University of Alberta

Short and long-term effects of winter seismic exploration on low arctic plant communities of the Kendall Island Migratory Bird Sanctuary, Northwest Territories.

by

©

John Todd Kemper ©

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ABSTRACT

Exploration and development associated with the petrochemical industry is the leading source of anthropogenic disturbance in the western Canadian arctic. I studied the short (2-3 years) and longer-term (18-33 years) responses of various tundra plant communities to winter seismic exploration in the Mackenzie Delta, NT. Vegetation on recent (2-3 years) seismic lines was characterized by significant reductions in vascular plant cover (vs. controls) in all community types (reductions ranged from 59.50±13.8% in upland communities to 18.36±7.67% in wet graminoid communities). Depth to permafrost was greater (from 2.37±2.22cm in wetlands to 6.61±3.43cm in uplands) along recent seismic lines (vs. controls) in all but one community type. For most parameters, change was greatest in the upland community types, which were also the only community types in which community composition was altered. Older seismic lines (assessed upland communities only) were characterized by increases (vs. controls) in deciduous shrub cover, total vascular plant cover, and reduced lichen cover. Results indicate that modern winter seismic programs have significant effects on tundra plant communities, and that there is potential for effects to persist for >30yrs.

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LIST OF ABBREVIATIONS

ANWR:	Arctic National Wildlife Refuge
a.g.l.:	Above Ground Level
CL:	Confidence Limit
GLM:	General Linear Model
ISA	Indicator Species Analysis
KIBS:	Kendall Island Migratory Bird Sanctuary
LSH:	Low Shrub – Heath plant community type
LSMean:	Least Square Mean
MLM:	Mixed Linear Model
MRPP:	Multi-Response Permutation Procedures
MSH:	Medium Shrub – Heath plant community type
NMS:	Non-metric Multidimensional Scaling
TSH:	Tall Shrub – Herb plant community type
WG:	Wet Graminoid plant community type

Chapter 1: General Introduction

Arctic plant communities exist in among the most climatically severe locations on earth (Billings and Mooney 1968), are floristically depauperate in comparison with milder regions (Bliss 1971; Billings 1987), and are often considered to be particularly sensitive to anthropogenic disturbance (e.g. Billings 1973; Billings and Peterson 1992; Reynolds and Tenhunen 1996; Vavrek *et al* 1999). Recent and growing interest in resource extraction in the arctic has led to a widening anthropogenic influence that is expected to continue to increase in the foreseeable future. Because of this growing human footprint, there is a need to better understand the responses of tundra plant communities, soils, and permafrost, to industrial disturbances in both the short and long term.

Plant Communities of the Arctic Coastal Plain

The circumpolar arctic flora is relatively small in comparison with temperate and tropical floras, and has been shaped by severe climatic constraints, both past and present. Historically, the size and composition of the arctic flora has been influenced by periods of glaciation, and most of the present day plant species are thought to have emigrated to the arctic through connections with areas of alpine tundra post glaciation (Hultén 1937; Murray 1995). As such, the environmental selection of phenotypes capable of long-term survival in the arctic has resulted in a flora that is relatively depauperate in both species and functional groups. Perennial C_3 species completely dominate the arctic flora; there are very few biennial species, and almost no annual or ruderal species (Billings and Mooney 1968).

The growth and reproduction of arctic plants is similarly constrained by the short growing season, low air temperatures, and a shallow active layer with cold, nutrient poor soils (Billings and Mooney 1968; Bliss 1971; Billings 1987). Plant communities in the arctic are assembled along several ecological gradients including: temperature, aspect and elevation (Walker 1995), microtopography and soil moisture (Peterson and Billings 1980; de Molenaar 1987), snow cover (Shaefer and Messier 1995), soil pH (Gough *et al* 2000), and nutrient availability and nitrogen form (McKane *et al* 2002). Several of these gradients are likely related, and therefore not orthogonal to one another; the relative contribution of each to community structure has yet to be adequately determined. The distribution and steepness of these gradients across the arctic landscape is typically related to periglacial features that affect topography at varying scales, including thaw lakes, pingos, and ice wedge polygons (Walker 1995).

Despite being subjected to similar selective pressures, arctic plant species have evolved a variety of adaptive mechanisms (Bliss 1971), and neither species nor communities should be expected to respond equally to disturbance. For example: as an adaptation to cold temperatures and late spring frosts, slow growing evergreen shrubs break bud dormancy much later than do faster growing deciduous shrubs, which risk losing a years growth to a late frost (Billings and Mooney 1968). The evergreen shrubs are able to use older leaves to photosynthesize during the early days in spring (Starr and Oberbauer 2003), and as storage organs (Bliss 1971), which allows them to compete well with the faster growing deciduous species under harsh climatic conditions. However, following a sudden perturbation that results in species removal, faster growing species would clearly be at an advantage.

Disturbance and Succession in Arctic Plant Communities

There has been some diversity of opinion regarding succession in arctic ecosystems, much of which stems from the difficulty in drawing comparisons between high-arctic and low-arctic ecosystems. For a variety of reasons, mostly relating to the relative importance of "safe sites" versus biological interactions (see Bliss and Peterson [1992] and Svoboda and Henry [1987] for a more thorough review), cross regional generalizations regarding succession are not possible. The remainder of this discussion, and comparisons to literature throughout this thesis are therefore restricted to low-arctic ecosystems.

Low-arctic plant communities are subject to both natural and anthropogenic disturbances at various frequencies and scales (Walker and Walker 1991). Succession following disturbance in low-arctic ecosystems typically differs from that in more temperate climates in that there is usually not a replacement of seral stages as succession proceeds (Bliss and Peterson 1992). While the more 'classical' mode of species replacement does occur in riparian habitats due to channel meander (Bliss and Cantlon 1957), as well as within the context of the thaw lake cycle (Billings and Peterson 1980; Bliss and Peterson 1992), secondary succession in the low arctic usually follows a 'directional non-replacement' pattern (*sensu* Svoboda and Henry 1987). In this mode of succession the species which colonize a disturbance are members of the surrounding 'climax' plant community (rather than an earlier successional sere), and there are directional (predictable) changes in the presence and relative abundance of species (from the surrounding matrix) on the disturbed site through time.

Within this framework of directional succession without species replacement, the more familiar models of succession (facilitation, inhibition, and tolerance) proposed by Connell and Slatyer (1977) may still operate, although these concepts must now be limited to species interactions, rather than interaction between communities or successional seres. Cargill and Chapin (1987) suggested that facilitation might play an important role in succession on climatically severe sites, whereas sites with less severe conditions would be more likely to experience inhibition. These concepts can be extended to the intensity and size of the initial disturbance, as this generally dictates the environmental 'severity' of a disturbed site. Disturbances that alter the environmental gradients at a site would, in turn, affect the relative suitability of sites for initial colonizers.

General Responses to Disturbance

The type and intensity of disturbance are important predictors of changes to the environmental conditions at a site, and therefore to disturbance response (Billings 1973; Rickard and Brown 1974; Walker *et al* 1987a). In the low-arctic, the soil thermal and hydrological conditions are paramount to the plant community composition and productivity, and disturbances which alter these can greatly affect revegetation of disturbed sites (Billings 1973; Walker *et al* 1987; Walker and Walker 1991; Shirazi *et al* 1998).

Removal of plant cover and organic material affects the energy budget of tundra systems by exposing darker mineral or organic soils, thereby reducing surface albedo (Haag and Bliss 1974; Hinzman *et al* 1996). At its most dramatic, such changes can result in thermokarst (thermal subsidence), where the thawing of frozen soils (particularly those that are ice-rich) causes the soil surface to subside. Such disturbances have often led to changes in hydrology and drainage, resulting in vastly different post-disturbance plant communities, often with higher productivity than surrounding tundra (undisturbed by seismic activity) (Komárková 1983; Truett and Kertell 1992). Even in the absence of thermokarst, changes to surface reflectance can lead to warmer soils, increased active layer depth, and subsequently, altered nutrient cycles, increased primary productivity, and changes in plant species composition (Chapin and Shaver 1981). This would suggest that even small scale anthropogenic disturbances may exceed the resilience threshold (*sensu* Walker *et al* 1987a) of tundra ecosystems.

Damage or removal of the organic mat in low arctic ecosystems can also have a substantial impact on the biotic processes of a plant community. The soil organic layer contains the native seed bank (McGraw 1980; Gartner *et al* 1983); natural revegetation is therefore severely hampered by its removal and subsequent exposure of mineral soil (Cargill and Chapin 1987; Ebersole 1989).

Arctic tundra response to disturbance hinges not only on changes in abiotic conditions, but also on the influence of those changes on the natural relationships between species and environmental gradients. Walker and Walker (1991) suggested that because the type of vegetation present on a site is an "integrated expression of the system's reaction" to the underlying environmental gradients and the disturbance/successional history, the community type at a site is the best predictor of disturbance response. Thus, if the type and intensity of a disturbance is known, the resistance of various community or vegetation types should be consistent and predictable.

Interactions between the degree of alteration to the environment and the life history traits of species surviving in the seed bank and surrounding matrix shape the initial post-disturbance plant community. For example, slow growing evergreen shrubs have typically been shown to be disproportionately affected by disturbance (Hernandez 1973; Felix and Reynolds 1989) and are slow recolonizers of disturbed sites (Emers *et al* 1995), likely due to their relatively low rates of photosynthesis and seed production (Billings and Mooney 1968). In contrast, rhizomatous graminoids can often recolonize sites relatively quickly (Bliss and Wein 1972; Hernandez 1973), and have been shown to increase in abundance where disturbance created wetter sites (Chapin and Shaver 1981).

Oil and Gas Exploration in the Arctic

When petrochemical exploration was first conducted in the Alaskan low arctic in the 1940s it was almost exclusively performed in the summer months (Walker and Walker 1991), typically resulting in severe disturbances that persisted several decades later (e.g.

Komárková 1983). With increased environmental awareness in the late 1960s, techniques to minimize disturbance to arctic terrain were adopted; the most significant of which was the re-timing of seismic exploration to winter months, when snow cover and frozen ground provide some protection for tundra plant communities (Bliss and Wein 1972; Webber and Ives 1978). Early winter seismic programs typically employed a bulldozer blade to level the ground surface, providing a level surface for geophone placement (Kerfoot 1972). This technique often resulted in the clipping of hummocks and some removal of the organic mat, particularly where inexperienced and/or disinterested operators were in control of machinery (Rickard and Brown 1974).

Exploration for oil and gas in the outer Mackenzie Delta also began as summer seismic programs in the mid 1960s; winter programs were adopted relatively quickly, however, and were the predominant form of exploration through the 1970s. Exploration activity was subsequently limited due to the cancellation of the Mackenzie Valley pipeline project following the Berger inquiry in 1977 (CARC 2001). Market forces, along with the resolution of aboriginal land-claims in the 1990s has renewed interest in a Mackenzie Valley pipeline and caused a resurgence in development interest within the outer Mackenzie Delta. Exploration has increased rapidly in recent years and is expected to continue doing so in the foreseeable future.

To date the major component of this exploration has been winter seismic programs, which involve the passage of tracked and/or wheeled vehicles over frozen tundra habitat, followed by sending energy charges (from vibration or dynamite) into the ground to produce a return echo which is recorded for analysis of sub-surface geology. These programs present two potential sources of disturbance to tundra ecosystems: linear disturbances caused by off-road vehicle travel, and point disturbances where energy charges are transmitted into the ground. Although individually small, the accumulation of seismic lines across the landscape, both spatially and temporally, could potentially affect a substantial area of tundra. The focus of environmental research into oil and gas activities in the arctic is now largely with concern for these types of cumulative effects (Walker 1996). Tundra ecosystems may be particularly sensitive to such disturbance; due to the complex relationships between permafrost and hydrology indirect impacts of oil field development at Prudhoe Bay, Alaska have greatly exceeded the direct impacts associated with exploration and construction there (Walker *et al* 1987b).

Kendall Island Migratory Bird Sanctuary:

The Kendall Island Migratory Bird Sanctuary (hereafter KIBS) was established in 1961 to protect the nesting habitat of lesser snow geese and other migratory birds. Information regarding the type and magnitude of impacts associated with oil and gas exploration is required for the effective management of the Kendall Island sanctuary, which sits atop two major underground gas fields, making it an area of intense interest for petrochemical companies. The Canadian Wildlife Service (Environment Canada) is seeking to maintain a combined exploration and development footprint of less than 1% of the sanctuary area.

Environmental research regarding oil and gas exploration in northern Canada has typically followed major waves of exploration, the most recent of which occurred in the 1970s employing different vehicle types and techniques. The impacts of early seismic programs were studied during the 1970s (e.g. Bliss and Wein 1972, Hernandez 1973), however modern seismic programs are sufficiently different to warrant a re-investigation of the short term (<3 years) impacts. Further, sufficient time has passed so that the longer-term (>10 years) impacts of earlier exploration activity in this region can now be assessed.

Thesis Objectives:

The purpose of this research was to determine precisely what statistically significant effects winter seismic programs have on the plant communities and permafrost terrain of the KIBS, and to evaluate the persistence of these impacts through time. In addition, I considered the potential ecological importance of the observed effects. Information regarding the effects of modern exploration activities is required to understand and mitigate impacts associated with these activities and to properly manage this area under the mandate of a migratory bird sanctuary. Unfortunately, this information is currently unavailable. The objective of this thesis research was to provide this information by documenting the short-term impacts associated with current winter seismic exploration practices, as well as the longer-term impacts associated with earlier exploration practices.

Thesis Outline:

In Chapter 2 I present an analysis and description of the plant community types in which I studied winter seismic impacts. In Chapter 3 I present an analysis of the impacts associated with recent (<3yrs post disturbance) winter seismic exploration, including changes to the vegetation, soils, and permafrost. In Chapter 4 I analyze differences between old (>10yrs post-disturbance) seismic lines and surrounding tundra which was not exposed to seismic activity, to determine the persistence of any impacts to the vegetation, soils, or permafrost over this period. In Chapter 5 I review the implications of these findings, and provide recommendations for mitigation and future research.

Literature Cited:

Billings, W.D. 1973. *Arctic and alpine vegetations: similarities, differences, and susceptibility to disturbance.* BioScience 23:697-705

Billings, W.D. 1987. *Constraints to plant growth, reproduction, and establishment in arctic environments.* Arctic and Alpine Research 19:357-365

Billings, W.D., and H.A. Mooney. 1968. *The ecology of arctic and alpine plants.* Biological Reviews 43:481-529

Billings, W.D., and K.M. Peterson. 1980. *Vegetational change and ice-wedge polygons through the thaw-lake cycle in arctic Alaska.* Arctic and Alpine Research 12:413-142

Billings, W.D., and K.M. Peterson. 1992. *Some possible effects of climatic warming on arctic tundra ecosystems of the Alaskan North Slope. In:* Peters, R.L., and T.E. Lovejoy (*Eds.*) Global Warming and Biological Diversity. Yale University Press, New Haven. pps 233-243

Bliss, L.C. 1971. *Arctic and alpine plant life cycles.* Annual Review of Ecology and Systematics 2:405-438

Bliss, L.C., and J.E. Cantlon. 1957. *Succession on river alluvium in northern Alaska.* American Midland Naturalist 58:452-469

Bliss, L.C., and R.W. Wein. 1972. *Plant community responses to disturbance in the western Canadian arctic.* Canadian Journal of Botany 50:1097-1109

Bliss, L.C., and K.M. Peterson. 1992. *Plant succession, competition, and physiological constraints of species in the arctic.* pps. 111-136 *In*: Chapin, F.S. III, Jefferies, J.F., Reynolds, J.F., Shaver, G.R., and J. Svoboda (*Eds.*) Arctic Ecosystems In a Changing Climate: An ecophysiological perspective. Academic Press, New York.

C.A.R.C. 2001. *Oil and gas in the Canadian north - a historical overview.* Canadian Arctic Resources Committee: Northern Perspectives 27:6-8

Cargill, S.M., and F.S. Chapin III. 1987. *Application of successional theory to tundra restoration: a review.* Arctic and Alpine Research 19:366-372

Chapin, F.S. III, and G.R. Shaver. 1981. *Changes in soil properties and vegetation following disturbance of Alaskan arctic tundra.* Journal of Applied Ecology 18:605-617

de Molenaar, J.G. 1987. *An ecohydrological approach to floral and vegetational patterns in arctic landscape ecology.* Arctic and Alpine Research 19:414-424

Ebersole, J.J. 1989. *Role of the seed bank in providing colonizers on a tundra disturbance in Alaska.* Canadian Journal of Botany 67:466-471.

Emers, M.E., Jorgenson, J.C. and M.K. Raynolds. 1995. *Response of arctic tundra plant communities to winter vehicle disturbance.* Canadian Journal of Botany 73:905-917

Felix, N.A., and M.K. Raynolds. 1989. *The effects of winter seismic trails on tundra vegetation in northeastern Alaska, U.S.A.* Arctic and Alpine Research 21:188-202

Gartner, B.L., Chapin, F.S. III., and G.R. Shaver. 1983. *Demographic patterns of seedling establishment and growth of native graminoids in an Alaskan tundra disturbance.* Journal of Applied Ecology 20:965-980

Gough, L., Shaver, G.R., Carroll, J., Royer, D.L., and J. A. Laundre. 2000. *Vascular plant species richness in Alaskan arctic tundra: the importance of soil pH.* Journal of Ecology 88:54-66

Haag, R.W., and L.C. Bliss. 1974. *Energy budget changes following surface disturbance to upland tundra.* Journal of Applied Ecology 11:355-374

Hernandez, H. 1973. *Natural plant recolonization of surficial disturbances, Tuktoyaktuk Peninsula region, Northwest Territories.* Canadian Journal of Botany 51:2177-2196

Hinzman, L.D., Kane, D.L., Beson, C.S., and K.R. Everett. 1996. *Energy balance and hydrologic processes in an arctic watershed.* pps. 131-154 *In*: Reynolds, J.F., and J.D. Tenhunen (*Eds*). Landscape Function and Disturbance in Arctic Tundra. Ecological Studies v.120. Springer Verlag, Berlin.

Hultén, E. 1937. *Outline of the history of arctic and boreal biota during the Quaternary period; their evolution during and after the glacial period as indicated by the equiformal progressive areas of present day species.* Thule, Stockholm.

Kerfoot, D.E. 1972. *Topographic aspects of artificial disturbance to the tundra in the Mackenzie Delta area, N.W.T.* pp. 157-174 *In*: D.E. Kerfoot (ed.) Mackenzie Delta Area Monograph, Brock University Press, St. Catherines Ontartio.

Komárková, V. 1983. *Recovery of plant communities and summer thaw at the 1949 Fish Creek Test Well 1, arctic Alaska.* pp. 645-650 *In*: Permafrost: Fourth International Conference, Proceedings. National Academy Press, Washington.

McKane, R.B., Johnson, L.C., Shaver, G.R., Nadelhoffer, K.J., Rastetter, E.B., Fry, B., Giblin, A.E., Kielland, K., Kwiatkowski, B.L., Laundre, J.A., and G. Murray. 2002. *Resource-based niches provide a basis for plant species diversity and dominance in arctic tundra.* Nature 415:68-71

Murray, D.F. 1995. *Causes of arctic plant diversity: origin and evolution.* pps. 21-32 *In:* Chapin, F.S. III, and C. Körner (*Eds.*) Arctic and Alpine Biodiversity: patterns, causes, and ecosystem consequences. Springer Verlag, New York.

Peterson, K.M., and W.D. Billings. 1980. *Tundra vegetation patterns and succession in relation to microtopography near Atkasook, Alaska.* Arctic and Alpine Research 12:473-482

Reynolds, J.F., and J.D. Tenhunen. 1996. *Ecosystem response, resistance, resilience, and recovery in arctic landscapes: Introduction.* pps 3-18 *In:* Reynolds, J.F., and J.D. Tenhunen (*Eds.*) Landscape Function and Disturbance in Arctic Tundra. Ecological Studies v.120. Springer Verlag, Berlin.

Rickard, W.E., and J. Brown. 1974. *Effects of vehicles on arctic tundra.* Environmental Conservation 1:55-62

Schaefer, J.A., and F. Messier. 1995. *Scale-dependant correlations of arctic vegetation and snow cover.* Arctic and Alpine Research 27:38-43

Shirazi, M.A., Haggerty, P.K., Hendricks, C.W., and M. Reporter. 1998. *The role of thermal regime in tundra plant community restoration.* Restoration Ecology 6:111-117

Starr, G., and S.F. Oberbauer. 2003. *Photosynthesis of arctic evergreens under snow: implications for tundra ecosystem carbon balance.* Ecology 84:1415-1420

Svoboda, J., and G.H.R. Henry. 1987. *Succession in marginal arctic environments.* Arctic and Alpine Research 19:373-384

Truett, J.C. and K. Kertell. 1992. *Tundra disturbance and ecosystem production: implications for impact assessment.* Environmental Management 16:485-494

Vavrek, M.C., Fetcher, N., McGraw, J.B., Shaver, G.R., Chapin, F.S. III., and B. Bovard. 1999. *Recovery of productivity and species diversity in tussock tundra following disturbance.* Arctic, Antarctic, and Alpine Research 31:254-258

Walker, M.D. 1995. *Patterns and causes of arctic plant community diversity. In:* Chapin, F.S. III, and C. Körner (Eds.) Arctic and Alpine Biodiversity: patterns, causes, and ecosystem consequences. Springer Verlag, New York. pps. 3-20

Walker, D.A. 1996. *Disturbance and recovery of arctic Alaskan vegetation.* pps. 35-71 *In:* J.F. Reynolds and J.D. Tenhunen (*Eds.*) Landscape Function and Disturbance in Arctic Tundra. Ecological Studies v.120. Springer Verlag, Berlin.

Walker, D.A., and M.D. Walker. 1991. *History and pattern of disturbance in Alaskan arctic terrestrial ecosystems: a hierarchical approach to analyzing landscape change.* Journal of Applied Ecology 28:244-276

Walker, D.A., Cate, D., Brown, J., and C. Racine. 1987a. *Disturbance and recovery of arctic Alaskan tundra terrain: a review of recent investigations.* United States Army Cold Regions Research and Engineering Laboratory Report. CRREL Report 87-11

Walker, D.A., Webber, P.J., Binnian, E.F., Everett, K.R., Lederer, N.D., Nordstrand, E.A., and M.D. Walker. 1987b. *Cumulative impacts of oil fields on northern Alaskan landscapes.* Science 238:757-761

Webber, P.J., and J.D. Ives. 1978. *Damage and recovery of tundra vegetation.* Environmental Conservation 5:171-182

Chapter 2: A preliminary classification of selected low arctic plant communities found in the Kendall Island Migratory Bird Sanctuary

Introduction:

In order to properly assess the impacts of winter seismic exploration and compare the relative resistance and resilience of a diverse assemblage of plant communities within the Kendall Island sanctuary, it was necessary to first delineate the communities within the area of interest. Although there is considerable agreement that community types, as discreet entities, do not exist in nature (e.g. Gleason 1926, 1939; Cottam and McIntosh 1966; Austin and Smith 1989) the use of classification to structure vegetation data into "fuzzy" units remains a useful tool to manage heterogeneous datasets and to create vegetation classes or categories within which hypotheses can be tested, and management applied (Biondi *et al* 2004). Such a classification was important for this particular study because the scope of investigation covered a broad range of habitats from wetland mires of the Mackenzie Delta to upland shrub tundras of Richards Island. It was of particular importance to properly delineate the community types in this study, as the type of vegetation at a site has been proposed to be the best predictor of response to disturbance in low-arctic ecosystems (Walker and Walker 1991). Because of the long history of different vegetation classifications in the arctic, with poor collaboration across regions, there is some degree of disagreement between any two classifications of tundra vegetation (Walker *et al* 1994).

Despite the great deal of scientific inquiry that the outer Mackenzie Delta and Richards Island have received, a complete phytosociological treatment that includes both areas is not available. Although vegetation classifications have been applied to each separately (e.g. Corns 1974; Jaques 1991), the lack of a regional classification is an impediment to understanding and predicting the pattern and scope of vegetation responses to change or disturbance throughout the study area.

Corns (1974) described and delineated primarily upland plant communities of parts of Richards Island east of the Mackenzie Delta and the Tuktoyaktuk Peninsula. Five distinct community types were identified, four of which were subdivided into subgroups and/or zones. The division of vegetation into community types and subgroups by Corns appears to have been based partly on ordination results, and partly on personal field observation and is not always clear. In addition, Corns (1974) was somewhat inconsistent in the nomenclature applied to the communities described therein, often applying different labels to the same community type. Nevertheless, Corns (1974) remains the most scientific (rather than observational) treatment of the plant communities of Richards Island and the Tuktoyaktuk peninsula. The limitation of Corns' (1974) classification for the present purposes was the omission of the deltaic lowlands that comprise much of the Kendall Island Migratory Bird Sanctuary (KIBS) from the Corns' study area.

Jaques (1991, unpublished data) performed a Landsat5 Thematic Mapper (TM) assisted survey of the vegetation of the outer Mackenzie Delta which was later translated into 'habitat types' by Gratto-Trevor (1996) and adopted as a tool for identifying vegetation complexes which comprise important shorebird habitat. Unfortunately however, Gratto-

Trevor (1996) also reported that the Landsat TM survey was insufficiently accurate to properly identify vegetation more than 10km away from the original ground-truthed area. This shortcoming is compounded by the grouping of the Land Class Units (LCUs) from the original data into 'habitat types', which fail to properly separate plant communities that, on the ground, bear little if any resemblance to one another. As an example the "Dense Willow" habitat of Gratto-Trevor (1996) includes some, but not all, riparian willow communities as well as upland willow and alder communities with high canopy cover. Although these communities are likely quite similar with respect to canopy cover, they share very few species (none of the dominant species), and occur on dissimilar soils with vastly different drainage. The grouping of LCUs into habitat types was done primarily from the standpoint of shorebird habitat and for "ease of ground recognition by non-botanists" (Gratto-Trevor 1996), and was therefore not designed to capture important variation in plant communities. It should not be surprising therefore that this classification is inappropriate to address investigations of anthropogenic or natural disturbances at the plant community scale. The usefulness of this classification is further limited by the fact that the original report (Jaques 1991) and Landsat data were not formally published and are, apparently, no longer available.

Several treatments of the plant communities of the arctic coastal plain of Alaska (e.g. Hanson 1953; Churchill 1955; Walker *et al* 1982) are available, each of which however, has at least one shortcoming with respect to application to the present study area. Walker *et al* (1982) presented a Landsat assisted survey of vegetation in the Arctic National Wildlife Refuge (ANWR) of Alaska's north slope. The land cover categories produced by Walker *et al* (1982) were subsequently used (with some modification) in a large number of publications resulting from a multi-year study of winter 2D seismic program impacts in ANWR (Felix and Raynolds 1989a; Felix and Raynolds 1989b; Raynolds and Felix 1989; Felix *et al* 1992; Emers *et al* 1995; Emers and Jorgenson 1997). Comparisons between the ANWR studies, as well as those from earlier periods of exploration in Canada (e.g. Bliss and Wein 1972), and the present one are desirable if broad conclusions are to be made regarding winter seismic disturbance to tundra ecosystems.

The objectives of this chapter were therefore to: 1) discern groupings for select vegetation communities of the Kendall Island Sanctuary and adjacent areas and classify these into discernable 'types' which could then be used for subsequent analyses of seismic impacts and recommendations for management, and 2) compare the results of this classification to available studies of vegetation in this area and elsewhere in the North American arctic so that comparisons can be made between the subsequent chapters of this thesis and similar or future studies.

Methods and Materials:

Study area:

The study area for this investigation consisted of the Kendall Island Migratory Bird Sanctuary (KIBS) and adjacent areas of Richards Island, NT (Fig.2.1). The study area spans from approximately 69°00' to 69°24'N latitude and 135°35' to 134°05'W longitude (UTM Zone 8). The study area is bordered by the Beaufort Sea to the north and lies entirely within the Tuktoyaktuk Coastlands division of the Arctic Coastal Plain physiographic region (Rampton 1988). Wetlands and other areas of minimal topographic relief (lowlands) predominate over much of KIBS and occur within the Big Lake Delta Plain physiographic subdivision of Rampton (1988), which is a north-eastwardly extension of the Mackenzie Delta composed of thin, poorly drained deltaic sediments somewhat dissimilar to those of the true Mackenzie Delta. Topographically elevated areas (uplands) within the study area occur within the Tununuk Low Hills physiographic subdivision and are characterized by coarser textured soils deposited during the Pleistocene by rivers other than the contemporary Mackenzie (Rampton 1988). Continuous permafrost exists throughout the study area, and soils are predominately cryosols.

The study area is completely north of the latitudinal treeline and is within the Central Canada subprovince of the Canada-Greenland floristic province of Yurtsev (1994). The region is generally referred to as sub-arctic, but is more properly placed in the Low-

Arctic of Bliss and Matveyeva (1992), or the Southern Hypoarctic Tundra subzone of Yurtsev (1994). The study area would fall within the more recent Low-Shrub Arctic Tundra subzone of Gould *et al* (2002). The latitudinal climatic gradient is steep, particularly near the coast, and despite spanning less than one degree of latitude the study area includes both bioclimatic subzones D and E of the recent Circumpolar Arctic Vegetation Map (CAVM Team 2003).

Site Selection:

To delineate select plant communities of the study area I used vegetation samples from 127 1m x 1m quadrats placed in areas which had not been exposed to seismic activity or other anthropogenic disturbance (hereafter referred to as "undisturbed tundra") at 43 sites. Sites were chosen to represent an approximately equal proportion of four habitat types defined by Gratto-Trevor (1996) and, within these, to capture as much of the full range of topographic positions and latitudinal gradients (proximity to coast) within the study area as possible. The samples used for the analyses in this chapter represent one half (the undisturbed controls) of the total samples collected for a study of the impacts of winter seismic exploration (see Chapter 3) the plant communities of the study area, and were therefore not chosen specifically for the purpose of circumscribing all plant communities in the study area.

Data Collection:

Within each quadrat I identified all the vascular plants present, and estimated the percent cover for each according to a set of precision guidelines (Table 2.1). To minimize error percent cover estimates were made with the aid of a 1% (10cm^2) reference card, and were made by the same observer throughout the study. Wherever individual specimens could not be identified *in situ* they were collected and identified later in the field by comparison to flowering specimens (if possible) or returned to the University of Alberta Vascular Herbarium for later identification. Individuals that could not be identified to the species level (usually seedlings or young non-flowering shoots) were assigned to higher taxonomic levels (e.g. grass spp, *Salix* spp), and were removed from the dataset prior to analysis.

Nomenclature follows Porsild and Cody (1980); a full list of the vascular plant species encountered in this study is available in Appendix 1.

Analysis:

Prior to performing any analysis of the data the data matrix was screened for outliers using a frequency distribution of the ecological distance between each quadrat and every other quadrat in species space. Sørensen (Bray-Curtis) distance was used to create the matrix of ecological distance. All quadrats with an average distance of >2.3 SDs were considered outliers (McCune and Grace 2002) and subsequently removed if they were determined to be sampling or recording errors. Three quadrats attributable to sampling error were removed from this and subsequent analyses. No other outliers were detected.

Species which occurred rarely in the dataset were *not* removed, so that the maximum amount of information could be retained and used in clustering.

The resulting dataset of 124 quadrats x 84 species was subjected to cluster analysis to produce groupings of quadrats with similar species composition. Clustering was performed via hierarchical agglomerative clustering using Sørensen (Bray-Curtis) distance as a community distance measure and employing a flexible-beta linkage method, with ß set to –0.25. The Beta value –0.25 was chosen for its ability to minimize space distortion in the analysis (McCune & Grace 2002).

To identify the optimum clustering stopping point (the ideal number of clusters) I used Indicator Species Analysis (Dufrêne & Legendre 1997) to 'prune' the cluster dendogram. During the process of agglomeration group membership at each level of clustering (number of groups) was written to a file. By calculating indicator values (and testing their significance) for each species, at each level of the clustering, the most ecologically meaningful number of groups (clusters) could be chosen. The level of clustering which provided the lowest average indicator value probability (averaged across all species) was selected as the optimum stopping point. The groups produced at this level of clustering were then defined as the community types for this dataset.

Following the identification of the number of community types present in the dataset, I identified the quadrats belonging to each group and examined their species composition. To identify the species unique and descriptive of each community type (Indicator

Species) I again used Indicator Species Analysis (Dufrêne & Legendre 1997). In this instance the group memberships at the optimum clustering point were tested, using 999 Monte-Carlo permutations to determine the significance of the resulting indicator values. The ISA was performed simultaneously for all community types; none were excluded from each step in the calculation.

All analyses presented in this chapter were carried out using the PC-ORD (V.4.25) software package of MjM Software (McCune and Mefford 1999).

Results:

Cluster Analysis:

The clustering dendogram is presented in Fig. 2.2. The ISA pruning technique produced the lowest average probability at four groups (Fig. 2.3), at which point clustering was stopped. The four groups of plots produced by the clustering are presented here as community types. Two of the clusters appear to be typified by upland species, and two by wetland species. The broader agglomeration into two clusters, although not as statistically informative as four, remains useful as this clearly shows the division between upland and lowland communities (Fig.2.2).

The Indicator species analysis produced significant Indicator Species for each community type which are presented in Table 2.2.

Community Descriptions:

Upland Communities:

The quadrats assigned to the upland community types were those which were located on elevated hilltops near the middle channel of the Mackenzie River and on Richards Island, as well as on flat or gently sloping plateaus with scattered patches of well developed polygons (both low and high-centered) with pronounced ice-wedge ridges. These areas of upland polygonal tundra are quite distinct from polygonal tundra in low lying areas nearer the coast, both in appearance and in species composition. *Eriophorum vaginatum* tussocks occur throughout these uplands, as does *Carex consimilis* (*C. bigelowii*).

The 'Medium Shrub - Heath' community type (MSH) was indicated by *Ledum decumbens*, *Vaccinium vitis-idaea*, and *Betula glandulosa*, (Table 2.2) and also has a prominent sedge component, often *Carex consimilis* but also with *Eriophorum vaginatum*. *Alnus crispa* is also prominent, attaining its highest cover here, although it usually did not form a dominant shrub layer or closed canopy. This community was most often found on gentle leeward slopes with relatively mesic soils. The vascular plants of this community were usually underlain by a nearly continuous blanket of mosses, both living and dead, except where *Eriophorum* tussocks occur and directly beneath *Alnus crispa* individuals.

The 'Low Shrub - Heath' community (LSH) is also an upland community, but is more often found on higher ridge tops and flatter upland plateaus. This community is fairly diverse and not consistently dominated by any one species. *Dryas integrifolia* and *Vaccinium uliginosum* occur most frequently here and have the highest indicator values for this community type along with *Sausurea angustifolia* (Table 2.2). *Salix glauca, Betula glandulosa* and *Salix reticulata* are the most common shrub species, although *Salix pulchra* also occurs here, particularly where polygons are present. Low growing (<50cm) *Salix glauca* often forms an important component of this community type although it is usually scattered and did not form a continuous closed canopy, with the exception of some higher areas along hilltops directly east of the Mackenzie River.

Lowland Communities:

The quadrats assigned to lowland communities always occurred on the flat delta plains and were usually poorly drained. Because the study area is interwoven by stream channels of varying size these communities often grade into one another along a gradient moving away from stream channels, with the Tall Shrub – Herb type community along the channels gradually grading into the Wet Graminoid type community further inland from stream courses.

The 'Tall Shrub - Herb' community (TSH) occurs on deltaic soils along stream channels throughout the study area. This community type is characterized by a fairly closed canopy of *Salix lanata* ssp. *richardsonii*, with a varying understory which usually includes *Equisetum arvense* and *Equisetum variegatum*. Other species are common in the understory, including *Carex aquatilis* in wetter areas closer to stream channels and *Hedysarum alpinum* and *Festuca rubra* in dryer areas. *Parnassia palustris*, *Pedicularis verticillata*, and *Valeriana capitata* occurred with varying frequently here, and appeared to be limited to this community type. The overstory of *Salix lanata* spp *richardsonii* varied in height and density along a steep latitudinal gradient. Towards the southern margins of the study area shrubs >1.5 m in height and with >60% cover on sites were common, whereas closer to the coast shrub heights were usually less than 1m and cover was more scattered and often less than 30%. *Salix alaxensis* and *Alnus crispa* occur alongside *S. lanata* spp *richardsonii* particularly in the southern regions of the study area.

The 'Wet Graminoid' community (WG) is also restricted to deltaic sediments. This community type is usually restricted to flat poorly drained areas, usually somewhat removed from the major stream channels. *Eriophorum angustifolium* and *Carex aquatilis* completely co-dominate these sites, although there is often a component of *Salix lanata* ssp *richardsonii* or *Salix pulchra*, particularly where this community types grades into the TSH type, and along the raised borders of low-centered polygons near the coast. *Salix arctica*, *Eriophorum russoleum* and *Dupontia fisheri* also occur most frequently in this community type.

Discussion:

Three of the four communities discerned in my analysis were similar to ones presented by Corns (1974), allowing for the adoption of his terminology for those communities.

The Medium Shrub – Heath (MSH) community type presented here appears to be quite similar to the 'Medium Shrub Heath Type' of Corns (1974). This community appears to include part (LCU10) of Gratto-Trevor's (1996) 'upland tundra', as well as that portion of her 'dense-willow' (LCU4) that includes backslope communities. The MSH community type here is also similar to the 'alder – heath – frostboil' community of Bliss and Wein (1972). Comparisons to the ANWR studies are somewhat more difficult, but the MSH community here appears to include both the 'moist sedge tussock tundra' and 'moist shrub tundra' of these studies (Felix and Raynolds 1989a; Felix *et al* 1992; Emers *et al* 1995).

The Low Shrub – Heath (LSH) community type presented here appears to be very similar to the Low Shrub – Heath type of Corns (1974), particularly the Willow – Heath subgroup that he described from Tununuk Point. Corns considered the 'low shrub-heath type' to be a feature of higher hilltops and ridges, and a separate type, the 'herb-low shrub-heath type', to be characteristic of 'nearly level' ground and upland plateaus. Because the LSH type appears to encompass part or both of these communities I have adopted the terminology of Corns, and will refer to this community as a Low Shrub –

Heath type, but it should be understood to be more complex than an exact match for the LSH of Corns (1974).

The LSH community presented here would include part of Gratto-Trevor's (1996) 'upland tundra', specifically the dwarf-shrub and tussock tundra (LCU14) portions of that habitat type. My LSH type also compares well to the 'moist graminoid/barren tundra complex' of the ANWR studies (Felix and Raynolds 1989a; Felix *et al* 1992; Emers *et al* 1995), and is at least somewhat floristically similar to their 'dryas terrace' community, although differing in geological context. The 'heath – sedge – cottongrass' habitat discussed by Bliss and Wein (1972), would also most likely fall under this category.

The Tall Shrub - Herb community type (TSH) presented here appears to be almost identical to the 'tall shrub-herb' community of Corns (1974). This community would include only the riparian portion (LCU5) of Gratto-Trevor's (1996) 'dense willow' habitat, and probably those portions of her 'wet sedge willow' habitat with higher cover of *S. lanata*. This community is directly analogous to Felix and Raynolds (1989a)'s 'riparian shrubland', which is derived from Walker *et al* (1982)'s 'shrub tundra – watertrack complex'.

The Wet Graminoid community type (WG) is not well represented by Corns (1974), but is similar to his 'herb type – sedge subgroup' which Corns considered to be restricted to the wet centers of low-centered polygons. Although my community is not confined solely to low-centered polygons but also occurs as wet, graminoid dominated meadows with no patterning it does share the dominant species (*Carex aquatilis* and *Eriophorum angustifolium*) with the 'herb type – sedge subgroup' of Corns (1974). A near perfect description of this community type would be the 'wet sedge tundra' of Walker *et al* (1982) including their 'non complex', 'very wet complexes', 'moist complexes' and 'saline facies' subgroups. This community type was referred to as 'wet graminoid tundra' by Felix and Raynolds (1989a), Felix *et al* (1992), and Emers *et al* (1995), and would also include their 'moist sedge – shrub tundra' where there is higher willow cover. The Wet Graminoid community type presented here would encompass the 'sedge/low centered polygon' habitat of Gratto-Trevor (1996), as well as those portions of her 'wet sedge/willow' habitat type with relatively low scattered cover of *Salix*.

It is important to note that the results of this analysis should not be considered as a detailed phytosociological investigation of all plant communities of the study area. Rather it is a tool for understanding the plant communities surveyed for this study, providing a common and simple nomenclature to describe each one, and to facilitate examination of the effects of seismic exploration and comparisons between similar studies of seismic impacts that have occurred at different times and places, employing different community classification and nomenclature.

Literature Cited:

Austin, M.P., and T.M. Smith. 1989. *A new model for the continuum concept.* Vegetatio 83:35-47

Biondi, E., Feoli, E., and V. Zuccarello. 2004. *Modelling environmental responses of plant associations: a review of some critical concepts in vegetation study.* Critical Reviews in Plant Science 23:149-156

Bliss, L.C., and R.W. Wein. 1972. *Plant community responses to disturbance in the western Canadian arctic.* Canadian Journal of Botany 50:1097-1109.

Bliss, L.C., and N.V. Matveyeva. 1992. *Circumpolar arctic vegetation.* pps 59-89 *In:* Chapin F.S. III., Jefferies, R.L., Reynolds, J.F., Shaver, G.R., and J. Svoboda (*Eds.*) Arctic Ecosystems in a Changing Climate: an Ecophysiological Perspective. Academic Press, New York.

CAVM Team. 2003. Circumpolar Arctic Vegetation Map. Scale 1:7,500,00. Conservation of Arctic Flora and Fauna (CAFF) Map No.1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

Churchill, E.D. 1955. *Phytosociological and environmental characteristics of some plant communities in the Umiat region of Alaska.* Ecology 36:606-627

Corns, I.G.W. 1974. *Arctic plant communities east of the Mackenzie Delta.* Canadian Journal of Botany 52:1731-1745

Cottam, G., and R.P. McIntosh. 1966. *Vegetational continuum.* Science 152:546-547

Dufrêne, M. and P. Legendre. 1997. *Species assemblages and indicator species: the need for a flexible asymmetrical approach.* Ecological Monographs 67:345-366

Emers, M., Jorgenson, J.C., and M.K. Raynolds. 1995. *Response of arctic tundra plant communities to winter vehicle disturbance.* Canadian Journal of Botany 73:905-917

Emers, M., and J.C. Jorgenson. 1997. *Effects of winter seismic exploration on tundra vegetation and the soil thermal regime in the Arctic National Wildlife Refuge, Alaska.* pps 443-454 *In*: R.M.M Crawford (*Eds.*) Disturbance and Recovery in Arctic Lands. Kluwer Academic Press, the Netherlands.

Felix, N.A., and M.K. Raynolds. 1989a. *The effects of winter seismic trails on tundra vegetation in northeastern Alaska, U.S.A.* Arctic and Alpine Research 21:188-202

Felix, N.A., and M.K. Raynolds. 1989b. *The role of snow cover in limiting surface disturbance caused by winter seismic exploration.* Arctic 42:62-69

Felix, N.A., Raynolds, M.K., Jorgenson, J.C. and K.E. DuBois. 1992. *Resistance and resilience of tundra plant communities to disturbance by winter seismic vehicles.* Arctic and Alpine Research 24:69-77

Gleason, H.A. 1926. *The individualistic concept of the plant association.* Bulletin of the Torrey Botanical Club 53:7-26

Gleason, H.A. 1939. *The individualistic concept of the plant association.* American Midland Naturalist 21: 92-110

Gould, W.A., Edlund, S., Zoltai, S., Raynolds, M, Walker, D.A., and H. Maier. 2002. *Canadian arctic vegetation mapping.* International Journal of Remote Sensing 23:4597-4609.

Gratto-Trevor, C.L. 1996. *Use of Landsat TM imagery in determining important shorebird habitat in the outer Mackenzie Delta, N.W.T.* Arctic 49:11-22

Hanson, H.C. 1953. *Vegetation types in northwestern Alaska and comparisons with communities in other arctic regions.* Ecology 34:111-140

Jaques, D. 1991. *Landsat Thematic Mapper imagery for mapping vegetation of the outer Mackenzie Delta, Northwest Territories, Canada.* Unpublished report for the Canadian Wildlife Service, by Ecosat Geobotanical Surveys Inc., North Vancouver, B.C.

McCune, B., and J.B. Grace. 2002. Analysis of Ecological Communities. MjM Software Design, Gleneden Beach, OR.

McCune, B., and M.J. Mefford. 1999. PC-ORD: Multivariate Analysis of Ecological Data, Version 4.0. MjM Software, Gleneden Beach, OR.

Porsild, A.E., and W.J. Cody. 1980. Vascular Plants of Continental Northwest Territories, Canada. National Museums of Canada, Ottawa, ON.

Rampton, V.N. 1988. *Quaternary geology of the Tuktoyaktuk Coastlands, Northwest Territories.* Geological Survey of Canada Memoir 423.

Raynolds, M.K., and N.A. Felix. 1989. *Airphoto analysis of winter seismic disturbance in northeastern Alaska.* Arctic 42:362-367

Walker, D.A., and M.D. Walker. 1991. *History an pattern of disturbance in Alaskan arctic terrestrial ecosystems: a hierarchical approach to analyzing landscape change.* Journal of Applied Ecology 28:244-276

Walker, D.A., Acevedo, W., Everett, K.R., Gaydos, L., Brown, J., and P.J. Webber. 1982. *Landsat-assisted environmental mapping in the Arctic National Wildlife Refuge,* *Alaska.* U.S. Army Cold Regions Research and Engineering Laboratory CCREL Report 82-27.

Walker, M.A., Daniels, F.J.A., and E. van der Maarel. 1994. *Circumpolar arctic vegetation: introduction and perspectives.* Journal of Vegetation Science 5:758-764

Yurtsev, B.A. 1994. *Floristic division of the arctic.* Journal of Vegetation Science 5:765-776

Table 2.1 Precision guidelines for percent cover estimates.

Actual Cover	*Estimation Precision*
1 – 10%	within 1%
11 – 40%	within 5%
>40%	within 10%

Table 2.2. Significant indicator species for each of four community types of the KIBS. All species with Indicator Values >40 are shown, as are the strongest three indicators for each community type. Results are from Indicator Species Analysis, using 999 Monte Carlo permutations to test for significance. *p*= probability of Type 1 error for H_0: no difference in indicator value for community type groups versus randomly allocated groups. MSH = Medium Shrub – Heath, LSH = Low Shrub – Heath, TSH = Tall Shrub – Herb, WG = Wet Graminoid. IndVal= Indicator Value

Community Type	Indicator Species	IndVal	*p*
MSH	*Vaccinium vitis-idaea*	97.5	0.001
	Ledum decumbens	88.4	0.001
	Betula glandulosa	78.7	0.001
	Arctostaphylos alpina	62.5	0.001
	Empetrum nigrum	59.2	0.001
	Rubus chamaemorus	49.6	0.001
	Carex consimilis	48.2	0.001
LSH	*Dryas integrifolia*	82.7	0.001
	Vaccinium uliginosum	71.6	0.001
	Saussurea angustifolium	51.8	0.001
	Pedicularis lanata	45.9	0.001
	Cassiope tetragona	43.9	0.001
TSH	*Salix lanata ssp richardsonii*	84.3	0.001
	Equisetum arvense	55.4	0.001
	Equisetum variegatum	37.3	0.001
WG	*Eriophorum angustifolium*	87.7	0.001
	Carex aquatilis	83.5	0.001
	Salix arctica	27.6	0.001

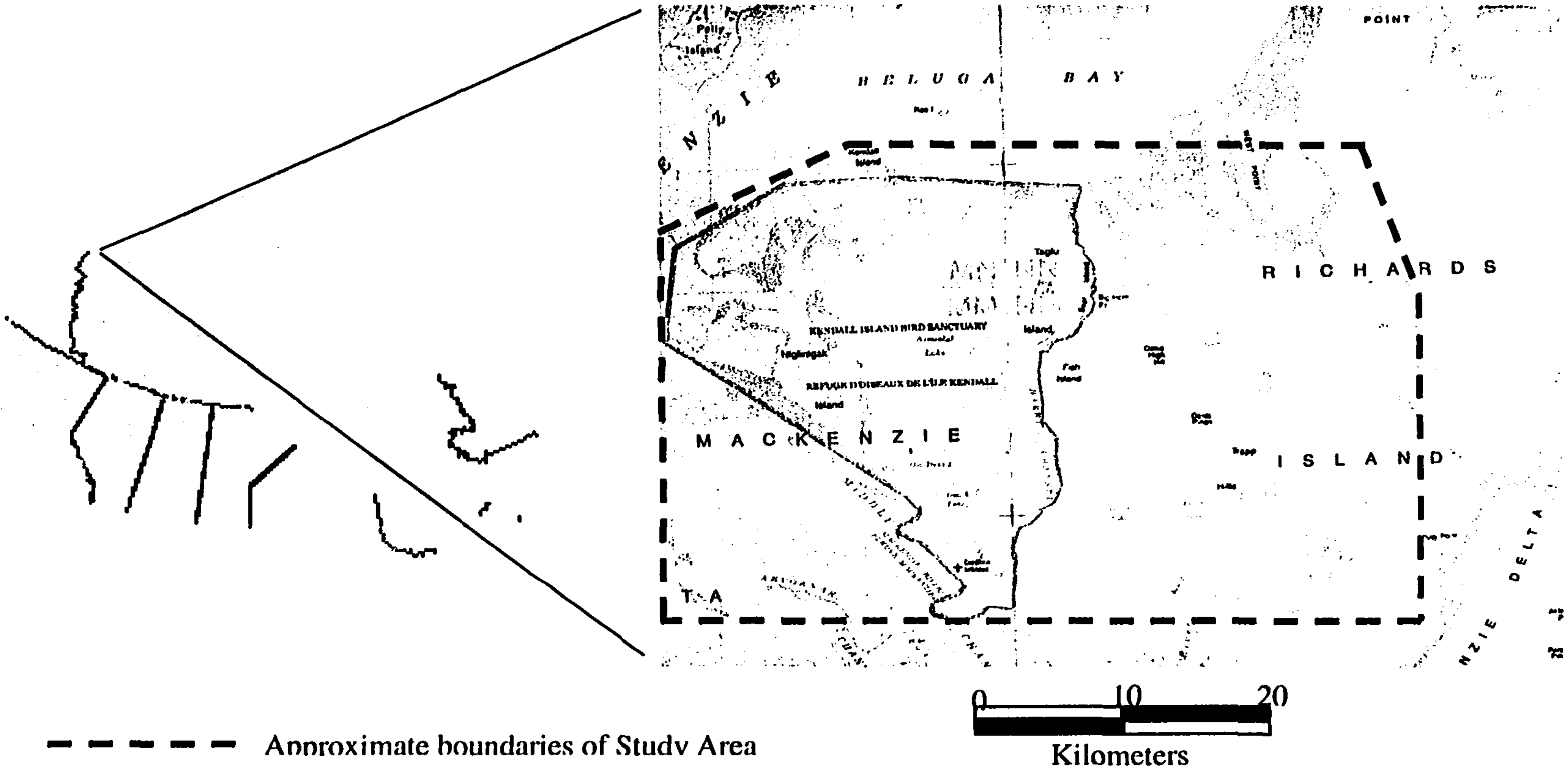

Fig. 2.1. Location and outline of study area. Topographic map from 1:250 000 scale, Mackenzie Delta 107C (Edition 2) from Energy, Mines and Resources Canada, 1988.

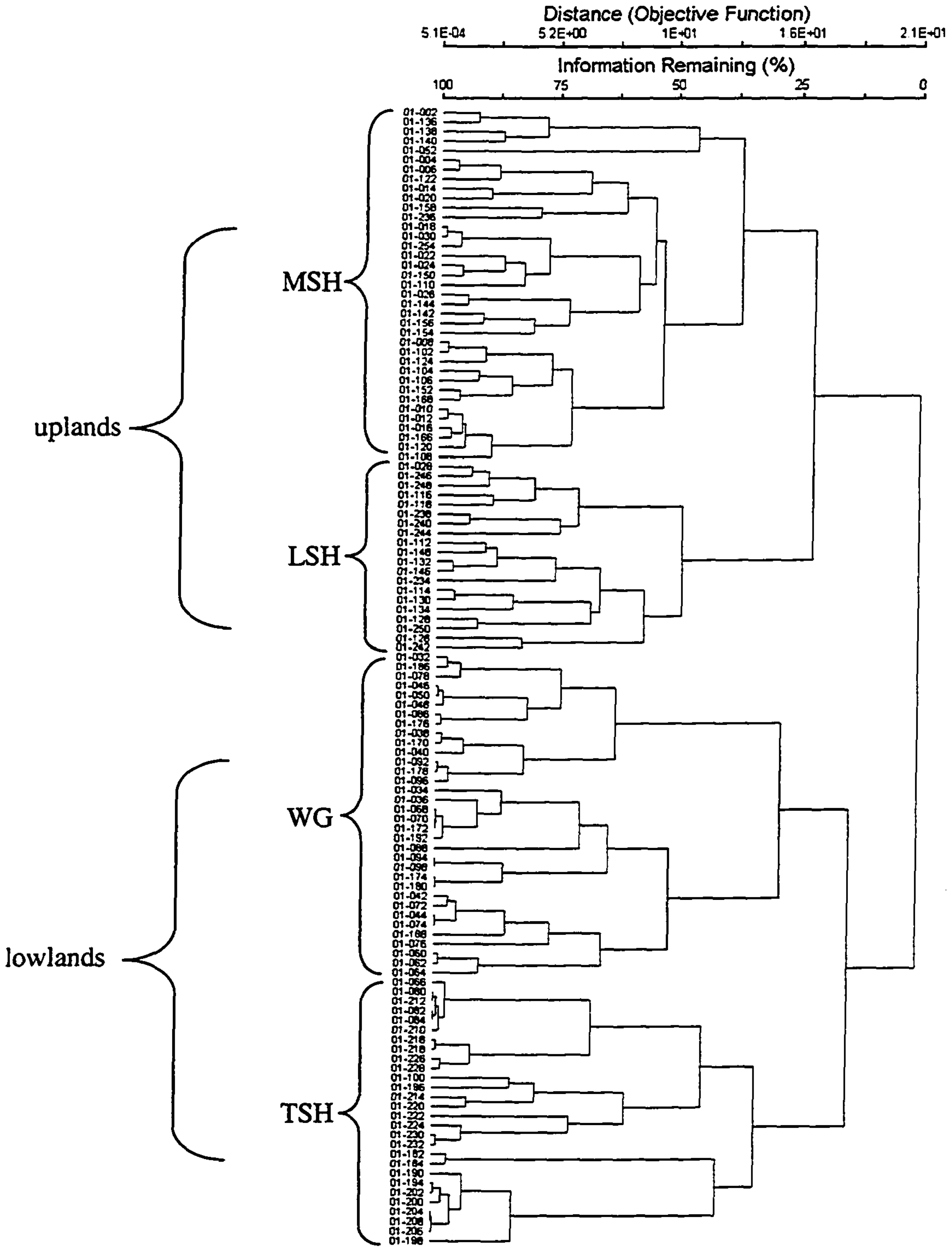

Fig. 2.2. Dendogram from hierarchical agglomerative clustering of all undisturbed vegetation quadrats using Sørensen distance as a resemblance measure. Linkage method was flexible beta, ß= -0.25. Dendogram was pruned at four groups using Indicator Species Analysis to select the optimum number of groups. The four resulting groups are community types. Community types: MSH= Medium Shrub – Heath, LSH= Low Shrub – Heath, TSH= Tall Shrub – Herb, WG= Wet Graminoid. The larger agglomeration of community types into 'uplands' and 'lowlands' is for illustrative purposes.

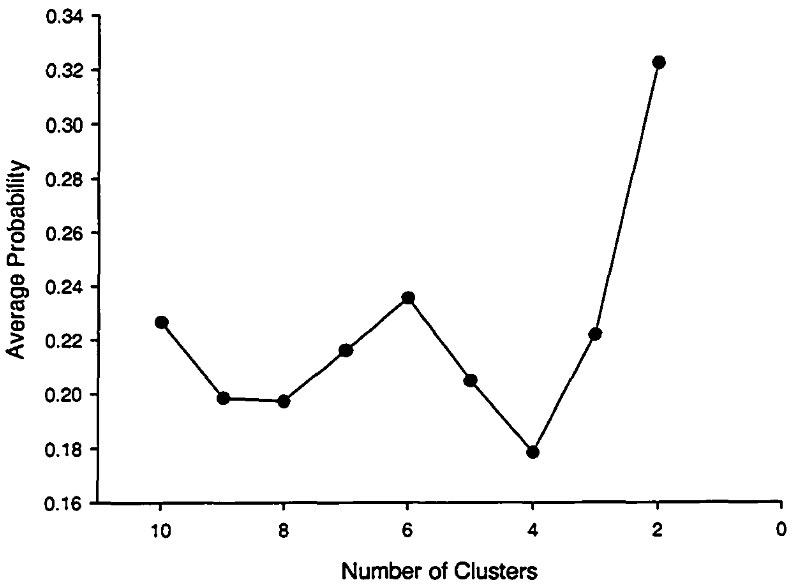

Fig. 2.3. Average probability values from Indicator Species Analyses of all species in groups defined by cluster analysis, with the total number of groups (clusters) ranging from 10 to 2. Probabilities were calculated using 999 Monte Carlo permutations to assess significant indicator value differences between groups defined by cluster analysis and random groups, for each level of clustering (number of groups).

Chapter 3: Effects of recent seismic exploration on selected low arctic plant communities and soils.

Introduction:

There is a substantial gap in knowledge surrounding the impacts of contemporary two dimensional (2D) winter seismic programs on plant communities of the arctic coastal plain of North America (National Academy of Sciences 2003). To date the bulk of scientific understanding surrounding this issue comes from a single suite of investigations from the Arctic National Wildlife Refuge (ANWR), Alaska, which tracked short and long-term impacts associated with a 1984 and 1985 2D winter seismic program (Felix and Raynolds 1989a; Felix *et al* 1992; Emers *et al* 1995; Emers and Jorgenson 1997). Currently, similar information is completely lacking for low-arctic Canada where the most recent investigations followed the period of intense exploration during the late 1960s and 1970s (e.g. Bliss and Wein 1972; Kerfoot 1972a,b; Hernandez 1973). Environmental research into this issue in Canada has not kept pace with the expansion of exploration activity, nor with the development of new seismic technologies and techniques.

The short-term impacts associated with the 1984 and 1985 winter seismic programs in ANWR, Alaska, were extensive, with only 14% of randomly chosen points along seismic trails showing no disturbance (Raynolds and Felix 1989). Felix and Raynolds (1989a) reported highly visible trails, significant decreases in total live plant cover (as much as 87%), and little recolonization of disturbed sites 2-3 years post exploration. Evergreen shrubs (primarily Ericaceae) were found to be most sensitive to winter seismic disturbance, showing the highest reduction in cover, while riparian willows were also highly sensitive, experiencing reductions in cover as well as height (Felix and Raynolds 1989a). Felix and Raynolds (1989a) also found mosses and lichens to be sensitive to winter seismic disturbance, although less so than the aforementioned species; non-tussock forming sedges (*Eriophorum angustifolium* and *Carex aquatilis*) were found to be the most resistant species. Four to five growing seasons post-disturbance Felix *et al* (1992) reported that some revegetation had occurred on seismic lines, but that active layer depths had continued to increase along seismic lines in the years post-disturbance, suggesting that severe or even permanent changes to the edaphic (thermal) conditions had occurred on these sites.

The importance of thermal stability to the recovery of a 'natural' vegetation state has been emphasized by several authors (Walker *et al* 1987; Walker and Walker 1991; Shirazi *et al* 1998). Because tundra ecosystems are underlain by continuous permafrost and are incompletely drained, small changes in the microtopography of a site can produce steep soil moisture gradients (Peterson and Billings 1980). Permafrost degradation that results in thermokarst typically causes such changes in hydrology, with denuded areas becoming wetter; this leads to changes in species composition towards those species adapted to hydric conditions (Peterson and Billings 1980; Truett and Kertell 1992). The standing vegetation crop (Walker *et al* 2003) and soil organic mat (Haag and Bliss 1974; Hinzman *et al* 1996) are important insulators of soil permafrost; disturbance to either or both may affect the seasonal depth of thaw. Even small changes in thaw depth can apparently result in depressions within which water can accumulate (Hinzman *et al*

1996). Such changes, resulting in shifts in species composition towards more hydric adapted species have been previously reported from both summer (Chapin and Shaver 1981) and winter (Felix *et al* 1992) 2D seismic lines.

Disturbance to the soil organic layer can also have significant direct effects on plant community development, as this layer contains the soil seed bank (McGraw 1980; Gartner *et al* 1983) as well as underground rhizomes upon which revegetation depends. In tundra communities the seed bank usually includes propagules of the present 'climax' species assemblage rather than an earlier seral stage (Ebersole 1989), and is therefore crucial to the recovery of a natural vegetation state following disturbance. Experimental tests of impacts by a variety of off-road vehicles in summer (Abele *et al* 1984) suggested that tundra vegetation should recover to 'nearly its original state' within several years provided the soil organic layer is left intact, regardless of the level of initial damage to vegetation. It has been suggested, however, that winter vehicle travel may be more detrimental to the soil organic mat than summer, because hard frozen mosses are more likely to be abraded or fractured in winter, rather than simply compressed, followed by rebounding, as they do in summer (Kerfoot 1972b; Felix and Raynolds 1989a).

Whether due to differences in sensitivity of their constituent species to disturbance, or to the relative sensitivity of terrain, soils, or permafrost, it should be expected that different plant communities respond uniquely to disturbance (Walker and Walker 1991). During earlier periods of seismic exploration in low-arctic Canada, upland plant communities were typically found to be more affected by winter vehicle travel than wetland communities (Bliss and Wein 1972; Hernandez 1973). These findings were more recently supported by similar results from Alaska (Raynolds and Felix 1989; Felix and Raynolds 1989a). Reynolds (1982) however, reported no difference in visibility of winter seismic lines between wet sedge meadows and dry upland meadows only two years after exploration. Rickard and Brown (1974), and Walker and Walker (1991) have suggested that tundra wetlands are less resistant to anthropogenic disturbance than upland tundras, but it is unclear whether these authors were referring to summer or winter disturbance.

Along with differences in their relative resistance to disturbance, species and communities likely also differ in their rate of recolonization or redevelopment following winter seismic disturbance (short-term resilience). Those communities which are dominated by species that have the ability to reproduce vegetatively (e.g. rhizomatous graminoids) should be better adapted to quickly recolonize the narrow swaths disturbed by seismic exploration than those with species dependant on seed germination or dispersal for recolonization (Fahrig *et al* 1994; Kotanen 1997; Forbes and Jefferies 1999). Where the pool of potential recolonizing species is relatively large, or functionally diverse, the initial post-disturbance community may also differ somewhat in composition from that which it replaced, reflecting either changes in the underlying gradients that favor some colonizers over others (e.g. Tilman 1985; Chapin and Shaver 1985), or disparity in the rate at which species or functional groups in the surrounding matrix colonize available sites.

In the Kendall Island Migratory Bird Sanctuary (KIBS) the wetland communities are often species poor and dominated by rhizomatous graminoids, while the riparian willow communities are slightly richer in both species and growth forms. The upland communities are the most diverse types, with higher diversity of both species and growth forms (see Chapter 2).

The objectives of this study were to: 1) determine the effects of recent 2D winter seismic exploration activity on the abundance, composition, and diversity of vascular plants in different plant communities of the KIBS, 2) determine whether such winter seismic programs affect the soil organic layer and permafrost regime, and 3) compare the relative resistance and short-impacts between the major plant community types within the study area.

Methods and Materials:

Site Selection:

A detailed description of the study area is available in Chapter 2.

I sampled plant communities and soil properties within 178 $1m^2$ quadrats at 28 sites distributed throughout the study area. At each site half of the quadrats were placed along a seismic line (separated from one another by 50 to 75m) while the other half were placed

~50m distant from the seismic line, in an area with a similar plant community but which had not been exposed to seismic activity or other anthropogenic disturbance ("undisturbed tundra"; Fig. 3.1). The choice of sites was limited to seismic lines in their second or third growing season of recovery.

Each quadrat along a seismic line was paired with an adjacent control quadrat; each of these pairs represents a sample unit (Fig. 3.1), providing 89 sample units total. Seismic lines varied in width from ~6 to ~13m, sample plots were placed randomly between the visible margins of a seismic line. The sites were initially chosen in a stratified random design to represent a roughly equal representation of seismic programs and habitat types (*sensu* Gratto-Trevor 1996); subsequently data from the 'control' quadrats at each site were used to assign sites to the community types identified using the cluster analysis presented in Chapter 2. Wherever the cluster analysis determined that a sampling site actually included quadrats of more than one community type the site was divided so that for final analysis each site was identified as belonging to only one community type.

The resulting breakdown of sites and quadrats was as follows: 6 Sites (40 quadrats) in the Medium Shrub - Heath (MSH) community type, 3 sites (10 quadrats) in the Low Shrub - Heath (LSH) community type, 12 Sites (56 quadrats) in the Tall Shrub - Herb (TSH) community type, and 9 sites (72 quadrats) in the Wet Graminoid (WG) community type.

Sampling:

Within each quadrat I identified all vascular plant species present, and estimated the cover of each according to a set of precision guidelines (Table 2.1), and with the aid of a 1% cover reference card. Total cover of bryophytes and lichens were similarly assessed. Bryophytes and lichens were not identified to the species level. Cover was also estimated for "bare ground" which included exposed mineral soil as well as areas where the predominant ground cover (mosses) had been damaged or killed to the extent that the underlying organic mat was exposed and available sites, devoid of vegetation, were present. In saturated wetland areas "bare ground" also included areas that were devoid of vegetation where water was ponding above the soil surface.

Height of each upright growing shrub species was measured, and recorded as the average height (across all individuals) for each species within the quadrat. Upright growing species were defined as woody species which frequently reach heights greater than 40cm within the study area; heights were not measured for dwarf, prostrate, and hemi-prostrate woody species (e.g. *Ledum decumbens*, *Salix reticulata*, *Vaccinium uliginosum*). The number of stems for each upright growing shrub species within the quadrat was also recorded. A categorical assessment of physical damage (breakage) was also made for each upright growing shrub species, averaged across all individuals of a species within each quadrat, by assigning one of four damage categories: High (>50% of stems broken), Moderate (15-50% of stems broken), Slight (1-14% of stems broken) or None (no apparent damage). The cover of standing dead shrubs in each quadrat was also assessed, and recorded as a combined cover value for all species.

The soil organic layer depth was measured with a ruler by first cutting two trenches immediately outside each quadrat at opposite corners. The trenches were cut to the level of permafrost, or until the organic/mineral horizon was clearly visible. Thaw depth (active layer depth at time of sampling) was measured by pushing a steel probe into the soil until permafrost was reached, at four points in a diagonal transect (opposite the corners from where organic layer depth was measured) across each quadrat. The depth of penetration was marked, and measured against an aluminum meter-stick after removal of the probe.

Analysis:

Analysis of winter seismic impacts was performed separately for each community type. Prior to analysis each quadrat was assigned to a community type, as defined by the cluster analysis (Chapter 2); each 'seismic' (treatment) quadrat was placed in the same community type with its paired control quadrat. The two upland community types, Medium Shrub – Heath (MSH) and Low Shrub – Heath (LSH), were grouped due to the relatively small number of quadrats in the Low Shrub – Heath type.

Richness of vascular plants was calculated as the total number of species occurring within each quadrat, and did not include species present in the immediate surrounding area. Individuals that could not be properly identified to species were assigned to higher taxonomic levels (e.g. grass spp, *Salix* spp) and were excluded from richness and diversity calculations.

Species diversity of vascular plants was calculated using the Shannon Index (H') [Equation 3.1]

$$H' = -\sum_{i=1}^{s} p_i \ln p_i \qquad \text{[Eq. 3.1]}$$

where s= the number of species and p_i=the proportional representation of the i^{th} species (the cover of each species divided by the combined cover of all species) in each quadrat.

The effects of seismic exploration on the richness and diversity of vascular plants, as well as the total cover of vascular plants, mosses, and lichens, as well as soil properties (organic layer depth, thaw depth, and cover of bare ground) were assessed using mixed linear models (PROC MIXED in SAS v.8.02 1999-2000). Prior to analysis each variable was tested for normality and homogeneity of variance. Normality test were performed by examination of frequency distribution and normal probability plots, and using Shapiro-Wilk tests in PROC UNIVARIATE (SAS v.8.02 1999-2000). Homogeneity of variance was evaluated by examination of frequency distribution plots and tested using Levene's test for homogeneity of variance in PROC GLM (SAS v.8.02 1999-2000). Where moderate to strong departures from normality existed, and wherever heterogeneity of variance was encountered, suitable transformations were applied.

In some instances the assumption of homoscedasticity could not be met because the variance of response variables along seismic lines exceeded the variance of controls by several orders of magnitude. In these instances the data were tested by applying a paired non-parametric test of the paired quadrat difference between treatment levels (seismic and control). This was accomplished by first calculating the difference in response variable(s) between each pair of treatment and control quadrats, and then applying the Wilcoxon-Signed Rank test using PROC UNIVARIATE to test the null hypothesis of a median difference of zero. Although this method of non-parametric testing could not completely account for the nested design it was determined to be the best available test of data which could not fit the assumptions of parametric testing.

For each mixed linear model 'site' and 'sample unit' were considered random effects, and treatment (seismic vs. control) the fixed effect. Sample units (pairs of quadrats – seismic and control) were nested within sites as a random effect. Two models were tested, one with a treatment * site interaction term [equation 3.2], and one without [equation 3.3]. The basic equations for these models were:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_{k(j)} + \varepsilon_{ijkl} \qquad \text{[Eq. 3.2]}$$

and

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_{k(j)} + \varepsilon_{ijkl} \qquad \text{[Eq. 3.3]}$$

where: Y_{ijkl} is the dependant variable, μ is the grand mean, α_i is the fixed effect of treatment level i, β_j is the random effect of site j, $(\alpha\beta)_{ij}$ is the random effect of interaction between treatment and site, $\gamma_{k(j)}$ is the random effect of sample unit k within site j, and ε_{ijkl} is the residual error.

The model which provided the lowest value of Akaike's Information Criterion (AIC) was chosen for the test of treatment (fixed) effects. The test of fixed effects in PROC MIXED employs a Type III F-test, automatically selecting the optimum error term for the denominator in the F-test. The denominator degrees of freedom were calculated using the Kenward Roger method (Kenward and Roger 1997), which inflates the variance/covariance matrix of fixed and random effects and then performs a Satterthwaite denominator degrees of freedom calculation to produce a more accurate F test for small sample sizes. Random effects were tested using F-tests from general linear models (PROC GLM in SAS v.8.02 1999-2000) as the Wald's Z-tests of the covariance parameter estimates in PROC MIXED provide a less reliable estimation of random effects than do GLMs (Littell *et al* 1996).

Plant community composition was assessed using Non-metric Multidimensional Scaling (NMS), and Multi Response Permutation Procedures (MRPP). Both analyses were performed using percent cover data (untransformed) for all vascular plant species that occurred in >5% of quadrats within a community type; thus, species which were rare in the dataset were excluded. For each community type I used NMS to ordinate quadrats in species space using Sørensen (Bray-Curtis) distance as a community resemblance measure. Before performing the ordinations each distance matrix was screened for outliers using the procedures outlined in Chapter 2. The three quadrats removed from the cluster analysis in Chapter 2 were removed, along with their corresponding paired treatment quadrats. No other strong outliers were found in the data matrices, although several weak outliers were detected. In these instances the influence of the outliers on the final solution was tested by comparing the results of the analyses with and without the outliers. In all cases the presence of weak outliers did not have an influence on the final solution, and they were included in the final data matrices. For each ordination preliminary runs on the data were performed using the 'NMS Autopilot – slow and thorough' function of PC-ORD v.4.25 (McCune and Mefford 1999), to assess the dimensionality of the data, and select an optimum dimensionality and starting configuration for the final ordinations. The final ordinations were performed with no step-down in dimensionality, 500 iterations, and using 999 Monte-Carlo permutations to assess the significance of the reduction in stress of the final solution. The final solution was not subjected to rotation. Variance explained by the ordinations was expressed as the 'coefficient of determination' between Euclidean distances in the ordination space and Sørensen distance in the original species matrices.

Multi-Response Permutation Procedures (MRPP) were used to test for significant species composition differences between seismic lines and undisturbed tundra. The screened data matrices used to construct the ordinations were also used for these analyses. MRPP operates by testing whether the multivariate distance between objects within pre-defined groups is less than that expected if objects (quadrats) were randomly assigned to groups. The value δ (delta) is calculated by a weighting of the average distance within each group. The objects within the dataset are then permuted (i.e. randomly assigned to groups) a number of times to provide a distribution for δ against which the observed δ can be tested. The MRPP test also provides a measure of effect size: the *chance-corrected within group agreement* (A). Values of A are highest (A=1) when all objects within groups are 100% identical and lowest ($A \leq 0$) when within group homogeneity equals or is less than that expected by chance. Values for A between 0-1 therefore provide an estimate of the strength of the similarity between objects (quadrats) within each pre-defined group (seismic and control).

To maximize compatibility with the NMS ordinations the distance matrices used in the MRPP analyses were created using Sørensen distance and were rank transformed prior to analysis. The technique of performing MRPP analyses on rank transformed distance matrices was referred to as "nonmetric MRPP" by McCune *et al* (2000), who also used the technique to provide results more analogous to NMS. To calculate δ, the average within group distance was weighted by n/sum(n), the default procedure in PC-ORD (McCune and Mefford 1999).

To further examine potential differences in species composition between seismic and control quadrats, Indicator Species Analysis (Dufrêne and Legendre 1997) was used to determine whether any species were strongly negatively or positively associated with quadrats on seismic lines. This was accomplished using treatment level (seismic vs. control) as the grouping variable, and using 999 Monte-Carlo permutations to test whether the calculated indicator values were significantly greater for the seismic and control grouping than for randomly assigned groups. These analyses were performed using PC-ORD (McCune and Mefford 1999), on the screened data matrices.

The shrub damage, height, and stem density data were analyzed for the three most common upright woody species in each community type, provided those species occurred in more than 10 quadrats. The categorical shrub damage data were assessed by simple comparison of the number of quadrats in each damage class. Goodness of fit tests could not be applied, as the sample sizes were usually too small to generate a 'control distribution' against which to test the distribution of damage classes along seismic lines, or because the number of cells with expected frequencies less than 5 was high. The shrub height and stem density data were assessed using a one-tailed Wilcoxon 2 Sample test (PROC NPAR1WAY in SAS v8.02 1999-2000) with the expectation that both variables would be decreased by recent seismic exploration.

Results:

Plant Cover and Bare Ground:

Vascular plant cover was significantly lower along recent seismic lines in all community types (Table 3.1, Fig. 3.2). The magnitude of this effect was greatest in the upland communities (MSH and LSH), followed by the Tall Shrub – Herb (TSH) communities and the Wet Graminoid (WG) communities (Fig. 3.2). In the upland community types vascular plant cover was reduced, on average, by 59.5 ± 13.8 (95% CL) percent cover.

The decrease in vascular plant cover coincided with significant increases in percent cover of bare ground in each community type (Table 3.2, Fig. 3.3). The Wet Graminoid communities experienced the smallest increase in bare ground with a median increase of only 2%, while the Medium Shrub – Heath and Low Shrub – Heath types (MSH/LSH) had the largest median increase at 20.0% (Fig. 3.3).

Moss cover was significantly lower along seismic lines in the upland community types (MSH/LSH), with a mean decrease of 17.10 % cover along seismic lines (Table 3.1, Fig.3.4). Moss cover was not significantly different along seismic lines in either the Tall Shrub – Herb or Wet Graminoid type communities (Table 3.1, Fig. 3.4). Lichens were only present in the upland community types, where their cover was significantly lower along seismic lines, with an average decrease of 4.95% cover, from 11.64% total cover in undisturbed tundra, to 6.68% along seismic lines.

Organic Layer Depth and Thaw Depth:

Thaw depth was significantly deeper along seismic lines in the upland (Medium Shrub – Heath and Low Shrub - Heath) and Wet Graminoid (WG) community types, but not in the Tall Shrub – Herb (TSH) type (Table 3.2, Fig. 3.5). In the TSH communities the variability in thaw depth response was much greater than for the other communities (Fig. 3.5). As with vascular plant cover and bare ground the magnitude of the increase in thaw depth was greatest in the MSH/LSH community types, averaging 6.61cm and least in the

WG community type, averaging 2.37cm (Fig 3.5). No significant differences in organic layer depth were observed along seismic lines in any community type (Table 3.2).

Vascular Plant Diversity:

There was a significant decrease in vascular plant species richness along seismic lines in the Medium Shrub – Heath/Low Shrub – Heath communities, with quadrats on seismic lines having on average 1.88 fewer species than controls (Table 3.1, Fig. 3.6). In the Wet Graminoid and Tall Shrub – Herb community types there were no significant effects of seismic exploration on species richness (Table 3.1, Fig. 3.6).

Shannon Index diversity was significantly higher along seismic lines than at controls in the Tall Shrub – Herb community type (Table 3.1, Fig. 3.7). There was a marginally significant (p=0.06) decrease in vascular plant diversity along seismic lines in the MSH/LSH communities, and no significant effects of seismic on diversity in the WG communities (Table 3.1, Fig 3.7).

Community Composition:

There were no effects of winter seismic on plant community composition in the wetland (TSH and WG) community types but more marked effects in the upland community types (MSH/LSH).

Upland Communities (MSH/LSH)

For the NMS ordination of quadrats in the MSH and LSH communities a three dimensional solution produced the strongest reduction in stress (p=0.001) over randomized data and was selected for the final ordination (Fig 3.8). The first three axes explained 83.4% of variation in the species data, with the most variation explained by axes 1 and 3 respectively. Quadrats from seismic lines tended to separate from the control quadrats along these two axes (Fig 3.8). The final stress for the solution was 13.74, and final instability 0.0001.

The non-metric MRPP results showed significant differences in species composition between seismic lines and undisturbed tundra in these upland communities (Table 3.3), with a fairly strong chance corrected within group agreement (*A*) of 0.059.

The ISA revealed three species which were significant indicators of undisturbed tundra, and therefore negatively associated with quadrats on seismic lines, for the upland community types: *Betula glandulosa*, *Vaccinium vitis-idaea*, and *Pyrola grandiflora* (Table 3.4). *Betula* and *Vaccinium* both had strongly reduced cover along seismic lines, with only slight decreases in quadrat frequency, while *Pyrola grandiflora* was present in only one seismic line quadrat.

Tall Shrub – Herb Communities (TSH)

The NMS ordination of quadrats from TSH communities also produced a three dimensional solution as the strongest reduction in stress (p=0.005) over randomized data. The first three axes of the ordination explained 85.4% of variation in the species data, with axes 2 and 3 explaining the most variation. There did not appear to be any separation of quadrats from seismic lines or controls along any axis (Fig. 3.9). The final stress for the solution was 11.53; final instability did not meet the 10-4 criteria in 500 iterations (final instability = 0.00018).

The non-metric MRPP did not reveal any significant differences in species composition between seismic lines and undisturbed tundra in the TSH communities (Table 3.3).

The ISA did not reveal any species that were significantly associated (either negatively or positively) with quadrats from seismic lines in the TSH communities (Table 3.4)

Wet Graminoid Communities: (WG)

For the NMS ordination of quadrats from the WG communities a three dimensional solution again provided the best reduction in stress from randomized data (p=0.001). The three axes in the solution explained 85.4% of the variance in the species data, with axis 1 explaining the greatest portion (Fig. 3.10). There was no discernable separation between quadrats from seismic lines and undisturbed tundra in the ordination space. Final stress for the solution was fairly low at 12.22. The instability criterion, however, was not met in 500 iterations (final instability = 0.0027).

The non-metric MRPP did not detect any significant differences in species composition between seismic lines and undisturbed tundra in the WG communities (Table 3.3). The negative value for the chance corrected within group agreement (*A*= -0.002) revealed that there was actually less homogeneity in species compositions within the seismic and control grouping of quadrats than from the random allocation of quadrats to groups.

No species were found to be significant indicators of seismic lines or undisturbed tundra in ISA of the WG communities (Table 3.4).

Shrub Abundance and Damage

The cover of still-standing dead shrubs was significantly higher in seismic quadrats in the upland and Tall Shrub – Herb communities, but not in the Wet Graminoid communities (Table 3.1). Physical damage of shrubs, and reductions in shrub height were also observed in seismic quadrats for the MSH/LSH and TSH communities, but were absent in the WG communities (Table 3.5; Table 3.6)

The three most common species of upright shrubs in the upland community types were *Betula glandulosa*, *Salix glauca ssp. acutifolia*, and *Alnus crispa*. For all three species most control quadrats were classified with class 0 damage (none), while seismic line quadrats were most often classified in the high (class 3) damage category (Table 3.5). For *B. glandulosa* there was a fairly even distribution of seismic line quadrats in each damage class (0-3), while neither *S. glauca* nor *A. crispa* had any seismic line quadrats classified as level 0 damage. All five seismic line quadrats in which *A. crispa* was present were classified as class 3 damage; in many instances individuals (especially those which were mature) of this species were completely eliminated along seismic lines. Not surprisingly therefore, the height of *A. crispa*, as well as that of *S. lanata*, was significantly lower along seismic lines than at controls (Table 3.6, Figs. 3.11, 3.12). Stem density, however, was not affected by winter seismic for either species (Table 3.6, Figs. 3.11, 3.12). There were no significant effects of winter seismic on either the height or number of stems of *B. glandulosa* (Table 3.6, Fig 3.13) in the upland communities.

The Tall Shrub – Herb communities were dominated by a single shrub species, *Salix lanata* ssp *richardsonii*, although *Alnus crispa* was also present in ten quadrats. Most control quadrats (19 of 28) were classified as class 1 (slight) damage for *S. lanata*, whereas most seismic line quadrats (15 of 28) were classified with level 3 damage (Table 3.5). *Alnus crispa* had a roughly equal proportion of control quadrats in damage classes 0 and 1, with higher damage levels (2 and 3) along seismic lines (Table 3.5). Height of both *S. lanata* and *A. crispa* was significantly lower along seismic lines than at controls, while the number of stems did not differ significantly between seismic lines and controls for either species (Table 3.6, Figs. 3.14, 3.15). The height difference was most pronounced in *A. crispa* (Fig. 3.15) with a difference in median height of 160cm, and less so *S. lanata* (Fig. 3.14) where the difference in median height between treatments was 19.25cm .

In the Wet Graminoid communities the only upright shrub species present in more than 10 quadrats was *Salix lanata* ssp *richardsonii*. There did not appear to be any patterns in the distribution of damage classes between seismic lines and undisturbed areas for this species (Table 3.5) although a slightly greater proportion (8 of 12) of control quadrats were classified as having no damage (class 0) compared to seismic line quadrats (3 of 8). Height and stem density of *S. lanata* were similarly unaffected by seismic exploration in the WG communities (Table 3.6, Fig. 3.16).

Discussion:

The most prominent effects of recent winter seismic exploration in all the community types studied were a decrease in living plant cover and an increase in the amount of exposed mineral soil or scoured organic soil. The removal of vegetation and exposure of darker organic or mineral soils presumably altered the energy budget at disturbed sites (e.g. Haag and Bliss 1974) and led to the measured increases in thaw depth.

Community types clearly differed in their resistance to winter seismic disturbance. Impacts were greatest in the upland community types (MSH and LSH), which experienced the largest decrease in vascular plant cover and increase in bare ground, the largest increase in active layer depth, as well as reduced species richness and diversity of vascular plants. In addition, the upland types were the only communities for which species composition was measurably different along seismic lines. Impacts were less in the Tall Shrub-Herb communities, although there were significant decreases in the total cover of vascular plants, and increases in the diversity of vascular plants and cover of bare ground. There was also a significant decrease in the height of the two most common species of deciduous shrubs along seismic lines in these communities. Impacts of winter seismic were least in the Wet Graminoid communities, where effects were limited to significantly lower vascular plant cover, and higher cover of bare ground; there was also a significant but relatively small increase in thaw depth. These results support the hypothesis that upland communities are less resistant to the impacts of winter seismic exploration than wetland communities, and are consistent with those of previous studies from this area (Bliss and Wein 1972, Hernandez 1973), as well as from Alaska (Felix and Raynolds 1989a).

The relatively low level of disturbance measured in the Wet Graminoid communities probably relates to several factors. The flat topographic relief of these areas makes winter vehicle travel easier, and results in less potential scuffing by vehicles churning up small slopes. The saturated soils of these communities also would provide a very hard frozen platform for vehicle travel, which may ensure the survival of below ground biomass. While the above ground portions of these species may be damaged or removed by seismic vehicle passage the underground rhizomes probably remain intact, allowing for relatively rapid recolonization. Bliss and Wein (1972) reported that the rhizome mass of both *Carex aquatilis* and *Eriophorum angustifolium* survived two years of winter road travel in similar wetlands, and that revegetation was relatively rapid. Wet low-arctic soils have also been reported to have higher nutrient turnover rates (Ebersole 1987; Chapin *et al* 1988) which, combined with the compression of standing dead and living vegetation into contact with the soil surface following seismic exploration (Rickard and Brown 1974) may enable these communities to rapidly revegetate. The dominant vascular plant species in these communities, the rhizomatous sedges *E. angustifolium* and *C. aquatilis*, may have already begun to revegetate areas of bare ground on seismic lines in the two growing seasons post disturbance, resulting in an underestimation of the initial impacts of winter seismic in this study. In either instance, these communities are likely to be the most resistant, and most resilient to winter seismic disturbance. The dominance of the Wet Graminoid communities by a small number of species also provides little room for declines in species richness or diversity. These communities are typically found in low-lying positions in close proximity to the Beaufort Sea coast or to major stream channels, and are likely predisposed to higher frequencies of natural disturbance. Damage to vegetation and soil exposure attributable to ice and/or driftwood scouring was noticed at several locations within the KIBS, as was flooding of low-lying areas due to spring breakup or storm surges. The increase in thaw depth along seismic lines in these communities was quite small, yet was similar to that reported from the ANWR seismic studies (Felix *et al* 1992) in most cases. It should be noted that thaw depth measurements were made at the time of sampling in this study (July) and do not represent maximum active layer depths. Therefore, comparisons to other studies may not be valid.

In the Tall Shrub – Herb communities the decrease in vascular plant cover was primarily due to effects on the dominant shrub species, with herbaceous plants being relatively unaffected. Similar reductions in cover and height of the dominant shrubs following seismic exploration in riparian areas have been reported elsewhere (Felix and Raynolds 1989a), and should not be unexpected; given the height of the dominant vegetation large portions of these shrubs probably remain above the snow level in winter and would be broken off by vehicle passage. The increase in diversity of vascular species along seismic lines in the TSH communities is therefore likely attributable to the reduced dominance of these overstory shrub species and a concomitant increase in evenness. Despite the measured change in diversity there were no effects of seismic exploration on community composition in the TSH communities. Although the decrease in both vascular plant cover and shrub heights were relatively large, the small increase in cover of bare ground at these sites probably allowed little opportunity for new colonists, or for changes in relative abundance large enough to measurably affect species composition. The relatively small increase in bare ground compared to undisturbed sites may also have contributed to the lack of significant effects of winter seismic on thaw depth in these communities. The much greater variability in thaw depth in the TSH communities, however, might also imply the presence of another factor, or factors, which regulate permafrost depth in these communities but are absent (or unimportant) in the other community types in this study. The Tall Shrub – Herb communities of the KIBS are riparian; the proximity to the relatively warm waters of shallow delta stream courses may have a stronger influence on permafrost depth than insulation by vegetation or organic mats, although to my knowledge this hypothesis has not been explicitly tested.

The high percentage of bare ground in the Medium Shrub – Heath and Low Shrub – Heath communities indicates an abundance of open sites that had yet to be occupied by colonizing or regenerating species. In addition, the significant difference in species composition along seismic lines in the MSH/LSH communities suggests either the presence of particularly sensitive species in these communities, or an influx of colonizers from outside the range of normal community assemblage. The ISA results would seem to support the former conclusion. All three species determined to be negatively associated with seismic lines in this study have been reported to be particularly sensitive to winter seismic in other studies (Hernandez 1973; Felix and Raynolds 1989a).

The increase in thaw depth measured in the MSH/LSH communities may also be of significance to the changes in community composition detected there. The differing ability of species to exploit soil resources previously trapped by permafrost could result in shifts in the relative abundance of species at these sites. McKane *et al* (2002) have shown that temporal and spatial (i.e. depth) partitioning in resource use are dominant factors determining the species composition and relative abundance of tundra ecosystems, and Chapin and Shaver (1981) demonstrated that some species acclimated to disturbance by increasing rooting depth into newly thawed soil regions while others did not. The duration of the disturbance to the soil thermal regime is not clear. Abele *et al* (1984) reported that initial recovery of thaw depth (the point at which thaw depth began to decrease below vehicle tracks) occurred within two to three years, and that even the sites with the most disturbed thermal regimes had recovered natural thaw depths in 10 years. Emers *et al* (1995) however, reported impacts to the active layer from winter seismic lasting 8 years or more, and showing no signs of recovery at most sites.

The precise mechanisms behind the large changes in vascular plant cover in the Medium Shrub – Heath and Low Shrub – Heath communities (beyond the presence of sensitive species) cannot be directly ascertained from the type of post-hoc survey I conducted. It has been suggested, however, that topography (Hernandez 1973; Raynolds and Felix 1989) and snow depth (Felix and Raynolds 1989b) are important factors in determining the extent of damage from winter seismic. The high topographic position, and relief, in upland areas of the KIBS most likely leads to a much greater degree of wind scouring in the upland plant communities, and a subsequent decrease in snow depth.

The current study captures only the initial damage from winter seismic, and the very early periods of initial revegetation along these disturbances. Although it is difficult to speculate as to longer-term impacts some comparison to the longer-term results from the ANWR seismic programs (e.g. Felix *et al* 1992; Emers *et al* 1995) is warranted, given the similarity in the short term responses between my study and theirs. Felix *et al* (1992) reported little resilience to winter seismic exploration in tundra vegetation four to five years post disturbance, with community dissimilarity continuing to increase. Eight years post-disturbance Emers *et al* (1995) found that thermal stability had still not reestablished on most sites, and that on highly disturbed sites plant community composition had changed towards greater abundance of hydrophilic sedges and "ruderal" grasses.

In summary, I found significant effects of winter 2D seismic exploration in all the plant community types studied. The effects were most prominent in the upland plant communities, where the magnitude of the decrease in vascular plant cover, increase in thaw depth, and initial changes in plant community composition suggest that these communities have the highest potential to undergo long term changes as a result of seismic disturbance. Because of the evolving nature of seismic technologies and techniques, future long-term studies are required to provide accurate information regarding the long-term consequences of contemporary winter seismic exploration. Despite differences in the nature of the disturbance between recent and older seismic programs, investigations of older winter seismic disturbances can provide some information on the potential for longer-term effects in arctic ecosystems, as well on the patterns of vegetation recovery and succession along these disturbances.

Literature Cited:

Abele, G., Brown, J., and M.C. Brewer. 1984. *Long-term effects of off-road vehicle traffic on tundra terrain.* Journal of Terramechanics 21:283-294

Bliss, L.C., and R.W. Wein. 1972. *Plant community responses to disturbance in the western Canadian arctic.* Canadian Journal of Botany 50:1097-1109.

Chapin, F.S. III, and G.R. Shaver. 1981. *Changes in soil properties and vegetation following disturbance of Alaskan arctic tundra.* Journal of Applied Ecology 18:605-617

Chapin, F.S. III, and G.R. Shaver. 1985. *Individualistic growth response of tundra plant species to environmental manipulations in the field.* Ecology 66:564-576

Chapin, F.S. III, Fetcher, N., Kielland, K., Everett, K.R., and A.E. Linkins. 1988. *Productivity and nutrient cycling of Alaskan tundra: enhancement by flowing soil water.* Ecology 69:693-702

Dufrêne, M. and P. Legendre. 1997. *Species assemblages and indicator species: the need for a flexible asymmetrical approach.* Ecological Monographs 67:345-366

Ebersole, J.J. 1987. *Short-term vegetation recovery at an Alaskan arctic coastal plain site.* Arctic and Alpine Research 19:442-450

Ebersole, J.J. 1989. *Role of the seed bank in providing colonizers on a tundra disturbance in Alaska.* Canadian Journal of Botany 67:466-471

Emers, M., Jorgenson, J.C., and M.K. Raynolds. 1995. *Response of arctic tundra plant communities to winter vehicle disturbance.* Canadian Journal of Botany 73:905-917

Fahrig, L., Coffin, D.P., Lauenroth, W.K., and H.H. Shugart. 1994. *The advantage of long-distance clonal spreading in highly disturbed habitats.* Evolutionary Ecology 8:172-187

Felix, N.A., and M.K. Raynolds. 1989a. *The effects of winter seismic exploration on tundra vegetation in northeastern Alaska, U.S.A.* Arctic and Alpine Research 21:188-202

Felix, N.A., and M.K. Raynolds. 1989b. *The role of snow cover in limiting surface disturbance caused by winter seismic exploration.* Arctic 42:62-68

Felix, N.A., Raynolds, M.K., Jorgenson, J.C., and K.E. DuBois. 1992. *Resistance and resilience of tundra plant communities to disturbance by winter seismic vehicles.* Arctic and Alpine Research 24:69-77

Forbes, B.C., and R.L. Jefferies. 1999. *Revegetation in arctic landscapes: constraints and applications.* Biological Conservation 88:15-24

Gartner, B.L., Chapin, F.S.III., and G.R. Shaver. 1983. *Demographic patterns of seedling establishment and growth of mature graminoids in an Alaskan tundra disturbance.* Journal of Applied Ecology 20:965-980

Haag, R.W., and L.C. Bliss. 1974. *Energy budget changes following surface disturbance to upland tundra.* Journal of Applied Ecology 11:355-374

Hernandez, H. 1973. *Natural plant recolonization of surficial disturbances, Tuktoyaktuk Peninsula region, Northwest Territories.* Canadian Journal of Botany 51:2177-2196

Hinzman, L.D., Kane, D.L., Beson, C.S., and K.R. Everett. 1996. *Energy balance and hydrologic processes in an arctic watershed. In*: Reynolds, J.F., and J.D. Tenhunen (*Eds*). Landscape Function and Disturbance in Arctic Tundra. Ecological Studies 120:131-154

Kerfoot, D.E. 1972a. *Topographic aspects of artificial disturbances to the tundra in the Mackenzie Delta area, N.W.T.* In: Mackenzie Delta Area Monograph, 22nd International Geographical Congress, Canada.

Kerfoot, D.E. 1972b. *Tundra disturbance studies in the western Canadian arctic.* ALUR report 71-71-11. 115pps

Kotanen, P.M. 1997. *Effects of gap area and shape on recolonization by grassland plants with differing reproductive strategies.* Canadian Journal of Botany 75:352

Littell, R.C., Milliken, G.A., Stroup, W.W., and R.D. Wolfinger. 1996. *SAS System for Mixed Models.* SAS Institute Inc., Cary, NC.

McCune, B., Rosentreter, R., Ponzetti, J.M., and D.C. Shaw. 2000. *Epiphyte habitats in an old conifer forest in western Washington, U.S.A.* The Bryologist 103:417-427

McGraw, J.B. 1980. *Seed bank size and distribution of seeds in cottongrass tussock tundra, Eagle Creek, Alaska.* Canadian Journal of Botany 58:1607-1611

McKane, R.B., Johnson, L.C., Shaver, G.R., Nadelhoffer, K.J., Rastetter, E.B., Fry, B., Giblin, A.E., Kielland, K., Kwiatkowski, B.L., Laudre, J.A., and G. Murray. 2002. *Resource-based niches provide a basis for plant species diversity and dominance in arctic tundra.* Nature 415:68-71

National Academy of Science. 2003. *Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope.* National Academies Press, Washington. 288pps

Peterson, K.M., and W.D. Billings. 1980. *Tundra vegetational patterns and succession in relation to microtopography near Atkasook, Alaska.* Arctic and Alpine Research 12:473-482

Raynolds, M.K., and N.A. Felix. 1989. *Airphoto analysis of winter seismic disturbance in northeastern Alaska.* Arctic 42:362-367

Reynolds, P.C. 1982. *Some effects of oil and gas exploration activities on tundra vegetation in northern Alaska.* In: Rand, P.J. (ed): Land and Water Issues Related to Energy Development. Ann Arbor Science, Ann Arbor Michigan pp 403-417

Rickard, W.E., and J. Brown. 1974. *Effects of vehicles on arctic tundra.* Environmental Conservation 1:55-62

Shirazi, M.A., Haggerty, P.K., Hendricks, C.W., and M. Reporter. 1998. *The role of thermal regime in tundra plant community restoration.* Restoration Ecology 6:111-117

Tilman, D. 1985. *The resource-ration hypothesis of plant succession.* The American Naturalist 125:827-852

Truett, J.C., and K. Kertell. 1992. *Tundra disturbance and ecosystem production: implications for impact assessment. Environmental Management* 16:485-494

Walker, D.A., and M.D. Walker. 1991. *History an pattern of disturbance in Alaskan arctic terrestrial ecosystems: a hierarchical approach to analyzing landscape change.* Journal of Applied Ecology 28:244-276

Walker, D.A., Cate, D., Brown, J., and C. Racine. 1987. *Disturbance and recovery of arctic Alaskan tundra terrain: A review of recent investigations.* CCREL Report 87-11. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Walker, D.A., Jia, G.J., Epstein, H.E., Raynolds, M.K., Chapin, F.S.III., Copass, C., Hinzman, L.D., Knudson, J.A., Maier, H.A., Michaelson, G.J., Nelson, F., Ping. C.L., Romanovsky, V.E., and N. Shiklomanov. 2003. *Vegetation-soil-thaw-depth relationships along a low-arctic bioclimate gradient, Alaska: Synthesis of information from the ATLAS studies.* Permafrost and Periglacial Processes 14:103-123

Table 3.1. Effects of recent seismic exploration on vegetation properties in a) medium shrub – heath and low shrub heath communities, b) tall shrub – herb communities, and c) wet graminoid communities. Treatment (*T*) effect results are from mixed linear models or Wilcoxon Signed Rank tests (**). Random effects (Site, T*Site, Su(Site)) in the mixed linear models were tested using general linear models (GLMs). Fixed effect *p*=probability of Type 1 error for H_0: no difference between seismic and control. df= numerator and denominator degrees of freedom used to construct F-tests. S= Wilcoxon Signed Rank statistic.

a) Medium Shrub – Heath and Low Shrub – Heath communities

	Vascular Cover			Dead Shrub Cover**			Species Diversity(vasc)			Species Richness (vasc)			Moss Cover			Lichen Cover		
	df	*F*	*p*	*n*	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
T	1,37	75.91	***<0.0001***	25	-101	***<0.0001***	1,40.8	3.67	0.0623	1,40.1	10.83	***0.0021***	1,7.95	9.69	***0.0145***	1,24	6.54	***0.0173***
Site	8,16	2.32	0.0721				8,16	2.09	0.0988	8,16	8.39	***0.0002***	8,16	21.52	***<0.0001***	8,16	7.23	***0.0004***
*T*Site*	8,16	1.63	0.1932				8,16	0.37	0.9221	8,16	1.81	0.1477	8,16	2.63	0.0687	8,16	1.19	0.3613
Su(Site)	16,16	0.82	0.6515				16,16	0.78	0.6876	16,16	1.11	0.4181	16,16	3.19	***0.0130***	16,16	2.29	0.0542

b) Tall Shrub – Herb communities

	Vascular Cover			Dead Shrub Cover**			Species Diversity(vasc)			Species Richness (vasc)			Moss Cover**		
	df	*F*	*p*	*n*	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*	*n*	*S*	*p*
T	1,24.5	19.02	***0.0002***	28	-161	***<0.0001***	1,41.8	5.65	***0.0221***	1,26.8	0.32	0.5738	28	24	0.4776
Site	11,16	2.13	0.0918				11,16	8.19	***0.0002***	11	9.31	***0.0001***			
*T*Site*	11,16	1.19	0.3731				11,16	3.09	***0.0252***	11	1.72	0.1688			
Su(Site)	16,16	1.37	0.2782				16,16	1.42	0.2585	16	1.76	0.1462			

c) Wet Graminoid communities

	Vascular Cover			Dead Shrub Cover**			Species Diversity (vasc)			Species Richness (vasc)			Moss Cover**		
	df	*F*	*p*	*n*	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*	*n*	*S*	*p*
T	1,35	30.49	***<0.0001***	36	16.5	0.3661	1,35	0.91	0.3458	1,35	0.59	0.4463	36	51	0.3016
Site	8,27	14.60	***<0.0001***				8,27	5.49	***0.0004***	8	4.39	***0.0017***			
*T*Site*	8,27	0.80	0.6040				8,27	0.53	0.8207	8	0.97	0.4783			
Su(Site)	27,27	2.25	***0.0200***				27,27	1.76	0.0742	27	1.27	0.2705			

Table 3.2. Effects of recent seismic exploration on soil and permafrost properties in the major plant community types of the Kendall Island sanctuary. Treatment (T) effect results are from mixed linear models, or from paired Wilcoxon (signed rank) tests (**). Random effects (Site, T*Site, Su(Site)) tests were conducted using general linear models. Fixed effect *p*=probability of Type 1 error for H_0: no difference between seismic and control. S= Wilcoxon Signed Rank statistic.

a) Medium Shrub – Heath and Low Shrub – Heath communities

	Bare Ground**			Organic Layer Depth			Thaw Depth		
	n	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
T	25	-105	***<0.0001***	1,41	0.12	0.7318	1,24	24.36	***<0.0001***
Site				8,16	3.65	***0.0132***	8,16	5.06	***0.0029***
*T*Site*				8,16	0.44	0.8786	8,16	0.87	0.5572
Su(Site)				16,16	0.71	0.7534	16,16	1.31	0.2964

b) Tall Shrub – Herb communities.

	Bare Ground**			Organic Layer Depth			Thaw Depth		
	n	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
T	28	-119	***0.0001***	1,18.9	0.51	0.4854	1,10.1	0.35	0.5690
Site				6,7	6.33	***0.0205***	11,16	9.97	***<0.0001***
*T*Site*				6,7	0.24	0.9459	11,16	3.45	***0.0162***
Su(Site)				7,7	0.22	0.9665	16,16	3.40	***0.0132***

c) Wet Graminoid communities

	Bare Ground**			Organic Layer Depth			Thaw Depth		
	n	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
T	36	-98.5	***0.0303***	1,26	0.12	0.7279	1,35	4.36	***0.0440***
Site				5,21	29.17	***<0.0001***	8,27	17.49	***<0.0001***
*T*Site*				5,21	0.84	0.5389	8,27	1.57	0.1806
Su(Site)				21,21	1.18	0.3565	27,27	3.25	***0.0016***

Table 3.3 Results of non-metric MRPP tests of community composition comparing seismic lines and undisturbed tundra in four plant community types common to the KIBS. *A*= chance corrected within group agreement, *p*= probability of Type 1 error for H_0: no difference between seismic and control

Community Type	A	*p*
Medium Shrub – Heath and Low Shrub - Heath	0.059597	***0.0008***
Tall Shrub – Herb	0.014832	0.1211
Wet Graminoid	-0.00216	0.4617

Table 3.4. Results of indicator species analysis for disturbed (seismic) and control communities in Medium Shrub – Heath and Low Shrub – Heath tundra. P-values based on 999 Monte Carlo permutations Cover= average % cover (when present), Freq = quadrat frequency, *IV*= Indicator value, *P*= probability of Type 1 error for H_0: no difference in IV between seismic/control groups and randomly allocated groups.

Community Type	**Indicator Species**	**Cover (control)**	**Cover (seismic)**	**Freq (control)**	**Freq (seismic)**	**IV**	**P**	**Treatment Level Indicated**
MSH/LSH	*Betula glandulosa*	17.57%	6.27%	0.88	0.80	65.8	0.024	Control
	Vaccinium vitis-idaea	21.27%	6.33%	0.88	0.80	64.1	0.008	Control
	Pyrola grandiflora	1.75%	0.5%	0.40	0.04	36.0	0.003	Control
TSH	None							
WGT	None							

Table 3.5. Distribution of shrub damage classes for the major shrub species in a) MSH and LSH, b) TSH, and c) WG communities. Cell values are the number of quadrats with the assigned level of shrub damage for a particular species. 0 = none, 1= slight (1-14% stems broken), 2= moderate (15-50% stems broken), 3= high (>50% of stems broken).

a) Medium Shrub – Heath and Low Shrub – Heath type

Species	**Treatment Level**	**Damage Class**			
		0	**1**	**2**	**3**
Betula glandulosa	control	21	1	0	0
	seismic	4	3	4	8
Salix glauca	control	8	0	1	0
	seismic	0	1	2	4
Alnus cispa	control	4	3	0	0
	seismic	0	0	0	5

b) Tall Shrub – Herb type

Species	**Treatment Level**	**Damage Class**			
		0	**1**	**2**	**3**
Salix lanata	control	9	19	0	0
	seismic	0	6	7	15
Alnus crispa	control	3	2	0	0
	seismic	1	0	1	3

c) Wet Graminoid type

Species	**Treatment Level**	**Damage Class**			
		0	**1**	**2**	**3**
Salix lanata	control	8	3	0	1
	seismic	3	0	4	1

Table 3.6. Effects of winter seismic on shrub height and stem density in a) Medium Shrub – Heath and Low Shrub – Heath, b) Tall Shrub – Herb, and c) Wet Graminoid communities. Results are from Wilcoxon 2-Sample tests of one tailed hypotheses. n^1 and n^2 are number of occurrences for each species along seismic lines and at controls, respectively, Z= standardized test statistic (includes continuity correction of 0.5), *p*= probability of Type 1 error for the H_0: seismic = control.

a) MSH/LSH	Sample Size		Height		Number of stems	
	n^1	n^2	*Z*	*p*	*Z*	*p*
Betula glandulosa	19	22	-1.073.5	0.1415	-0.6956	0.2433
Salix glauca	7	9	-1.9597	**0.0250**	0.1745	0.4307
Alnus crispa	5	7	-1.7082	**0.0438**	-1.0987	0.1359

b) TSH	Sample size		Height		Number of Stems	
	n^1	n^2	*Z*	*p*	*Z*	*p*
Salix lanata	28	28	-1.7129	**0.0434**	-0.2718	0.3929
Alnus crispa	5	5	-2.5067	**0.0061**	0.0000	0.5000

c) WGT	Sample size		Height		Number of Stems	
	n^1	n^2	*Z*	*p*	*Z*	*p*
Salix lanata	8	12	-1.127	0.1310	-0.1244	0.4505

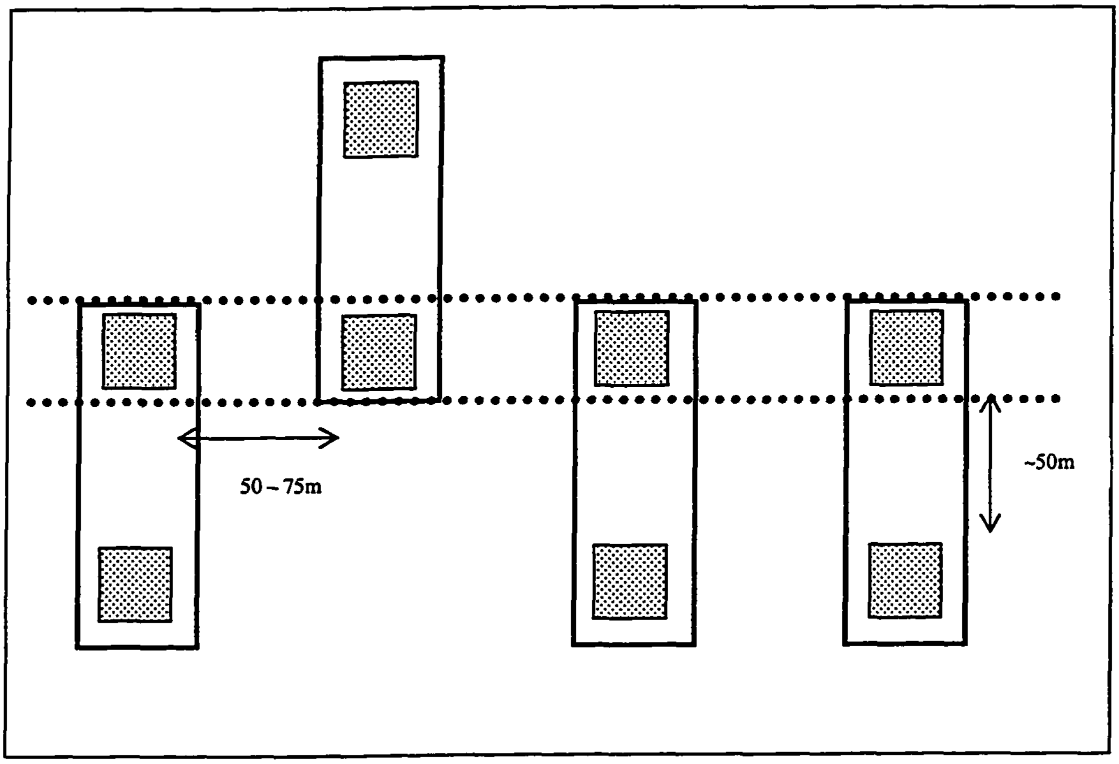

Fig. 3.1. Typical sampling site, showing the relationship between quadrats, sample units, and sites. Each quadrat (filled squares) along a seismic line (dashed line) is paired with a control quadrat. Each pair of quadrats represents a sample unit (darker solid line), which are nested within sites (thin solid line). The number of sample units per site varied among sites and ranged from 2-6. Diagram is for illustrative purposes and is not shown to scale.

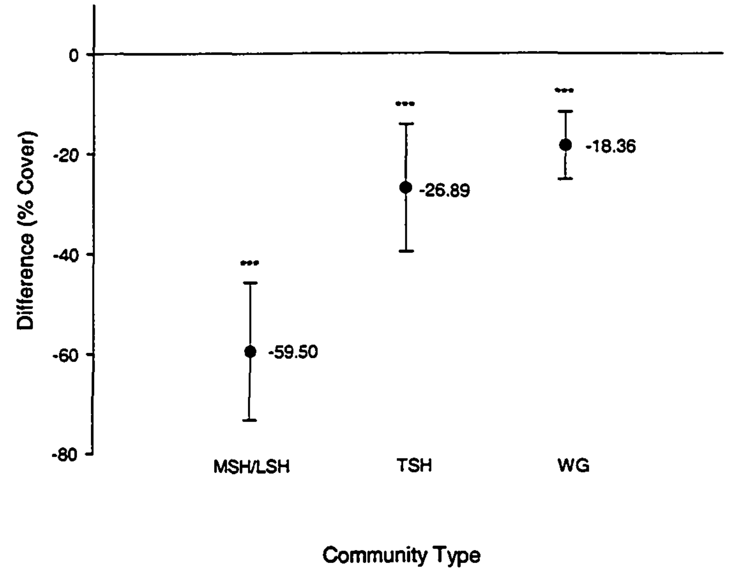

Fig. 3.2. Difference in vascular plant cover along recent seismic lines as compared to undisturbed tundra in four community types of the KIBS. Points are the difference between LSMean cover for the two treatments (control – seismic) ± 95CLs. ***significant difference between the two treatments ($p<0.001$). Mean vascular plant cover in undisturbed MSH/LSH = 106.5% ; TSH = 87.3%, WG = 80.4%. n (number of sample units): MSH/LSH=25, TSH=28, WG=36.

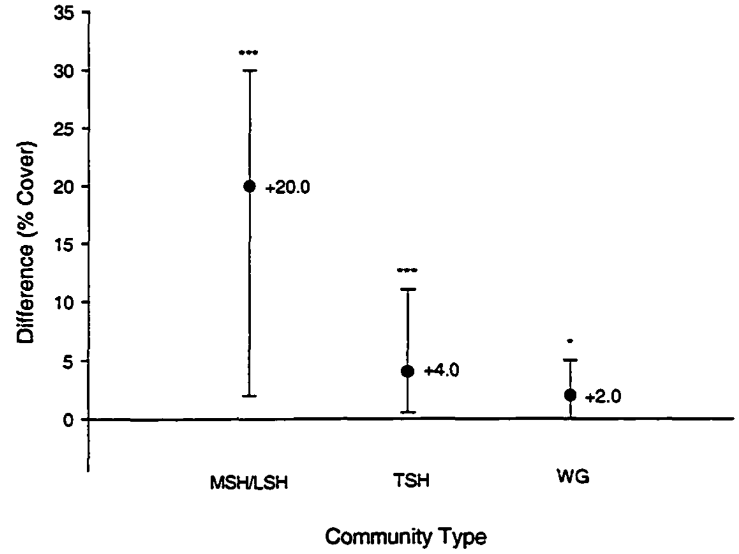

Fig. 3.3. Difference in cover of bare ground along recent seismic lines as compared to undisturbed tundra in four community types of the KIBS. Points are median difference ± 95% CLs (distribution free); analysis was by Wilcoxon-Signed Rank tests. ***significant at $p<0.001$, *significant at $p<0.05$. Median bare ground cover in undisturbed MSH/LSH= 0.0%, in TSH = 0.0%, in WG = 2.5%. n (number of sample units): MSH/LSH=25, TSH=28, WG=36

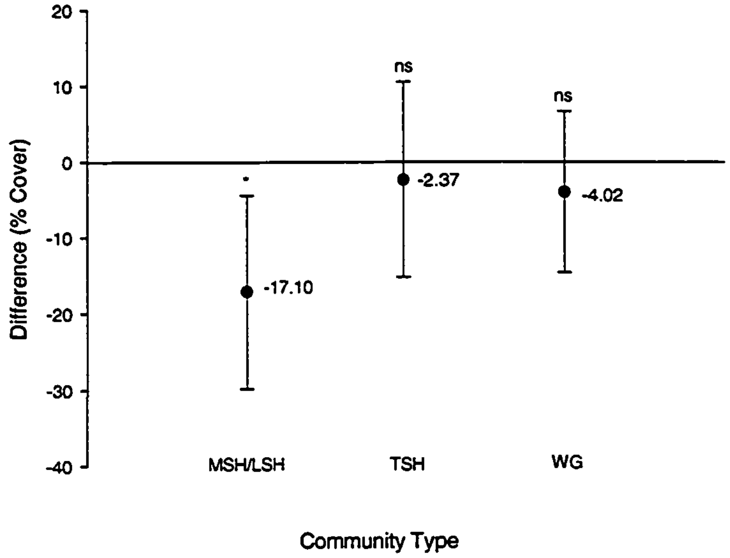

Fig. 3.4. Difference in moss cover along recent seismic lines as compared to undisturbed tundra in four community types of the KIBS. For the MSH/LSH type points are the difference between LSMean cover for the two treatments (control – seismic) ± 95% CLs; analysis was by mixed linear models. For the TSH and WG community types points are the median difference ± 95% CLs; analysis was by Wilcoxon-Signed Rank tests. *significant at $p<0.05$, ^{ns}: not significant. Mean moss cover in undisturbed MSH/LSH = 54.6%. Median moss cover in undisturbed TSH = 8.5%, in WG = 67.5%. n (number of sample units): MSH/LSH=25, TSH=28, WG=36

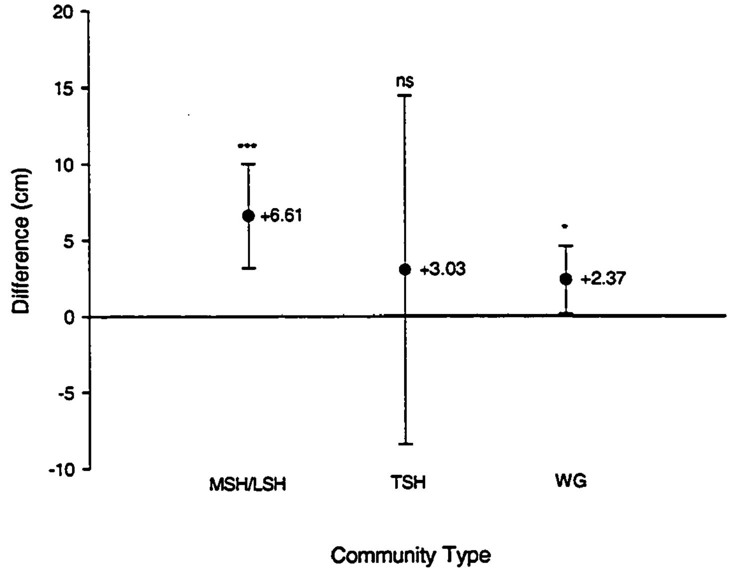

Fig. 3.5. Difference in thaw depth along recent seismic lines as compared to undisturbed tundra in four community types of the KIBS. Points are the difference between LSMean thaw depth for the two treatments (control – seismic) ± 95% CLs; from analysis by Mixed Linear Models. * significant difference between treatments at $p<0.05$, *** significant at $p<0.001$, ^{ns} not significant. Mean thaw depth in undisturbed MSH/LSH=16.88cm, TSH=45.68cm, WG=32.68cm. n (number of sample units): MSH/LSH=25, TSH=28, WG=36

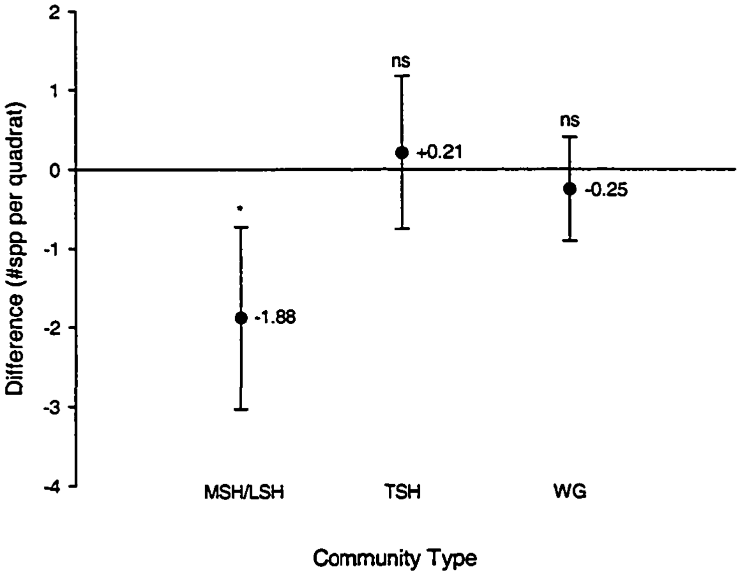

Fig. 3.6. Difference in species richness (per quadrat) along recent seismic lines as compared to undisturbed tundra in four community types of the KIBS. Points are the difference between LSMean species richness for the two treatments (control – seismic) ± 95%CLs, from analysis by Mixed Linear Models. *significant difference between treatments at $p<0.05$, ^{ns} not significant. Mean species richness per plot in undisturbed MSH/LSH=11.32, TSH=5.91, WG=4.13. n (number of sample units): MSH=25, TSH=28, WG=36.

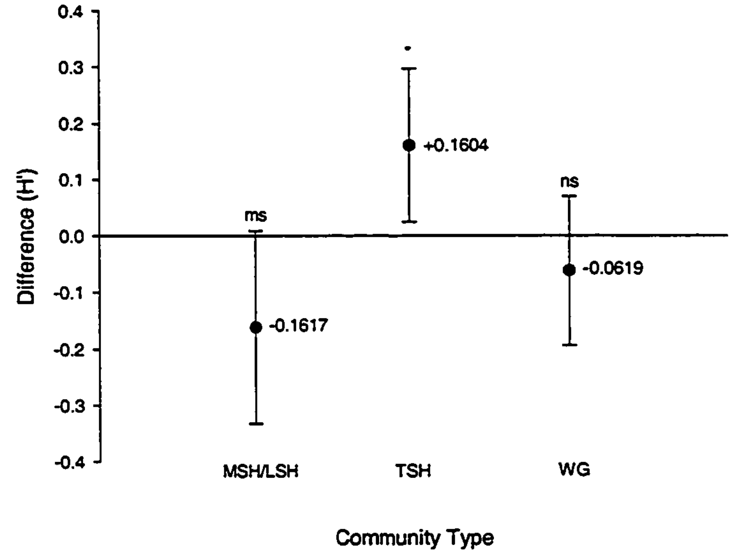

Fig. 3.7. Difference in Shannon-Index diversity of vascular plants along recent seismic lines as compared to undisturbed tundra in four community types of the KIBS. Points are the difference between LSMean diversity for the two treatments (control – seismic) ± 95% CLs, from analysis by Mixed Linear Models. *significant difference between treatments at $p<0.05$, ^{ms} marginally significant ($p=0.06$), ^{ns} not significant. Mean diversity (H') in undisturbed MSH/LSH=1.847, TSH=1.023, WG=0.912. n (number of sample units): MSH/LSH=25, TSH=28, WG=36.

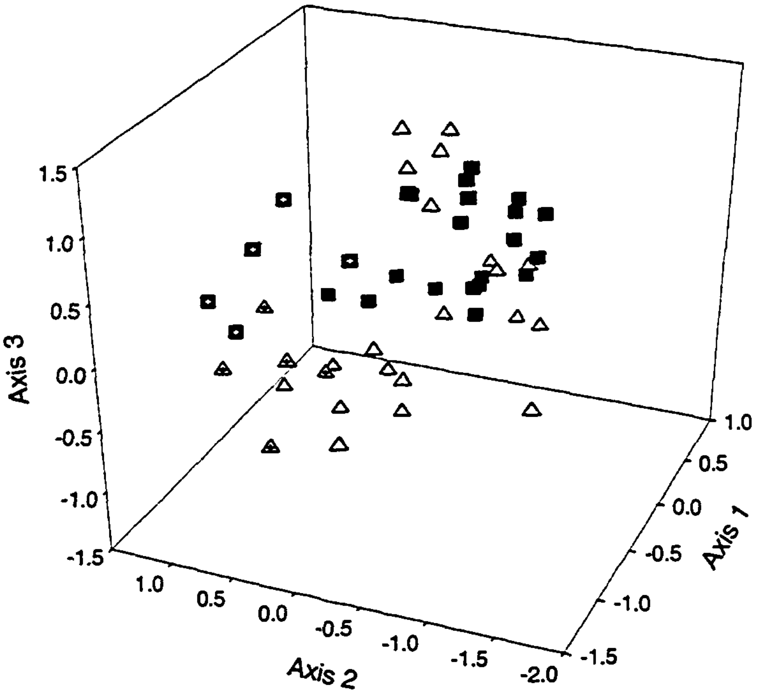

Fig. 3.8. Non-metric Multidimensional Scaling of quadrats in species space for Medium Shrub – Heath and Low Shrub – Heath communities. Distances matrix was created using Sørensen distance, from untransformed cover data for all vascular plant species occurring in >5% of quadrats. Three dimensional solution with significant ($p=0.001$) reduction in stress from randomized data, tested using 999 Monte Carlo permutations. Total variance captured = 83.4%; proportion of variance represented by: Axis 1=0.310, Axis 2=0.246, Axis 3=0.278. Final stress = 13.74, Final Instability = 0.0001. Original distance matrix was composed of 50 quadrats and 36 species.

Symbols: Triangles are quadrats from seismic lines; squares are quadrats from undisturbed tundra. Symbols with internal crosshairs are from Low Shrub – Heath communities.

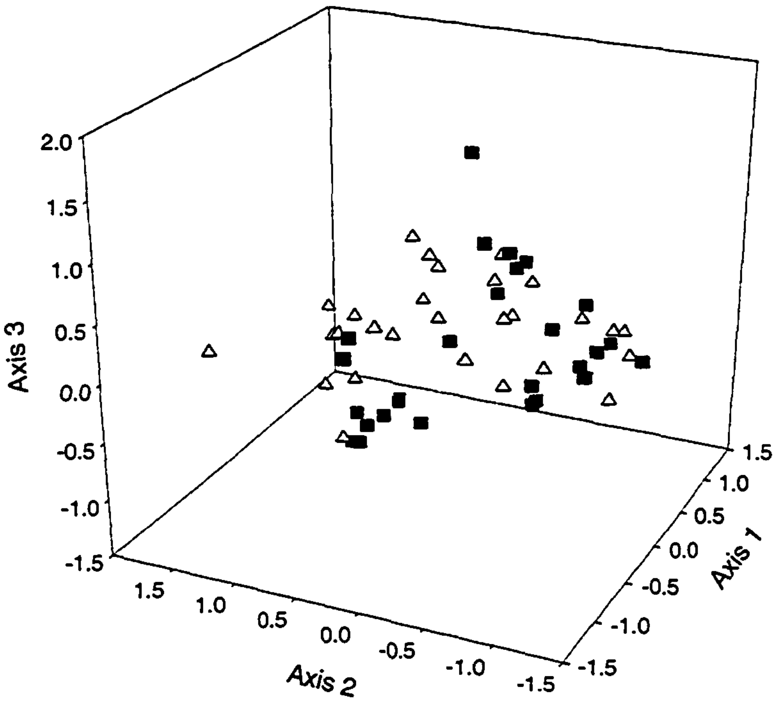

Fig. 3.9. Non-metric Multidimensional Scaling of quadrats in species space for Tall Shrub – Herb communities. Distances matrix was created using Sørensen distance, from untransformed cover data for all vascular plant species occurring in >5% of quadrats. Three dimensional solution with significant (p=0.005) reduction in stress from randomized data, tested using 999 Monte Carlo permutations. Total variance captured = 85.4%; proportion of variance represented by: Axis 1=0.175, Axis 2=0.447, Axis 3=0.232. Final stress = 11.53, Final Instability = 0.00018. Original distance matrix was composed of 56 quadrats and 27 species.

Symbols: triangles are quadrats from seismic lines; squares are quadrats from undisturbed tundra.

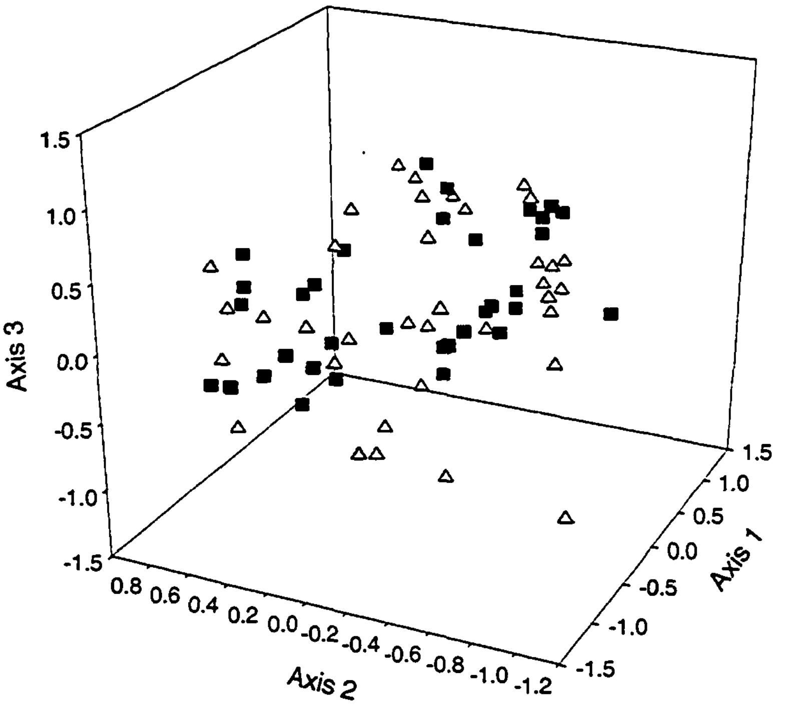

Fig. 3.10. Non-metric Multidimensional Scaling of quadrats in species space for Wet Graminoid communities. Distances matrix was created using Sørensen distance, from untransformed cover data for all vascular plant species occurring in >5% of quadrats. Three dimensional solution with significant (p=0.001) reduction in stress from randomized data, tested using 999 Monte Carlo permutations. Total variance captured = 89.6%; proportion of variance represented by: Axis 1=0.540, Axis 2=0.193, Axis 3=0.163. Final stress = 12.22, Final Instability = 0.00271. Original distance matrix was composed of 72 quadrats and 13 species.

Symbols: Triangles are quadrats from seismic lines; squares are quadrats from undisturbed tundra.

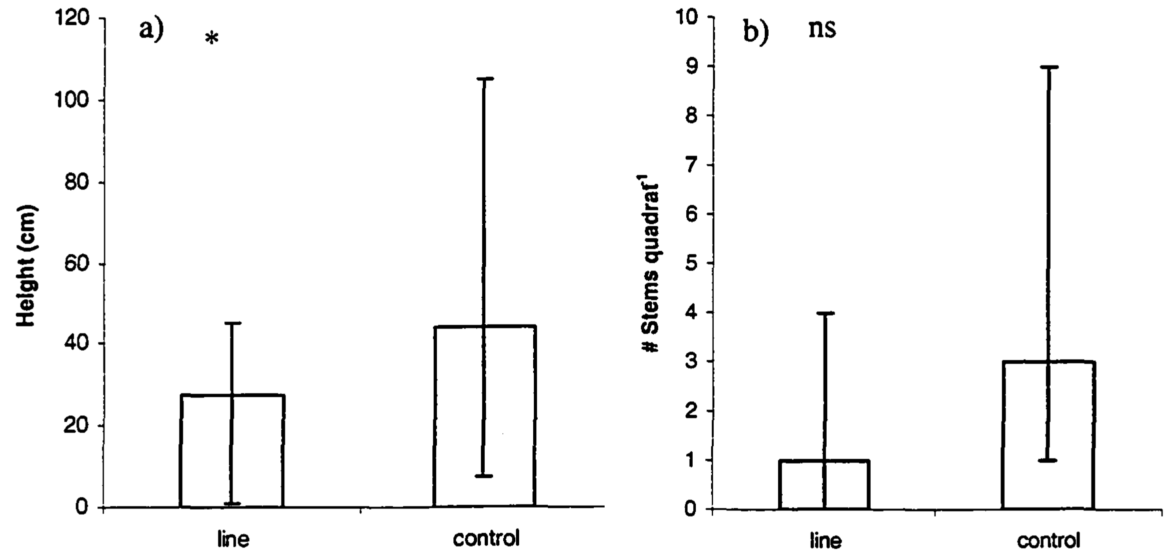

Fig. 3.11. Effect of recent seismic on a) height and b) stem density of *Alnus crispa* in Medium Shrub – Heath and Low Shrub – Heath communities. Bars are median height or stem number ± 95% CLs, not assuming normality. Results are from Wilcoxon 2-Sample tests, with a one tailed hypothesis of greater height and stem density at controls. *significant difference between treatments at $p<0.05$, ^{ns} not significant. Sample size = 5 (seismic) and 7 (control).

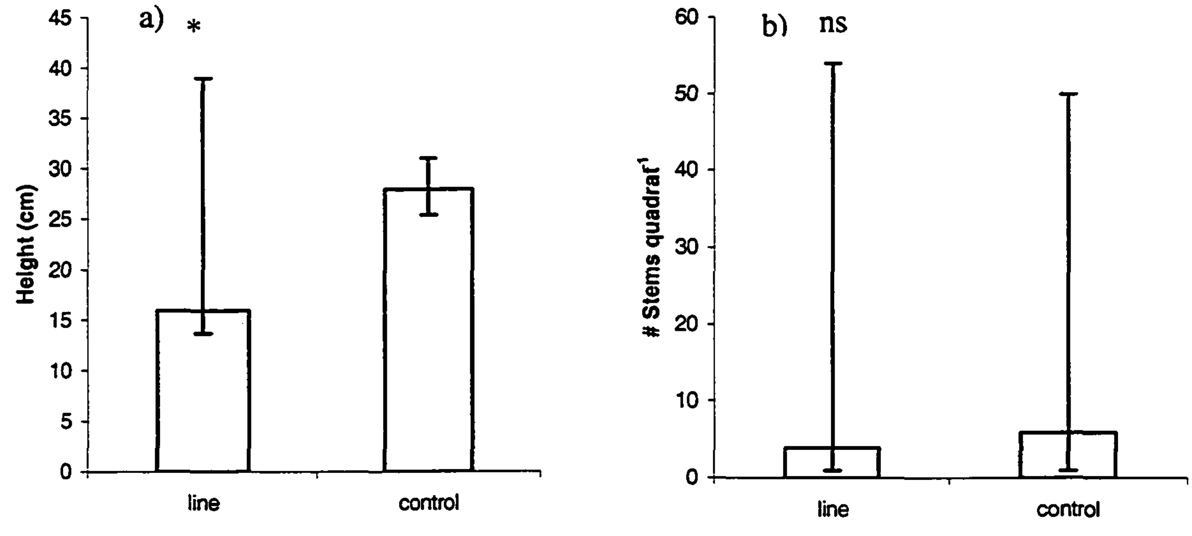

Fig. 3.12. Effect of recent seismic on a) height and b) stem density of *Salix glauca* in Medium Shrub – Heath and Low Shrub – Heath communities. Bars are median height or stem density ± 95% CLs not assuming normality. Results are from Wilcoxon 2-Sample tests, with a one tailed hypothesis of greater height and density at controls. *significant difference between treatments ($p<0.05$), ^{ns} not significant. Sample Size = 7 (seismic) and 9 (control).

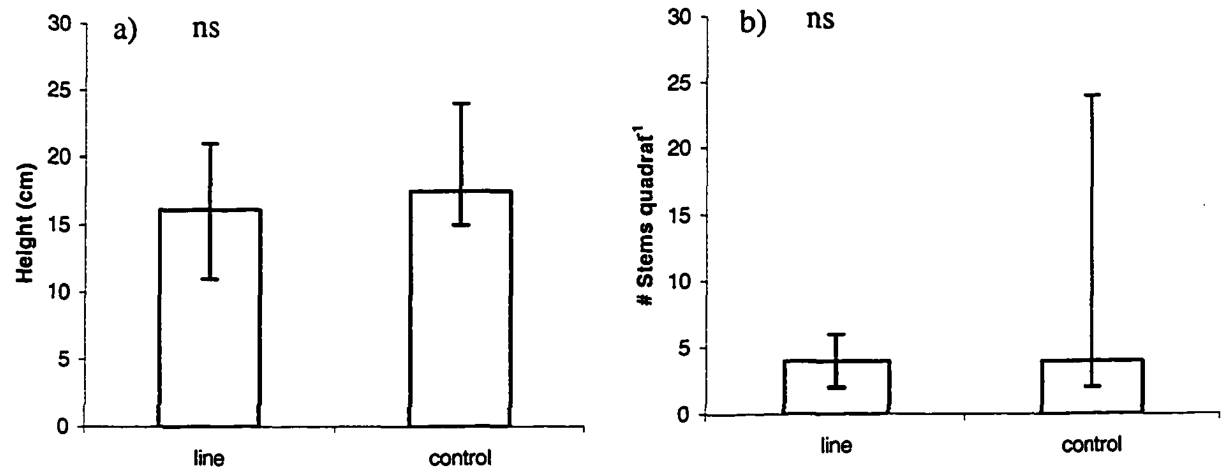

Fig. 3.13. Effect of recent seismic on a) height and b) stem density of ***Betula glandulosa*** in Medium Shrub – Heath and Low Shrub – Heath communities. Bars are median height or stem density ± 95% CLs not assuming normality. Results are from Wilcoxon 2-Sample tests, with a one tailed hypothesis of greater height and density at controls. ^{ns} not significant. Sample Size = 19 (seismic) and 22 (control).

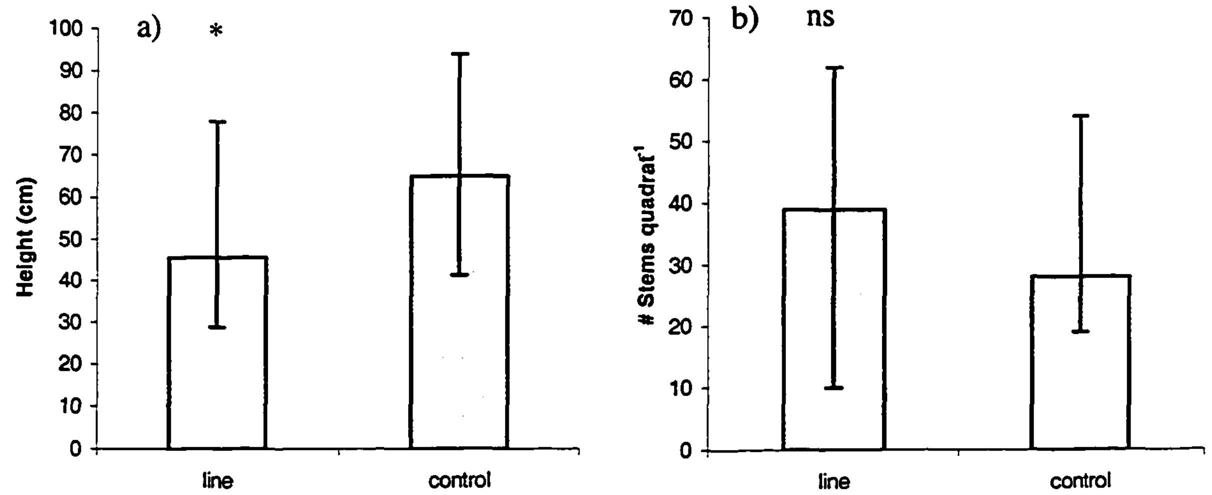

Fig. 3.14. Effect of recent seismic on a) height and b) stem density of *Salix lanata* in Tall Shrub –Herb communities. Bars are median height or stem density ± 95% CLs not assuming normality. Results are from Wilcoxon 2-Sample tests, with a one tailed hypothesis of greater height and density at controls. *significant difference between treatments ($p<0.05$) ^{ns} not significant. Sample Size = 28 (seismic) and 28 (control).

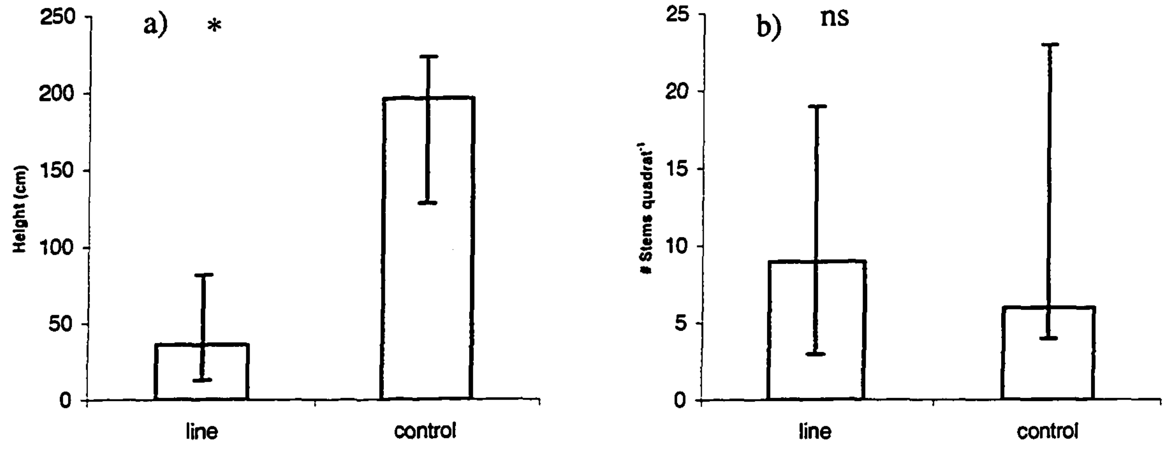

Fig. 3.15. Effect of recent seismic on a) height and b) stem density of *Alnus crispa* in Tall Shrub – Herb communities. Bars are median height or stem density ± 95% CLs not assuming normality. Results are from Wilcoxon 2-Sample tests, with a one tailed hypothesis of greater height and density at controls. *significant difference between treatments ($p<0.05$) ^{ns} not significant. Sample Size = 5

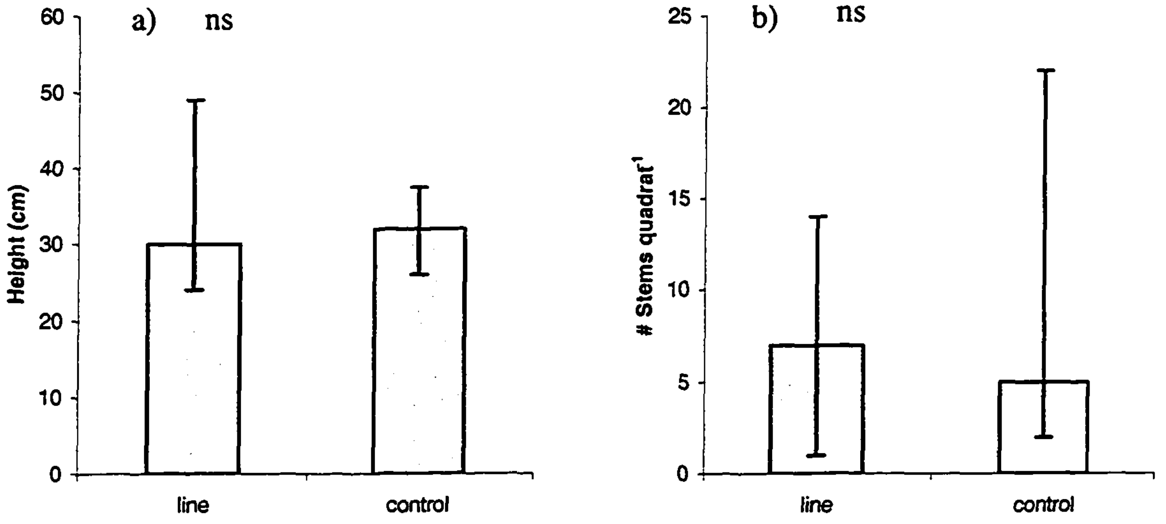

Fig. 3.16. Effect of recent seismic on a) height and b) stem density of *Salix lanata* in Wet Graminoid communities. Bars are median height or stem density ± 95% CLs not assuming normality. Results are from Wilcoxon 2-Sample tests, with a one tailed hypothesis of greater height and density at controls. ^{ns} not significant. Sample Size = 8 (seismic) and 12 (control).

Chapter 4: Vegetation of selected low arctic plant communities 18-33 years following winter seismic exploration

Introduction:

Industrial anthropogenic disturbance is a relatively new phenomenon in the arctic. As such, there is relatively little information regarding the long-term dynamics of vegetation recovery following these disturbances. It had been suggested that secondary succession following anthropogenic disturbance in low arctic sites should be complete within five to ten years (Webber and Ives 1978), however the end point of this succession is not entirely clear. Some authors have suggested that, while revegetation may be complete within a 10 year period, successional inhibition (*sensu* Connell and Slatyer 1977) may delay the return to a natural vegetation state by 50 to 100 years due to the slow ingress of seeds (and poor success thereafter) from some evergreen shrub species (Cargill and Chapin 1987). Inhibition has been directly reported in some studies of low arctic disturbances (Ebersole 1987) and suggested in the meta-data of others (Forbes *et al* 2001).

Based on a review of available studies, Walker *et al* (1987) proposed several potential outcomes of secondary succession following disturbance in arctic tundra and related these to the intensity of the initial disturbance and its immediate effects on substrates. In one state of recovery termed “complete recovery with succession” the substrates are not *permanently* changed and the plant community eventually recovers to a completely natural condition (Walker *et al* 1987). Alternatively, if the magnitude of the initial disturbance exceeds the resilience threshold of the vegetation and the substrates are *severely* changed succession would proceed to either a state of “positive functional recovery" whereby the original plant community does not return but the productivity of the system is equal to, or greater than the system it replaced, or "negative functional recovery" where the new community remains compositionally dissimilar and is also less productive than undisturbed tundra (Walker *et al* 1987).

Unfortunately most studies of low arctic disturbances to date have been of a short- to medium-term nature, with few follow up investigations of longer-term secondary succession. In one notable exception Vavrek *et al* (1999) re-examined a disturbance previously studied by Chapin and Chapin (1980) and provided evidence to suggest that short to medium term observations of tundra vegetation were indeed inadequate to assess the final outcome of succession following anthropogenic disturbance. In that instance, observations 7-10 years post disturbance (Chapin and Chapin 1980) indicated that the site had recovered to natural levels of productivity, despite altered species composition, while observations 23 years post disturbance (Vavrek *et al* 1999) indicated that productivity was then significantly *greater* than undisturbed tundra, while species diversity remained lower. It appears, therefore, that measurements made in the first decade of recovery can be potentially misleading, and that longer-term investigations are necessary to properly determine the post-disturbance status of low-arctic plant communities, where secondary succession may take considerably longer than Webber and Ives (1978) originally suspected.

In one of the only available studies to include decades-old seismic lines, Chapin and Shaver (1981) studied several vehicle trails of varying ages, including a 25 year old summer seismic line which was characterized by an increase in primary productivity and decreases in species richness coinciding with a wholesale change in species composition. In this instance the typical upland community of the undisturbed tundra was replaced by wetland graminoid species because the initial disturbance led to thermokarst and an altered (wetter) hydrologic state (Chapin and Shaver 1981). The importance of a stable physical system, in particular the recovery of thermal equilibrium (permafrost), for natural revegetation has been emphasized by several authors (Lawson 1986; Walker *et al* 1987, Walker and Walker 1991; Shirazi *et al* 1998).

Impacts from winter seismic lines are typically thought to be substantially less than those reported from summer lines by Chapin and Shaver (1981), as damage to permafrost and hydrology are usually substantially less than in summer seismic disturbances (Bliss and Wein 1972; Hernandez 1973). The majority of studies investigating the first phases of arctic winter seismic exploration in the 1970s concluded that the effects would be short term (Bliss and Wein 1972; Hernandez 1973) or primarily aesthetic (Reynolds 1982). Initial impacts to the vegetation were often quite severe, however, especially during the earliest period of exploration where the soil organic layer was bulldozed aside during surveys (Bliss and Wein 1972). Disturbance to the soil organic layer can be of particular importance to the rate and outcome of revegetation (Forbes *et al* 2001), as this layer contains the rhizomes, seed bank (Gartner *et al* 1983; Ebersole 1989), and soil nutrients (Bliss and Wein 1972; Cargill and Chapin 1987) essential to recovery of a natural vegetation state.

Studies which have examined short to medium term impacts of winter seismic lines or vehicle tracks from the 1970s and 1980s (the period in which the disturbances in the current study were created) typically found that some groups of species were more susceptible to damage than others. Heaths, lichens and mosses were often shown to be most adversely affected (Hernandez 1973; Felix and Raynolds 1989), and slowest to recover (Emers *et al* 1995), while graminoids often responded with increases in abundance following disturbance (Bliss and Wein 1972; Hernandez 1973; Chapin and Shaver 1981). Whether or not these impacts have persisted through longer periods of time has not been adequately addressed.

Given that ~30 years have now passed since the earliest arctic winter seismic programs were conducted, there is now an opportunity to examine their longer-term consequences. In addition, the accumulation of seismic activity over the past 30 years provides the opportunity for greater replication and examination of lines from a variety of dates and programs. In this chapter I present a broad survey of seismic lines from a variety of programs ranging from 18 to 33 years post disturbance. My objectives were to: 1) assess the resilience of selected upland tundra plant communities to winter seismic exploration by comparing vegetation of undisturbed tundra to that along seismic lines several years after seismic exploration, 2) determine whether any long-term changes in soil and permafrost properties have occurred along winter seismic lines, and 3) re-evaluate the hypothesis of rapid secondary succession and short term impacts along winter seismic lines.

Methods and Materials:

Site Selection and Sampling

The study area is identical to that presented in Chapter 2. The scope of this study, however, was limited to the two upland community types, Medium Shrub – Heath (MSH), and Low Shrub – Heath (LSH) (Chapter 2). Sites were selected from a list of sites visited by Ashenhurst (2004). The choice of sites from this list was limited to those for which National Energy Board (NEB) data existed which positively identified the disturbance as a seismic line that could be attributed to a given geophysical program and year. Because there is no database of *precise* geographic locations of seismic lines the choice of sites was further limited to seismic lines which could be visually detected, either on the ground or from the air. Thus the impacts I report only apply to such lines. However, much effort was undertaken to include seismic lines which were barely visible. This most often involved spending considerable time locating a line on the ground which could easily be seen from the air; this was accomplished by having a helicopter hover over the line to assist a ground crew in determining the boundaries of a seismic line. It was also possible to verify sampling locations on barely detectable seismic lines by the presence of survey stakes, shot holes, or wire. The time since disturbance for the selected seismic lines ranged from 18 to 33 years. Sites were chosen to reflect a roughly equal number of samples of the plant community types [7 sites (32 quadrats total) in Medium Shrub – Heath; and 6 sites (36 quadrats total) in Low Shrub – Heath].

Sampling of vegetation, soils and permafrost was identical to that presented in Chapter 3.

Analysis:

The two community types were analyzed separately. The analyses of soil and vegetation properties were conducted as in Chapter 3, using mixed linear models when possible, and Wilcoxon Signed Rank tests where necessary. The mixed linear models used to analyze these data were identical to those presented in Chapter 3 and are given by equations [3.1] and [3.2]. Similar selection criteria, relying on Akaike's Information Criterion, were applied to these models. I used identical mixed linear models to test for differences in abundance for four functional groups: deciduous shrubs, heaths, graminoids, and herbs. Wherever mixed linear models were used to test fixed (treatment) effects, general linear models (GLMs) were used to test the associated random effects, as the random effects test in PROC MIXED does not provide adequate results as compared to PROC GLM (Littell *et al* 1996).

Non-metric MRPP tests and Indicator Species Analyses were used to examine variation in species composition following the same procedures outlined in Chapter 3. Ordinations were constructed from a data matrix of 32 quadrats x 27 vascular species in MSH communities, and 36 quadrates x 29 vascular species in LSH communities. Data screening and ordination procedures were also identical to those used in Chapter 3.

Results:

Soils and Permafrost

Most soil and permafrost properties appeared to have recovered to an approximately natural (pre-disturbance) condition along older winter seismic lines. Neither thaw depth nor thickness of the soil organic layer along seismic lines were significantly different from undisturbed tundra in either of the community types (Table 4.1, Fig. 4.1, Fig. 4.2) There was, however, significantly higher cover of bare ground along seismic lines than at controls for both community types (Table 4.1, Fig. 4.3). In both instances the median difference was close to zero, however there were quadrats along seismic lines with as much as 4-6% cover of bare ground. Average cover of bare ground along seismic lines was 1.88% in the Medium Shrub – Heath (MSH) communities and 2.72% in the Low Shrub – Heath (LSH) communities compared to less than 0.5% in undisturbed tundra for both communities.

Vascular Plants

Vascular plant cover was significantly higher along seismic lines than in undisturbed tundra in Low Shrub – Heath communities (Table 4.2, Fig. 4.4). A similar response was measured in Medium Shrub – Heath communities (Fig 4.4), where vascular plant cover averaged 98.88% along seismic lines and 80.78% in undisturbed tundra. In this case however the effect was only marginally statistically significant ($p = 0.09$; Table 4.2). The increase in vascular plant cover was consistent across all sites, regardless of age, in the LSH communities and at all but one site in the MSH communities. In both the MSH and LSH communities the cover of deciduous shrubs was significantly higher along seismic lines than in undisturbed tundra, while the cover of heaths, graminoids, and herbs, was unaffected (Table 4.3, Fig. 4.5).

Diversity of vascular plant species did not differ significantly between seismic lines and controls in either community type (Table 4.2, Fig. 4.6), although average Shannon-Index values were slightly lower for seismic lines in both. Richness of vascular plant species per plot also showed no significant differences between seismic lines and undisturbed tundra, irregardless of community type (Table 4.2, Fig. 4.7). In the Low Shrub – Heath communities there was a significant treatment*site interaction for both diversity and richness. Examination of these interactions did not reveal any consistent patterns which could be related to other site or vegetation characteristics. Most sites showed no strong differences in either diversity or richness, however one site had higher richness and diversity values along seismic lines, while one site had lower values of these indices on seismic lines.

Non-Vascular Plants

Total cover of mosses was not significantly different on seismic lines in Medium Shrub – Heath communities, but in Low Shrub – Heath communities was significantly less on seismic lines than on undisturbed tundra (Table 4.2, Fig. 4.8). In the LSH communities total moss cover averaged 56.28% in undisturbed communities and 38.83% along seismic lines.

Lichen cover was significantly lower along seismic lines in both community types (Table 4.2, Fig. 4.9). In the Medium Shrub – Heath communities there was a median decrease of 8% cover of lichens, while in the Low Shrub – Heath the median difference was –6% cover. In both community types the median difference represented a ~50% reduction in total lichen abundance compared to undisturbed tundra

Dead Shrubs

There was no difference in the cover of standing dead shrubs along seismic lines compared to undisturbed Medium Shrub – Heath communities (Table 4.2, Fig 4.10). In the Low Shrub – Heath communities there was a small but statistically significant increase in cover of dead shrubs compared to undisturbed tundra (Table 4.2, Fig. 4.10). In this community type the median increase in dead shrub cover was 0%, and is likely not biologically relevant, however the results were significant because the lower 95% confidence limit was also zero.

Community Composition

Despite the observed increase in total vascular plant and deciduous shrub cover there appeared to be few differences in overall plant community composition along old seismic lines compared to undisturbed sites.

Ordinations

Ordination using NMS Autopilot in PC-ORD selected a three dimensional solution as providing the best reduction in stress over randomized data for both the Medium Shrub –

Heath and Low Shrub – Heath community types. Final Stress for the ordination solutions was 13.55 in the MSH and 12.73 in the LSH community types, and stable solutions were reached for both types. The first three axes captured 82.3% of community variation in the MSH community type, and 85.4% of community variation in the LSH. The final NMS ordinations of quadrats in species space did not reveal any detectable separation between quadrats from seismic lines *versus* undisturbed tundra for either the MSH (Fig 4.11) or LSH (Fig. 4.12) communities.

MRPP

The non-metric MRPP tests also showed no significant difference in community composition between seismic lines and undisturbed sites for either community type (Table 4.4).

Indicator Species Analysis

Indicator species analysis revealed species which were both positively and negatively associated with seismic lines (Table 4.5). In the Medium Shrub – Heath communities *Betula glandulosa* was found to be a significant indicator of seismic lines due increased abundance (despite high quadrat frequency in both seismic *and* control groups). In the Low Shrub – Heath type communities *Saussurea angustifolia* was negatively associated with seismic lines, with reduced abundance and quadrat frequency along these disturbances, while *Arctagrostis latifolia* was found to be positively associated with seismic disturbance (Table 4.5).

Discussion:

Secondary succession along seismic lines over 18 to 33 years in the study area has resulted in functional plant communities, as well as soil and permafrost characteristics that are generally not distinguishable from undisturbed tundra. The outcome of this succession fits somewhere between the 'complete recovery with succession' and 'positive functional recovery' states proposed by Walker *et al* (1987), in that the substrates and vascular plant communities are quite similar to surrounding undisturbed tundra, but the plant communities appear to have higher productivity, increased abundance of one functional group (deciduous shrubs) and lower abundance of lichens, and mosses (in the Low Shrub – Heath community only).

The ordination and MRPP results show that the vascular plant communities re-establishing over 18 to 33 years following disturbance by winter seismic exploration are not substantially different in composition than those of undisturbed tundra. Nevertheless, there was a significantly greater cover of deciduous shrubs along these old seismic lines, as well as significantly lower cover of lichens in both communities, and mosses in the Low Shrub – Heath community. The increased cover of deciduous shrubs did not occur at the expense of other vascular plant groups but drove an overall increase in plant cover. This suggests that, although the successional communities are compositionally similar, there is more vertical layering of vegetation along seismic lines. In addition, the abundance of lichens was lower on seismic lines in both community types, and moss abundance was lower on seismic lines than controls in the Low Shrub – Heath communities. Although the plant communities along old seismic lines were not *greatly* different from those of undisturbed tundra, the higher abundance of deciduous shrubs on seismic lines may affect the quality of these sites as habitat for ground nesting birds, as well as the availability of, and access to, lichen forage for ungulates. Although lichens remain present in these communities, the higher shrub cover may potentially affect the use of this resource by the caribou and semi-domestic reindeer herds in the area, through changes in the perceived patch quality of older seismic lines, stemming from higher snow cover in winter, or greater expenditure to locate and browse lichens through a relatively dense shrub 'canopy'.

The increased deciduous shrub cover is also most likely responsible for the visible signature of older seismic lines on the landscape. Although most of these disturbances were quite difficult to detect on the ground without prior knowledge of their location they were readily visible from the air (120-300m a.g.l). Aerial surveys conducted in 2003 and 2004 showed that more than 90% of older seismic lines in upland habitats were visible to some degree (Kemper *unpublished data*).

The increase in total vascular plant cover measured in both communities was largely due to increases in the cover of deciduous shrubs, although there were also small increases in the cover of some grasses. This concurs with the review of Forbes *et al* (2001), who reported that the abundance of deciduous shrubs is often higher in low arctic tundra recovering from vehicle tracks, although he found that this typically resulted in lower cover of other species. In the case of my study the increased productivity of deciduous shrubs did not appear to cause declines in the abundance of other vascular species. Indeed the lack of differences in the cover of heaths, graminoids, and herbs between seismic lines and undisturbed tundra in both communities suggests that successional inhibition by these shrubs, as proposed by Cargill and Chapin (1987), has not played a major role in determining the community composition of these sites.

In the Medium Shrub – Heath communities the increase in deciduous shrub cover was attributable primarily to *Betula glandulosa*, and to a lesser extent *Alnus crispa*, and *Salix* species. Although *B. glandulosa* was identified as a significant indicator of old seismic lines, the term ‘indicator species’ should be applied with caution, as the quadrat frequency for this species was high on both seismic lines and undisturbed areas. The significant result for *B. glandulosa* in the Indicator Species Analysis appears to have arisen from the higher cover of this species on seismic lines relative to controls, rather than an increase in quadrat frequency. Bret-Harte *et al* (2001) demonstrated, in experimental fertilization and warming trials, that *Betula* is capable of outcompeting other native tundra species through light limitation, via increases in the rate of branching and production of new meristems. It is possible that *B. glandulosa* individuals that survived the initial disturbance by seismic vehicles were similarly able to exploit an associated release from competition for soil nutrients, and increase production of above ground tissues.

The positive association of *Arctagrostis latifolia* with seismic lines in Low Shrub – Heath communities is not surprising. *Arctagrostis* has been reported to increase in abundance on low arctic disturbances across the circumpolar north (Bliss and Wein 1972; Hernandez 1973; Komárková 1983; Ebersole 1987; Ebersole 1989; Sumina 1994). Although the average cover of *A. latifolia* was increased by less than 3%, the quadrat frequency of this species was nearly double on seismic lines. At some sites along seismic lines there were small patches (usually less than $1 m^2$) of dense growth of *Arctagrostis* which may represent highly disturbed microsites. *Arctagrostis* is typically thought to be dependant on seed rain for colonization, as it is usually not present in the seed bank (Ebersole 1989), yet it is often an important post-disturbance colonizer, particularly of drier microsites (Bliss and Wein 1972; Emers *et al* 1995). In this instance it is possible that *Arctagrostis* has been successful in colonizing, and persisting, on those areas where the moss cover and organic mat were initially damaged to the extent that drier mineral soils were exposed. The persistence of *A. latifolia* on older disturbances has been reported elsewhere, and has been attributed its ability to compete for nutrients in an enriched environment (Komárková 1983), and to subsequently inhibit other colonists (Emers *et al* 1995).

The increase in *total* vascular plant cover along seismic lines indicates increased primary productivity at these sites, which suggests an altered resource state. Increases in primary productivity have been reported elsewhere in tundra disturbance studies (Chapin and Shaver 1981; Hernandez 1973; Vavrek *et al* 1999), and have traditionally been thought to be associated with hydrologic changes, accelerated nutrient cycling (Rickard and Brown 1974; Chapin and Shaver 1981; Abele *et al* 1984; Truett and Kertell 1992), or feedbacks arising from changes in the community composition (Chapin and Shaver 1981). Because there was no apparent thermal erosion at any of the sites in this study changes in the hydrologic status cannot be implicated as the cause of any increased plant cover measured along seismic lines.

Increased nutrient availability is often thought to be associated with the compression of standing dead or living plant matter into the soil (Abele *et al* 1984; Rickard and Brown 1974), along with increased soil temperature (Chapin and Shaver 1981), which together result in increased rate of decomposition. As such, the higher vascular plant cover I observed along seismic lines could be due to an increase in the rate of decomposition (the duration of which is uncertain), resulting from compression of live and dead plant matter into contact with soils immediately post disturbance.

Alternatively, if species were initially able to exploit an increase in active layer depth to capture nutrients in areas of the soils horizon that were previously permanently frozen, these additional nutrients could also have contributed to the increase in productivity along seismic lines. Chapin and Shaver (1981) reported that some graminoid species (*Calamagrostis canadensis* and *Eriophorum angustifolium*) were able to exploit deeper and recently thawed soil horizons following disturbance, while others (*Eriophorum vaginatum*) were not. Although I did not measure any differences in thaw depth along older seismic lines, it is reasonable to assume that the depth to permafrost must have initially increased along these seismic lines, given the results of Bliss and Wein (1972) and Hernandez (1973), who studied seismic disturbances in the nearby area during the same period in which the lines I studied here were created, and reported increases in active layer depth.

The decline in lichen abundance along seismic lines may be due their initial sensitivity to disturbance (e.g. Felix and Raynolds 1989), their slow growth (and recovery) rate (Brodo *et al* 2001), or competition and shading from other species. Cornelissen *et al* (2001) demonstrated that increasing the nutrient status and temperature of low arctic vegetation resulted in decreased abundance of lichens because of increased shading from vascular plants, which increased in cover. Given the greater shrub cover along seismic lines in this study, it seems possible that such mechanisms might be at play here, and that lichen abundance may not recover to levels of undisturbed tundra. Given the faster growth rate, and greater phenotypic plasticity (Bret-Harte *et al* 2001) of deciduous shrubs, it seems likely that the dominance of deciduous shrubs in these communities may persist, with predictably negative effects on lichens. Interactions with a warming climate may also be important: increased dominance by deciduous shrubs under warmer climatic conditions or higher nutrient availability has been well documented (Chapin *et al* 1995; Bret-Harte *et al* 2001), and might be expected to occur in this area if current climate forecasts are accurate. What effects future disturbances would have under this scenario are uncertain, however it has been suggested that the recovery to "pre-disturbance" plant communities in the arctic might not occur, as the 'natural' undisturbed community structure is itself an artifact of past climatic conditions (Webber and Ives 1978).

Although they bear strong resemblance to undisturbed plant communities, the post-disturbance plant communities along 18-33 year old seismic lines are clearly different in some respects. To my knowledge this is the first documentation of such changes from winter seismic lines, over these periods of time. The increase in deciduous shrub cover and decrease in lichen cover along seismic lines, despite the lack of persistent differences in organic layer depth and permafrost conditions, suggests that biotic interactions have played an important role in determining the composition of plant communities on these sites, and that stabilization of thermal conditions after a disturbance may not be sufficient to guarantee the return of a natural vegetation state in periods of less than 30 years.

Literature Cited:

Abele, G., Brown, J., and M.C. Brewer. 1984. *Long-term effects of off-road vehicle traffic on tundra terrain.* Journal of Terramechanics 21:283-294

Ashenhurst, A.R. 2004. *The effects of seismic lines and drill pads on breeding migratory birds in the Kendall Island Migratory Bird Sanctuary, N.W.T.* MSc thesis, University of Alberta, Edmonton, AB. 79pps

Bliss, L.C., and R.W. Wein. 1972. *Plant community responses to disturbances in the western Canadian Arctic.* Canadian Journal of Botany 50:1097-1109

Bret-Harte, M.S., Shaver, G.R., Zoerner, J.P., Johnstone, J.F., Wagner, J.L, Chavez, A.S., Gunkelman, F.F.IV, Lippert, S.C., and J.A. Laundre. 2001. *Developmental plasticity allows* Betula nana *to dominate tundra subjected to an altered environment.* Ecology 82:18-32

Brodo, I.M., Sharnoff, S.D., and S. Sharnoff. 2001. *Lichens of North America.* Yale University Press, New Haven, NJ.

Cargill, S.M., and F.S. Chapin III. 1987. *Application of successional theory to tundra restoration: a review.* Arctic and Alpine Research 19:366-372

Chapin, F.S. III, and M.C. Chapin. 1980. *Revegetation of an arctic disturbed site by native tundra species.* Journal of Applied Ecology 17:449-456

Chapin, F.S. III, and G.R. Shaver. 1981. *Changes in soil properties and vegetation following disturbance of Alaskan arctic tundra.* Journal of Applied Ecology 18:605-617

Chapin, F.S. III, Shaver, G.R., Giblin, A.E., Nadelhoffer, K.J., and J.A. Laundre. 1995. *Responses of arctic tundra to experimental and observed changes in climate.* Ecology 76:694-711

Connell, J.H., and R.O. Slatyer. 1977. *Mechanisms of succession in natural communities and their role in community stability and organization.* American Naturalist 111:1119-1144

Cornelissen, J.H.C., Callaghan, T.V., Alatalo, J.M., Michelsen, A., Graglia, E., Hartley, A.E., Hik, D.S., Hobbie, S.E., Press, M.C., Robinson, C.H., Henry, G.R.H., Shaver, G.R., Pheonix, G.K., Gwynn Jones, D., Jonasson, S., Chapin, F.S.III., Molau, U., Neill, C., Lee, J.A., Melillo, J.M., Sveinbjornsson, and R. Aerts. 2001. *Global change and arctic ecosystems: is lichen decline a function of increases in vascular plant biomass?* Journal of Ecology 89:984-994

Ebersole, J.J. 1987. *Short-term vegetation recovery at an Alaskan arctic coastal plain site.* Arctic and Alpine Research 19:442-450

Ebersole, J.J. 1989. *Role of the seed bank in providing colonizers on a tundra disturbance in Alaska.* Canadian Journal of Botany 67:466-471

Emers, M., Jorgenson, J.C., and M.K. Raynolds. 1995. *Response of arctic tundra plant communities to winter vehicle disturbance.* Canadian Journal of Botany 73:905-917

Felix, N.A., and M.K. Raynolds. 1989. *The effects of winter seismic exploration on tundra vegetation in northeastern Alaska, U.S.A.* Arctic and Alpine Research 21:188-202

Forbes, B.C., Ebersole, J.J., and B. Strandberg. 2001. *Anthropogenic disturbance and patch dynamics in circumpolar arctic ecosystems.* Conservation Biology 15:954-969

Gartner, B.L., Chapin, F.S.III., and G.R. Shaver. 1983. *Demographic patterns of seedling establishment and growth of native tundra graminoids in an Alaskan tundra disturbance.* Journal of Applied Ecology 20:965-980

Hernandez, H. 1973. *Natural plant recolonization of surficial disturbances, Tuktoyaktuk Peninsula region, Northwest Territories.* Canadian Journal of Botany 51:2177-2196

Komárková, V. 1983. *Recovery of plant communities and summer thaw at the 1949 Fish Creek Test Well 1, arctic Alaska. In*: Permafrost: Fourth International Conference, Proceedings. National Academy Press, Washington. pp. 645-650

Lawson, D.E. 1986. *Response of permafrost terrain to disturbance: a synthesis of observations from northern Alaska, U.S.A.* Arctic and Alpine Research 18:1-17

Littell, R.C., Milliken, G.A., Stroup, W.W., and R.D. Wolfinger. 1996. *SAS System for mixed models.* SAS Institute Inc., Cary, NC.

Rickard, W.E., and J. Brown. 1974. *Effects of vehicles on arctic tundra.* Environmental Conservation 1:55-62

Reynolds, P.C. 1982. *Some effects of oil and gas exploration activities on tundra vegetation in northern Alaska.* pps 403-417 *In*: Rand, P.J. (*Ed.*): Land and Water Issues Related to Energy Development. Ann Arbor Science, Ann Arbor Michigan

Shirazi, M.A., Haggerty, P.K., Hendricks, C.W., and M. Reporter. 1998. *The role of thermal regime in tundra plant community restoration.* Restoration Ecology 6:111-117

Sumina, O.L. 1994. *Plant communities of anthropogenically disturbed sites on the Chukotka Peninsula, Russia.* Journal of Vegetation Science 5:885-896

Truett, J.C. and K. Kertell. 1992. *Tundra disturbance and ecosystem production: implications for impact assessment.* Environmental Management 16:485-494

Vavrek, M.C., Fetcher, N., McGraw, J.B., Shaver, G.R., Chapin, F.S.III, and B. Bovard. 1999. *Recovery of productivity and species diversity in tussock tundra following disturbance.* Arctic, Antarctic, and Alpine Research 31:254-258

Walker, D.A., and M.D. Walker. 1991. *History and pattern of disturbance in Alaskan arctic terrestrial ecosystems: a hierarchical approach to analyzing landscape change.* Journal of Applied Ecology 28:244-276

Walker, D.A., Cate, D., Brown, J., and C. Racine. 1987. *Disturbance and recovery of arctic Alaskan tundra terrain: A review of recent investigations.* CCREL Report 87-11. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Webber. P.J., and J.D. Ives. 1978. *Damage and recovery of tundra vegetation.* Environmental Conservation 5:171-182

Table 4.1. Long term effects of winter seismic exploration on soil and permafrost properties in a) Medium Shrub – Heath type communities, and b) Low Shrub – Heath type communities. Treatment (seismic) effects are from mixed linear models for organic layer depth and thaw depth, and from Wilcoxon Signed Rank tests for bare ground. Random effects results are from general linear models where treatment effects were tested using MLMs. Su= sample unit. S= Wilcoxon Signed Rank statistic. Fixed effect *p*= probability of Type I error for H_0: no difference between seismic and control

a) Medium Shrub – Heath communities

	Bare ground (% cover)			Organic Layer Depth			Thaw depth		
	n	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
Treatment	16	-13	**0.0313**	1,15	0.54	0.4722	1,24.3	1.72	0.2026
Site				6,9	8.03	**0.0033**	6,9	5.96	**0.0092**
T*Site				6,9	2.50	0.1050	6,9	2.02	0.1642
Su(Site)				9,9	2.71	0.0765	9,9	1.34	0.3361

b) Low Shrub – Heath communities

	Bare ground (% cover)			Organic Layer Depth			Thaw depth		
	n	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
Treatment	18	-24.5	**0.0177**	1,17	1.53	0.2333	1,17	0.29	0.5946
Site				5,12	28.23	**<0.0001**	5,12	3.86	**0.0275**
T*Site				5,12	1.15	0.3877	5,12	0.63	0.6794
Su(Site)				12,12	4.74	**0.0058**	12,12	1.02	0.4887

Table 4.2. Longer term effects of winter seismic exploration on vegetation properties in a) Medium Shrub – Heath type communities, and b) Low Shrub – Heath type communities. Fixed effect (treatment) results are from mixed linear models or paired Wilcoxon tests (**). Random effects results are from general linear models. T= treatment (seismic line vs. control), Su= sample unit. S= Wilcoxon Signed Rank statistic. Fixed effect *p*= probability of Type 1 error for H_0: no difference between seismic and control.

a) Medium Shrub – Heath communities

	Vascular Cover			Dead Shrub Cover**			Moss Cover**			Lichen Cover**			Spp Richness (vasc)			Spp Diversity (vasc)		
	df	*F*	*p*	*n*	*S*	*p*	*n*	*S*	*p*	*n*	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
T	1,11.4	3.41	0.0909	16	-5.5	0.6914	16	13.5	0.4185	16	47	**0.0052**	1,15	0.54	0.7054	1,15	2.37	0.1445
Site	6,9	2.31	0.1243										6,9	4.18	**0.0276**	6,9	3.49	**0.0456**
T*Site	6,9	2.49	0.1055										6,9	0.42	0.8472	6,9	0.76	0.6202
Su(Site)	9,9	0.36	0.9281										9,9	2.41	0.1029	9,9	2.33	0.1121

b) Low Shrub – Heath communities

	Vascular Cover			Dead Shrub Cover**			Moss Cover			Lichen Cover**			Spp Richness (vasc)			Spp Diversity (vasc)		
	df	*F*	*p*	*n*	*S*	*p*	*df*	*F*	*p*	*n*	*S*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
T	1, 34	6.01	**0.0196**	18	-22.5	**0.0215**	1, 29.2	4.33	**0.0463**	18	47.5	**0.0369**	1,8.5	0.35	0.5682	1,8.5	0.34	0.5778
Site	5,12	0.46	0.7967				5,12	1.62	0.2283				5,12	5.64	**0.0067**	5,12	2.75	0.0704
T*Site	5,12	0.27	0.9222				5,12	0.88	0.5243				5,12	6.16	**0.0047**	5,12	8.89	**0.001**
Su(Site)	12,12	0.83	0.6215				12,12	0.63	0.7838				12,12	2.48	0.0646	12,12	3.89	**0.013**

Table 4.3. Longer term effects of winter seismic exploration on vascular plant cover for different functional groups in a) Medium Shrub – Heath and b) Low Shrub – Heath communities. Fixed effect (treatment) results are from mixed linear models, random effects results are from general linear models. T=treatment, Su=sample unit. Fixed effect p= probability of Type 1 error for H_0: no difference in cover between seismic lines and undisturbed tundra.

a) Medium Shrub – Heath communities

	Deciduous shrubs			Heaths			Graminoids			Herbs		
	df	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*	*df*	*f*	*p*
T	1,15	10.61	**0.0053**	1,24.1	0.00	0.9789	1,15	0.00	0.9605	1,15	0.02	0.8806
Site	6,9	2.66	0.0906	6,9	1.66	0.2372	6,9	5.49	**0.0119**	6,9	0.83	0.5726
T*Site	6,9	1.68	0.2318	6,9	0.81	0.5857	6,9	0.74	0.6307	6,9	0.45	0.8296
Su(Site)	9,9	1.27	0.3636	6,9	0.67	0.7162	9,9	1.98	0.1621	9,9	2.37	0.1076

b) Low Shrub – Heath communities

	Deciduous shrubs			Heaths			Graminoids			Herbs		
	df	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*	*df*	*f*	*p*
T	1,17	4.51	**0.0487**	1,17	0.02	0.8972	1,17	2.18	0.1583	1,29	0.03	0.8677
Site	5,12	2.55	0.0856	5,12	4.28	**0.0182**	5,12	8.52	**0.0012**	5,12	3.33	**0.0409**
T*Site	5,12	1.54	0.2485	5,12	0.76	0.5978	5,12	1.39	0.2965	5,12	1.00	0.4573
Su(Site)	12,12	4.94	**0.0048**	12,12	1.10	0.4338	12,12	3.46	**0.0203**	12,12	0.97	0.5240

Table 4.4. Results of non-metric MRPP tests of community composition comparing seismic lines and undisturbed tundra in Medium Shrub – Heath and Low Shrub – Heath tundra. A= chance corrected within group agreement, P= probability of Type 1 error for H_0: no difference between seismic and control.

Community Type	*A*	*P*
MSH	0.01237	0.259
LSH	0.00159	0.378

Table 4.5. Results of indicator species analysis for disturbed (seismic) and control communities in Medium Shrub – Heath and Low Shrub – Heath tundra. P-values based on 9999 Monte Carlo permutations. Cov= average % cover (when present), Freq = quadrat frequency, IV= Indicator value, P= probability of Type 1 error for H_0: no IV difference between seismic/control groups and randomly allocated groups.

Community Type	Indicator Species	Cover (control)	Cover (seismic)	Freq (control)	Freq (seismic)	IV	P	Treatment Level Indicated
MSH	*Betula glandulosa*	5.68%	11.59%	0.88	1.00	69.7	0.008	Seismic
LSH	*Saussurea angustifolia*	4.29%	1.61%	0.78	0.50	63.0	0.013	Control
	Arctagrostis latifolia	1.88%	4.28%	0.22	0.50	41.8	0.040	Seismic

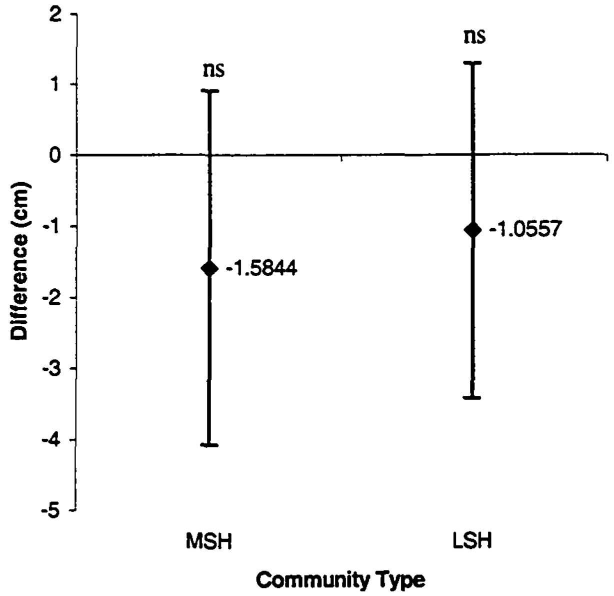

Fig. 4.1. Difference in thaw depth along older seismic lines in Medium Shrub – Heath and Low Shrub – Heath communities as compared to undisturbed tundra. Points are the difference between LSMean thaw depth for the two treatment levels (control – seismic) ±95% CLs; analysis was by mixed linear models. ^{ns} non significant. Mean thaw depth in undisturbed MSH= 20.74cm, in LSH= 28.23cm. n (number of sample units): MSH=16, LSH=18

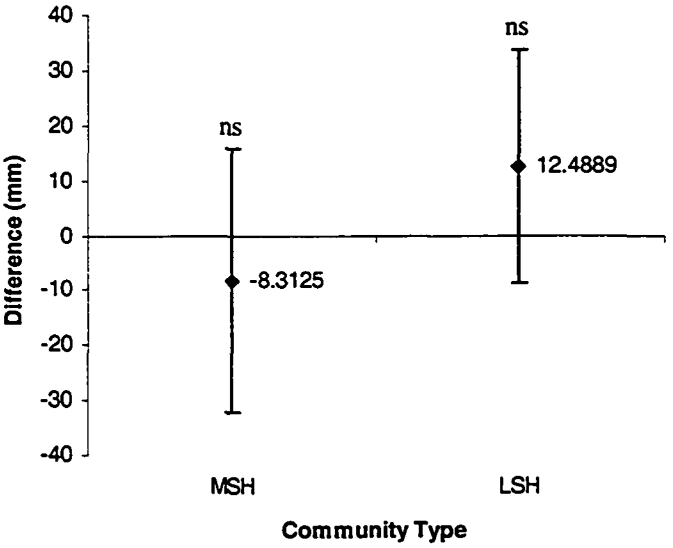

Fig. 4.2. Difference in organic layer depth along older seismic lines in Medium Shrub – Heath and Low Shrub – Heath communities as compared to controls. Points are the difference between LSMean organic layer depth for the two treatment levels (control – seismic) ± 95% CLs; analysis was by mixed linear models. ^{ns} non significant. Mean organic layer depth in undisturbed MSH= 168.69mm, in LSH= 125.52mm. n (number of sample units): MSH=16, LSH=18

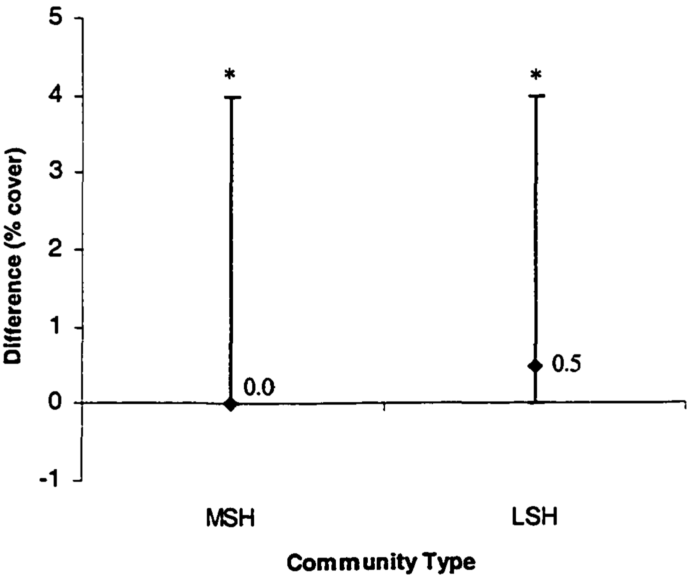

Fig. 4.3. Difference in cover of bare ground along older seismic lines in Medium Shrub -Heath and Low Shrub -Heath communities, as compared to undisturbed tundra. Points are median difference +/- 95% CLs (distribution free); analysis was by Wilcoxon-Signed Rank tests *significant at $p<0.05$. Median bare ground cover in undisturbed MSH= 0.0%, in LSH=0.0%. n (number of sample units): MSH=16. LSH=18

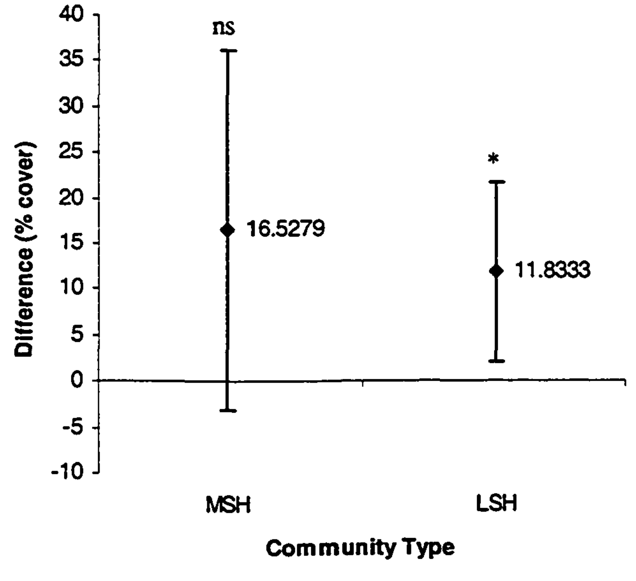

Fig. 4.4. Difference in vascular plant cover along older seismic lines in Medium Shrub – Heath and Low Shrub -Heath communities, as compared to undisturbed tundra. Points are the difference between LSMean vascular plant cover for the two treatment levels (control – seismic) ± 95% CLs; analysis was by mixed linear models. *significant at $p<0.05$, ^{ns}non significant. Mean cover in undisturbed MSH=89.91%, in LSH=78.50%. n (number of sample units): MSH=16, LSH=18

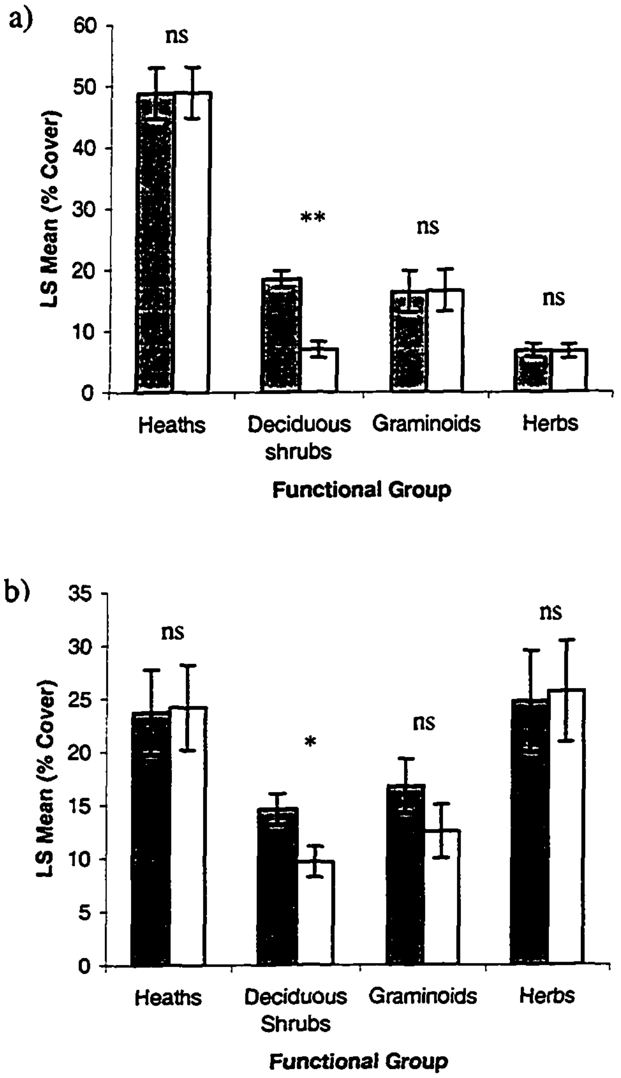

Fig. 4.5. Cover by different plant functional groups along older seismic lines (shaded bars) and in undisturbed tundra (open bars) in a) Medium Shrub – Heath, and b) Low Shrub – Heath communities. Bars are means ± SE, from LSMean estimate in PROC MIXED. *significant at $p<0.05$, **significant at $p<0.01$, ^{ns}not significant.

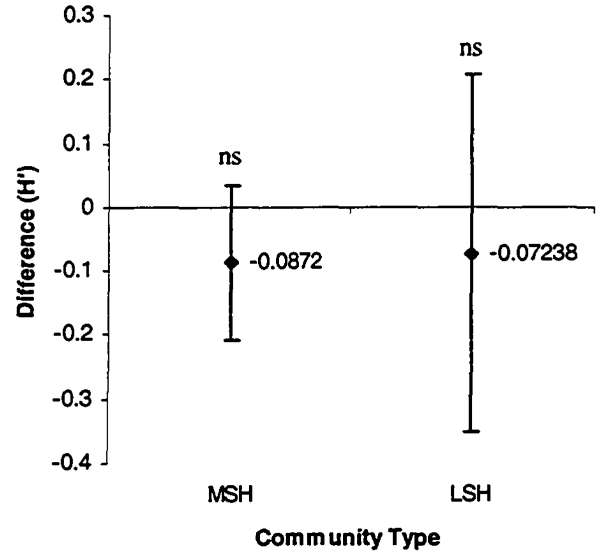

Fig. 4.6. Difference in vascular plant diversity (Shannon Index) along older seismic lines in Medium Shrub – Heath and Low Shrub – Heath communities as compared to undisturbed tundra. Points are the difference between LSMean diversity for the two treatment levels (control – seismic) ± 95% CLs; analysis was by mixed linear models. ^{ns}non significant. Mean diversity (H') in undisturbed MSH= 1.983, in LSH=2.000. n (number of sample units): MSH=16, LSH=18

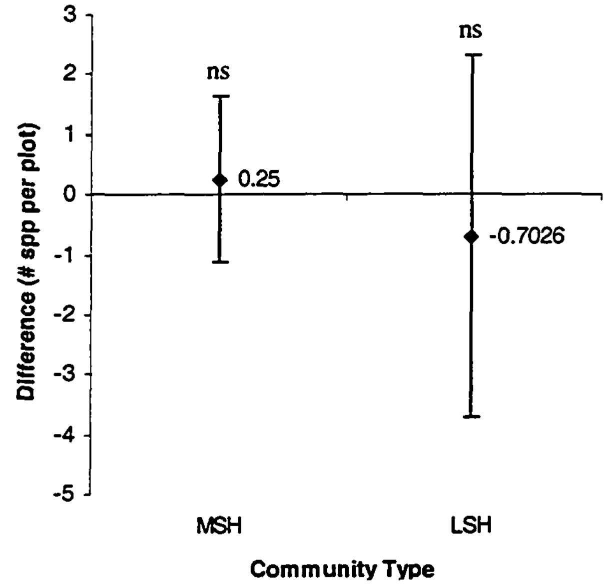

Fig. 4.7. Difference in species richness of vascular plants (per quadrat) along older seismic lines in Medium Shrub –Heath and Low Shrub – Heath communities, as compared to undisturbed tundra. Points are the difference between LSMean species richness at the two treatment levels (control – seismic) ± 95% CLs; analysis was by mixed linear models. Mean species richness in undisturbed MSH=11.30, in LSH=14.16. n (number of sample units): MSH=16, LSH=18

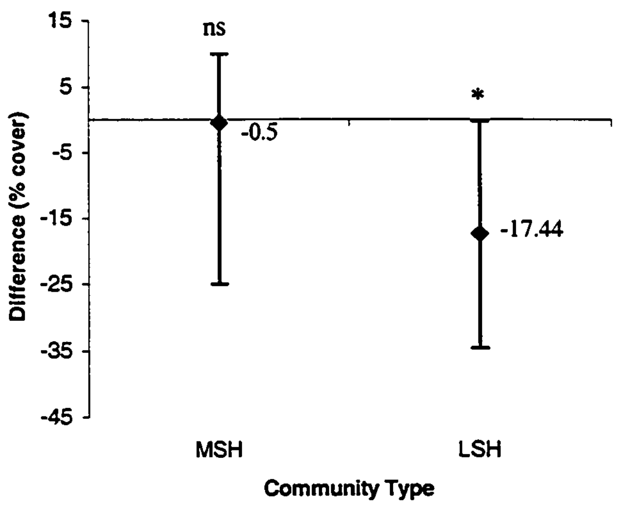

Fig. 4.8. Difference in moss cover along older seismic lines in Medium Shrub – Heath and Low Shrub – Heath communities, as compared to undisturbed tundra. For the LSH points are difference between LSMean moss cover between treatment levels (control – seismic) ± 95% CLs; analysis was by mixed linear models. For the MSH points are median difference ± 95% CLs (distribution free); analysis was by Wilcoxon-Signed Rank test. *significant at $p<0.05$, ^{ns}non significant. Mean moss cover in undisturbed LSH= 56.40%, median moss cover in undisturbed MSH= 70.0%. n (number of sample units): MSH=16, LSH=18

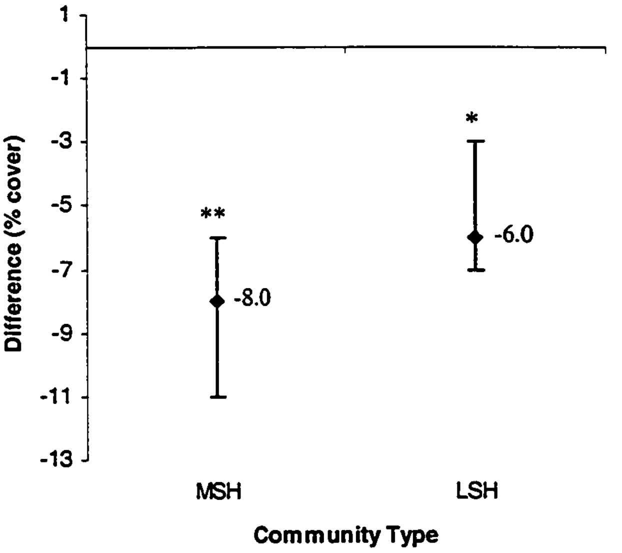

Fig. 4.9. Difference in lichen cover along older seismic lines in Medium Shrub – Heath and Low Shrub – Heath communities, as compared to undisturbed tundra. Points are median difference ± 95% CLs (distribution free); analysis was by Wilcoxon-Signed Rank tests. *significant at $p<0.05$, **significant at $p<0.01$. Median lichen cover in undisturbed MSH=16.0%, in LSH=12.0%. n (number of sample units): MSH=16, LSH=18

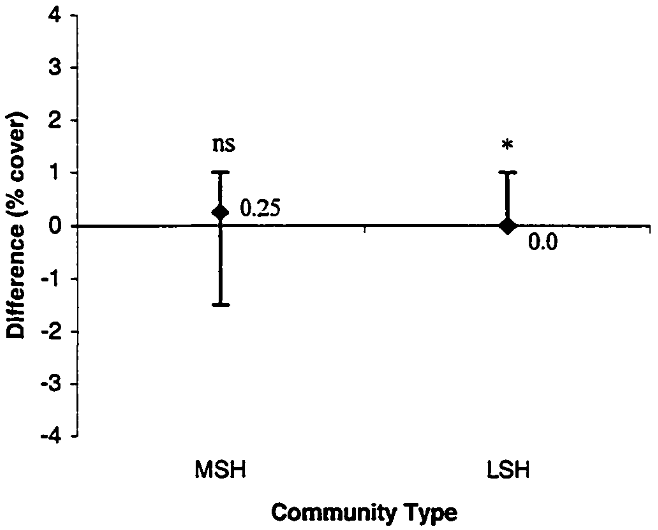

Fig. 4.10. Difference in cover of dead shrubs along older seismic lines in Medium Shrub – Heath and Low Shrub – Heath communities, as compared to undisturbed tundra. Points are median difference ± 95% CLs (distribution free); analysis was by Wilcoxon-Signed Rank tests. *significant at $p<0.05$, ^{ns}non significant. Median dead shrub cover in undisturbed MSH=0.0%, in LSH=0.0%. n (number of sample units): MSH=16, LSH=18

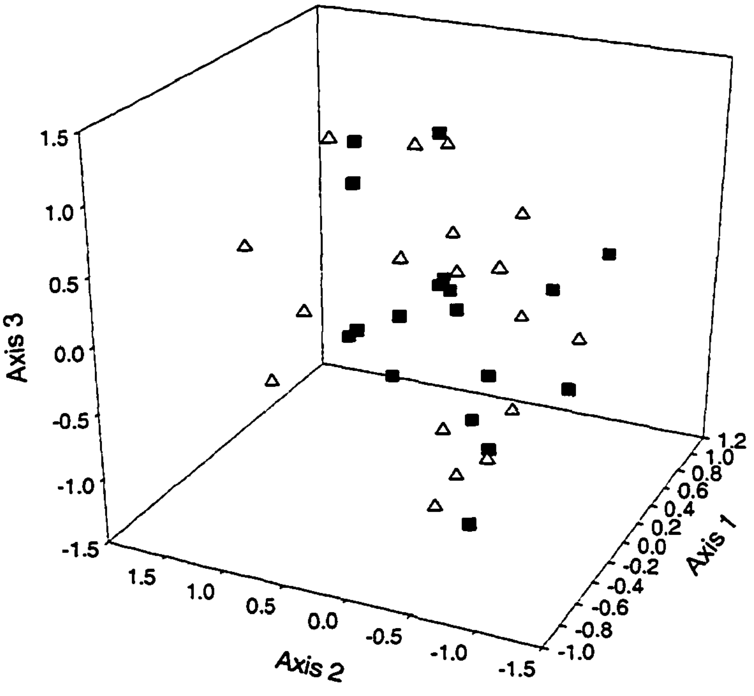

Fig. 4.11 Non-metric multidimensional scaling of quadrats in species space for Low Shrub - Heath communities. Distance matrix was created using Sørensen distance, from untransformed cover data for all vascular plant species occurring in >5% of quadrats. Three dimensional solution with significant (p=0.001) reduction is stress over randomized data, tested using 999 Monte Carlo permutations. Total variance captured = 85.4%; proportion of variance represented by: Axis 1=0.047, Axis 2=0.301, Axis 3=0.506. Final Stress = 12.73, Final Instability= 0.00009. Original distance matrix was composed of 36 quadrats and 39 species.

Symbols: triangles are quadrats from seismic lines; squares are quadrats from undisturbed tundra.

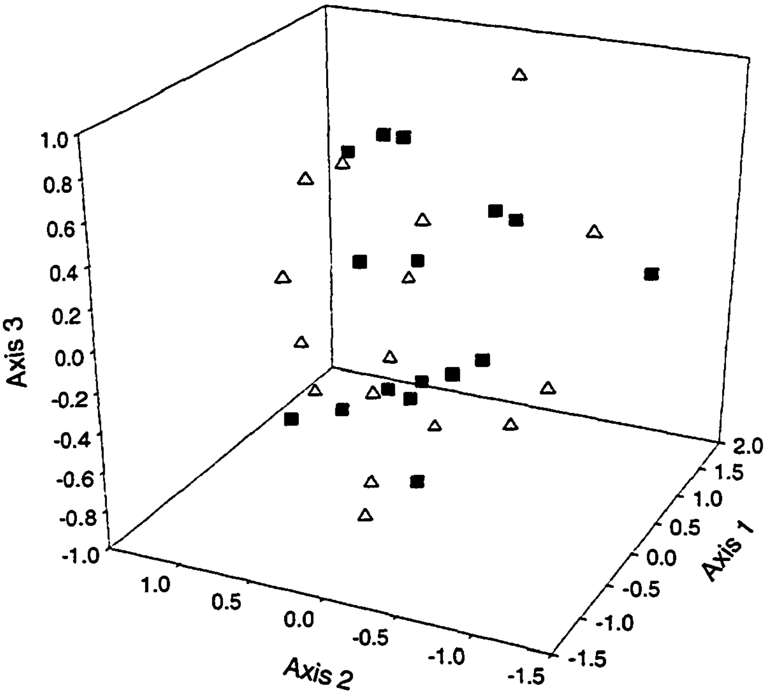

Fig. 4.12. Non-metric multidimensional scaling of quadrats in species space for Medium Shrub – Heath communities. Distance matrix was created using Sørensen distance, from untransformed cover data for all vascular plant species occurring in >5% of quadrats. Three dimensional solution with significant (p=0.001) reduction is stress over randomized data, tested using 999 Monte Carlo permutations. Total variance captured = 82.3%; proportion of variance represented by: Axis 1=0.401, Axis 2=0.209, Axis 3.213. Final Stress = 13.55, Final Instability= 0.00009. Original distance matrix was composed of 32 quadrats and 27 species.

Symbols: triangles are quadrats from seismic lines; squares are quadrats from undisturbed tundra.

Chapter 5: General Conclusions

General Conclusions and Implications

Modern methods of winter seismic exploration result in statistically significant differences in low arctic tundra plant communities, as compared to tundra which has not been exposed to seismic exploration. These differences likely arise primarily through the removal and/or damage of the aboveground portions of plants, which in turn affects the thermal balance of soils and depth to permafrost in most community types. Despite changes in seismic techniques and equipment, which were designed to mitigate environmental impacts of seismic exploration, the practices employed in current winter seismic programs exert a significant disturbance on tundra ecosystems, particularly in upland areas. Differences in the techniques used to conduct seismic surveys between the older and recent seismic lines in this study prevent the use of a chronosequence approach to predict the longer-term outcome of secondary succession and recovery on recent seismic lines. Nevertheless, the study of older seismic disturbances did provide valuable information about secondary succession on small linear disturbances in upland plant communities, and suggested that the recovery of a completely natural vegetation state may require decades, rather than years.

The short-term effects of recent winter seismic exploration in the Kendall Island Migratory Bird Sanctuary (KIBS) were generally on par with, and in a few cases greater than, those reported from the 1984 and 1985 winter seismic programs in the Artic National Wildlife Refuge (ANWR), Alaska by Felix and Raynolds (1989a). In particular, the level of disturbance to vascular plant cover in upland communities seems to be somewhat higher than that reported for the upland communities of ANWR (Felix and Raynolds 1989a), which was unexpected. The reasons for this are not clear. However, it was noticed during the field work for this study that one or two of the recent seismic lines, which were surveyed using the older techniques of drilling with dynamite, appeared to have lower levels of disturbance than seismic lines surveyed using the currently more common vibroseis technique. Unfortunately there was an insufficient number of these non-vibroseis lines to test for statistical differences. It is interesting to note, however, that Raynolds and Felix (1989) reported that heavier vibroseis vehicles generally dug more deeply into the soil and organic mat than did lighter drill units, which resulted in slightly higher levels of disturbance from the vibroseis vehicle types (though non-significant). In addition to the linear disturbances associated with vehicle travel the point disturbances associated with energy transmission may be greater for vibroseis programs, as these involve lowering heavy plates onto the ground with great contact pressure. In contrast, the point disturbances associated with energy transmission in drilled and dynamited programs are relatively small (usually around $1m^2$) circular areas of churned soil that, at least in upland the upland communities, closely resemble natural frostboil disturbances. This is clearly an issue which requires further investigation.

Upland Communities

It is not clear to what extent the observed impacts of recent seismic exploration on upland plant communities will persist, and what longer-term changes in plant communities may occur. In the ANWR studies the difference in active layer depth between seismic lines and undisturbed upland tundra continued to increase up to four years post disturbance in one community type (Felix *et al* 1992), and persisted in all upland communities for at least eight years (Emers *et al* 1995). Given the magnitude of the decrease in vascular plant cover along seismic lines I have reported, I would suspect that increases in active layer depth along the seismic lines in this study may persist for similar periods of time. The lack of significant differences in thaw depth between older seismic lines and undisturbed tundra (Chapter 4), however, suggests that the active layer should eventually recover such that is does not differ from that of undisturbed tundra on most or all recent seismic lines in the study area.

Along with the persistent differences in active layer depth, Emers *et al* (1995) reported lasting changes (>8yrs) in plant community composition at seismic lines in upland tundra sites, typified by increases in cover of *Arctagrostis latifolia* and *Poa* spp. Given the status of *Arctagrostis* as a significant indicator of older seismic lines in this study it seems likely that if this species were to colonize disturbances on recent seismic lines it would persist. In contrast, while evergreen shrubs are often reported to be sensitive to this type of disturbance (Hernandez 1973; Felix and Raynolds 1989a), and showed no recovery eight years post disturbance in ANWR (Emers *et al* 1995), the data from older seismic lines in my study suggests that these species are able to recover to natural cover values in somewhere less than 20 – 30 years. Although this conclusion rests on the assumption that these species were also initially reduced in cover by the older seismic lines in this study (which cannot be verified) the assumption is probably valid, given the results of Hernandez (1973) and Bliss and Wein (1972).

The disturbance dynamics of *Betula glandulosa* in this study are also quite interesting. *Betula* was both a significant indicator of undisturbed tundra in the study of recent seismic lines, and of older seismic lines in Chapter 4. Although seemingly incongruous, these results would seem to indicate that although *Betula* experiences a disproportionate negative affect by winter seismic exploration, it has the ability to recover to at least the abundance of undisturbed tundra, and likely greater abundance, on these disturbances. This response could be due to the ability of surviving individuals of *Betula* to exploit a release from competition for nutrients, and use their high phenotypic plasticity and meristem availability to become a dominant component of the post-disturbance plant community (Bret-Harte *et al* 2001). The results from Chapter 4 would suggest that, if this were the case, these shrubs would not likely inhibit other vascular plants over the long term, but might possibly inhibit the recovery of lichens through light competition.

Older seismic lines in the upland plant communities of this study were characterized by higher productivity than undisturbed tundra (as evidenced by greater plant cover), and by some changes to the vegetation structure. The vascular plant communities which have developed along these lines are for the most part, however, similar to those of undisturbed tundra, which suggests that upland plant communities are at least somewhat resilient to winter seismic exploration over the two- to three-decade period. Nevertheless, the difference in vascular plant cover and shrub cover, and lower cover of lichens along older seismic lines suggests the potential for some ecologically important impacts to persist.

Lowland Communities

Given the lower levels of disturbance associated with recent seismic exploration in the Tall Shrub – Herb and Wet Graminoid communities, these would seem to be less likely candidates for longer-term effects. In addition, these communities are probably subject to natural disturbances (channel meander, flooding, ice-scouring etc) of greater frequency and severity than upland communities, and have a relatively high proportion of disturbance adapted species (willows, rhizomatous graminoids). A conservative approach to such conclusions is necessary however, as other studies have demonstrated the potential for longer-term effects in these communities and suggested that such effects may not begin to manifest themselves over the timeframes used in this study. For example, Felix *et al* (1992) found that significant differences in community composition between seismic lines and undisturbed communities (driven by increased sedge cover along seismic lines) only began to appear 4 years post disturbance in their ‘wet graminoid tundra’ and ‘moist sedge-shrub tundra’ communities, and that active layer depth continued to increase along seismic lines throughout this period. No long-term differences in active layer depth were reported in riparian habitats from the ANWR seismic programs (Felix *et al* 1992), and given that no significant difference occurred on recent seismic lines in the Tall Shrub – Herb communities in this study, I would not anticipate any long term effects to permafrost in this community type. Although I did not study older seismic lines in the Tall Shrub – Herb and Wet Graminoid communities, many were visible on the landscape (particularly in the Wet Graminoid communities), usually as swaths of greener vegetation, or more homogenous vegetation than surrounding tundra. Swaths of greener vegetation would seem to indicate that some type of change, possibly in tissue nutrient content, had occurred. Increases in tissue nutrient content have been previously reported from winter vehicle disturbances in Alaskan tundra (Chapin and Shaver 1981; Walker *et al* 1987), however Emers *et al* (1995) showed that such increases persisted past 8 years on only the most heavily disturbed sites.

Cumulative Effects

In all instances the disturbances reported in this study were limited to the seismic trails themselves (with the exception of some refuse scattered on and near trails), and did not appear to affect the surrounding vegetation. The total impact to the ecosystem from a single seismic line of 6 to 13m wide is, therefore, relatively small. Nevertheless, winter seismic programs clearly do constitute a disturbance and there is significant potential for cumulative effects, particularly in such an ecosystem where plant communities are slow to return to their natural condition following disturbance. Walker (1996) outlined the problem:

> *"While we have seen a heightening of environmental concern, the development of engineering and planning techniques to minimize small-scale direct impacts to the tundra, and the adoption of techniques to return disturbed tundra areas to their original condition, we have*

> *simultaneously seen a many-fold increase in the number of impacts and size of areas affected. A focus on issues relating to cumulative impacts is needed"* [pg 63].

The evolution of seismic data collection and processing techniques, in combination with the proprietary nature of geophysical data has somewhat exacerbated this problem in that it often leads to "re-surveying", where new seismic programs are placed on or near older seismic lines.

Management and Research Recommendations

There are several ways in which the impacts of winter seismic exploration might be mitigated in the Kendall Island Migratory Bird Sanctuary. First, regulatory guidelines could limit the total amount of seismic within the KIBS itself, and set a maximum allowable level of seismic exploration. Secondly, seismic programs should be permitted in upland areas only when *on-site* measurements indicate that adequate snow cover is present to protect vegetation and permafrost from severe damage. Although what constitutes "adequate" snow cover is not fully understood, a modestly conservative measure for protecting tundra plant communities, such as the 25cm proposed by Felix and Raynolds (1989b), could be adopted. Such a regulation would require that seismic vehicles avoid more barren and windswept hilltops, and focus vehicle travel into areas with better snow protection (e.g. watercourses, small valleys etc.). Third, wherever possible, exploration activities should be directed to lowland areas in order to avoid the more sensitive upland plant communities. Finally, the number of vehicles traversing seismic trails should be kept to an absolute minimum by using fixed camps, and using helicopters to move crews.

Further research, in order to better understand the mechanisms and consequences of impacts from oil and gas exploration in this, and other, areas of the arctic is also warranted. Rickard and Brown (1974) called for a series of permanent study sites to experimentally test and monitor the long-term effects of vehicles on different types of tundra vegetation. Although their recommendation was not fulfilled I believe there is now the need for just such a scientific program, where observers can record the number and types of vehicles traversing seismic lines, the depth of snow cover at the time of vehicle passage, and associated off-trail activity (e.g. camp move trails). Particular effort should be made to compare the effects of vibroseis programs with those of more traditional drill and shot programs. Subsequent, and long-term investigations of the vegetation dynamics, permafrost, soil microbes and arthropods, nutrient dynamics, and herbivory, will be necessary at these sites to accurately detail the precise nature and mechanisms of impact and predict the long-term effects associated with oil and gas exploration practices in tundra biomes.

Literature Cited:

Bliss, L.C., and R.W. Wein. 1972. *Plant community responses to disturbance in the western Canadian arctic.* Canadian Journal of Botany 50:1097-1109.

Bret-Harte, M.S., Shaver, G.R., Zoerner, J.P., Johnstone, J.F., Wagner, J.L, Chavez, A.S., Gunkelman, F.F.IV, Lippert, S.C., and J.A. Laundre. 2001. *Developmental plasticity allows* Betula nana *to dominate tundra subjected to an altered environment.* Ecology 82:18-32

Chapin, F.S. III, and G.R. Shaver. 1981. *Changes in soil properties and vegetation following disturbance of Alaskan arctic tundra.* Journal of Applied Ecology 18:605-617

Emers, M., Jorgenson, J.C., and M.K. Raynolds. 1995. *Response of arctic tundra plant communities to winter vehicle disturbance.* Canadian Journal of Botany 73:905-917

Felix, N.A., and M.K. Raynolds. 1989a. *The effects of winter seismic exploration on tundra vegetation in northeastern Alaska, U.S.A.* Arctic and Alpine Research 21:188-202

Felix, N.A., and M.K. Raynolds. 1989b. *The role of snow cover in limiting surface disturbance caused by winter seismic exploration.* Arctic 42:62-68

Felix, N.A., Raynolds, M.K., Jorgenson, J.C., and K.E. DuBois. 1992. *Resistance and resilience of tundra plant communities to disturbance by winter seismic vehicles.* Arctic and Alpine Research 24:69-77

Hernandez, H. 1973. *Natural plant recolonization of surficial disturbances, Tuktoyaktuk Peninsula region, Northwest Territories.* Canadian Journal of Botany 51:2177-2196

Raynolds, M.K. and N.A. Felix. 1989. *Airphoto analysis of winter seismic disturbance in northeastern Alaska.* Arctic 42:362-367

Rickard, W.E., and J. Brown. 1974. *Effects of vehicles on arctic tundra.* Environmental Conservation 1:55-62

Walker, D.A. 1996. *Disturbance and recovery of arctic Alaskan vegetation.* pps. 35-71 *In:* J.F. Reynolds and J.D. Tenhunen (*Eds.*) Landscape Function and Disturbance in Arctic Tundra. Ecological Studies v.120. Springer Verlag, Berlin.

Walker, D.A., Cate, D., Brown, J., and C. Racine. 1987. *Disturbance and recovery of arctic Alaskan tundra terrain: A review of recent investigations.* CCREL Report 87-11. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Appendix 1. List of terrestrial vascular plant species encountered during the study. All species encountered within the sanctuary in undisturbed and disturbed communities are presented, as are those encountered only outside of the sanctuary (marked with an asterisk). This should not be considered an exhaustive species list for the study area. Nomenclature follows Porsild and Cody (1980)

Equisetaceae
Equisetum arvense L.
Equisetum scirpoides Michx.
Equisetum variegatum Schleich.

Selaginellaceae
**Selaginella sibirica* (Milde) Hieron.

Gramineae
Arctagrostis latifolia (R.Br.) Griseb.
ssp. *latifolia*
Arctophila fulva (Trin.) Rupr.
Calamagrostis canadensis (Michx.) Beauv.
var. *landsdorfii* (Link) Inman
Calamagrostis neglecta (Ehrh.) Gaertn., Mey. and Schreb.
Calamagrostis purpurascens R. Br.
Dupontia fisheri R. Br.
ssp. *fisheri*
ssp. *psilosantha* (Rupr.) Hultén
Festuca baffinensis Polunin
Festuca rubra L.
ssp. *richardsonii* (Hook) Hultén
Hierochloë alpina (Sw.) R. & S.
Hierochloë pauciflora R.Br.
Poa arctica R. Br.
ssp. *arctica*
Poa glauca M. Vahl

Cyperaceae
Carex aquatilis Wahlenb.
var. *aquatilis*
var. *stans* (Drej.) Boot
Carex capillaris L.
ssp. *capillaris*
Carex consimilis Holm
Carex lugens Holm
Carex membranacea Hook
Carex obtusata Liljeb. (?)
Carex podocarpa R. Br.
Carex rariflora (Wahlenb.) Sm.
Carex rotundata Wahlenb.
Carex scirpoidea Michx.
Carex subspathacea Wormskj.
Carex vaginata Tausch
Eriophorum angustifolium Honck.
Eriophorum russeolum Fr.
var. *albidum* Nyl.
Eriophorum vaginatum L.
Kobresia hyperborea Porsild
Kobresia myosuroides (Vill.) Fiori & Paol.

Juncaceae
Juncus biglumis L.
Luzula nivalis (Laest.) Beurl.

Liliaceae
Tofieldia coccinea Richards.
Tofieldia pusilla (Michx.) Pers.

Orchidaceae
Corallorhiza trifida Chat.
Habenaria obtusata (Pursh) Richards.

Salicaceae
Salix alaxensis (Anderss.) Cov.
Salix arctica Pall. s. lat.
Salix arctophila Cockerell
Salix farriae Ball
Salix glauca L. s. lat.
Salix lanata L.
ssp. *richardsonii* (Hook.) Skvortsov
Salix ovalifolia Trautv.
var. *arcolitoralis* (Hult.) Argus
Salix pulchra Cham.
Salix reticulata L.

Betulaceae
Alnus crispa (Ait.) Pursh
Betula glandulosa Michx.

Polygonaceae
Polygonum bistorta L.
ssp. *plumosum* (Small) Hult.
Polygonum viviparum L.
Rumex arcticus Trautv.

Caryophyllaceae
Melandrium affine J. Vahl
Melandrium apetalum (L.) Fenzl
ssp. *arcticum* (Fr.) Hult.
Stellaria longipes Goldie s. str.
Cerastium spp.

Ranunculaceae
Anemone parviflora Michx.
Anemone richardsonii Hook.
Caltha palustris L.
var. *arctica* (R.Br.) Huth.
Pulsatilla ludoviciana (Nutt.) Heller
Ranunculus lapponicus L.

Papaveraceae
Papaver spp.

Cruciferae
Cardamine digitata Richards.
Cardamine pratensis L. s. lat.
Draba spp.
Erysimum inconspicuum (S. Wats.) MacMill.
Parrya nudicaulis (L.) Regel

Crassulaceae
Rhodiola integrifolia Raf.

Saxifragaceae
Parnassia palustris L.
var. *neogaea* Fern.
Saxifraga hirculus L.
var. *propinqua* (R. Br.) Simm.

Rosaceae
Dryas integrifolia M. Vahl
Potentilla palustris (L.) Scop.
**Rosa acicularis* Lindl. s. lat.
Rubus chamaemorus L.

Leguminosae
Astragalus bodinii Sheld..
Hedysarum alpinum L.
Lupinus arcticus Wats.
Oxytropis arctica R. Br.
Oxytropis spp.
Oxytropis maydelliana Trautv.
Oxytropis nigrescens (Pall.) Fisch.

Onagraceae
Epilobium angustifolium L.
Epilobium latifolium L.

Empetraceae
Empetrum nigrum L.
ssp. *hermaphroditum* (Lge.) Böcher

Umbelliferae
Bupleurum americanum Coult. & Rose
Conioselinum cnidifolium (Turcz.) Porsild

Pyrolaceae
Pyrola grandiflora Radius

Ericaceae
Andromeda polifolia L.
Arctostaphylos alpina (L.) Spreng.
Arctostaphylos rubra (Rehd. & Wils.) Fern.
Cassiope tetragona (L.) D.Don
ssp. *tetragona*
Chamaedaphne calyculata (L.) Moench
Ledum decumbens (Ait.) Lodd.
Rhododendron lapponicum (L.) Wahlenb.
Vaccinium uliginosum L. s. lat.
Vaccinium vitis-idaea L.
var. *minus* Lodd.

Primulaceae
Androsace septentrionalis L.
Primula egaliksensis Wormsk.

Plumbaginaceae
Armeria maritima (Mill.) Willd.

Polemoniaceae
Polemonium acutiflorum Willd.

Gentianaceae
Gentiana propinqua Richards.

Scrophulariaceae
Castilleja caudata (Pennell) Rebr.
Castilleja elegans (Ostenf.) Malte
Pedicularis arctica R. Br.
Pedicularis capitata Adams
Pedicularis labradorica Wirsing
Pedicularis lanata Cham. & Schlecht.
Pedicularis lapponica L.
Pedicularis sudetica Willd.
Pedicularis verticillata L.

Orobanchaceae
Boschniakia rossica (Cham. & Schleccht.) Fedtsch.

Lentibulariaceae
Pinguicula villosa L.
Pinguicula vulgaris L.

Valerianaceae
Valeriana capitata Pall.

Asteraceae
**Arnica alpina* (L.) Olin
Aster sibiricus L.
Petasites frigidus (L.) Fries
Saussurea angustifolia (Willd.) DC.
Senecio atropurpureus (Ledeb.) Fedtsch.
Senecio congestus (R.Br.) DC.
Senecio lugens Richards

Appendix 2. Quadrat frequency of all species on recent and older seismic lines in a) Medium Shrub – Heath communities, b) Low Shrub – Heath communities, and quadrat frequencies of all species along recent seismic lines in c) Wet Graminoid, and d) Tall Shrub – Herb communities. Number of quadrats in a) = 20 recent seismic, 20 controls; 16 older seismic, 16 controls; b) = 5 recent seismic, 5 controls, 18 older seismic, 18 controls; c) 36 seismic, 36 controls, and d)= 28 seismic, 28 controls

a) Medium Shrub – Heath

	Recent Seismic		Older Seismic	
Species	Freq. (line)	Freq. (cont)	Freq. (line)	Freq. (cont)
Betula glandulosa	0.90	1.0	1.0	0.88
Alnus crispa	0.15	0.25	0.44	0.44
Salix glauca	0.20	0.30	0.06	0.00
Salix pulchra	0.00	0.05	-	-
Vaccinium vitis-idaea	0.90	1.0	1.00	1.00
Vaccinium uliginosum	0.45	0.30	0.56	0.38
Cassiope tetragona	0.10	0.20	0.56	0.56
Ledum decumbens	0.85	0.85	1.00	1.00
Empetrum nigrum	0.55	0.70	0.63	0.50
Arctostaphylos alpina	0.30	0.60	0.56	0.69
Arctostaphylos rubra	0.30	0.00	0.00	0.06
Andromeda polifolia	0.20	0.20	0.38	0.50
Lupinus arcticus	0.20	0.30	0.06	0.00
Cardamine digitata	0.10	0.10	0.25	0.13
Eriophorum vaginatum	0.35	0.40	0.56	0.69
Carex consimilis	0.50	0.80	0.69	0.88
Carex vaginatum	0.05	0.00	0.13	0.19
Carex podocarpa	0.00	0.05	-	-
Petasites frigidus	0.45	0.30	0.25	0.25
Senecio atropurpureus	0.05	0.20	0.56	0.44
Pyrola grandiflora	0.00	0.25	0.44	0.38
Pedicularis lanata	0.00	0.15	-	-
Pedicularis lapponica	0.00	0.10	0.06	0.00
Pedicularis capitata	0.10	0.15	0.063	0.19
Pedicularis labradorica	-	-	0.00	0.06
Ranunculus lapponica	0.00	0.10	-	-
Arctagrostis latifolia	0.25	0.10	0.31	0.25
Hierochloë alpina	0.05	0.05	-	-
Calamagrostis neglecta	0.05	0.05	-	-
Calamagrostis canadensis	0.05	0.00	-	-
Poa arctica	0.15	0.00	-	-
Pinguicula vulgaris	0.00	0.05	-	-
Pinguicula villosa	0.05	0.00	0.06	0.00
Tofieldia pusilla	0.00	0.05	0.00	0.06
Tofieldia coccinea	-	-	0.00	0.06
Dryas integrifolia	0.05	0.15	0.13	0.13
Rubus chamaemorus	0.45	0.45	0.69	0.63
Epilobium angustifolium	0.05	0.00	-	-
Stellaria longipes	0.15	0.20	0.25	0.25
Polygonum viviparum	-	-	0.06	0.06
Saussurea angustifolia	0.45	0.35	0.31	0.31
Carex membranacea	-	-	0.06	0.06
Carex scirpoidea	-	-	0.06	0.13
Luzula nivalis	-	-	0.06	0.00
Mosses	1.00	1.00	1.00	1.00
Lichens	0.95	1.00	0.94	1.00

b) Low Shrub – Heath

	Recent Seismic		Older Seismic	
Species	Freq. (line)	Freq. (cont)	Freq. (line)	Freq. (cont)
Betula glandulosa	0.40	0.40	0.33	0.33
Alnus crispa	0.20	0.40	-	-
Salix glauca	0.60	0.60	0.67	0.56
Salix pulchra	-	-	0.17	0.17
Salix reticulata	0.20	0.20	0.67	0.56
Vaccinium vitis-idaea	0.40	0.40	0.11	0.11
Vaccinium uliginosum	1.00	1.00	0.72	0.83
Cassiope tetragona	0.80	1.00	0.61	0.61
Ledum decumbens	0.40	0.60	0.06	0.17
Empetrum nigrum	0.40	0.20	0.11	0.22
Arctostaphylos alpina	-	-	0.28	0.06
Arctostaphylos rubra	0.60	0.80	0.67	0.72
Andromeda polifolia	-	-	0.11	0.06
Rhododendron lapponicum	0.00	0.40	0.11	0.28
Oxytropis arctica	-	-	0.22	0.17
Lupinus arcticus	0.40	0.20	0.50	0.39
Hedysarum alpinum	-	-	0.06	0.11
Corallorhiza trifida	-	-	0.06	0.11
Cardamine digitata	0.00	0.20	0.61	0.56
Cardamine pratensis	0.00	0.60	-	-
Parrya nudicaulis	-	-	0.06	0.11
Eriophorum vaginatum	0.20	0.60	0.39	0.27
Carex consimilis	1.00	1.00	0.61	0.72
Carex capillaris	-	-	0.11	0.06
Carex rotundata	-	-	0.00	0.06
Carex scirpoidea	-	-	0.22	0.33
Carex vaginata	-	-	0.33	0.44
Kobresia hyperborea	-	-	0.06	0.00
Kobresia myosuroides	-	-	0.06	0.00
Petasites frigidus	0.40	0.40	0.06	0.06
Senecio atropurpureus	0.40	0.80	0.39	0.61
Saussurea angustifolia	1.00	0.80	0.50	0.78
Pyrola grandiflora	0.20	1.00	0.33	0.72
Pedicularis lanata	0.00	0.40	0.61	0.67
Pedicularis capitata	0.20	0.20	0.39	0.50
Arctagrostis latifolia	0.60	0.50	0.50	0.22
Poa arctica	0.00	0.20	0.17	0.06
Poa glauca	-	-	0.06	0.06
Festuca baffinensis	-	-	0.06	0.06
Tofieldia pusilla	0.00	0.40	0.22	0.11
Tofieldia coccinea	-	-	0.06	0.06
Dryas integrifolia	0.60	0.80	1.00	1.00
Rubus chamaemorus	0.40	0.20	0.06	0.06
Stellaria longipes	0.00	0.20	0.44	0.50
Equisetum scirpoidea	-	-	0.11	0.06
Polygonum bistorta	-	-	0.06	0.06
Polygonum viviparum	-	-	0.22	0.22
Luzula nivalis	-	-	0.06	0.22
Mosses	1.00	1.00	1.00	1.00
Lichens	1.00	1.00	1.00	1.00

c) Wet Graminoid

Species	Recent Seismic	
	Freq. (line)	Freq. (cont)
Salix lanata	0.22	0.33
Salix farriae	0.03	0.00
Salix arctica	0.42	0.33
Salix arctophila	0.08	0.03
Salix ovalifolia	0.00	0.03
Eriophorum russeolum	0.08	0.28
Eriophorum angustifolium	0.86	0.92
Carex capillaris	0.03	0.00
Carex aquatilis	0.78	0.89
Pedicularis sudetica	0.33	0.28
Arctagrostis latifolia	0.00	0.03
Hierochloë pauciflora	0.03	0.00
Dupontia fisheri	0.17	0.08
Calamagrostis neglecta	0.08	0.00
Pinguicula vulgaris	0.00	0.03
Equisetum variegatum	0.39	0.47
Equisetum arvense	0.14	0.06
Polygonum viviparum	0.08	0.11
Primula egaliksensis	0.00	0.03
Cardamine pratensis	0.03	0.08
Mosses	0.81	0.94
Lichens	-	-

d) Tall Shrub Herb

Species	Recent Seismic	
	Freq. (line)	Freq. (cont)
Salix lanata	1.00	1.00
Salix glauca	0.07	0.04
Salix alaxensis	0.07	0.14
Salix farriae	0.04	0.04
Salix arctica	0.11	0.18
Salix reticulata	0.04	0.07
Salix ovalifolia	0.04	0.04
Alnus crispa	0.18	0.18
Arctostaphylos rubra	0.14	0.25
Hedysarum alpinum	0.46	0.29
Habenaria obtusata	0.07	0.07
Eriophorum russeolum	0.11	0.04
Eriophorum angustifolium	0.39	0.21
Carex capillaris	0.14	0.21
Carex rotundata	0.00	0.04
Carex aquatilis	0.54	0.36
Pyrola grandiflora	0.11	0.17
Pedicularis verticillata	0.11	0.06
Pedicularis sudetica	0.50	0.29
Castilleja caudata	0.04	0.14
Anemone parviflora	0.04	0.11
Caltha palustris	0.04	0.07

Arctagrostis latifolia	0.21	0.07
Dupontia fisheri	0.07	0.00
Festuca rubra	0.25	0.25
Dryas integrifolia	0.11	0.14
Equisetum variegatum	0.61	0.54
Equisetum scirpoidea	0.07	0.07
Equisetum arvense	0.46	0.57
Polygonum viviparum	0.39	0.21
Valeriana capitata	0.07	0.07
Parnassia palustris	0.00	0.18
Polemonium acutiflorum	0.04	0.00
Primula egaliksensis	0.00	0.04
Aster sibiricus	0.04	0.07
Mosses	0.93	1.00
Lichens	-	-

Appendix 3. Location and time since disturbance for all sampling sites in a) Medium Shrub – Heath, b) Low Shrub – Heath, c) Wet Graminoid, and d) Tall Shrub – Herb communities. Age is the number of growing seasons since disturbance, UTM Zone = 08W, NAD 27 Canada datum. Location place names are taken from 1:250 000 map: Mackenzie Delta (107C), Energy Mines and Resources Canada, 1988. Site Identifier is shorthand nomenclature used to identify individual sites on datasheets and in the field.

a) Medium Shrub – Heath

Site Identifier	UTM E	UTM N	Age	Date Sampled	Location
2000/2001 1a)†	0513286	7688646	2	05 July, 2002	near Dennis Lake, Richards Is.
2000/2001 2a)†	0504739	7686315	2	05 July, 2002	E. of Harry Channel, Richards Is.
2000/2001 3a)†	0502597	7679532	2	06 July, 2002	E. of Harry Channel, Richards Is.
UT 1	0495046	7689214	2	15 July, 2002	NE. of Old Trout Lake
03-UT-3	0516348	7680826	3	09 July, 2003	near Mid Lake, Richards Island
03-UT-4	0526712	7683667	2	12 July, 2003	near Lousy Point, East Channel
03-UT-1	0518990	7677039	33	08 July, 2003	near Wolf Lake, Richards Is.
03-UT-2	0503870	7681893	33	08 July, 2003	near Grassy Lake, Richards Is.
03-UT-5	0504487	7683877	29	14 July, 2003	near Grassy Lake, Richards Is.
03-UT-6	0513614	7666030	29	18 July, 2003	near Yaya River, Richards Is.
03-85-04	0498006	7688495	18	03 August, 2003	N. of Old Trout Lake
F-UT-2	0494663	7682802	31	12 July, 2003	W. of Trench Lake
P-UT-1	0491833	7686278	31	14 July, 2003	W. of NW tip of Old Trout Lake

† datums unknown

b) Low Shrub – Heath

Site Identifier	UTM E	UTM N	Age	Date Sampled	Location
UT-1	0494962	7689300	2	15 July, 2002	NE. of Old Trout Lake
AN-UT-1	0490730	7688256	2	08 July, 2003	N.NW. of Old Trout Lake
AN-UT-2	0490743	7689390	2	09 July, 2003	N.NW. of Old Trout Lake
N-UT-1	0481191	7695896	31	12 July, 2003	Niglintgak Island
N-UT-2	0486170	7695027	28	14 July, 2003	Niglintgak Island
K-UT-1	0491318	7708338	33	18 July, 2003	Kendall Island
F-UT-1†	0496559	7678269	29	11 July, 2003	E.NE. of Camp Farewell
03-85-02	0493796	7688782	18	02 August, 2003	N. of Old Trout Lake
03-85-03	0494426	7689814	18	03 August, 2003	N. of Old Trout Lake

† datums unknown

c) Wet Graminoid

Site Identifier	UTM E	UTM N	Age	Date Sampled	Location
2000/2001 1b)	0502525	7705437	2	12 July, 2002	N. tip of Taglu Island
2000/2001 4a)	0506124	7700803	2	12 July, 2002	Island directly E. of Taglu
2000/2001 4b)	0490302	7692001	2	13 July, 2002	b/w Kimialuk Lake and Niglintgak Is.
2000/2001 2b)	0501595	7683610	2	13 July, 2002	W. of Harry Channel
LCP-2	0501442	7697589	2	19 July, 2002	E. of Big Lake
LCP-3	0503543	7703967	2	21 July, 2002	Taglu Island
03-WS-01	0490235	7692668	3	18 July, 2003	b/w Kimialuk Lake and Niglintgak Is.
03-WS-02	0492271	7696499	2	19 July, 2003	E. of Kimialuk Lake
03-TA-02	0499593	7704545	2	21 July, 2003	N. tip of island W. of Taglu Is.

d) Tall Shrub – Herb

Site Identifier	UTM E	UTM N	Age	Date Sampled	Location
LCP-2	0501233	7697755	2	19 July, 2002	W. of Big Lake
TW-1	0500768	7691718	2	13 July, 2002	Small Island in Harry Channel
W3	0501420	7683864	2	13 July, 2002	W. of Harry Channel
03-TA-01	0499727	7701287	2	19 July, 2003	W. of Big Lake
03-TA-03	0502321	7705311	2	22 July, 2003	N. tip of Island W. of Taglu Is.
03-TA-04	0499765	7704592	2	22 July, 2003	W. of Taglu Island
03-DW-01	0499814	7672356	3	29 July, 2003	Middle Channel, S. of KIBS
03-DW-02/03	0503334	7685486	3	29 July, 2003	E. of Harry Channel
03-DW-04	0491735	7680588	2	30 July, 2003	W. of Middle Channel
03-DW-05	0490295	7677928	2	30 July, 2003	near Arvoknar Channel
03-DW-06	0498782	7670855	2	31 July, 2003	Middle Channel, S. of KIBS
03-WS9-01	0490768	7692967	2	22 July, 2003	W. of Kimialuk Lake