transportation trucks, recreational vehicles including cars and trucks, motorcycles, bicycles and all-terrain vehicles (Western Arctic Handbook Society, 2007). Road maintenance occurs regularly in the summer, and consists of additional gravel deposition, grading, culvert replacement and the application of calcium and water to control dust (Scott, 2011). In winter, the road remains open and snow removal occurs, although winter winds can result in snow drifting and road closures.

Site selection

To examine the impact of the road on tundra vegetation and soil, we focused on the zone of most intense impacts, within 15 m of the toe of the embankment (Walker and Everett, 1987). We selected study sites directly adjacent to the Dempster Highway (15 m from the embankment), and in undisturbed tundra at least 500 m from the highway, where dust deposition and hydrological alterations are negligible (Auerbach et al., 1997; Santelmann and Gorham, 1988). To explore the role of vegetation in mediating the impacts of the road we used 2007 Quickbird satellite imagery to select sites that are dominated by tall shrubs, and sites dominated by dwarf shrubs with sparse tall shrub cover. A total of twenty-four sites were sampled, including six road sites dominated by tall shrubs, six road sites dominated by dwarf shrubs, six undisturbed sites dominated by tall shrubs, and six undisturbed sites dominated by dwarf shrubs (Figures 2.1 and 2.2). Throughout this paper, these sites are referred to as: roadside tall shrub, roadside dwarf shrub, control tall shrub, and control dwarf shrub. All sites were at least 300 m apart and distributed on both the north and south sides of the highway (Figure 2.1).

Figure 2.2 Plant community composition at four site types: (A) roadside dwarf shrub and (B) roadside tall shrub sites, and (C) control dwarf shrub and (D) control tall shrub sites

Biotic response variables

At each site we established a 200 m transect parallel to the highway on flat terrain (0-3° slope). Transects excluded hydrologic features such as water tracks, creeks and ponds. Along each transect, we measured plant community composition by visually estimating the percent cover of tall shrub and tree species in ten randomly located $5m^2$ plots. The cover of understory species was estimated using $0.0625m^2$ sub-plots. *Salix* spp., *Sphagnum* spp., acrocarpous mosses, pleurocarpous mosses and lichens were grouped. To assess the impacts of the road on green alder growth and population dynamics, we made detailed measurements of this species on three sample plots along each transect, totalling 72 of the community composition plots. To avoid bias we sampled the same three plots (#3,5,7) on each transect regardless of the alder cover. Since alders were never present in the selected plots at control dwarf shrub sites, this site type is excluded from this component of our study. In each $5m^2$ plot sampled for alder we measured the height and basal diameter of all stems within the plot. To determine the number of individuals in the plot and their ages we traced each stem back to a root crown and collected a stem section above the top of the root collar. Stem sections were dried, sanded and examined under a dissecting microscope to record stem age by counting growth rings on two radii. The diameter of each stem section was also measured using calipers. We used these data to estimate alder growth rates (vertical growth = stem height / age; radial growth = stem basal diameter / age).

Abiotic response variables

In March 2012, we measured snow depth at each site along a 75 m snow transect parallel to the highway by inserting a graduated avalanche probe every 5 m. To measure active layer thickness, in late August 2012 we inserted a graduated soil probe at ten random locations along the 200 m transect to the depth of refusal. In hummocky terrain active layer measurements were taken in the centre of the hummock in order to minimize the effects of within-site microtopographic variation. Two measurements of litter and organic layer thickness were also made in the same ten locations using a metal ruler inserted into the soil to visually demarcate horizons. To measure the supply rate of plant-available nutrients, we used Plant Root Simulator (PRS) nutrient probes (Western Ag Innovations, Saskatoon, SK, Canada). PRS probes consist of paired cation and anion exchange resin membranes, and provide nutrient supply rates in milliequivalents / cm^2 exchange membrane / days of burial (Western Ag Innovations Inc., 2012). In 2012, we installed 6 pairs of probes at each of our four site types (n=24) for 30 days (July 23-August 23, 2012). In 2011, we deployed probes at four roadside tall shrub sites, three control dwarf shrub sites and three control tall shrub sites between July 22-August 22, 2011. All probes were inserted in the top 15 cm of soil. To measure soil pH, we collected 100 cm^3 organic soil samples from between hummocks at two locations along each transect. In the lab, we mixed 10 mL of soil with 40 mL of deionized water (Kalra and Maynard 1991), agitated the solution for three minutes, and left it standing for two hours before measuring the pH.

To measure ground temperatures, we installed HOBO data loggers (U23 Pro v2, Onset Computing) at five roadside tall shrub sites, five control tall shrub sites, and five control dwarf shrub sites. Each data logger was attached to 2 thermistors (U23-002, Onset Computing) anchored along a PVC tube inserted and positioned at 10 cm and 100 cm belowground. Temperatures were logged every hour for one year before collection in August 2012. Thermistors were not installed at roadside dwarf shrub sites because these sites had not yet been selected in 2011.

Statistical analyses

To explore differences in community composition among site types (roadside tall shrub, roadside dwarf shrub, control tall shrub, and control dwarf shrub), we used PRIMER (Plymouth Marine Laboratories, Plymouth, UK) to perform a non-metric multidimensional scaling (NMDS) ordination of a Bray-Curtis resemblance matrix calculated using percent cover data (Clarke and Gorley, 2001). To reduce noise prior to analysis, abundance data were log(1+x) transformed and rare species (occurred in fewer than two subplots) were deleted (Clarke, 1993). The NMDS analysis was repeated 25 times and the two-dimensional ordination plot with the least stress was automatically selected by PRIMER. We also performed an ANOSIM with 999 permutations on the resemblance matrix to test whether community composition was significantly different among site types. To determine the contribution of each species or species group to pairwise dissimilarities between site types and similarities within site types, we performed a SIMPER analysis of log(1+x) transformed cover data (Clarke and Gorley, 2001).

To test whether the road significantly altered biotic and abiotic response variables, we used the PROC MIXED procedure in SAS (SAS Institute, Cary, NC, USA). PROC MIXED uses maximum likelihood to estimate variance components of a general linear model (Littell et al., 2006). We set disturbance (road-disturbed or control) and vegetation type (tall shrub or dwarf shrub) as fixed factors, and plot and site as random factors, and used the Kenward-Roger approximation to estimate degrees of freedom (Kenward and Roger, 1997). To examine the importance of random spatial variation in our models we removed random terms one at a time and compared models using Akaike information criteria (AIC) (Johnson and Omland, 2004). We retained the plot and site terms for models of alder height and age, and used a model with site as the only random factor for all other variables. Multiple comparisons were made using the LS

MEANS procedure to detect significant differences in least squares means ($\alpha = 0.05$, Tukey-Kramer adjusted p-values). Residuals were plotted to check deviations from normality.

Results

Plant community composition was affected by the Dempster Highway in both tall and dwarf shrub tundra. The plant community at roadside tall shrub sites was distinct from all other site types (R_{ANOSIM} values 0.315-0.640, Table 2.1).

Table 2.1 Pairwise comparisons of plant community composition between site types using the ANOSIM procedure. RANOSIM values for sites that can be readily distinguished based on their species composition are shown in bold (Clarke & Gorley, 2001).

		Tall Shrub		Dwarf Shrub	
		Roadside	Control	Roadside	Control
Dwarf Shrub	Control	**0.640**	**0.265**	**0.333**	
	Roadside	**0.345**	0.196		
Tall Shrub	Control	**0.315**			
	Roadside				

These differences were driven primarily by a higher abundance of alders and a lower abundance of acrocarpous mosses, lichens, peat mosses, and dwarf shrubs (*Rubus chamaemorus, Empetrum nigrum, Ledum decumbens,* and *Vaccinium vitis-idaea*) at roadside tall shrub sites (Table 2.2). Roadside and control dwarf shrub sites were also distinguished by a lower abundance of lichens, acrocarpous mosses and *Petasites* spp. at the road, and a higher abundance of *Eriophorum vaginatum* and most dwarf shrubs at the road (Table 2.2). The only site types with similar community composition were control tall shrub and roadside dwarf shrub sites; although there were fewer alders at the latter, both had understory vegetation dominated by sedges and dwarf shrubs (Table 2.1). The magnitude of differences in plant community composition among site types is shown visually in an NMDS ordination (Figure 2.3). At the road, the abundance of species harvestable for edible berries was lower at tall shrub compared to dwarf shrub sites. Away from the road, berry plants were also less abundant at tall shrub sites. Exotic species were not encountered along transects, but were occasionally observed in the highway corridor (eg. *Matricaria discoidea*).

Table 2.2 Results of the SIMPER analysis showing the top six species or species groups contributing to between-group dissimilarity for pairwise comparisons of site types.

Species or Species Group	Abundance Site Type 1	Abundance Site Type 2	% Dissimilarity	Cumulative % Dissimilarity
Roadside (Tall Shrub) and **Roadside** (Dwarf Shrub)				
Alnus crispa	2.96	0.49	11.69	11.69
Acrocarpous Mosses	1.37	2.24	8.83	20.52
Eriophoru vaginatum	0.45	1.91	7.93	28.45
Rubus chamaemorus	1.89	2.16	6.69	35.14
Empetrum nigrum	0.95	1.85	6.45	41.58
Ledum decumbens	1.67	2.39	6.15	47.74
Roadside (Tall Shrub) and **Control** (Tall Shrub)				
Alnus crispa	2.96	1.41	9.51	9.51
Lichens	0.17	1.97	8.14	17.65
Acrocarpous Mosses	1.37	1.86	8.1	25.74
Rubus chamaemorus	1.89	2.33	6.9	32.65
Vaccinium vitis-idaea	1.54	2.82	6.56	39.21
Sphagnum spp.	0	1.57	6.53	45.74
Roadside (Dwarf Shrub) and **Control** (Tall Shrub)				
Acrocarpous Mosses	2.24	1.86	8.35	8.35
Eriophorum vaginatum	1.91	0.74	7.93	16.29
Lichens	1.28	1.97	7.71	24
Sphagnum spp.	0.3	1.57	6.79	30.79
Rubus chamaemorus	2.16	2.33	6.47	37.26
Empetrum nigrum	1.85	0.94	6.41	43.66
Roadside (Tall Shrub) and **Control** (Dwarf Shrub)				
Lichens	0.17	3.56	12.2	12.2
Alnus crispa	2.96	0.17	10.42	22.62
Acrocarpous Mosses	1.37	2.69	7.74	30.36
Rubus chamaemorus	1.89	1.02	5.85	36.21
Ledum decumbens	1.67	2.82	5.64	41.85
Vaccinium vitis-idaea	1.54	2.6	5.29	47.14
Roadside (Dwarf Shrub) and **Control** (Dwarf Shrub)				
Lichens	1.28	3.56	10	10
Eriophorum vaginatum	1.91	0.61	7.58	17.57
Acrocarpous Mosses	2.24	2.69	7.41	24.99
Rubus chamaemorus	2.16	1.02	6.95	31.93

Empetrum nigrum	1.85	1.54	5.51	37.44
Vaccinium vitis-idaea	1.95	2.6	5.34	42.78
Control (Tall Shrub) and **Control** (Dwarf Shrub)				
Lichens	1.97	3.56	8.53	8.53
Acrocarpous Mosses	1.86	2.69	7.53	16.06
Rubus chamaemorus	2.33	1.02	7.42	23.48
Sphagnum spp.	1.57	0.77	7.03	30.51
Alnus crispa	1.41	0.17	5.66	36.17
Empetrum nigrum	0.94	1.54	5.55	41.72

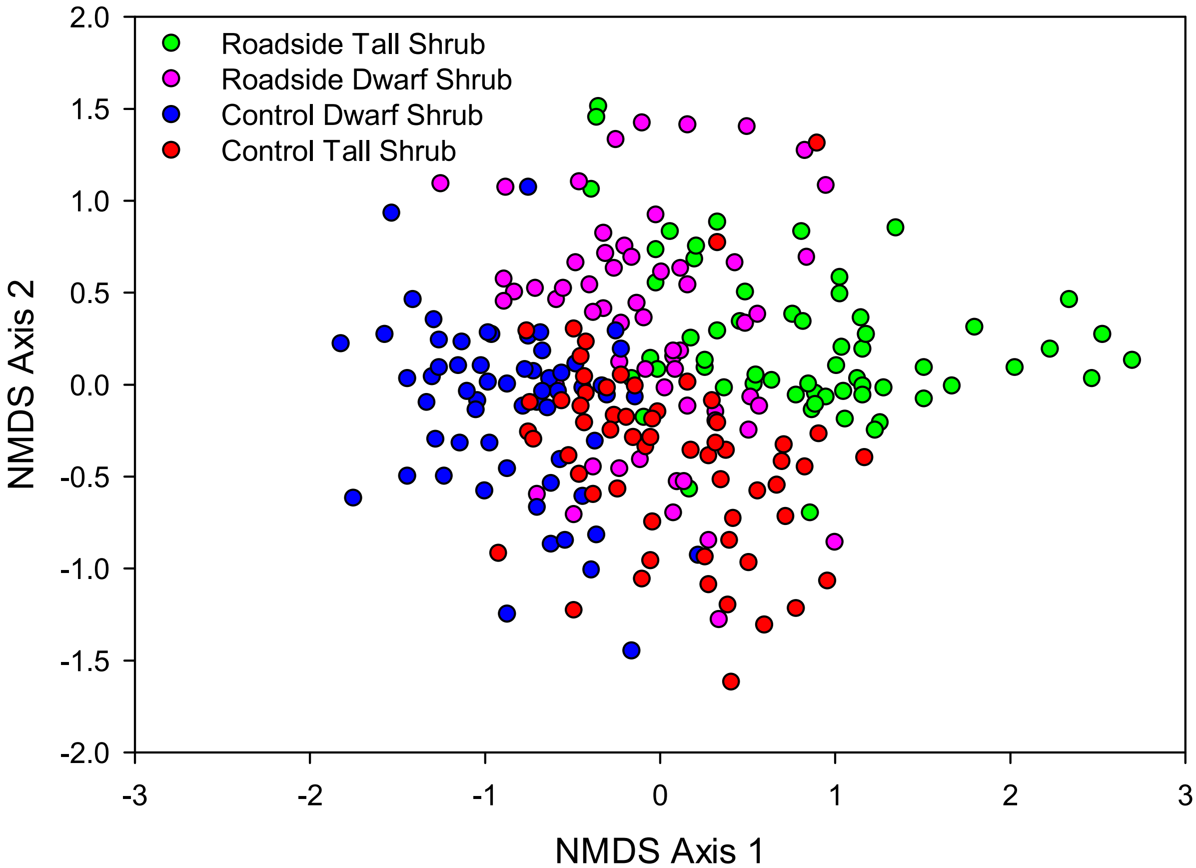

Figure 2.3 Non-metric multidimensional scaling ordination of plant community composition based on Bray-Curtis similarity matrix. Symbols represent individual plots sampled at road-disturbed and undisturbed sites in tall and dwarf shrub dominated tundra.

The presence of the road also had a strong impact on alder abundance and growth. Alder cover was significantly greater at roadside tall shrub sites than at all other site types, including control tall shrub sites (p<0.001) (Figure 2.7a). Other upright shrubs (*Betula glandulosa*, *Spiraea beauverdiana* and *Salix* spp.) were not influenced by the road and had similar abundances across site types. Alders at roadside tall shrub sites were significantly younger, taller and faster growing compared to controls (Figure 2.4). Alders at roadside dwarf shrub sites were slightly younger and shorter, but were faster growing than at roadside tall shrub sites, but the differences were not significant (Figure 2.4).

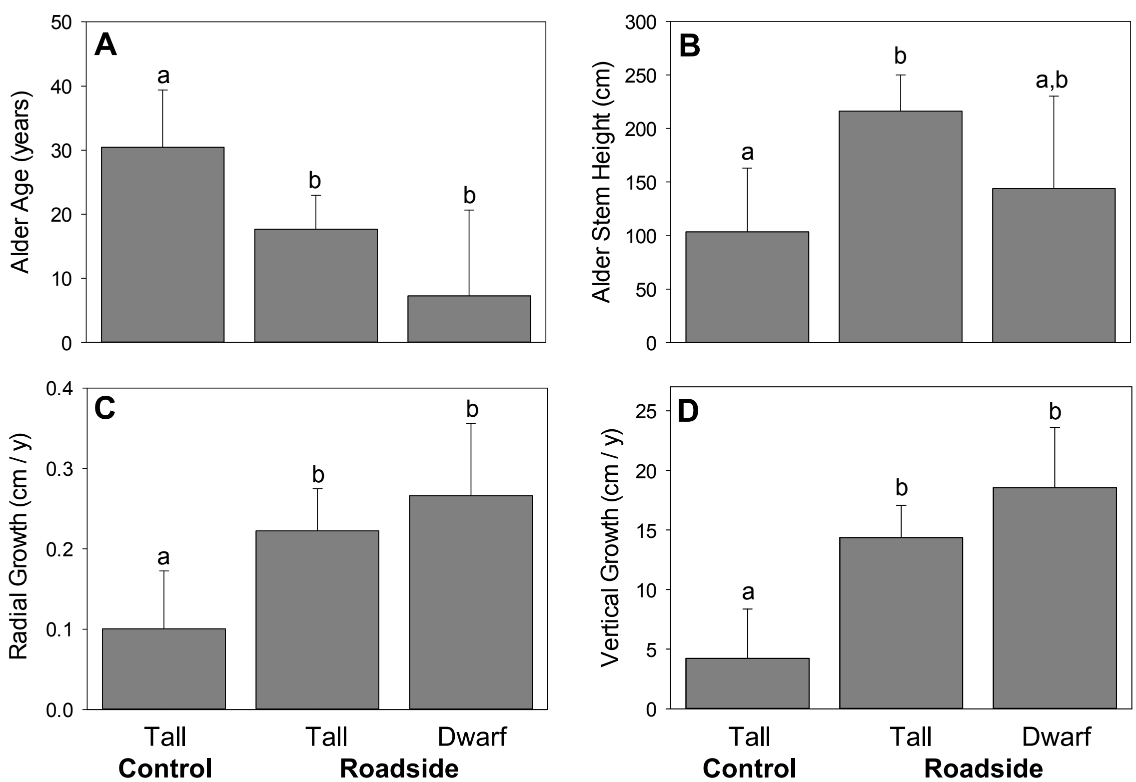

Figure 2.4 Alder response variables measured in undisturbed tall shrub tundra (control tall) and beside the Dempster Highway (roadside tall), and in dwarf shrub tundra beside the highway (roadside dwarf): (A) average age (years), (B) stem height (cm), (C) radial growth rate (cm/year), and (D) vertical growth rate (cm/year). Alders did not occur in the sampled plots at undisturbed dwarf shrub sites. Bars show means for each site type and error bars are 95% confidence intervals of the mean (untransformed). Bars sharing the same letter are not significantly different ($\alpha = 0.05$, mixed model and Tukey adjusted LSD).

Both roadside site types had a higher proportion of young individuals than control sites where the population was dominated by individuals > 25 years (Figures 2.4a and 2.5). Alders were not encountered in surveys of control dwarf shrub sites, but recent alder recruitment was evident at dwarf shrub sites adjacent to the road.

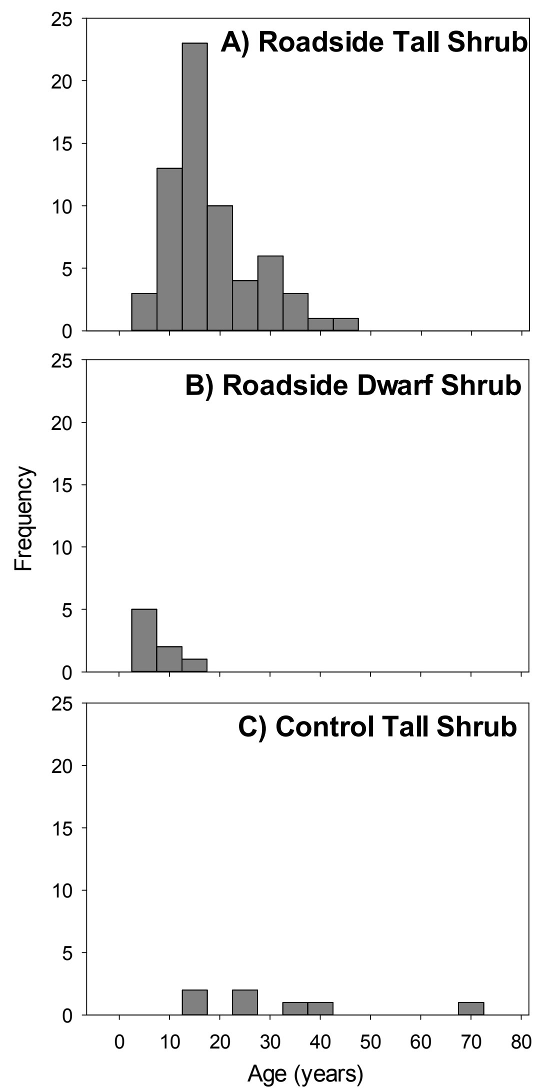

Figure 2.5 Alder age distributions at (A) roadside tall shrub tundra sites, (B) roadside dwarf shrub sites, and (C) control tall shrub sites. Alders did not occur in the sampled plots at undisturbed dwarf shrub sites. Bars indicate number of individual alders in each age category.

Comparisons of alder stem counts made using 1972 air photos and 2007 Quickbird satellite images confirm that alder proliferation within 100 m of the road has occurred more rapidly than in undisturbed tundra (Figure 2.6).

Figure 2.6 Vegetation surrounding the Dempster Highway in the Peel Plateau, Northwest Territories. Shrub proliferation, particularly of *Alnus crispa*, since the 1970s has been most extensive adjacent to the road.

Abiotic parameters including snow, active layer thickness, litter and organic soil thickness all mirrored the pattern of alder cover, with higher values at roadside sites compared to controls, and at tall shrub sites compared to dwarf shrub sites (Figure 2.7). Snow thicknesses at roadside tall shrub sites were significantly greater than at both dwarf shrub site types (Figure 2.7b, $p \leq 0.05$). Snowpack was similar amongst all other site types. Active layer thickness was also greatest at roadside tall shrub sites, but these differences were not significant. The greatest active layer thicknesses (>120 cm) occurred at roadside tall shrub sites under thick alder patches, but since our transects crossed through alder thickets to more open areas, measurements also included shallower active layers (Figure 2.7c). Organic soil and litter thickness were both influenced by the effects of the road on vegetation. Both parameters were greatest at roadside and control tall shrub sites (Figure 2.7d and 2.7e). Soil pH in both roadside site types was higher than the controls, but the differences were only significant where tall shrubs dominated (Figure 2.7f).

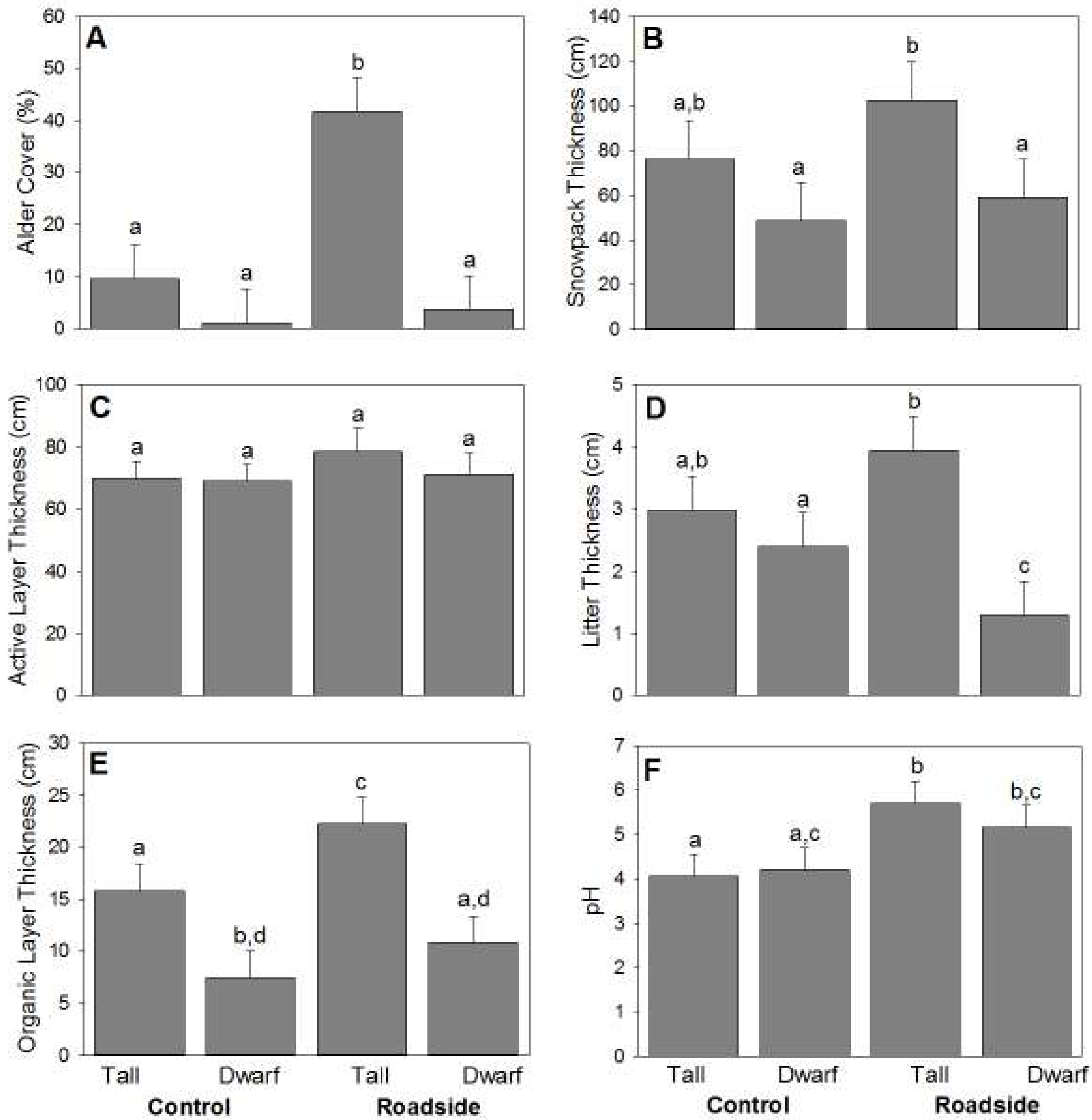

Figure 2.7 Biotic and abiotic response variables measured in undisturbed tall shrub tundra (Control Tall) and dwarf shrub tundra (Control Dwarf), and in disturbed tall shrub tundra (Roadside Tall) and dwarf shrub tundra (Roadside Dwarf): (A) alder cover (%), (B) snowpack thickness (cm), (C) active layer thickness (cm), (D) litter thickness (cm), (E) organic layer thickness (cm), and (F) soil pH. Bars show means for each site type and error bars are 95% confidence intervals of the mean (untransformed). Bars sharing the same letter are not significantly different ($\alpha = 0.05$, mixed model and Tukey adjusted LSD).

Soil chemistry was also significantly impacted by the road, but in some cases the differences were mediated by vegetation type (Figure 2.8). Total nitrogen, calcium, magnesium and sulphur all showed higher levels near the road, but significant differences were limited to tall shrub sites. Vegetation type also had a significant effect on sulphur and total nitrogen supply rates, showing the highest levels at roadside tall shrub sites (Figure 2.8; Table 2.3).

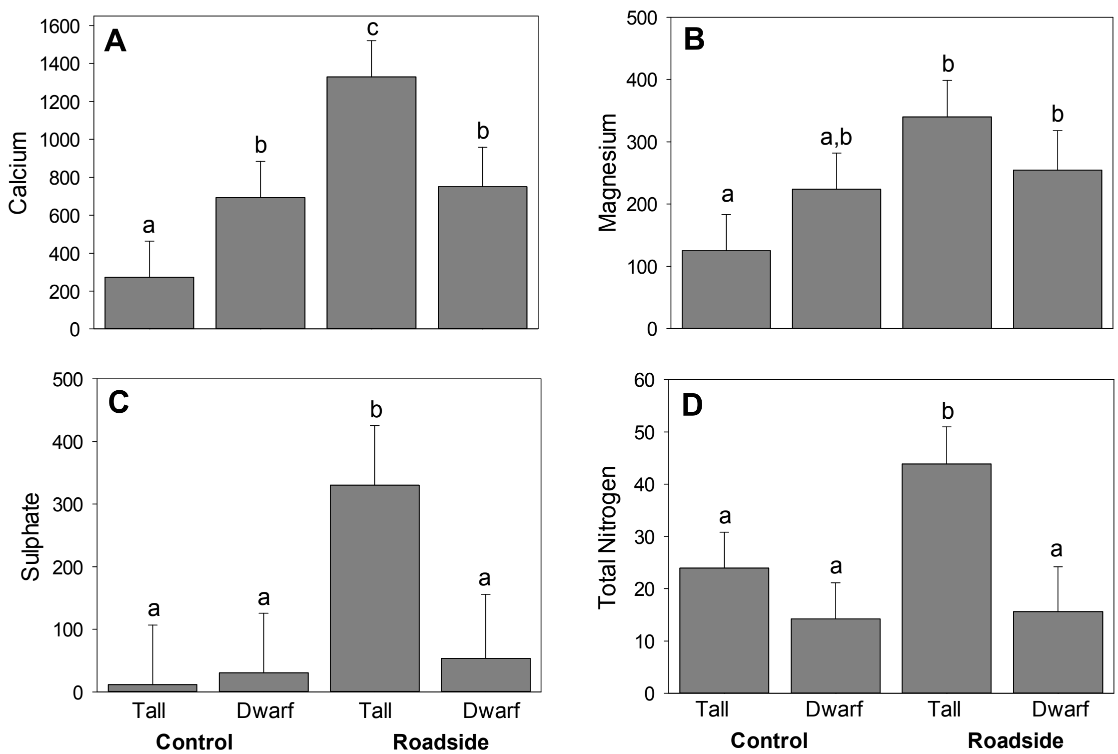

Figure 2.8 Plant-available nutrient supply rate (µg/cm2/d) at control tall shrub tundra sites (Control Tall), roadside tall shrub tundra sites (Roadside Tall), and roadside dwarf shrub tundra sites (Roadside Dwarf): (A) calcium, (B) magnesium, (C) sulphate, and (D) total nitrogen. Bars show means for each site type and error bars are 95% confidence intervals of the mean (untransformed). Bars sharing the same letter are not significantly different ($\alpha = 0.05$, mixed model and Tukey adjusted LSD).

Table 2.3 Results of mixed model ANOVAs of fixed effects for biotic and abiotic response variables. Vegetation type has two levels: tall shrub and dwarf shrub, and Disturbance includes two levels: road-disturbed and undisturbed. *No tests for interactions were performed since alders were not present at undisturbed dwarf shrub sites.

Response Variable	Effect	p	F Value	Degrees of Freedom
Active Layer Depth	Vegetation Type	0.1640	2.03	1, 32
	Disturbance	0.1446	2.28	1, 23
	Vegetation x Disturbance	0.2765	1.23	1, 32
Litter Depth	Vegetation Type	**<.0001**	33.88	1, 20
	Disturbance	0.8207	0.05	1, 20
	Vegetation x Disturbance	**0.0013**	13.90	1, 20
Organic Soil Depth	Vegetation Type	**<.0001**	56.68	1, 20
	Disturbance	**0.0013**	13.87	1, 20
	Vegetation x Disturbance	0.2536	1.38	1, 20
Snow Depth	Vegetation Type	**0.0008**	16.94	1, 16
	Disturbance	**0.0506**	4.47	1, 16
	Vegetation x Disturbance	0.3715	0.85	1, 16
Snow Density	Vegetation Type	0.0526	4.39	1, 16
	Disturbance	0.6725	0.19	1, 16
	Vegetation x Disturbance	0.4108	0.71	1, 16
Soil pH	Vegetation Type	0.4464	0.60	1, 20
	Disturbance	**<.0001**	27.42	1, 20
	Vegetation x Disturbance	0.1774	1.95	1, 20
Nitrogen Supply Rate	Vegetation Type	**<.0001**	25.32	1, 57
	Disturbance	**0.0063**	8.04	1, 57
	Vegetation x Disturbance	**0.0170**	6.04	1, 57
Calcium Supply Rate	Vegetation Type	0.4340	0.64	1, 20
	Disturbance	**<.0001**	31.27	1, 20
	Vegetation x Disturbance	**<.0001**	25.13	1, 20
Magnesium Supply Rate	Vegetation Type	0.8328	0.05	1, 20
	Disturbance	**0.0006**	16.33	1, 20
	Vegetation x Disturbance	**0.0068**	9.13	1, 20
Sulphate Supply Rate	Vegetation Type	**0.0159**	6.84	1, 22
	Disturbance	**0.0022**	12.02	1, 22
	Vegetation x Disturbance	**0.0067**	8.99	1, 22
Alder Height*	Vegetation Type	0.1369	2.35	1, 28
	Disturbance	**0.0028**	10.49	1, 32
Alder Age*	Vegetation Type	0.1708	1.99	1, 24
	Disturbance	**0.0233**	5.83	1. 26
Alder Vertical Growth*	Vegetation Type	0.1697	2.08	1, 15
	Disturbance	**0.0008**	15.94	1, 19

Alder Radial Growth*	Vegetation Type	0.4233	0.68	1, 14
	Disturbance	**0.0176**	7.11	1, 15
Alder Cover	Vegetation Type	**<.0001**	49.23	1, 20
	Disturbance	**<.0001**	27.66	1, 20
	Vegetation x Disturbance	**0.0002**	20.15	1, 20

Roadside sites dominated by tall shrubs had higher ground temperatures than controls. At 10 cm belowground, average daily temperatures were warmer at the roadside tall shrub sites than at control tall and dwarf shrub sites, except in the summer (July-August) when soils were slightly cooler underneath roadside tall shrubs (Figure 2.9). Temperatures at 10 cm-depth under tall shrubs in undisturbed tundra were also warmer in the winter and spring than in undisturbed dwarf shrub tundra. Roadside tall shrub ground temperatures at 100 cm-depth were also warmer than controls, and remained close to zero throughout the entire year. Minimum temperatures at tall and dwarf shrub control sites were 5-10 °C lower than at roadside sites, and freezeback was completed by February 27 and February 1, respectively (Figure 2.9).

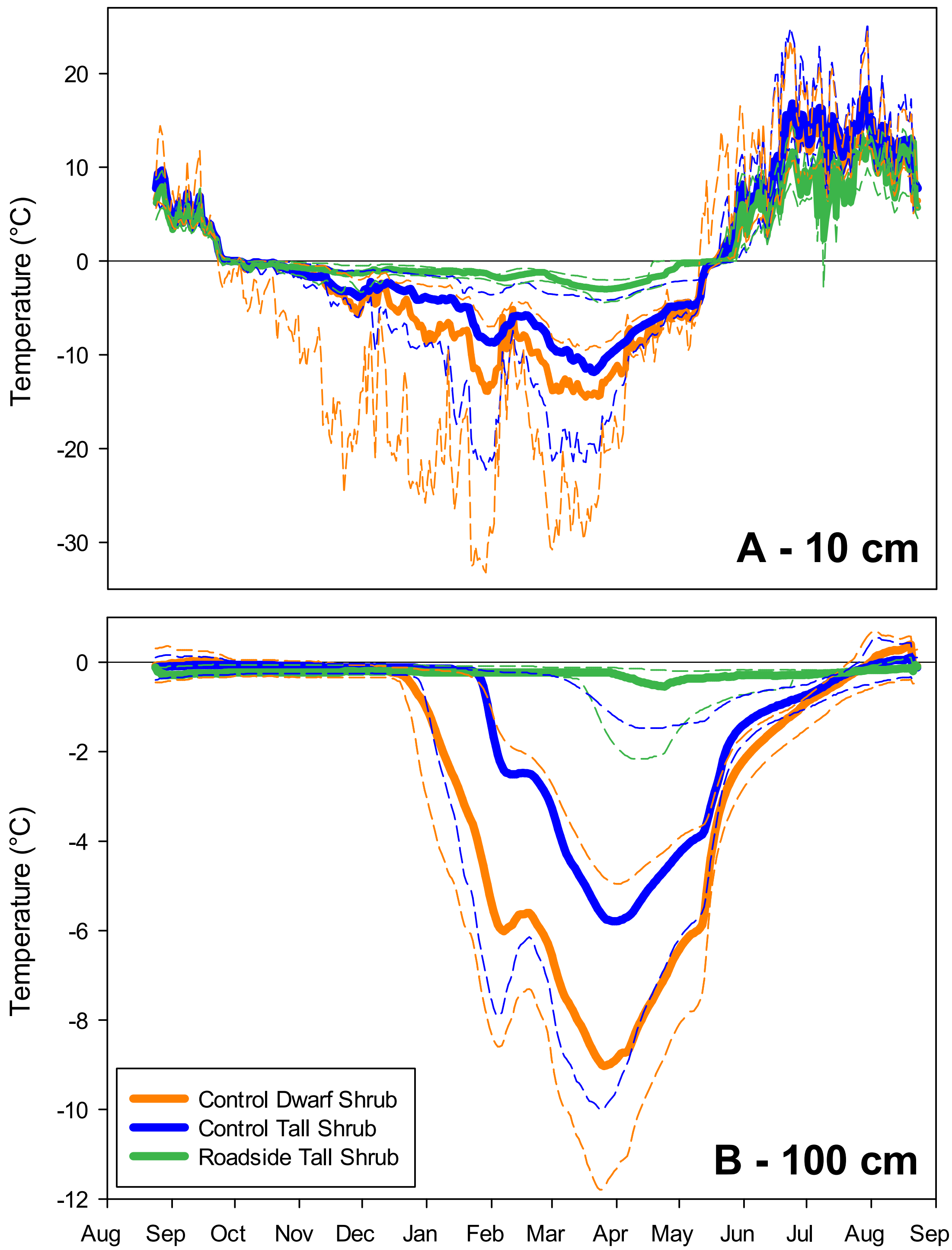

Figure 2.9 Median, maximum and minimum temperatures at 10 cm below ground (A) and 100 cm below ground (B) from August 2011 to August 2012 at disturbed tall shrub tundra sites (Roadside Tall Shrub), undisturbed tall shrub sites (Control Tall Shrub), and undisturbed dwarf shrub sites (Control Dwarf Shrub) tundra sites. Solid lines show median daily temperature across site type, and upper and lower broken lines show daily maximum and minimum temperatures, respectively.

Discussion

Differences in plant community composition and alder age structure between control and roadside tall shrub sites indicate that the Dempster Highway has significantly altered vegetation adjacent to the road. At tall shrub sites adjacent to the road, young alders formed closed canopies that often exceeded 3 meters height, and strongly influenced biotic and abiotic conditions. At roadside sites where tall shrubs dominated, moss, lichen and forb cover were significantly reduced, likely in response to increased shading and litter deposition from the closed canopy. Dwarf shrub cover was also reduced at roadside tall shrub sites, including several culturally important berry species (*E. nigrum, R. chamaemorus, V. uliginosum* and *V. vitis-ideae*). Of these, *R. chamaemorus* (cloudberry) was the only edible berry observed flowering under the alder canopies, but it almost never produced fruits. Dust deposition and increased soil alkalinity also likely contributed to reduced cover of moss, lichens and dwarf shrubs (Auerbach et al., 1997; Santelmann and Gorham, 1988). These findings are supported by previous studies on the effects of gravel roads on tundra plant communities, which found the greatest effects to be a decrease in peat mosses and lichens and an increase in graminoids (Myers-Smith et al. 2006). Similar differences in plant communities were found between tall shrub- and dwarf shrub-dominated sites undisturbed by the road, but the contrasts were smaller because alders did not form closed canopies away from the road.

Differences in alder response variables among sites indicate that environmental changes following road construction have facilitated alder growth and recruitment near the embankment. Alder populations near the road were between two to three times faster-growing than at control sites, and were dominated by individuals recruited in the last two decades. There are several mechanisms that may have facilitated alder growth and recruitment: microsite disturbance, dust deposition, and hydrological alterations due to snow distribution and drainage. Road construction itself may have promoted alder growth and recruitment by creating micro-disturbance sites, as a swath wider than the current embankment was disturbed during construction. The road also likely enhanced nutrient availability through dust deposition within a few years of use. The road embankment may also impede drainage and promote drifting and snow accumulation, which can cause pooling of surface water and increased soil moisture adjacent to the road. Other field studies show that shrub expansion is associated with mesic environments (floodplains, riparian zones), with disturbance, and may be mediated by soil conditions (Blok et al., 2011; Lantz et al., 2013; Tape et al., 2012). Soil moisture is also an important determinant of active layer thawing (Zhang and Stamnes, 1998), which influences shrub growth, so local hydrology may explain why shrubs expanded in some areas and not others. Deciduous shrub cover and biomass have also been observed to increase in other studies of gravel roads in tundra ecosystems, but the changes after 30 years were much less pronounced than the shifts we observed next to the Dempster (Myers-Smith et al., 2006).

Accumulation of snow could protect shrub vegetation from desiccation by winter winds and in conjunction with higher soil moisture contents, slow ground heat loss in winter, leading to an increase in ground temperatures. In summer, these conditions promote an increase in active layer thaw and greater nutrient availability. Collectively, these factors are highly favourable for tall shrub establishment and growth (Sturm et al. 2001; Essery and Pomeroy, 2004). These effects may be enhanced over time as terrain adjacent to the road embankment subsides due to permafrost thaw (Hayley, 2005), and because growing shrubs progressively trap more snow. Since snow drifts may extend several meters downwind of an earthwork or shrub thicket (Essery and Pomeroy, 2004; Johnstone and Kokelj, 2008) drifting caused solely by the embankment may be important in making conditions favourable for shrub growth immediately following construction of the road embankment. However, our observation that numerous sites adjacent to the road are not dominated by canopy-forming alders suggests that shrub proliferation adjacent to the road is mediated by existing biophysical conditions. Local differences in soil composition, moisture, slope, aspect, and possibly mechanical disturbance at the time of construction likely influenced the sites of successful recruitment and growth.

Even where tall shrubs have not come to dominate the plant community, the road has facilitated vegetation change, promoting sedge tussocks and reducing mosses, lichens and forbs. These differences were likely caused by increased soil alkalinity and shading from a vigorous sedge canopy. *Eriophorum* is a dust-tolerant genus that often increases adjacent to gravel roads in arctic dwarf shrub tundra (Everett, 1980; Farmer, 1993).

Tall shrub expansion has clearly been facilitated by the Dempster Highway, and the changes we observed are consistent with other forms of disturbance that also promote shrub growth (Forbes et al., 2001; Johnstone and Kokelj, 2009; Kemper and Macdonald, 2009; Lantz et al., 2010; Lantz et al., 2009; Lantz et al., 2013; Marsh et al., 2005). Although roads superficially appear to be a fine-scale disturbance, the degree and extent of hydrological disruption, dust redistribution, shrub proliferation, and feedbacks altering near surface ground thermal regime will impact large areas (Walker and Everett, 1987). At broader scales shrub encroachment may create positive feedbacks to regional warming, and alter fire regimes, nutrient dynamics and animal habitat and forage (Chapin et al., 2005; Joly et al., 2007; Liston et al., 2002; Swann et al., 2010). Similar to our observations along the Dempster highway, shrub proliferation throughout the Arctic has been heterogeneous (Tape et al., 2012). Further study is needed to clarify the drivers of shrub proliferation and explain the spatial heterogeneity of shrub growth. Additional research using historical airphotos should be conducted to examine the relationships between areas of shrub proliferation and landscape-scale variation in biophysical variables.

Our findings indicate that vegetation development adjacent to the highway initiates biotic and abiotic feedbacks that affect ground temperatures. We found warmer ground temperatures beneath alders growing 15 m from the toe of the road embankment, which were likely caused by increased snowpack where tall shrubs act as windbreaks. Although thawing of near-surface permafrost and terrain subsidence is common adjacent to road embankments, normal active layer thicknesses usually resume 5-10 m away from the toe of the embankment (Hayley, 2005; Walker and Everett, 1987). Directly adjacent to the road, warmer ground temperatures can result from soil disturbance during construction, reduced ground heat loss in winter because of deeper snowpack near the embankment,heat transfer from the road, and water pooling against the embankment (Figure 2.10) (Blok et al., 2011; Myers-Smith et al., 2011). Together, these alterations can lead to an increase in active layer thickness. As shrub proliferation increases, ground temperatures adjacent to existing roads are likely to continue to increase over time (Myers-Smith et al., 2006). The resulting increase in active layer thickness may lead to surface subsidence and water pooling. Warmer soils in conjunction with increased moisture may contribute to the further proliferation of alder shrubs.

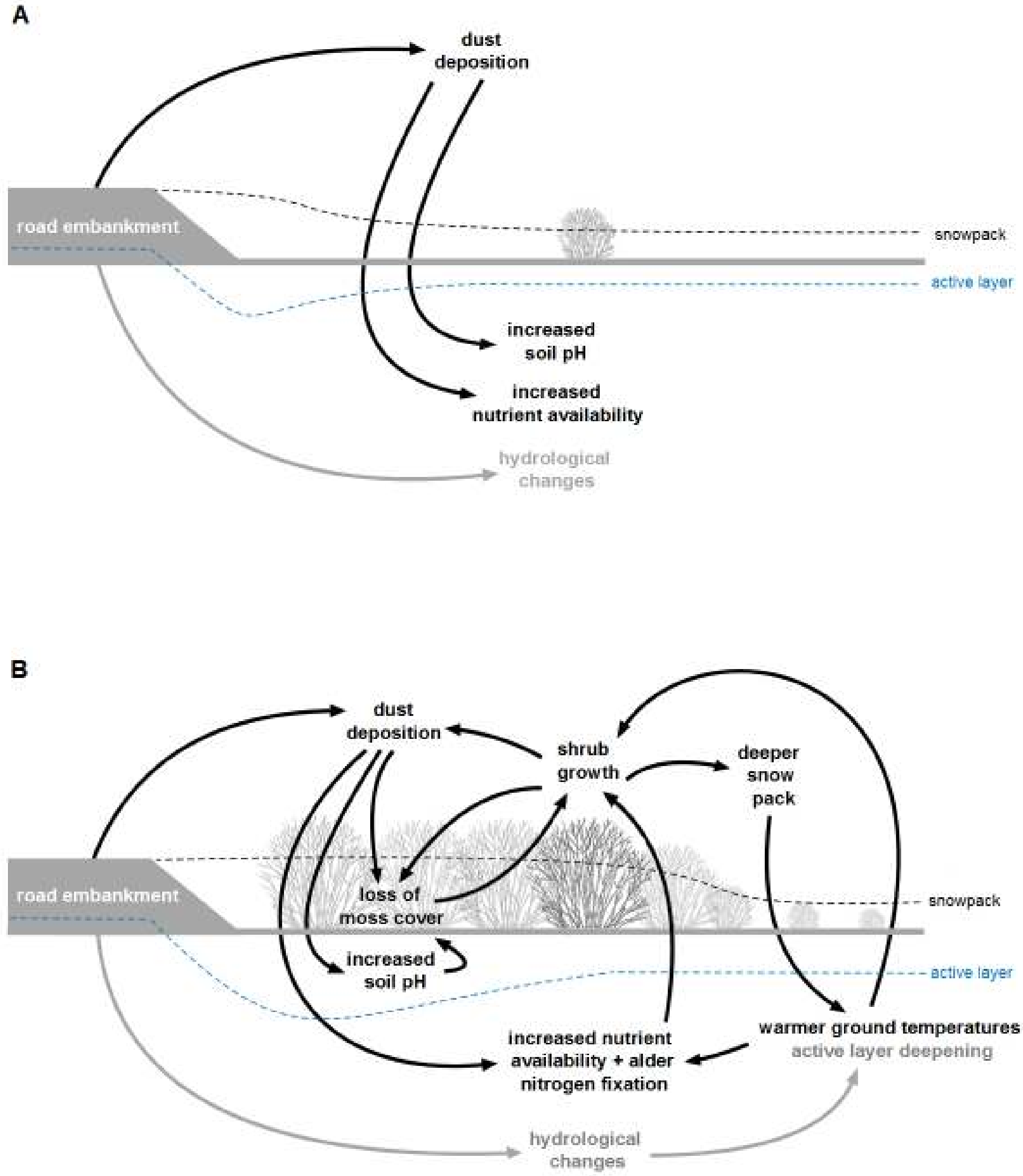

Figure 2.10 Cross section of a gravel road showing the development of ecological feedbacks in tundra ecosystems (A) immediately following gravel road construction (B) and after 35 years. When tall shrubs become dominant, several feedback loops are initiated: tall shrubs act as a windbreak to increase dust deposition; soil nutrient availability increases; mosses and acidophilous plants are reduced as soil pH and shading increase; and tall shrub growth is promoted through enhanced nutrient availability and reduced competition. Tall shrubs acting as a windbreak also trap deeper snow, insulating the ground and increasing ground temperatures and active layer deepening; this promotes tall shrub growth by increasing nutrient availability, soil moisture and rooting depth. Lastly, hydrological changes, particularly water pooling adjacent to the road, promote active layer deepening, and tall shrub growth is promoted and feeds back into further ecosystem alterations. Black text and arrows are processes observed in our study of the Dempster Highway; grey are hypothesized or known to occur in other studies of gravel roads in Arctic tundra.

In this study, warmer ground temperatures are observed beyond subsided areas immediately adjacent to the road, suggesting that by trapping snow, the proliferation of roadside alders has increased the intensity and spatial extent of the thermal disturbance that would normally be anticipated with the road embankment (Figure 2.10). Tall alder branches trap snow and prevent compaction of the snowpack, which insulates the ground and inhibits ground heat loss in winter (Sturm et al., 2001a). The impacts of alder may have a cooling effect in summer when shading from the closed canopy can keep near-ground temperatures cooler (Figure 2.9a) (Blok et al., 2010; Chapin et al., 2005; Lantz et al., 2013; Sturm et al., 2001a; Sturm et al., 2005). The hypothesis that warmer ground temperatures are promoted by shrub-snow interactions is strengthened by our observation of warmer temperatures in control tall shrub tundra compared to control dwarf shrub tundra (Figure 2.9). Although we did not find significantly thicker active layers at roadside tall shrub sites, ground temperatures were warmer at these sites and we encountered thaw depths greater than 120 cm only under roadside shrubs, an unusually thick active layer for tundra soils. We also observed a long freezeback period at roadside tall shrub sites, which is likely due to high moisture content of soils in conjunction with deep snow. Warmer soil temperatures and a prolonged period during which soil temperatures are warmer than −6°C enhance microbial activity and decomposition, leading to increased nutrient mineralization and greater plant nutrient availability (Sturm et al., 2001a; Zimov et al., 1993).

Shrub proliferation adjacent to the road also created a positive feedback with soil chemistry, as dust and nutrient deposition adjacent to the road were more pronounced where tall shrubs dominated (Figure 2.10). The dust load is greater closer to the road (Everett, 1980), but the taller vegetation likely traps more dust, leading to greater increases in levels of Ca, Mg and S than at roadside sites not covered with tall shrubs. Alder growth is enhanced by increased micronutrients deposited in road dust and runoff (calcium, sulphur, magnesium), increased pH, and warmer ground temperatures (Sturm et al., 2001b). An increase in pH and active layer thickness have been established as common abiotic effects of gravel roads in tundra (Myers-Smith et al., 2006), and as we observed, these effects interact with vegetation development. Alder plants themselves also influence and feedback with tundra soil chemistry, and their ability to fix nitrogen may allow them to outcompete other tall shrubs (Mitchell and Ruess, 2009; Rhoades et al., 2001).

The first order effects of gravel roads on tundra ecosystems are well known, including heat transfer to adjacent ground and resultant permafrost thaw (Hayley, 2005; Walker and Everett, 1987), altered plant communities and reduction in plant cover due to dust choking and increased soil pH, and microsite disturbance due to road construction and maintenance. Our results show that conditions generated by the maintenance and use of the road over time can interact with local ecosystem processes in a way that creates unexpected effects and possibly magnifies road effects on vegetation communities and substrate properties. In this study, we found that where the road facilitated shrub dominance, feedbacks were initiated that enhanced snow accumulation and altered ground temperatures and soil chemistry. In turn, these changes likely promote enhanced shrub recruitment and growth (Figure 2.10). When vegetation near the road is altered but maintains the same overall structure (ie. dwarf shrub tundra), the effects of the road are much less pronounced because snow and dust are distributed more sparsely without tall shrubs acting as a wind break.

The ecological changes we documented, as well as feedbacks with ground thermal conditions, may have significant implications for the long-term stability and hence, maintenance costs of transportation corridors through tundra environments. The stability of northern infrastructure relies on the maintenance of frozen ground in and adjacent to the road embankment (Andersland and Ladanyi, 2004; Couture et al., 2000). However, growing evidence indicates that anthropogenic and natural disturbances facilitate the establishment and proliferation of tall shrubs (Forbes et al., 2001; Johnstone and Kokelj, 2009; Kemper and Macdonald, 2009; Lantz et al., 2010; Lantz et al., 2009; Lantz et al., 2013; Marsh et al., 2005). Tall shrub proliferation on disturbances such as drilling mud sumps, roads and slumps has been shown to contribute to increased snow accumulation, increased ground temperatures, permafrost degradation, and subsidence (Johnstone and Kokelj, 2009; Kanigan and Kokelj, 2008; Kokelj et al., 2010; Lantz and Kokelj, 2008). The implications of ground warming and permafrost thaw include loss of ground bearing capacity and soil creep resistance, increase in thaw depth and ground settlement (Couture et al., 2000). Our research shows that active vegetation management should be considered as a potential method to maintain permafrost conditions in and around infrastructure constructed in tundra environments. Planned gravel roads in the Arctic, including the Inuvik-Tuktoyaktuk Highway and the proposed Mackenzie Valley Highway, which would connect the Arctic coast to southern Canada beginning at Tuktoyaktuk, NT (GNWT, 2005), need to take into account the cumulative effects of roads and their feedbacks with vegetation. This work illustrates the further need to investigate the cumulative effects of infrastructure, climate warming and long-term ecological change on the thermal stability of road infrastructure in tundra environments. Our data can provide context for thermal analyses that will be undertaken to understand the stability of the roadbed. Further thermal data collection in conjunction with modeling of ground temperatures would enable an examination of the cumulative effects of embankment configuration and shrub proliferation on snow accumulation and ground thermal conditions adjacent to highway infrastructure.

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Chapter 3

A community-based approach to mapping Gwich'in observations of environmental changes in the lower Peel River watershed, NT

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Keywords

Traditional ecological knowledge, participatory mapping, climate change, environmental monitoring, Arctic

Abstract

In Canada's western Arctic climate warming is driving rapid ecological changes. Ongoing and locally-driven environmental monitoring, in which systematic measurements or observations of environmental qualities are recorded and synthesized, is necessary in order to understand and respond to climate change and other human impacts. The traditional ecological knowledge of indigenous peoples is increasingly used as the basis for regional monitoring, as there is a need for detailed, place-specific information that is consistent with local ways of understanding and interacting with the environment. In this project, we used participatory multimedia mapping with Teetl'it Gwich'in land users and youth from Fort McPherson, Northwest Territories, Canada to record information about local environmental conditions. Gwich'in monitors made trips on the land to document environmental conditions and changes with photos and videos tagged with GPS locations. Subsequently, land users provided detailed information about each observation in follow-up interviews, and observations were added to a web-based map. Observations included ground subsidence and riverbank erosion due to permafrost degradation, culturally important places, and changes in animal and plant distributions. In this paper, we present the outcomes from the first year of monitoring, explore the diverse types of knowledge this approach can contribute to environmental monitoring, and identify areas of convergence between traditional knowledge and scientific research in the Arctic. Our work shows that this approach can make an important contribution to monitoring environmental changes associated with climate change in a way that is locally relevant and culturally appropriate.

Introduction

The circumpolar Arctic is experiencing accelerated environmental changes due to rising air temperatures and increasing human development (ACIA 2004; Chapin et al. 2005; Stefansson Arctic Institute 2004). Recent changes include shifts in the frequency and magnitude of natural disturbances, changes to vegetation structure, permafrost degradation and altered soil chemistry, decreasing land stability, shifts in animal population size and distribution, and changing water levels and quality (Jorgenson et al. 2001; Kokelj et al. 2005; Lantz et al. 2009; Serreze et al. 2000; Sturm et al. 2005; Tape et al. 2006; Tunnicliffe et al. 2009). These environmental changes immediately affect northern indigenous communities whose well-being and livelihoods are intimately linked to the health of the land (Chapin et al. 2006; Krupnik and Jolly 2002; Loovers 2010; Parlee et al. 2005). Northern land users are faced with climate conditions that are increasingly unpredictable, including new variations in freeze-thaw cycles of sea and inland ice and altered timing and duration of weather events, which have driven unprecedented erosion patterns that can interfere with peoples' mobility and lifestyles (Stammler-Gossmann 2010; ACIA 2004). Concomitant economic, cultural and technological changes also contribute to shifting social dynamics that influence how communities perceive and interact with their environment, and ultimately how vulnerable they are to climate change (Aporta and Higgs 2005; Ford and Smit 2004). In order for northern communities, researchers, and decision makers to manage and adapt to changing climate and environmental conditions, diverse information about the location, extent, and drivers of regional changes is needed (Berkes and Jolly 2002; Moller et al. 2004). In this paper, we describe a pilot monitoring program and explore its potential contributions as a locally responsive environmental monitoring program.

Environmental monitoring to assess changes in water, air, soil, biota and climate is challenging in northern regions because remote logistics are complex and expensive (Artiola et al. 2004; Lovett et al. 2007; Wiersma 2004). In some areas, changes in land cover are occurring so rapidly that maintaining an accurate inventory represents an ongoing challenge (Kokelj et al. 2012). Monitoring programs can also be constrained in their scope and timeliness by a lack of local expertise, language and cultural barriers, and reliance on externally-based institutions (Berkes et al. 2001; Moller et al. 2004; Usher 2000). Moreover, climate change adaptation projects and environmental co-management projects intended to help communities adapt and build resilience in the face of change can often be made less effective because of a failure to take into account local conditions and perceptions (Stammler-Gossmann 2010).

Research has shown that indigenous land users who spend significant time on the land are in a unique position to observe and monitor local environmental conditions and detect changes early (Davidson-Hunt and Berkes 2003; Gearheard et al. 2011; Hinkel et al. 2007; Hinzman et al. 2005; King et al. 2008; Kokelj et al. 2012; Krupnik and Jolly 2002; Moller et al. 2004). Local observations of the environment made by indigenous land users can be especially insightful when integrated with conventional approaches to environmental science because such observations are rooted in traditional ecological knowledge (TEK): "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings with one another and with the environment" (Berkes 2000: 7). TEK is embedded in the places and cultures from which it develops, and includes an intimate understanding of local ecological processes (Basso 1996; Berkes 2000). Consequently, environmental monitoring that is rooted in TEK can provide insight about subtle patterns and changes, and over longer time periods than many scientifically based studies of environmental change (Riedlinger and Berkes 2001).

Many TEK systems incorporate explicit environmental monitoring activities (Berkes 2000). These include qualitative indicators of climate and environmental variation based on sight, sound, feel, smell, and taste (Moller et al. 2004; Turner and Berkes 2006) that often focus on unusual patterns and occurrences, rather than averages, and rely on the experience, understanding, and memory of the observer (Berkes and Folke 2002; Moller et al. 2004). In short, because TEK provides a different kind of environmental monitoring at intimate local scales associated with traditions and memories that add time depth, ethnobiologists and increasingly ecologists recognize that local observations and TEK provide information that can increase the resilience of communities facing both social and ecological changes (Berkes and Jolly 2002). As a result TEK can make a significant contribution to environmental management and adaptation (Chapin et al. 2004).

In the Arctic, TEK has been the basis of both community-based and scientific investigations of environmental change (Luzar et al. 2011; Pulsifer et al. 2012; Riedlinger and Berkes 2001). While many elders and TEK holders are eager to share their insights and concerns with researchers and members of younger generations, recording TEK effectively and appropriately is a complex undertaking. It can be especially challenging to record and share information in a way that is respectful of knowledge holders and consistent with the holistic, place-specific nature of TEK (Chambers 2006; Gilmore and Eshbaugh 2011; Hardison and Bannister 2011; Moller et al. 2004; Stringer et al. 2006). Interactive multimedia web-based maps and databases are becoming popular ways to share and update local and traditional ecological knowledge, and their flexibility allows for less structured and more collaborative data management (Aporta et al. In Press; Gilmore and Eshbaugh 2011; McLain et al. 2013; Pulsifer et al. 2012).

In the lower Peel River watershed in northwestern Canada, climate change and shifting environmental conditions are of concern to the Teetl'it Gwich'in community of Fort McPherson, NT (Scott 2011). Climate change and human activities are influencing water quantity and quality, wildlife and fish populations, disturbance regimes (landslides, river bank erosion, and fires), transportation and municipal infrastructure, and heritage sites (Scott 2011).

In recent years, Gwich'in knowledge has guided several community-based environmental monitoring projects. The Arctic Borderlands Ecological Knowledge Cooperative Project has employed community members to administer surveys and collect first-hand accounts of environmental observations and changes from Gwich'in and Inuvialuit communities in the NT, YT and Alaska since 1994 (Kofinas 1997; Robinson and Nguyen 2011). Teetl'it Gwich'in adults, elders and youth have also participated in recent community climate change adaptation planning to identify areas of concern and recommendations for adaptation (Scott 2011). One limitation of these programs is that they have produced generalized descriptions of changes that are not directly linked to specific places on the landscape. Since understanding and responding to the consequences of climate change and environmental impacts require detailed information, it is vital that ongoing monitoring include place-specific reporting.

Monitoring and responding to the impacts of global climatic change and disturbance requires regionally specific data that meet the needs of local communities. To address this need in the lower Peel River watershed, we used participatory multimedia mapping in a pilot monitoring program to document environmental conditions and changes associated with climate change and other natural and anthropogenic disturbances. We anticipated that this approach would provide diverse and richly detailed information about local socio-ecological systems including environmental and social impacts of changes, how the Teetl'it Gwich'in community perceives and interacts with its environment, and how local communities can be empowered to share and gain knowledge in a way that is compatible with mainstream environmental monitoring programs (Gilmore and Young 2012).

Methods

Background

This project emerged from discussions between Teetl'it Gwich'in community members and scientists involved in a Northwest Territories Cumulative Impact Monitoring Program (CIMP) research project examining massive permafrost disturbances in the lower Peel River watershed (Kokelj et al. 2013). During these initial discussions, participants prioritized the development of a community-based monitoring program based on Gwich'in perspectives and knowledge. In November 2011, CIMP researchers (Harneet Gill and Trevor Lantz) partnered with the Gwich'in Social and Cultural Institute (Sharon Snowshoe and Ingrid Kritsch) to develop an environmental monitoring program using photography, videography, semi-structured interviews and web-based mapping.

Protocol development

In March 2012, we visited Fort McPherson to seek community input on project goals and methodology, and to identify potential participants. These discussions produced two additional project goals: 1) contribute to knowledge-sharing and relationship-building between youth and experienced land users (members of the community with established TEK), and 2) provide youth with learning and experience with digital tools. The participatory multimedia mapping (PMM) protocol was thus designed to pair up youth participants with more experienced land users and involve youth in data collection through learning and use of digital tools. A test field trip in March 2012 was followed by eight trips from May to September 2012, in which 12 participants used the protocol to make 101 observations. Trips lasted from a few hours to two days and routes were up to 70 km long. In March 2013, we formalized a steering committee to review results from the first eight trips and provide ongoing feedback and direction on project methodology and outcomes.

Participatory multimedia mapping

At the outset of this project in November 2011 we agreed to use participatory multimedia mapping (PMM), a process in which participants act as co-researchers to map information and knowledge using digital tools (such as digital cameras and audio-recorders) and in-depth interviewing. PMM consists of three stages: digital tools training, on-the-land trips to make observations, and follow-up interviews. Observations made by community members are then used to create a map representing the physical, social and cognitive environment. Similar approaches have been used in many contexts to allow participants to express their own perspectives and voices (Clark 2011; Dennis et al. 2009; Sherren et al. 2010). In our research project, Teetl'it Gwich'in community members chose where and when observations were made and decided how their knowledge was documented. After reviewing the information they shared, all participants consented to the sharing of information and their attribution in the web-based map and project publications (Appendix 4).

PMM was conducted by pairs of Gwich'in youth (under age 30) and experienced land users including elders. Potential participants were identified and contacted by the Gwich'in Social and Cultural Institute and Teetl'it Gwich'in Renewable Resource Council (Table 3.1). We selected land users who had extensive experience travelling and living on the land, because these individuals have a thorough knowledge of environmental conditions and changes, and are able to comment on changes over time, spanning at least several decades. Youth were selected based on an awareness of the environment, a desire to be on the land, and an interest in photography (Table 3.1). In a few cases participants decided to include extra people on the trip who were not directly involved in the research (e.g., hunting partners, family members). These individuals did not participate in trip planning, digital-tool training, or interviews.

Land users decided where and what to observe, planned trip logistics, and shared their personal knowledge, experiences and observations. Youth participants documented land-based observations using photos, videos and GPS, and contributed to semi-structured interviews. As facilitator, Harneet Gill provided digital tools training, helped with trip logistics, took back-up photos and videos, conducted the follow-up interviews, and maintained the web-based map. Participants were compensated for their time through the Renewable Resource Council at local rates.

Table 3.1 Teetl'it Gwich'in elders, land users and youth who participated in participatory multimedia mapping from May to September 2012.

Gwich'in Participant	Gender	Role	Trips made
Abe Peterson	M	land user (elder)	1
Angela Alexie	F	youth	1
Ashley Kay	F	youth	2
Billy Wilson	M	land user	1
Christine Firth	F	land user	2
Clarence Alexie	M	land user	1 (not interviewed)
Dorothy Alexie	F	land user (elder)	1
Emma Kay	F	land user (elder)	2
Herbie Snowshoe	M	youth	2
Robert Alexie	M	land user (elder)	0 (interview only)
Wade Vaneltsi	M	youth	1
Wanda Pascal	F	land user	1

Trip planning and digital tools training

Once a land user and youth pair was formed, we met with them to discuss the project objectives and decide where and what to observe. We consulted printed and online maps of the area to plan a trip lasting from a few hours to several days. Following this meeting, youth participants were given an orientation to digital tools, which included a waterproof point-and-shoot digital camera (Olympus Tough TG-820), a digital bridge camera (fixed lens with wide zoom range; Fujifilm Finepix s2980), a digital single-lens reflex (SLR) camera (Nikon D700), an audio recorder (Zoom Handy Recorder H2), and a GPS unit (Garmin GPSmap 60CSx). The youth selected his or her preferred camera and received more detailed instructions followed by practice taking photos and videos. When the youth selected the SLR camera, he or she was trained to adjust exposure manually by changing shutter speed, aperture, and ISO (the sensitivity of the image sensor to light). While on the trip, the facilitator gave youth tips on how to compose photos, create effects, and care for the cameras.

On the land media capture

In addition to pre-planned observations, each trip typically included impromptu stops. At each location, the youth and the facilitator took photographs and sometimes recorded videos, while the group chatted informally about what was being encountered. To avoid interrupting or inhibiting the discussion and photography, these conversations were not recorded. However, field notes were made to use as prompts during follow-up interviews. A GPS unit was used to record a tracklog of the trip, which allowed each observation to be georeferenced by matching the media time codes to the tracklog timecode using geolocation software (RoboGeo).

In-depth semi-structured interviews

After each trip, we returned to Fort McPherson, NT and arranged a time for a follow-up interview within two days of the trip. In advance of each interview we loaded all trip pictures and videos on a computer and chose the clearest and most representative photos or videos from each site. These media were used to guide an audio-recorded semi-structured interview with the land user and youth. As they looked at the photos or videos from each site, land users were asked to describe what was present, where it was, and why it was important (see questions in Appendix 1). They were also asked to describe how the site had changed, and how it affected individuals and the community. After the first few observations, land users would often begin descriptions without prompts, and follow-up questions were used to seek elaboration and clarification. Youth participants listened and contributed as opportunities arose.

Online mapping of observations

To organize and present participant observations, we used a Drupal-based web platform called Community Knowledge Keeper (Kwusen 2012). The website was constructed by the project team at University of Victoria, and participants reviewed and approved their interview transcripts and media in March 2013 before they were added to the site. Administrator privileges are currently held by University of Victoria and any member of the public can request a username and password for access. Observations added to the project website (http://gwichin.kwusen.com; Appendix 2) are organized by trip, location, participant, and topic. After logging in, map users are directed to an overview of the multi-media monitoring project. Viewers can explore a map with all observations made to date, and navigate separate lists of: 1) trips, 2) observations, 3) participants, 4) topics, and 5) species affected. Individual entries on these lists can be clicked to display more information. Trip pages provide details about the trip, a list of participants, a map and list of observations, an interview audio file, an interview transcript, and all photos and videos taken on that trip. Observation pages provide a map of the location, list the observer, date and time, and provide photos, videos, interview audio clips, transcripts, and additional media and notes pertaining to that observation. Each observation is also tagged with one or more topics according to the type of environmental phenomenon and knowledge it contains. Participant pages display a photo, biographical details, and in some cases a written or recorded comment on their experience doing this research.

Data organisation and analysis

To facilitate online mapping of observations, interviews were coded to identify individual observations, and each observation was labelled with a primary theme and a sub-theme using Microsoft Excel (Table 3.2). Each observation consists of a photo and/or video, an interview audio and transcript clip, and a map location. Themes were used to organize information into broad categories such as vegetation or development, whereas sub-themes generally reflected the reason we stopped at the site, such as shrub increase or a specific gravel quarry. Each observation was also given a brief description, name and site code. To summarize the nature of environmental changes and explore the types of knowledge and insights generated by the PMM approach, we identified all types of information and emergent themes in interviews by coding them using NVivo. We used both coding systems (NVivo and MS Excel) to explore the relationships between categories of knowledge and meaning from the perspective of Gwich'in participants.

Table 3.2 Themes and sub-themes for Gwich'in observations of environmental conditions and changes, indicating the primary reason an observation was made.

Theme	**No. of observations**	**Sub-theme**	**No. of observations**
Environmental Conditions	47	Riverbank erosion	21
		Melting permafrost	8
		Riverbank conditions	4
		Mud/sand bars	2
		Altered stream	2
		Water levels	2
		Ice conditions	2
		Changing environmental conditions	1
		Altered lake	1
		Drained lake	1
		Melting snow	1
		Water availability	1
		Weather	1
Traditional and Cultural Use	26	Culturally important place	17
		Berry harvesting	5
		Harvesting site	1
		Place of observation and hunting	1
		Travel Route	1
		Water levels	1
Vegetation	8	Bigger trees	3
		Increased willows	3
		Increased shrubs	1
		Dead willows	1
Development	6	Gravel quarry	5
		Dempster Highway	1
Wildlife	3	Wildlife populations	1
		Wildlife habitat	1
		Traditional food	1
Knowledge Transfer	1	Knowledge sharing	1

Results

In the pilot year of this project, we worked with eight land users and four youth to record their observations of environmental conditions and changes (Table 3.1). We made a total of eight trips out of Fort McPherson, NT, and recorded 101 observations (Figure 3.1). Trips in the pilot year were limited to areas that could be accessed by boat on the Peel River and its tributaries, or by truck on the Dempster Highway (Figure 3.1).

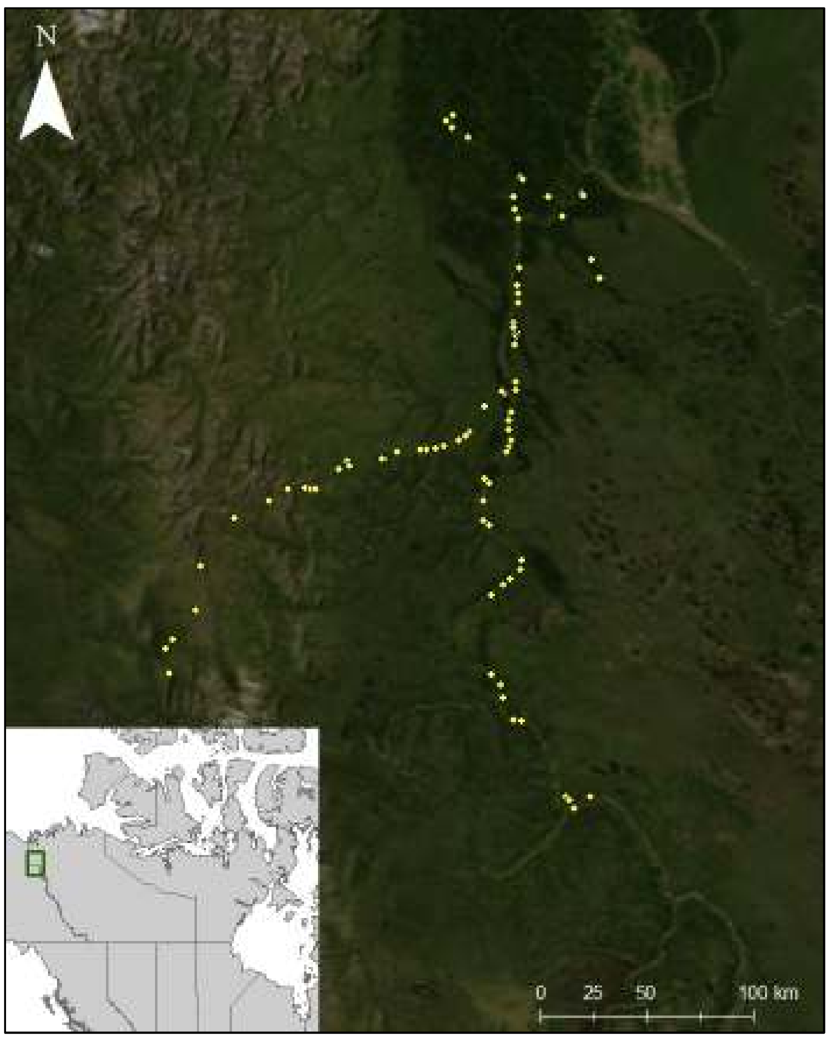

Figure 3.1 Distribution of 101 Gwich'in observations of environmental conditions and changes in the lower Peel River watershed, NT recorded from May to September 2012. Inset shows position of study area in northwestern Canada.

The majority of observations focussed on environmental conditions and traditional and cultural use sites (Table 3.2). The most common environmental observation was of erosion and melting permafrost driven by recent changes in climate (Table 3.2). Regtrogressive thaw slumping has become more common in the upland area southwest of Fort McPherson in recent decades (Kokelj et al. 2013). These dramatic changes, often involving large sections of earth caving in or rows of trees falling into lakes and streams, were noted by many observers. Observations of culturally important places included both man-made (e.g., a fish camp) and natural (e.g., a red ochre deposit) landscape features.

In follow-up interviews, land users provided detailed information about the physical nature of each environmental observation, including temporal and spatial dimensions, magnitude of change, and physical characteristics. Phenomena that occur over time, such as erosion, plant growth, and weather events, were described in terms of initiation time, duration, rate, seasonal timing, and frequency, and were often compared to normal or unusual patterns. Time was expressed using specific dates and durations (days, weeks, etc.) or references to other events. For example, to explain how long a specific example of riverbank erosion had been occurring, Abe Peterson made reference to the owner a camp about to fall into the river to describe riverbank erosion that "has been going ever since he drowned," without providing a date. The physical dimensions and locations of events, phenomena and landscape features were often described subjectively and involved analogies and personal references. For example, to describe the extent of willow growth around the Peel River ferry crossing, Emma Kay remembered, "in the [19]70s they were small little willows. If somebody set tent right in the middle you just could see them walking around. From their waist up, or even half the legs, that's how small they were in the '70s, '80s, like that."

In addition to describing environmental conditions and changes, participants shared their knowledge of the social and ecological causes of, and interactions among, the phenomena we observed. For example, when asked why more sand bars have been forming in the Peel River, Abe Peterson gave an explanation based on his knowledge of environmental processes: "see, what is happening, the current is so low, there's hardly any current. Dead water. And that's when the sand don't move, it just stays there." Conversely, Emma Kay explained changes in weather by referring to cultural teachings, explaining that "Elders from way back, they tell us everything [on the land] is going to change."

Climate change was referenced as an example of how environmental conditions have changed and was cited to explain why other environmental changes had occurred. For example, all four elders recounted how much colder average and minimum temperatures used to be when they were growing up. These comments were made while discussing changing environmental conditions in general and how they affect individuals, as Emma Kay recounted, "We're not used to heat. Cause we were brought up, when we were kids, we were brought up 60, 70 below. Now today we sit in the shade" because temperatures are warmer year-round. Climate change was often cited indirectly (i.e. referring to more or too much heat or warmth) and directly as a driver of observed environmental changes. Warmer air temperatures, along with rainfall events, were pointed to as a cause of permafrost melting and resultant riverbank erosion and lake drainage, for example Robert Alexie explained that mud slides occur when there is "too much rain, and too hot."

Participants' observations also focussed on the social and ecological implications of environmental changes, and frequently included predictions about future conditions. Land users provided insights into the significance of these changes for individuals and the community, including both negative and positive outcomes. Consequences associated with environmental changes ranged from practical considerations to community-wide repercussions, as Billy Wilson explained, “you don’t travel one year, and [willows are] already growing too fast. Some people just leave it, they can’t even see their portage trails. So it kind of discourages people from basically going back to their camp, lot of deserted camps up here. People don’t go out anymore.” Land users also expressed concerns about the effects of environmental change and development on human health and safety, and suggested questions that should be investigated. For example, when we observed a stream that had changed from clear to muddy brown, Dorothy Alexie recommended, “It would be really good to find out, you know. What’s in that water. It’s got to be something very powerful in it.”

While Gwich’in land users expressed apprehension and uncertainty about environmental challenges, their ideas and efforts also reflected the community’s capacity for adaptation and flexibility. Novel ways to accomplish tasks and interact with the land emerged during our trips, and participants learned from each other throughout the process. For example, when the Peel River jammed up with ice, Christine Firth exclaimed after watching Abe Peterson navigate his boat through the ice, “it was good to know that we could get out of there, like I’ve never in my life did this, but now I know I could get out of ice jams as long as it’s high water.”

Interviews also revealed how knowledge about the environment is learned and passed on within and between generations. Participants explained that common sources of knowledge include direct observations and experiences on the land with more experienced people, as well as stories and conversations with other community members, especially Elders. For example, Wanda Pascal explained that she knew of a good berry patch because “last year, I seen Sarah

Jerome and her sisters picking there for about four days [...] so I scanned around there, and now I know how much berries is there."

Gwich'in ways of expression were also preserved through the use of original transcripts, audio recordings and videos for each observation. Gwich'in speakers often made their points in a non-linear fashion and left unsaid key pieces of information, which might be found several minutes earlier in the conversation, or might rely on a presupposed knowledge of the community and territory. Consequently, the complete transcript, the details of the overall trip, and other observation topics, which are available from the trip page on the website, are needed to contextualize observations. Gwich'in words and place names were also important components of TEK shared through the observations of some land users, who frequently provided place names and provided translations and background information.

Places where we made observations often had special significance or value because of personal or shared history there. Participants often shared details about their own lives and families, exhibiting how culture and knowledge are tied to place (Basso 1996). This provides considerable insight into Gwich'in history, land use and how changing environmental conditions impact their daily life:

> *I've been here since I was five years old. I remember playing on this little lake here, I remember being up at that Fish Hole, that's way up in the mountains. I remember my dad, that's what I remember.* – Billy Wilson

The diversity of knowledge elicited through the PMM process during travels and interviews provides a rich and nuanced description of the processes that have shaped current environmental conditions, which can help understand and predict the social and ecological effects of climate and environmental changes.

Discussion

The knowledge and perspectives documented in this project highlight the vital role of traditional ecological knowledge in efforts to understand and respond to environmental change in the Arctic, including the impacts of climate change on regional landscapes. By recording the specific impacts climate change has had on local ecosystems and communities, the map of environmental observations produced through PMM will be useful to communities and researchers seeking to monitor and respond to changing conditions. The combination of precise locations, photos, videos and interviews provides qualitative and quantitative (eg. time and distance) information about the nature, causes and consequences of environmental changes and conditions associated with climate change.

This information is useful to the Teetl'it Gwich'in community because it will allow people to compare and confirm their knowledge about specific places, and gain new knowledge of changes, practices and perspectives from different people. This may be especially useful for people who are not able to be on the land frequently, because it can allow them to learn from more experienced members of the community. For example, map viewers can see a video of Abe Peterson navigating his boat through willows during an ice jam, and learn how to overcome travel barriers from his experience. By searching topics such as dangers and infrastructure damage, map users can also identify areas that might require additional vigilance, investigation or intervention. Because many of the changes observed in the lower Peel River watershed are related to global climate change, they will be relevant to other communities throughout the Arctic.

Our experiences in this project show that an experiential and inclusive approach to community-based environmental monitoring can also unlock other aspects of traditional ecological knowledge. These include social processes such as knowledge transmission, personal histories, and local understandings and expressions of knowledge. Attributing observations to specific participants respects the highly contextual and individual nature of TEK, while presenting all observations in the same map reflects the extent to which TEK is shared by a cultural group (Wenzel 1999). A participatory approach to multimedia mapping approach is able to capture both the ecological and social impacts of climate change and environmental disturbances; participant descriptions of environmental changes were always a blend of environmental and social considerations, reflecting the inextricable connections between Gwich'in identity and the land (Loovers 2010; Parlee et al. 2005). Map viewers, whether they are Gwich'in or are unfamiliar with Gwich'in culture, can learn not only about how the environment is changing, but also about Gwich'in identity, history, language and activities. The primacy of Gwich'in voices in the map makes it easier to understand by members of the same culture, and is instructive for members of other cultures who are working in Gwich'in territory and want to improve their understanding and communication of the social-ecological system in which environmental changes are occurring.

A holistic presentation of TEK from the perspective of the cultural insider preserves links between environmental knowledge and its cultural context, which facilitates interpretation (Berkes 2000). A more nuanced understanding of Gwich'in perspectives of the changing environment will encourage researchers and regional decision makers to be sensitive to local community concerns and interests. For researchers and decision makers inside and outside the community, the data contained in this project map can be used to develop hypotheses about how people will react to ecological variability, highlight areas of traditional use, and identify areas of special concern in reference to environmental conditions that require action (examples in McLain et al. 2013). The outcomes of this project as well as feedback from participants and community partners indicate that digital multimedia can be used to effectively record traditional ecological knowledge in a way that is consistent with Gwich'in culture and contemporary life. These insights will be useful in regional climate change adaptation strategies, where large-scale climate change impacts must be understood and responded to in terms of local consequences and local capacity for adaptation (ACIA 2004; Scott 2011).

In this project, involving and empowering youth was a key goal identified by the community. Monitoring trips provided opportunities for youth to participate in both traditional land-based activities and research. Our trips were not highly structured, and land users often included breaks to warm up by a fire, have a snack or meal, or harvest traditional foods. Youth volunteered or were encouraged to pick berries, shoot ducks, build fires, chop wood, and camp on the land with the guidance of more experienced land users. A lack of opportunities for youth and young adults to be on the land was identified by several land users as a problem in Fort McPherson that the project helped address. Abe Peterson explained that "there's a lot of boys want to go out in the bush you know, they got no kicker [motor], no boat, no skidoo you know they just can't get out."

In addition to being a stand-alone monitoring platform, the map of environmental changes produced through PMM can contribute to other environmental and climate monitoring initiatives. Qualitative data, particularly visual data, captured on the land by indigenous land users provides context-rich information about local environmental changes that can inform the interpretation of quantitative data (Bonny and Berkes 2008; Comiso et al. 1991). The participant-driven nature of the PMM approach also ensures that alternative perspectives and knowledge that may not seem directly related to environmental change are included. This allows communities to identify research parameters, often social, which would not likely be included in scientific research (Riedlinger and Berkes 2001). For example, Billy Wilson's observation that fewer people are going to their camps reveals an indicator which can be used to monitor land use and accessibility. Because the TEK presented is location-specific and integrates both social and ecological perspectives, it is likely to be extremely useful in environmental management and planning (McLain et al. 2013).

The use of TEK in long-term, community-based monitoring has been identified as an area of convergence with scientific research that can lead to a more nuanced and thorough understanding of the drivers and consequences changing environments (Riedlinger and Berkes 2001). Consequently, the map produced in this project may also provide a useful platform for direct collaboration between community-based monitoring and scientific monitoring initiatives. Participatory multimedia mapping makes TEK-based monitoring data accessible to both communities and scientists. By preserving the scale and place-based nature of TEK, specific comparisons with scientific observations are possible (Gagnon and Berteaux 2009), yet TEK-holders involved in research are unconstrained by scientific research agendas since monitoring parameters are community-driven. The spatial and visual representation of TEK lends itself to being presented alongside scientific information with equal weight, and framing individual studies and observations as part of a wider data management system helps emphasize the parallels between traditional resource management systems and western science-based management systems (Berkes 2009; Lertzman 2009).

A number of recent collaborations between TEK holders and researchers in Arctic indigenous communities have involved web-mapping, Participatory multi-media mapping has been used and evaluated favorably in Inuvialuit communities (Bennett 2012). Customized GPS technology has also been used by Inuit hunters to record their observations while travelling on the land by skidoo (Gearheard et al. 2011). A key strength of participatory multimedia mapping in general is that it allows participants to take ownership over the process and results, which empowers communities and builds local capacity by providing opportunities for research training and experience (eg. using digital tools and planning research goals and logistics) (Gilmore and Young 2012).

Bringing together community members and researchers as equal participants in research builds familiarity and trust between facilitators and participants, and placing decisions about how research is conducted and communicated in the community's hands helps avoid replicating power imbalances that tend to exist between western knowledge and TEK (Nadasdy 1999). Presenting knowledge collected in the images and words of knowledge holders in an accessible website ensures results are returned to the community in an appropriate way (Chambers 2006; Gilmore and Eshbaugh 2011). The participatory research approach is inclusive of local people's research priorities and perspectives (Wiber et al. 2004), and multimedia mapping produces information about environmental conditions and changes that is highly descriptive, context-rich and culturally rooted. This approach to research is also culturally coherent as it relies on land-based activities that are integrated with community members' everyday lives (Bennett 2012; Chambers 2006; Gearheard et al. 2011; McLain et al. 2013).

Conclusion

Participatory multi-media mapping was used to record Gwich'in observations of environmental changes and conditions, including the effects of climate change and human activities. Local land users and youth used geotagged photos, videos and interviews to provide context-rich information about specific places on the land that have experienced environmental changes or are culturally important. These observations were organized in an online map that will be used for ongoing monitoring. This participatory, community-based approach to document traditional ecological knowledge is useful for monitoring the impacts of climate change on regional socio-ecological systems because the information produced is highly detailed and reflects local perceptions and priorities. Linking traditional ecological knowledge shared in interviews to photos, videos, and map locations helps to preserve the context of TEK and can facilitate communication between TEK and science-based research, both of which are needed to understand and respond to climate change in the Arctic. Since observations are made in the words and images of Gwich'in land users, they are accessible to members of the same community, and can help researchers and decision-makers concerned with climate change develop adaptation strategies that are consistent with local understandings and practices.

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Appendix 1

Participatory Multimedia Mapping Protocol, updated July 2013

Gwich'in Social & Cultural Institute University of Victoria

Teetl'it Gwich'in Photo-Mapping Guide

If you have noticed something important on the land, please photo-map it! Your observations will be added to our photo-map: http://gwichin.kwusen.com/

At the RRC Office

1. With the RRC coordinator, decide what sites you are going to visit.
2. Set the time on the camera.
3. Charge the camera using the cord provided.
4. Return the camera to the RRC when you're finished.

On the land

1. As soon as you begin your trip: **Turn on the camera's GPS and track log.**
2. When you get to a site, walk around and take photos of the point of interest. Take a few pictures from different angles (3 or 4).
3. For each photo you take, **make sure the GPS and LOG symbol are on** in the corner of the display.
4. Once you have taken the photos, **press the VIDEO button*** and record yourself answering the following questions: (speak into the microphones; press VID
   - *Why did you stop at this place? What is happening?*
   - *How do you explain what you see?*
   - *Why is this area important to you? To the community?*
   - *How will you and the community be affected?*
   - *Are there Gwich'in place names or history here?*

Tips for photo-mapping

- Hold the camera still while taking photos so it doesn't shake.
- Review the photos after you take them, make sure they're clear and in focus. If not, try taking them again.
- Get close to what you want to photograph – the zoom is not very good.
- After several minutes the camera screen goes black. This is normal and does not mean that the camera or the GPS logging is turned off. Pressing the ON/OFF button will re-activate the screen.
- Don't worry about deleting pictures on the camera; that can be done more easily in town

* The PENTAX WG-II model does not have a video button. Instead, in shooting mode, press MODE, scroll to video, and press OK. Press the shutter button to start and stop recording.

Detailed Instructions

Setting the Camera Time

1. Turn the camera on by pressing the circular ON/OFF button on the top. It will blink green.
2. Go to the Setting Menu by pressing (►) for Playback mode and press (MENU).
3. Scroll (↓) to "Date Adjustment" and press (OK).
4. Make sure the date and time are correct. If not, scroll down to "Date" or "Time" and press (OK).
5. Use (↕) to change the numbers, and (↔) to switch between parts of date or time.
6. Press (OK) when you're done, and scroll (↓) to "Settings complete" and press (OK) to save the changes.
7. Press (MENU) to go back to Playback mode, or press the picture-taking (Shutter) button halfway to go back to shooting mode.

Turning on the GPS and Logging

1. Go to the Setting Menu by pressing (►) for Playback mode and press (MENU).
2. Scroll (↓) to "GPS" and press (OK).
3. If "GPS On/Off" is set to "Off," press (OK), scroll (↓) to "On" and press (OK) again.
4. If "GPS Time Sync" is set to "Off," press (OK), scroll (↔) to "On," and press (OK) again.
5. Scroll (↑) to "GPS Logging" and press (OK), press (OK) again on "Record log," and scroll down to "Logging duration."
6. Press (OK) and then (↕) to set the time and (OK) when you're done (make it at least two hours longer than you plan to be out).
7. Scroll (↑) to "Start" and press (OK). It will return to Playback mode. Press the shutter button halfway to return to picture Shooting mode.
8. If there is already an old log and you want to start a new log, you must save the last log. In "GPS Logging," scroll (↓) to "Save Log" and press (OK). Once it is done, you can select set the amount of time for the new log and press "Start" again.

Taking a Picture

1. Go to picture taking mode by pressing the picture-taking (Shutter) button halfway.
2. Make sure the GPS satellite symbol is at the top right corner of the screen, and is white with three signal bars, and says “LOG” underneath (pictured above). If the symbol is red, or is white with three flat lines, it does not have a GPS signal and you should wait or move to a more open area. If there is no satellite symbol on the screen at all and/or it does not say “LOG,” go back to the last section.
3. To take a picture, line up your image on the screen, and press the picture-taking (Shutter) button fully down. Pressing it halfway will focus the image but will not take a picture. Your picture will appear for 2 seconds, then the shooting screen will reappear.

Reviewing Your Picture

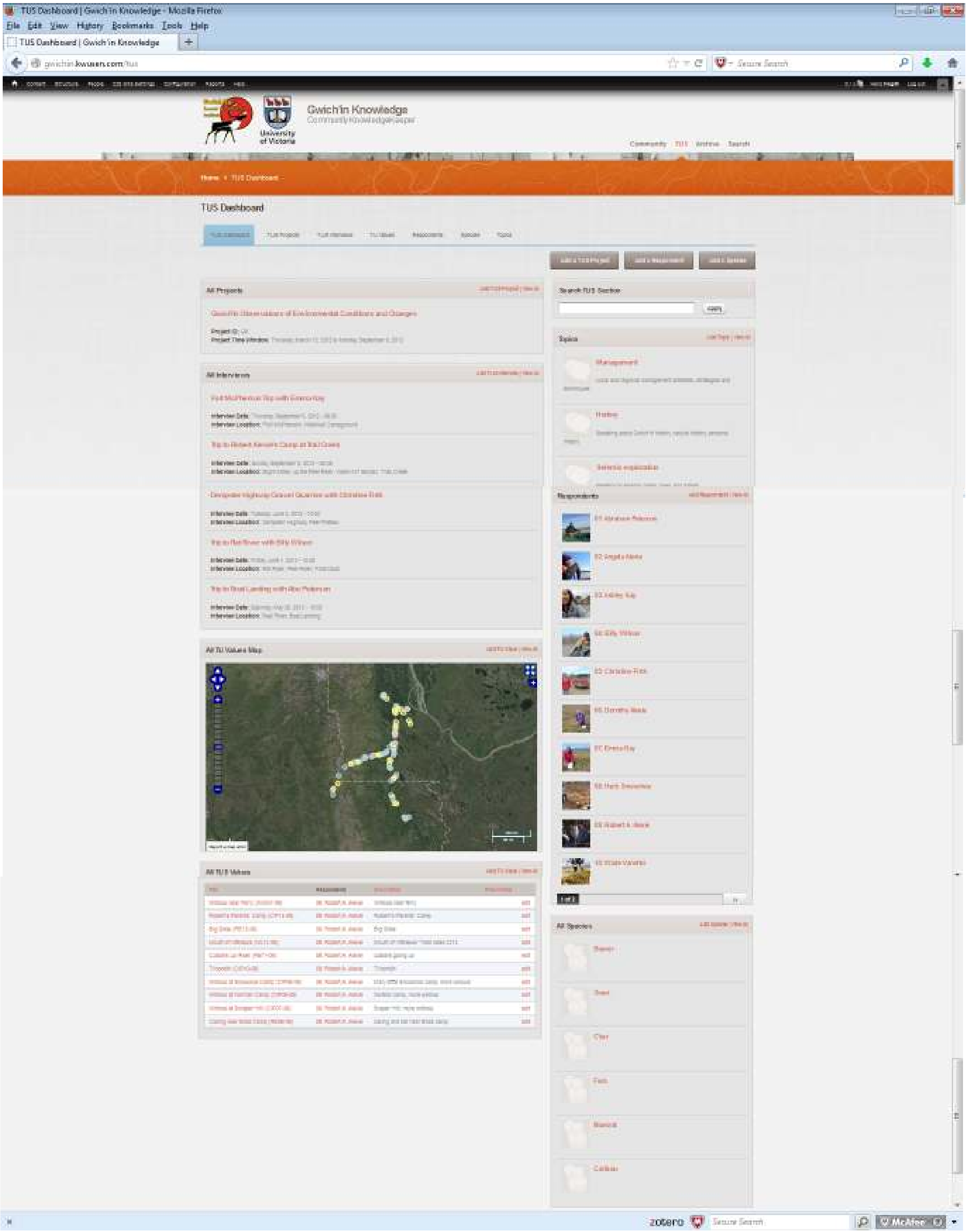
1. To view your picture and make sure the GPS location has been stamped, press (►) to go to Playback mode. Use (↔) to flip between pictures.
2. With the picture on the screen, press (OK) three times to flip between display modes, until you see the N and W coordinates in the bottom right corner. If there are only lines and no numbers, the GPS stamp did not work. Go back to Step 2.
3. To go back to shooting mode, press (►) again, or press the shutter button halfway.

Troubleshooting: If the Camera is fully charged but will not turn on, make sure the battery is in correctly. Unlock the battery door on the bottom of the camera and slide the second latch to open. Pop the battery out by sliding the orange holder. Make sure the battery goes in with the arrows pointing in toward the camera, and the PLUS and MINUS signs on the battery line up with the sticker in the battery slot. Push the battery back in and close and lock the door.

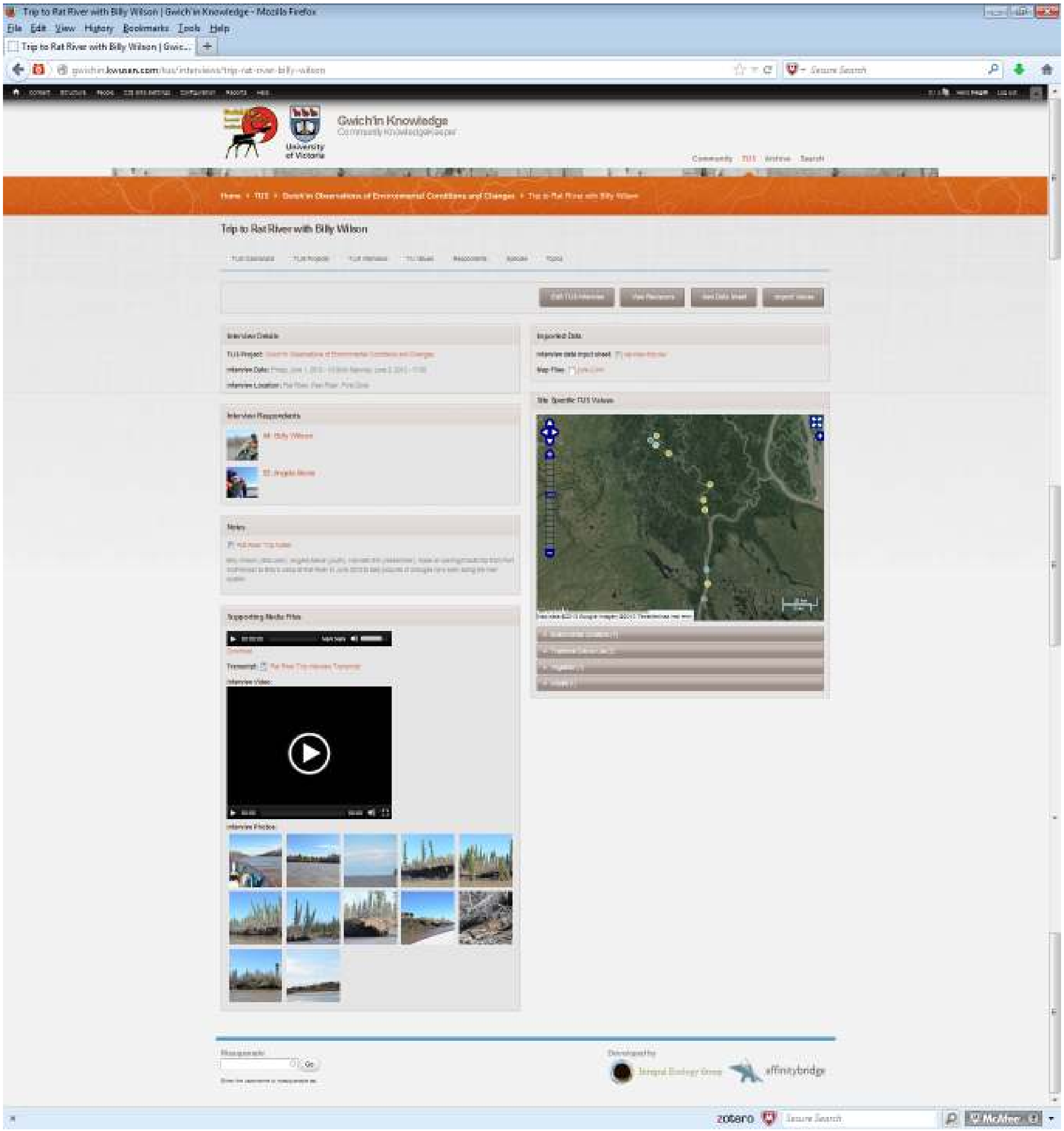
Appendix 2

Participatory Multimedia Mapping Website Screenshots (http://kwusen.gwichin.com)

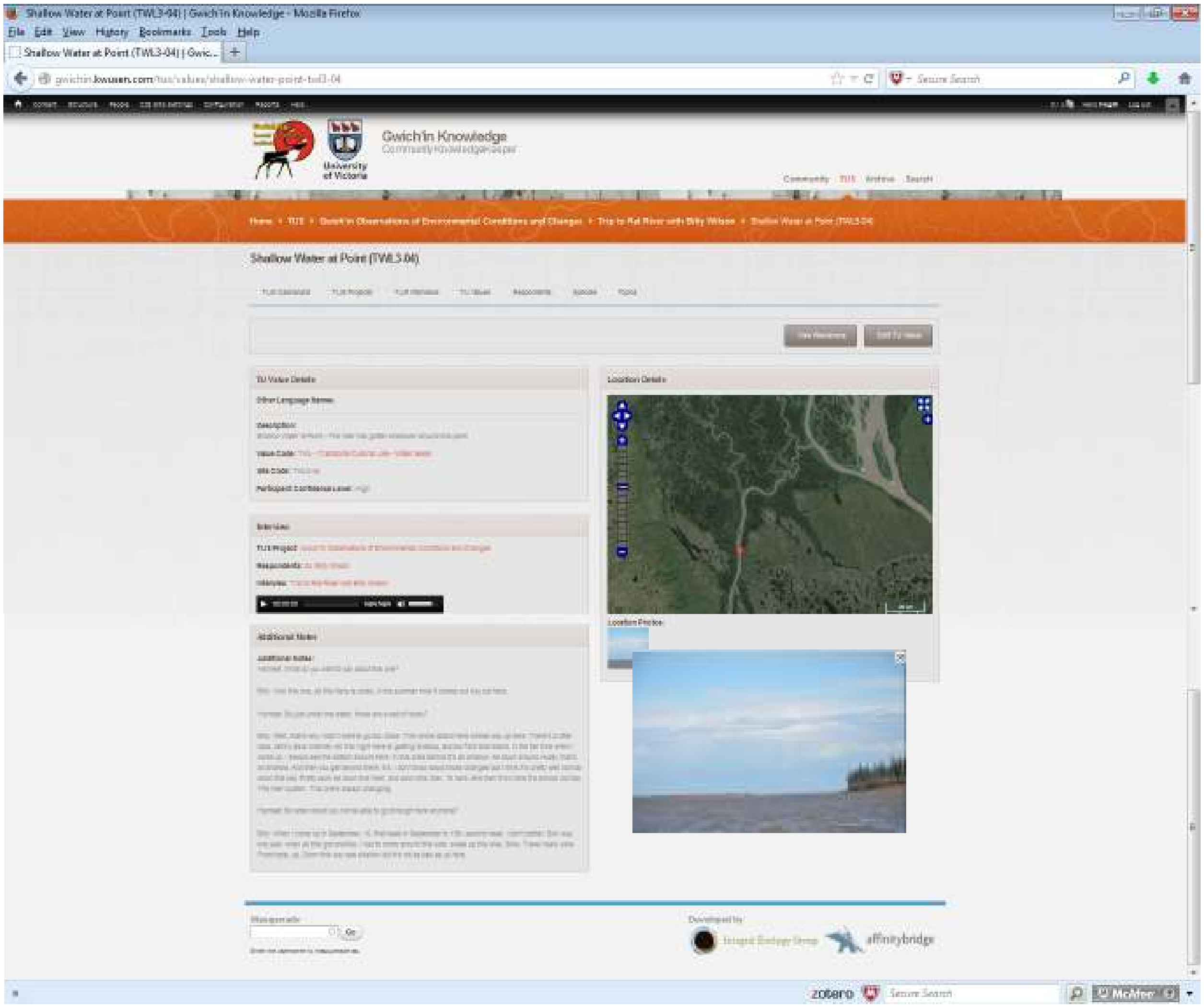
1. Home page



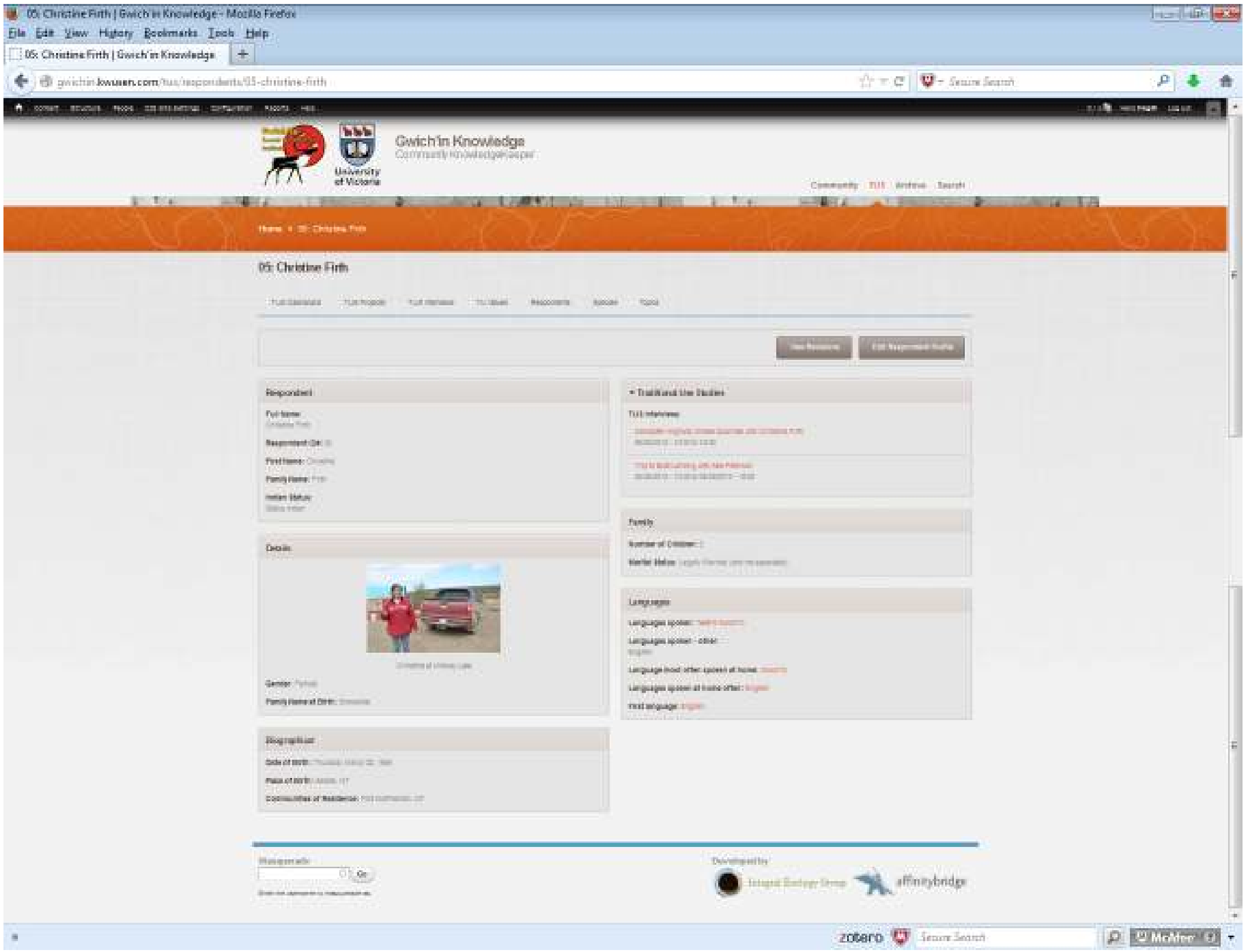
2. Trip Page


Trip to Rat River with Billy Wilson | Gwich'in Knowledge - Mozilla Firefox
File Edit View History Bookmarks Tools Help
Gwich'in Knowledge
University of Victoria
Trip to Rat River with Billy Wilson
Interview Details
Imported Data
Interview Respondents
Site Specific TUS Values
Supporting Media Files
Interview Photos
affinitybridge
zotero

3. Observation Page



4. Participant Page



Appendix 3

University of Victoria

Human Research Ethics Board
Office of Research Services
Administrative Services Building
PO Box 1700 STN CSC
Victoria British Columbia V8W 2Y2 Canada
Tel 250-472-4545, Fax 250-721-8960
Email ethics@uvic.ca Web www.research.uvic.ca

Certificate of Approval

PRINCIPAL INVESTIGATOR	**Harneet Gill**	**ETHICS PROTOCOL NUMBER**	**12-064**
UVic STATUS:	**Master's Student**	ORIGINAL APPROVAL DATE:	10-Feb-12
UVic DEPARTMENT:	**ENVI**	APPROVED ON:	10-Feb-12
SUPERVISOR:	**Trevor Lantz**	APPROVAL EXPIRY DATE:	09-Feb-13

PROJECT TITLE: **Scientific and Gwich'in Perspectives of Environmental Change in the Peel Plateau, NWT**

RESEARCH TEAM MEMBERS: None

DECLARED PROJECT FUNDING: **Northern Scientific Training Program Grant:**
Northwest Territories Cumulative Impact Monitoring Program

CONDITIONS OF APPROVAL

This Certificate of Approval is valid for the above term provided there is no change in the protocol.

Modifications
To make any changes to the approved research procedures in your study, please submit a "Request for Modification" form. You must receive ethics approval before proceeding with your modified protocol.

Renewals
Your ethics approval must be current for the period during which you are recruiting participants or collecting data. To renew your protocol, please submit a "Request for Renewal" form before the expiry date on your certificate. You will be sent an emailed reminder prompting you to renew your protocol about six weeks before your expiry date.

Project Closures
When you have completed all data collection activities and will have no further contact with participants, please notify the Human Research Ethics Board by submitting a "Notice of Project Completion" form.

Certification

This certifies that the UVic Human Research Ethics Board has examined this research protocol and concluded that, in all respects, the proposed research meets the appropriate standards of ethics as outlined by the University of Victoria Research Regulations Involving Human Participants.

Rachael Scarth

Dr. Rachael Scarth
Associate Vice-President, Research

12-064 Gill, Harneet

Certificate Issued On: 10-Feb-12

Appendix 4

University of Victoria

Informed Consent Statement

You are invited to take part in a research project entitled "Gwich'in Perspectives of Environmental Conditions in the Peel Plateau, NWT" that is being conducted by Harneet Gill. Harneet Gill is an MSc student in Environmental Studies at the University of Victoria, supervised by Trevor Lantz. She can be contacted by email if you have any questions or concerns at hkgill@uvic.ca.

This research is being funded by the NWT Cumulative Impact Monitoring Program.

Purpose and Objectives
The main objective of this project is to record and communicate Gwich'in observations of environmental conditions and changes in the lower Peel River watershed, focused on the Stony Creek and Vittrekwa River catchments. Gwich'in Traditional Knowledge will be communicated using photos, videos and audio recordings taken by Gwich'in knowledge holders and youth. This research is part of my MSc thesis.

Use and Accessibility of Information
Information collected in this study (geo-referenced photos, video, audio recordings, and associated text) will be compiled into a web-based map of the Peel Plateau area. After review and approval by participants including you, this map will be made available to the public.

Benefits of this Research
This community-based research project will provide the opportunity for local youth and elders to spend time together on the land, which will contribute to relationship building and knowledge sharing. Youth will have the opportunity to gain insights into environmental impacts and changes, and to gain technical research skills. This project will benefit the Teetl'it Gwich'in community by building capacity to monitor and communicate environmental change.

Participant Selection
You are being asked to participate in this study because you are from Fort McPherson and are (a) a Gwich'in youth with interest in environmental change in the Peel Plateau, or (b) a Gwich'in knowledge holder.

What is Involved
If you agree to voluntarily participate in this research, your participation will include taking part in activities out on the land where you will document observations of the environment. Trips on the land will take place in the Peel Plateau area, at locations of your choosing. In the first step of the study, you will be paired with a youth or Gwich'in knowledge holder, and you will be trained with your partner in using digital cameras, video recorders, audio recorders, and GPS units. Next, you will use these digital tools to document observations of environmental conditions and/or change in the research area.

The photos, videos, and audio recordings that you capture will then become the focus of interviews with me to record additional information about them. These interviews will be recorded with an audio recorder and the transcriptions will be added to the web-based map. You will be given opportunities to review or withdraw your data from the map before it is made available to others.

The digital tools training session will take 2-3 hours of your time; observations on the land will take a total of 1-2 days, but will be made during several day trips. Our interview about your observations will take 1-2 hours. All of these activities will be scheduled to suit your availability.

Risks and Inconvenience

The potential risks of this research are the same as those associated with walking out on the land, and traveling by vehicle or boat to various sites. All necessary safety precautions will be taken. Participation in this study may cause some inconvenience to you, associated with the time spent monitoring and participating in interviews.

Compensation

You will be compensated at a fixed daily rate set by the Renewable Resource Council (RRC). In addition, you will be given enlarged prints of some of the photos that you take out on the land. If you agree to participate in this study, your compensation must not be coercive. It is unethical to provide compensation to induce participation. If you would not consider participating in this study were the compensation not offered, then you should decline.

Voluntary Participation

Your participation in this research must be completely voluntary. If you do decide to participate, you do not have to answer any questions you are uncomfortable with and you may withdraw at any time without any consequences or any explanation. If you do withdraw from the study your data will be used in the analysis only if you agree.

On-going Consent

To make sure that you continue to consent to participate in this research, I will verbally confirm that you are comfortable participating in the study before each trip or interview.

Recognition and Confidentiality

You will be credited for all contributions you make to this research. Given the participatory nature of this project and the size of your community, it is impossible to keep your observations anonymous, so if you have concerns about your privacy, you should not participate. If you do choose to participate and later wish to remain anonymous, I will delete all of your observations from the project database.

Dissemination of Results

Before the results are shared, you will have opportunities to review your contributions and edit or delete them. The presentation of results will be reviewed by the GSCI and RRC, and at community meetings, to ensure they are accurate and appropriate, and to seek suggestions and changes for the final presentation. It is anticipated that the results of this study will be shared with others through a web-based map, community demonstrations, public presentations, and publications. A copy of the final presentation will be sent to you, in addition to several enlarged prints of your photos.

Storage of Data

Once this research is completed, the data, including tapes and memory cards, will be stored on a password-protected computer in the Ethnoecology Lab (University of Victoria), and at the Gwich'in Social and Cultural Institute (GSCI). Information captured with photos, videos and audio recordings will be copied once and stored at the GSCI.

Researcher Contact Information

Harneet Gill
School of Environmental Studies
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PO Box 3060, STN CSC
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250-853-3287
hkgill@uvic.ca

In addition, you may verify the ethical approval of this study, or raise any concerns you might have, by contacting the Human Research Ethics Office at the University of Victoria (250-472-4545 or ethics@uvic.ca).
Your signature below indicates that you understand the above conditions of participation in this study and that you have had the opportunity to have your questions answered by the researcher.

"Gwich'in Perspectives of Environmental Conditions in the lower Peel River watershed, NWT"

Visually Recorded Images/Data (Participant to provide initials)

Photos may be taken of me for: Analysis _______ Public Dissemination ________

Video/audio may be taken of me for: Analysis _______ Public Dissemination ________

I agree to allow the GSCI, University of Victoria researchers (Harneet Gill, Trevor Lantz), the Gwich'in Tribal Council and the Gwich'in Renewable Resource Councils to use this data in the future.

☐ (CHECK BOX)

Waiving Confidentiality

I agree to be identified by name and credited in the results of the study.

______________ (Participant to provide initials)

of Participant	ıtion of Participant	:ommunity of Participant
on of Interview	**ture** of Participant	Date

A copy of this consent will be left with you, and a copy will be taken by the researcher.

Chapter 4

Conclusions

Many parts of the subarctic are experiencing rapid environmental changes including rising air temperatures and increasing human development, with accompanying shifts in vegetation structure, wildlife distributions, permafrost and ground stability, and weather patterns (ACIA, 2005; Chapin et al., 2005; Stefansson Arctic Institute, 2004; Jorgenson et al. 2001; Kokelj et al. 2005; Lantz et al. 2009; Sturm et al. 2005; Tape et al. 2006; Tunnicliffe et al. 2009; Serreze et al. 2000). These changes have profound effects on local indigenous communities whose livelihoods are closely tied to the land, and on the infrastructure that links them to each other and to the South. This research took place in the lower Peel River watershed in Teetl'it Gwich'in territory near Fort McPherson, NT. In this region, massive retrogressive thaw slumps have created a convergence of interest between scientific investigators and community members, and have made it clear that there is a need to combine both scientific and traditional knowledge in monitoring and responding to environmental changes.

The overall goal of this research was to increase to our understanding of environmental changes in the lower Peel River watershed using both scientific and community-based perspectives. To do this, I led an investigation of the effects of the Dempster Highway on tundra ecosystems (Chapter 2). I also collaborated with the Gwich'in Social and Cultural Institute to develop and implement a participatory multimedia mapping protocol to record Gwich'in observations of the environment (Chapter 3). This chapter brings together the findings of the two research papers presented in this thesis, discusses the future of environmental monitoring in the lower Peel River watershed, and presents conclusions for the project as a whole.

My study of the effects of the Dempster Highway on tundra ecosystems provides baseline data for monitoring the impact of the highway over time, and provides insight into the relationships among infrastructure, vegetation structure and thermal regime changes. Data on these interactions and feedbacks will make an important contribution to efforts to proactively manage existing infrastructure, and to the design of proposed infrastructure in Arctic tundra ecosystems, including the Inuvik-Tuktoyaktuk and Mackenzie Valley Highways.

I employed participatory multimedia mapping to record local observations of environmental conditions and changes using images and descriptions created by Gwich'in land users and youth. This research approach builds local capacity to monitor change by training local participants as co-researchers, and provides context-rich information that is interpretable by a broad audience about the environment and the relationships between Gwich'in people and their land. The information was organized in a web-based map of environmental conditions and changes and will be useful for monitoring and responding to environmental changes, teaching map users about Gwich'in knowledge, culture and on-the-land practices, and creating a common platform for communication and collaboration between community members, researchers and decision makers.

A scientific investigation of environmental change: The effects of the Demspter Highway on tundra ecosystems

In Chapter 2 of this thesis, the vegetation and soils adjacent to the Dempster Highway were examined to assess the cumulative impacts of the highway. This study was developed in response to community concerns about increased shrub growth along the highway corridor near Fort McPherson, NT. Sampling was conducted along a 35 km stretch of the highway in the in the Peel Plateau, NT. To examine the relationships between roadside disturbance, plant community composition and green alder (*Alnus crispa*) abundance, we selected sites that reflect the natural heterogeneity in shrub cover across the landscape. We included sites adjacent to the road (15-20 m from the toe of the embankment) in dwarf shrub tundra and in tall shrub tundra dominated by green alder. We selected control sites at least 500 m from the road in dwarf shrub tundra and in tall shrub tundra. Sites were located on both the south and north sides of the highway.

We found that alder growth and recruitment were enhanced adjacent to the Dempster Highway, and we observed significant alterations to plant community composition, soil properties and ground temperatures where alder shrubs had formed closed canopies. Tall shrub sites adjacent to the road had reduced understory vegetation including mosses, greater litter and organic soil thickness, higher nutrient availability, and deeper snowpack than all other site types.

We also observed feedbacks between biotic and abiotic changes associated with the road. These changes have important implications for permafrost conditions adjacent to the roadbed. When tall shrubs become dominant adjacent to the road, they act as a windbreak, increasing dust deposition, soil nutrient availability, and pH. Combined with shading, this reduces the cover of mosses and acidophilous shrubs. Ultimately tall shrub growth is promoted through enhanced nutrient availability and reduced competition. Snow entrapment in dense alder stands insulates the ground and increases ground temperatures and active layer depth within 15 m of the road. Ultimately the thermal disturbance associated with shrubs adjacent to the road can impact road bed performance, as permafrost degradation becomes more likely.

Shrub proliferation adjacent to the highway is part of a wider trend of shrub proliferation across the Arctic tundra (Lantz et al., 2013; Tape et al., 2006), and will be an important consideration for the planning and maintenance of northern infrastructure. To improve our understanding of the spatial heterogeneity of shrub proliferation, research exploring the relationships between biophysical landscape features and shrub development is also needed.

A traditional knowledge-based investigation of environmental change: Using Gwich'in observations to monitor environmental conditions and changes

Chapter 3 of this thesis addresses the need for ongoing and locally-driven environmental monitoring to keep pace with rapid environmental changes associated with climate warming and human impacts. At presentations and discussions between scientists studying retrogressive thaw slumps and community members engaged and interested in this work, two research needs for environmental monitoring were identified by the Teetlit Gwich'in community of Fort McPherson, NT: the use of traditional knowledge in researching and communicating change, and a monitoring program that is community-driven. Traditional knowledge is increasingly used as the basis for generalized regional monitoring, but there is a need for detailed, place-specific information that is consistent with local ways of understanding and interacting with the environment.

In the pilot year of this community-based environmental monitoring program, we employed participatory multimedia mapping with Teetl'it Gwich'in land users and youth from Fort McPherson, NT. Gwich'in monitors made trips on the land to document environmental conditions and changes with photos and videos tagged with GPS locations. Following fieldwork, land users provided detailed information about each observation in follow-up interviews, and observations were added to a web-based map that will be used for ongoing monitoring. Participants were recommended by the TGRRC, GSCI and expert knowledge holders. Before and during the trip, I trained youth to use digital tools and oversaw trip logistics, and I conducted media-facilitated interviews and uploaded data to the web-based map. Observations of phenomena such as culturally important places, permafrost degradation and shrub increase will allow map users to identify specific areas of concern, and repeat observations over time will provide compelling evidence for change.

Using a participatory, land-based research approach facilitated knowledge-sharing between youth and land users, and the insights, explanations and anecdotes included in the web-based map provide a medium for learning by map users including land user peers and less experienced members of the community. Because observations are made in the words and images of Gwich'in land users, they are accessible to members of the same community and allow for the comparison and learning of knowledge from land user and/or youth peers. The details about Gwich'in history, culture, identity, and ways of expression contained within each observation can also help researchers and decision-makers understand and respond to changes in a way that is consistent with local understandings.

Convergence of approaches

Both of the studies presented in this thesis were concerned with environmental changes in the subarctic. Both projects emerged from discussions between scientific researchers involved with NWT CIMP and community members, and both projects engaged Teetl'it Gwich'in community as research assistants (Chapter 2) or co-researchers (Chapter 3). However, because of differences between Western and indigenous worldviews, methodologies, and sources of information (described below) they were carried out independently of each other.

Efforts to integrate research based on scientific knowledge and traditional ecological knowledge (TEK) can be valuable, but require a great deal of reflection and contributions among knowledge-holders. It is crucial to preserve the validity of both and draw conclusions that are understandable and relevant to both types of knowledge-holders (Bonny & Berkes, 2008; Duerden & Kuhn, 1998; Huntington et al., 2004). The use of traditional knowledge is increasingly valued in environmental monitoring, conservation and management in the North, but it is likely that power imbalances that favour scientific agendas, institutions and discourse are preserved in the collection and presentation of data (Gratani et al., 2011; Nadasdy, 1999, 2005). For example, research goals and parameters are often developed by scientists and traditional knowledge is "mined" for pieces of information that fit the dominant framework of understanding (Riedlinger & Berkes, 2001). Blending scientific and traditional knowledge in my study of the Dempster highway would have provided interesting perspectives about this specific disturbance, and discussions with community members have indicated that investigation is valued by the community. However, the highway is not the only research priority for Gwich'in expert knowledge-holders, and narrowing the focus of TEK-based research to questions that interest scientists would place a significant constraint on the contribution of TEK to environmental monitoring. Several observations of the impacts of the Dempster Highway were made during participatory multimedia monitoring trips, when they fit with participants' research agendas and priorities.

Detecting and monitoring environmental changes in remote northern landscapes benefits from a diversified research approach that responds to the concerns and priorities of local communities (Kokelj et al., 2012; Moller et al., 2004; Riedlinger & Berkes, 2001). Scientific investigations of shifts in ecosystem structure and processes are useful for understanding cumulative impacts due to anthropogenic and natural change, and for predicting the effects of new disturbances. Work focussed on local knowledge and more qualitative observations of environmental change provide a means to expand the geographic area being investigated. Engaging local knowledge holders in research also allows greater diversity in research parameters than scientific investigations tend to include, because parameters can be chosen by local participants (Berkes, 2009).

The research presented in this thesis suggests that traditional knowledge research that is community driven and organized around multimedia may provide a way to link distinct knowledge systems in equitable ways without seeking to integrate them directly. Uploading scientific research data to the web-based map was a recommendation of the Fort McPherson research steering committee, and is a planned activity. Maps are widely understood and are compatible with both traditional and western spatial understandings of the environment (Brody 1983). The PMM map could be a place to share overlaps in knowledge systems, presenting Gwich'in observations directly alongside scientific data wherever both are available. The non-scientific information in the web-based map could help facilitate the interpreting of scientific data and provide context for scientists to take local priorities and understandings into consideration when planning, executing and disseminating research.

This project is consistent with the Pathway Approach used by Aboriginal Affairs and Northern Development Canada' Northwest Territories Cumulative Impact Monitoring Program. NWT CIMP coordinates, supports and conducts environmental monitoring in order to ensure data is available to Northerners, decision-makers and industry. The Pathway Approach aims to incorporate both scientific and traditional knowledge in monitoring while maximizing partnerships and community involvement (Canada, 2012). A key goal is to help communities become leaders of monitoring and research that can influence decision makers and provide strong information bases about cumulative impacts for decision makers involved in assessing and planning development projects. My MSc research contributes to cumulative impact monitoring in the lower Peel River watershed by providing quantitative and qualitative baseline data on tundra ecosystems and environmental conditions, and by directly involving traditional knowledge holders in both scientific and community-based research.

Community Engagement and Ongoing Monitoring

Beyond the data collection described in this thesis, key research priorities identified by the Teetl'it Gwich'in community were collaboration between scientists and traditional knowledge holders, teaching youth about both types of knowledge while spending time on the land with Elders, and empowering Teetl'it Gwich'in land users to carry out their own research (Scott, 2011). Throughout this research project, the authors and their community partners have endeavoured to be responsive to these priorities and to engage community members in research before, during and after data collection. Approval of research proposals by the Teetl'it Gwich'in Renewable Resource Council (TGRRC) also stipulates that researchers must return their results to the community. In May 2013, we (HKG, TCL, GSCI) obtained funding to disseminate findings of both research projects in a way that involves community members and uses input from traditional knowledge. In August and September 2013, we organised a steering committee meeting to discuss research findings and strategize a dissemination strategy; we organised free workshops for community members to learn field protocols for permafrost, vegetation and stream sampling; we hired local youth as field and lab assistants for fieldwork along the Dempster Highway; we added culturally important sites to ongoing berry monitoring research; we made classroom presentations and led a field trip to research sites; and we displayed posters and spoke on the radio about our research and its links to the community.

To facilitate community monitoring of environmental changes as a community-driven effort that does not depend on the facilitation of externally-based researchers, we developed a protocol that will continue to operate out of the TGRRC office in Fort McPherson (see Chapter 3, Appendix 1). As of September 2013, two GPS-equipped digital cameras were available for sign-out, along with travel compensation to overcome financial barriers to participation. The easy-to-use camera and protocol instruction sheet ensure land users can contribute to monitoring as part of their regular travels on the land, and they are encouraged to take along youth who can help capture media. As the cameras are returned, the geotagged photos and videos will be sent to the Ethnoecology Lab at University of Victoria, where they will be added to the web-based map for on-going environmental monitoring. These research and engagement initiatives have received considerable interest and support from the community, and PMM has been received as an effective way to use TEK in environmental monitoring. It is our hope that this long-term project will be adopted by community-based organisations in Fort McPherson and other Gwich'in communities (Aklavik, Tsiigehtchic and Inuvik) in the NWT.

A long-term goal for the participatory multimedia monitoring program is to develop local capacity to monitor and respond to environmental changes. An important step toward ownership of the project by the community will be community-based data management. The PMM website is currently in development phase which requires consultation from technological experts (Kwusen Research & Media). However, we anticipate that once website settings are finalized, community-based data input and maintenance will be feasible because the website was designed to be very user-friendly and does not require the use of codes. PMM and scientific data management will require the ability to use the website interface, MS Word, MS Excel, photo and video editing software, transcription software, web-based maps, and GIS software. There is rich opportunity for capacity-building in the community, since the Band Council and Aurora College have resources and training for computers, GPS, and other technology, and the Renewable Resource Council has the capacity to oversee and conduct research and manage data. Challenges to overcome will include funding for training and job creation, creating a data backup strategy, and integrating the program with existing initiatives and community priorities. We anticipate that long-term partnerships that have already been established between the community, University of Victoria and NWT CIMP will continue to play a role in building capacity and furthering community-based monitoring. Because PMM has the potential to elicit and make public sensitive information, the management and access to data will be a key issue as the website is finalized and becomes more widely used. Although any member of the public is able to access the website, doing so requires a username and password issued by the administrator (currently the UVic Ethnoecology Lab operating with guidance from the community, but potentially a community-based organisation in the future), and access settings can be changed for each user. This provides control over information sharing and the ability to monitor website usage.

Data retention is another important component of long-term monitoring. The PMM website will be a way to store scientific and TEK-based monitoring data in an adaptive and accessible database, where shifts in knowledge can be immediately recognized and used. Uploading data to the website will ensure its long term continuity. Additionally, data will be stored by the University of Victoria ethnoecology lab and the Gwich'in Social and Cultural Institute traditional knowledge database. Our online database can serve as a community resource that is used to facilitate environmental planning and management, and as a learning resource that has potential to be integrated into school curricula.

This project is part of a stable partnership between academic (UVic), community (GSCI) and government (AANDC) organisations, and ongoing collaboration will help ensure continuity of the project and applications for the outcomes of research. Follow-up research and local capacity-building and engagement by future researchers, graduate students and research assistants affiliated with project partners will contribute to the long-term sustainability of this project. The relationships developed through our research and community engagement work will allow on-going involvement between researchers and community members in the lower Peel River watershed, providing opportunities for local residents to gain scientific and social-scientific research skills and contribute to regional environmental monitoring in a meaningful and mutually beneficial way.

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