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University of Alberta

Responses of Tundra Vegetation, Soil and Microclimate to Disturbances Associated with the 1943 Construction of the CANOL No. 1 Pipeline, N.W.T.

by

Wendy Alison Davis ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment

of the requirements for the degree of Master of Science

Department of Earth and Atmospheric Sciences

Edmonton, Alberta

Spring 1998

0-612-28930-3

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Responses of Tundra Vegetation, Soil and Microclimate to Disturbances Associated with the 1943 Construction of the CANOL No. 1 Pipeline, N.W.T. submitted by Wendy Alison Davis in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

Six disturbance types in the Decumbent Shrub Tundra associated with the construction of the CANOL No. 1 Pipeline were identified. Resultant plant associations are the product of >50yrs of natural revegetation. Relative abundance of individual plant species was measured to determine plant community composition. Soil development was analyzed using soil texture, nitrogen levels, moisture content, bulk density, near-surface temperatures and depths of thaw. The total flora of the undisturbed tundra was 125 species. *Salix polaris* was the most common species occurring in 86% of sample quadrats. Forbs and bryophytes were the richest taxonomic groups. Significant differences in measured variables within the control were due to patterned ground. Indirect ordination indicated a wide variation in species composition from poorly vegetated borrow pits to well vegetated vehicle tracks and overburden spoil piles. Near-surface temperatures in all disturbance types increased. NH_4 and NO_3 levels were highest in wet, organic rich samples. With direct ordination the most important environmental variable determining differences among disturbance types was percent gravel content. The replacement of topsoil material was an important factor in natural revegetation processes.

Acknowledgments

I would like to thank in particular Dr. G. P. Kershaw for his assistance in every aspect of this project. Members of the research committee, Dr. A. Naeth, Dr. R. Wein and Dr. I. Campbell provided assistance in the development of a clear research proposal and constructive help in the thesis development. Dr. Zoltai, who passed away before the completion of this work provided valuable insights into its development. I am grateful for the brief period of interaction I had with him.

Linda Kershaw helped in the identification of the numerous ecological samples of vascular plants obtained from the field. Derek Johnson and Dr. C. La Farge-England gave time to help with the identification of cryptograms. Dr. D. Gignac sent me on the path to enlightenment in some of the technicalities and interpretation of ordination diagrams.

For the main season of data collection I was assisted by Jennie Christensen. While conducting her own study Jennie helped me with every aspect of the field work. I was pleased to have her as a companion for the two month project. During the early season reconnaissance and microclimate station installation I was assisted by Dr. Kershaw. Micheal Smilski helped with the preparation and Dave Chesterman supplied some equipment for use during the summer.

Completion of this thesis was made easier through the support of fellow students Shulamit Gordon, Mandy Munroe-Stasiuk, Jerome Lesemann, Luke Copland, Kim Jardine and Nigel Atkinson. Special thanks to Kirsten Davis for frantic last minute help with lab work and a computer drafting project after regular work hours. Anthony Arendt helped both academically and emotionally throughout the entire time I was at the University of Alberta. I also thank my parents, Pauline and Gary Davis who supported and encouraged me through my entire academic and athletic careers

Financial Assistance for the field work was provided by NSTP and NSERC grants to Dr. G. P. Kershaw, a Royal Canadian Geographic Society grant to Jennie Christensen and NSTP funding specifically for lab analyses to myself. Personal funding was obtained through a graduate assistantship from the Department of Earth and Atmospheric Sciences, the Petro Canada Olympic Torch Scholarship Fund and the National Athlete Assistance Program. Logistic support was generously provided by the folks at Old Squaw Naturalist Lodge and Ursus Aviation.

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Chapter 1: Rational and Background Literature

Introduction

Disturbances to tundra caused by construction in the Arctic and Subarctic during the latter part of this century have been the focus of various studies concerned with vegetative reclamation. Much work has been initiated concerning short-term assisted and unassisted recovery of the plant community, but little is known for periods of >25yrs. An opportunity to study long-term vegetation responses 50yrs after disturbance is provided by the CANOL Project.

Construction of the CANOL Project commenced in 1942, and it was abandoned in 1945 after only 13 months of full-scale operation (Kershaw 1983b). Most of the Northwest Territories section remains abandoned, with only natural ecological processes gradually reclaiming disturbances, and thus the area offers an excellent opportunity to study long-term vegetation responses. Kershaw's regional study (1983b) was an examination of eight distinct types of disturbance in seven physiognomically-defined plant communities along the entire tundra section of the CANOL pipeline between 1977-79. Harper (1994) focused on the Erect Deciduous Shrub Tundra community 15yrs after Kershaw's regional survey was completed. This project builds upon the previous studies by focusing on Decumbent Shrub Tundra 52 growing seasons since abandonment of the CANOL pipeline. Substrate and vegetation data exist from the Decumbent Shrub Tundra 32-35yrs after disturbance (Kershaw 1983a; Kershaw 1983b; Kershaw and Kershaw 1986; Kershaw and Kershaw, 1987) and for Erect Deciduous Shrub Tundra 50yrs following disturbance (Harper 1994; Harper and Kershaw 1997). These data can be used to evaluate contemporary arctic tundra succession models in conjunction with new data collected from the Decumbent Shrub Tundra.

Short-term studies focused on reclamation in the Arctic and Subarctic are numerous (Densmore 1994; Densmore 1992; Cargill-Bishop and Chapin 1989; Callaghan 1987; Ebersole and Webber 1983; Gartner et al. 1983; Chapin and Shaver

1981; Kubanis 1980; Muc 1973). Many descriptive studies have portrayed the plant associations of northern tundra (Kershaw 1984; Kershaw 1983b; Simmons and Miller 1982; Barrett 1979; Bliss 1977; Bliss and Wein 1972; Lambert 1968). Yet little is known about the natural revegetation of specific communities for periods of greater than 35yrs because construction projects of that age in the subarctic are relatively few. Long-term, regional studies focusing on natural revegetation have been undertaken by Kershaw (1983a, 1983b) and Forbes (1993). Harper (1994) examined the Erect Deciduous Shrub Tundra at Macmillan Pass, N.W.T., 50yrs following the CANOL pipeline construction. Brady (1984) examined natural revegetation of placer mine tailings for periods of 2-80yrs after disturbance. Long-term studies of succession in temperate climates reveal that while succession is an accepted ecological process, the actual stages within the process are highly site specific. If succession is a repeatable, predictable process within a specific community, long-term natural revegetation studies will help reclaimers make decisions on appropriate short-term measures to take after disturbance. Reclamation efforts soon after disturbance can be properly designed to ensure that natural successional processes will continue in the long-term.

Succession in Tundra Environments:

Succession has been described by ecologists as a directional and repeatable process affecting most plant associations. The process is not however, as obvious in severely limited environments such as in deserts and the Arctic. Consequently it has been argued that succession does not exist in these environments (Muller 1952; Whittaker 1974). Succession may not be initially obvious in arctic environments because when a suitable colonization habitat does open up in the tundra there are relatively few species present to recolonize. Of those few species the proportion that are suitable colonizing species for the Arctic is very low (Forbes 1993; Forbes 1995). Arctic colonizing species are usually perennial herbs able to colonize quickly and persist. Even though the total flora of the Arctic is small there are few plants that exist in the Arctic that do not have at least a temperate counterpart (Bliss and Wein 1972). Succession processes will be different based on individual species' capabilities to adjust to the prevailing climatic conditions; thus it is the abiotic factors of arctic regions that will be important in determining the pattern of vegetation succession.

It is possible to construct successional models for the Arctic based on known processes from temperate regions. The most comprehensive deterministic models for marginal environments were developed by Svoboda and Henry (1987). Three models approximate the pattern of succession along an increasingly severe environmental gradient. In arctic environments the sum of biological driving forces is approximately equal to the counteracting resistances in the long-term, yet in favorable years some areas may reach a positive ecological balance and forms of succession may be observed. The critical factor in all these models is time. Since early-colonizing species in marginal environments are long-lived, the progression from early to late successional communities will occur slowly. Long periods of time are required to study arctic succession processes.

Terms:

For the purposes of this paper it will be useful to first define some terms as they are used here. Ecological concepts are often variously defined and clarification is necessary.

- Species' richness: The number of species in some area within a biological community (Barbour, *et al.* 1987). Used as a proxy for species' diversity.
- Reclamation: The return of disturbed land to a functional plant community.
- Natural revegetation: The return of disturbed land to a stable plant community without anthropogenic intervention.
- Native species: In the context of natural unassisted revegetation, native species are those that exist in the immediately surrounding undisturbed tundra and colonize the anthropogenic disturbance of the CANOL through natural means.
- Colonizing species: Those species which are able to successfully colonize a

disturbed site and persist for long periods of time in the Subarctic or Arctic (Forbes 1993). The natural colonizers in the north do not share all accepted 'weed' characteristics.

- Decumbent Shrub Tundra: In the 1977 survey Kershaw (1984) described the Decumbent Shrub Tundra as a ubiquitous plant community along the CANOL No. 1 pipeline corridor. It was subdivided into three floristic units which were separated along altitudinal and moisture gradients. The *Salix barrattiana*-Moss community occurred at lower elevations in wet sites. The *Salix polaris-Dactylina beringica* community was intermediate and the *Dryas integrifolia-Carex* species' communities occurred on dry gravel substrates on exposed hillsides. Floristically the *Salix polaris-Dactylina beringica* community was most similar to the association focused on in this study.

Intermediate Disturbance Hypothesis:

Currently the most widely accepted model for describing the process from catastrophic disturbance to the maintenance of species' diversity is the intermediate disturbance hypothesis (Connell 1978). This hypothesis predicts that the highest level of diversity will be maintained at intermediate levels of disturbance (fig 1.1). If the disturbance is too small or infrequent the patches will approach equilibrium and the few species that are the best competitors will dominate. If the disturbance is too harsh then the few species that are able to survive will dominate (Petaitis *et al.* 1989; Connell 1978) Equilibrium is most simply described as the balance between birth and death. In the Arctic where the influx of germinable species is greatly reduced the rates of immigration and extinction are important factors in the equilibrium equation. This hypothesis should apply to anthropogenic disturbances.

Primary and Secondary Succession on CANOL Disturbances:

Classic studies of natural succession processes in the Arctic have been done in glacier forelands. Quick retreat of glaciers has provided researchers with bare substrates on which to study the natural vegetation chronosequence (Viereck 1966). Over a period of 100yrs the community develops from a denuded landscape to a coniferous forest similar to that of the surrounding unglaciated areas (Svoboda and Henry 1987; Lawrence 1958). Another area used in this type of research in the High Arctic is Truelove Lowland where isostatic rebound and eustatic changes have exposed a series of raised beach ridges (Bliss 1977). Statistical analysis has revealed that the older beach ridges are richer floristically, have greater biomass and more soil development. Communities contain typical arctic and alpine floras such as wet sedge meadows and dry cushion plant tundra (Svoboda and Henry 1987; Svoboda 1977). In both these cases the disturbance was a large scale exposure of entirely bare substrate. Primary succession occurs on these bare substrates whereas secondary succession occurs from an altered stable plant community.

Borrow pits expose an entirely bare surface, removing all topsoil and organic layers. Vegetation development after such a disturbance is primary succession. Less disruptive disturbances such as vehicle tracks undergo secondary succession because the community structure is altered. Since natural processes are returning the disturbance to a stable plant community primary and secondary succession is an accepted way of characterizing the CANOL disturbances. It would be beneficial in a reclamation context to link these primary and secondary succession processes with respect to species' abundance and composition measures.

Objectives

The primary hypothesis is that there are biotic and abiotic differences among various disturbances associated with pipeline construction compared to the undisturbed Decumbent Shrub Tundra after >50yrs of natural revegetation. Succession is the process returning disturbed areas to stable plant communities. Three objectives can be outlined based on the collection of three successively smaller data sets.

1. To describe anthropogenic disturbance types and natural reference stands based on plant association composition within the Decumbent Shrub Tundra of the Mackenzie Mountain Barrens (Chapter 2, vegetation data set).

2. To describe anthropogenic disturbance types and natural areas based on soil development and full season microclimate records within the Decumbent Shrub Tundra of the Mackenzie Mountain Barrens (Chapter 3, soil and near-surface temperature data sets).

3. To combine plant association composition. soil development and microclimate characteristics of anthropogenic disturbances and natural areas of the Decumbent Shrub Tundra using ordination techniques to determine the most important factor defining the differences among disturbance types. (Chapter 4, all collected data).

Site Description

Location:

Field research was undertaken during the growing season between 18 June and 7 September 1996 along the CANOL pipeline corridor east of Macmillan Pass Northwest Territories (fig. 1.2). All sites were above timberline in the Mackenzie Mountain Barrens ecosection (Kershaw 1984; Kershaw 1983b) between original road mileposts (R.M.P.)212 and. 216 (fig. 1.3). The research area was at approximately 63° north and 130° west at 1700m in elevation.

Geology:

Mackenzie Mountain Barrens is composed of predominantly thin (generally < 2m) unconsolidated glacial and alluvial deposits. Underlying bedrock is Cambrian to Mississippian clastic sedimentary rock (shale, siltstone, chert, chert sandstone) (Douglas 1968). Parent material was important in borrow pit disturbances where the topsoil has been completely removed.

Permafrost:

The Mackenzie Mountain Barrens ecosection was located in an area of discontinuous permafrost. Evidence of underlying permafrost was seen in the well-drained substrates of the Decumbent Shrub Tundra as patterned ground (nonsorted circles and stripes). In wetter areas of the Mackenzie Mountain Barrens there are extensive palsa fields and peat plateaus. They were not encompassed in the Decumbent Shrub Tundra but provided further evidence of underlying permafrost. The active layer was rarely directly measurable due to proximity of bedrock to the surface. Using a linear regression technique, depth of thaw was estimated between 1 to 2m for most sites.

Soils:

Sites were chosen from the Decumbent Shrub Tundra, sometimes ranging towards a more mesic environment of Sedge Meadow Tundra. Soils of the Decumbent Shrub Tundra were classified as Humic Regosols which are well-drained sites characterized by high gravel content. Wetter sites of the Sedge Meadow Tundra were classified as Organic Cryosols with 100% vegetation cover and Humic Gleysols with 75% cover (Kershaw 1983a). In the Subarctic tundra variance in soil type is strongly related to topographic position and microrelief (Ebersole 1987). The sampled undisturbed tundra consisted of well-drained to intermediately-drained sites with patterned variation in microtopography. Vegetated raised circle edges were spaced at horizontal intervals of 1m and vertical microrelief of 0.25m. Soils of the dryer edges were separated into distinct layers of peaty organics, a poorly-developed B horizon overlying the C horizon. The low circles were water-saturated highly gleyed, clay material with little plant cover. Over the entire area was a discontinuous tephra layer in some instances mottled with ferrous compounds. Soils in anthropogenic disturbances ranged from complete removal of organic and B horizons exposing the underlying bedrock to piling of overburden. No soil development on C horizon substrates was observed after 50yrs. In vehicle track disturbances the soil horizons remained intact but compacted.

Plant Community:

The undisturbed Decumbent Shrub Tundra consisted of a complete bryophyte mat composed of *Polytrichum* spp. and *Dicranum* spp. The vascular component consisted of herbaceous perennials such as *Artemesia arctica* and sometimes pure stands of the prostrate shrub species *Salix polaris*. At irregular widely spaced intervals taller *Salix* spp. (*Salix planifolia, Salix glauca, and Salix alaxensis)* occurred. Within the Mackenzie Mountain Barrens the Decumbent Shrub Tundra was bordered by poorly-drained sites of Sedge Meadow Tundra.

Climate:

The Mackenzie Mountain Barrens occur within an alpine tundra environment. The Tischu River weather station N.W.T. from 1974 to 1981 had a mean annual temperature of -7.5°C; mean annual precipitation of 470mm and a mean annual snowfall of 278 cm. The mean July temperature was 10°C. Frost occurred during every month of the year with the mean daily temperatures above freezing only from late May to mid-September. Maximum precipitation occurred during the July to October period (Kershaw 1983b). The Tischu River station was at 1300m, approximately 300m lower in elevation than the Mackenzie Mountain Barrens, but the 1993 study of palsa microclimate characteristics in the Mackenzie Mountain Barrens along an altitudinal gradient (410m) concluded that rainfall, wind and mean annual temperature were similar for both high and low sites (Kershaw and Skaret, 1993).

Disturbance Types:

Various disturbance types were sampled within the Decumbent Shrub Tundra including vehicle tracks (fig. 1.4) and borrow pit excavations. Borrow pit disturbances were divided into pit center, pit edge, bladed areas and overburden spoil (fig. 1.5). Linear disturbances were associated with the passage of wheeled and tracked vehicles. Multiple vehicle tracks were the most severe with evidence of multiple passages (fig. 1.4). Single tracks were identified as lower intensity linear disturbances and were identifiable on aerial photographs as two dark parallel lines.

Methods

Prior to the 1996 field season, existing series of aerial photographs from 1944, 1974 and 1981 were examined to determine potential disturbance and control sites. Candidate sampling sites were selected based on air photo analysis and were sampled after a site visit to determined a lack of evidence of redisturbance since their abandonment in 1945.

Borrow pits were very easily identified both on the aerial photographs and in the field. Vehicle tracks were identified on the 1944 photographs and their location was verified by comparison to the 1974 and 1981 photographs. Vehicle tracks on the airphotos were identified as two parallel ruts that could be traced for several kilometers. In all cases the candidate sites selected prior to field selection were found. In 1997 as in 1983 the ruts consisted of two parallel track depressions sometimes holding ponded water or channelized runoff (Kershaw 1983b). The only instance when a candidate site was not used was when the vehicle track was not located within the Decumbent Shrub Tundra.

Control (undisturbed reference stands) and disturbed sites were grouped together to minimize differences in substrate and climate. Sampling was conducted exclusively in the Decumbent Shrub Tundra.

Microclimate:

Two microclimate stations Station 1 (STN1) and Station 2 (STN 2) were installed before snowmelt to compile a continuous record of environmental variables associated with each type of disturbance within the study area. Sensors at STN 1 (described in detail in Chapter 3) were located on two masts one in the undisturbed and one in the borrow pit center. This station began recording on 15 June 1996. Only one mast was placed at STN 2 which began logging on 15 June 1996.

Vegetation Analysis:

The vegetation sampling protocol consisted of a block sample design with fifteen random (25cm x 25cm) quadrats as used in Harper and Kershaw. (1996) and Harper (1994). Each block had an area of $200m^2$ and was subjectively chosen to represent the disturbance type being sampled. In most disturbances the block dimensions were 10m x 20m but in narrower disturbance types such as bulldozer and vehicle tracks the block was reduced in width to 5m and lengthened to 40m to eliminate sampling of the surrounding undisturbed tundra. Cover was determined for 15 randomly selected. 0.25m x 0.25m quadrats within the block. Identical sampling methods were used for disturbance sites and control sites. Plant cover for each species was visually estimated as percent cover of each quadrat in 1% units below 20% and in 5% units above 20%.

Soil pits:

Soil pits were dug to the maximum rooting depth next to three randomly-selected vegetation quadrats within both disturbed and undisturbed blocks. Each sample pit was described with respect to horizon thickness and depth, color and texture. Each horizon was tested for pH using pH paper. Bulk density samples were taken from each discernible horizon, double bagged and air dried before lab analysis in Edmonton. A modified analysis from Kalra and Maynard (1991) was completed for bulk density, moisture content (volumetric), organic matter content and particle size distribution. Nutrient analysis for Total N, NO_3 and NH_4 was done for surface layers of all soil pits. Specific methods for analysis techniques are presented in Chapter 3.

Depth of Thaw:

An attempt was made to determine depth of thaw layer by a probing technique, however due to large particle size in the borrow pits and close proximity to bedrock in undisturbed areas the depth to the 0°C level was seldom directly measurable. For each soil pit dug a temperature profile was obtained at 5cm increments to maximum coring depth. Depth of thaw was estimated through a linear regression analysis and extrapolation.

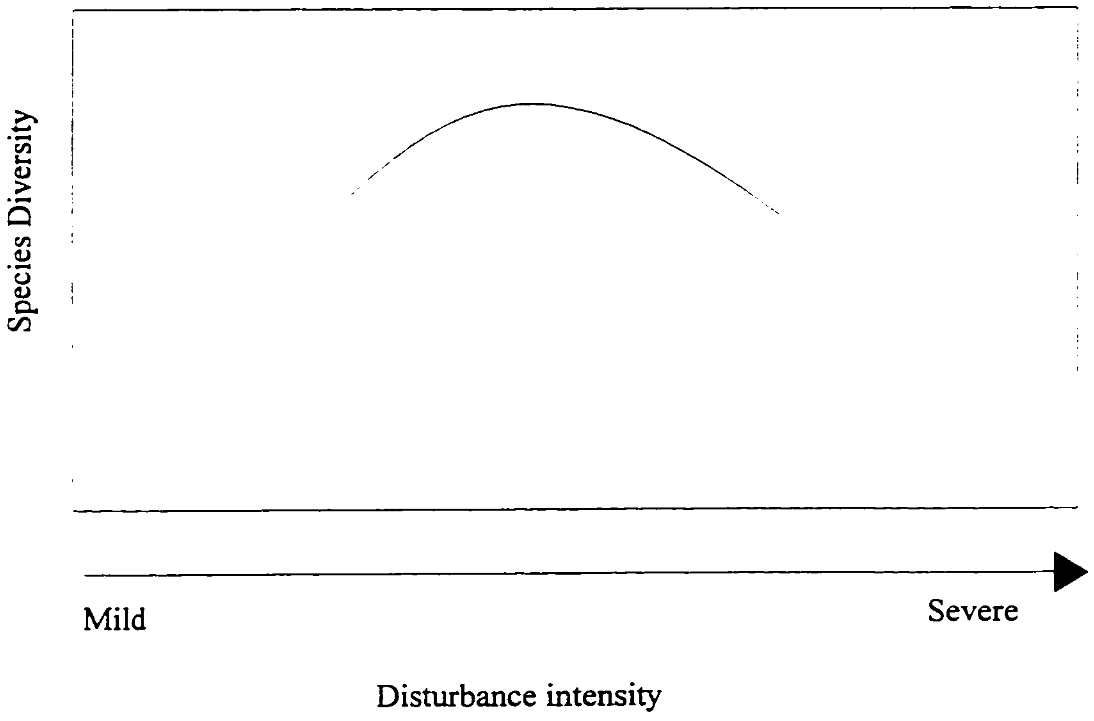

Figure 1.1. Graphic illustration of the Intermediate disturbance hypothesis (Connell 1978)

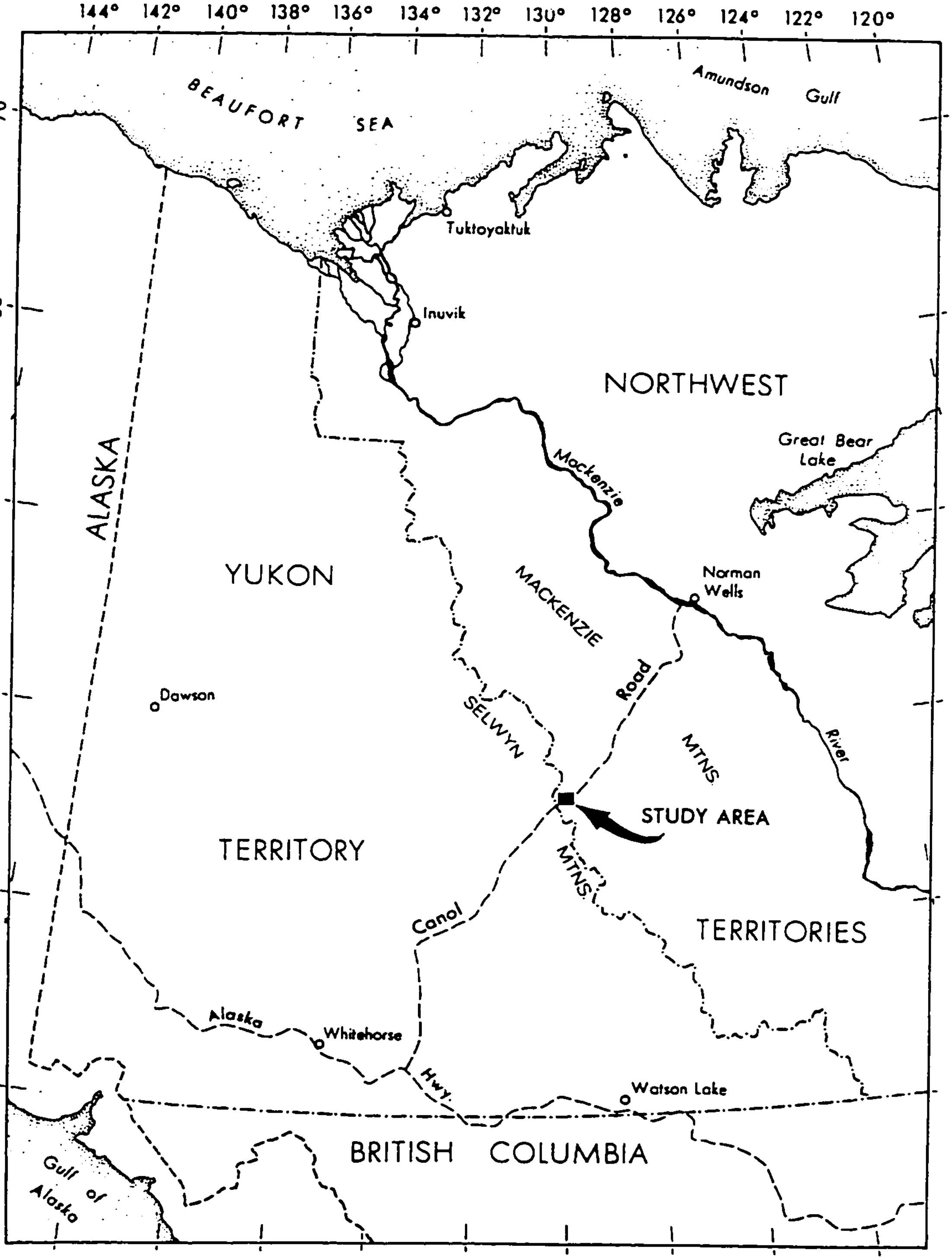

Figure 1.2. The study area is located in the Mackenzie Mountain Barrens, 340km southwest of Norman Wells along the CANOL Road (Kershaw and Gill 1979).

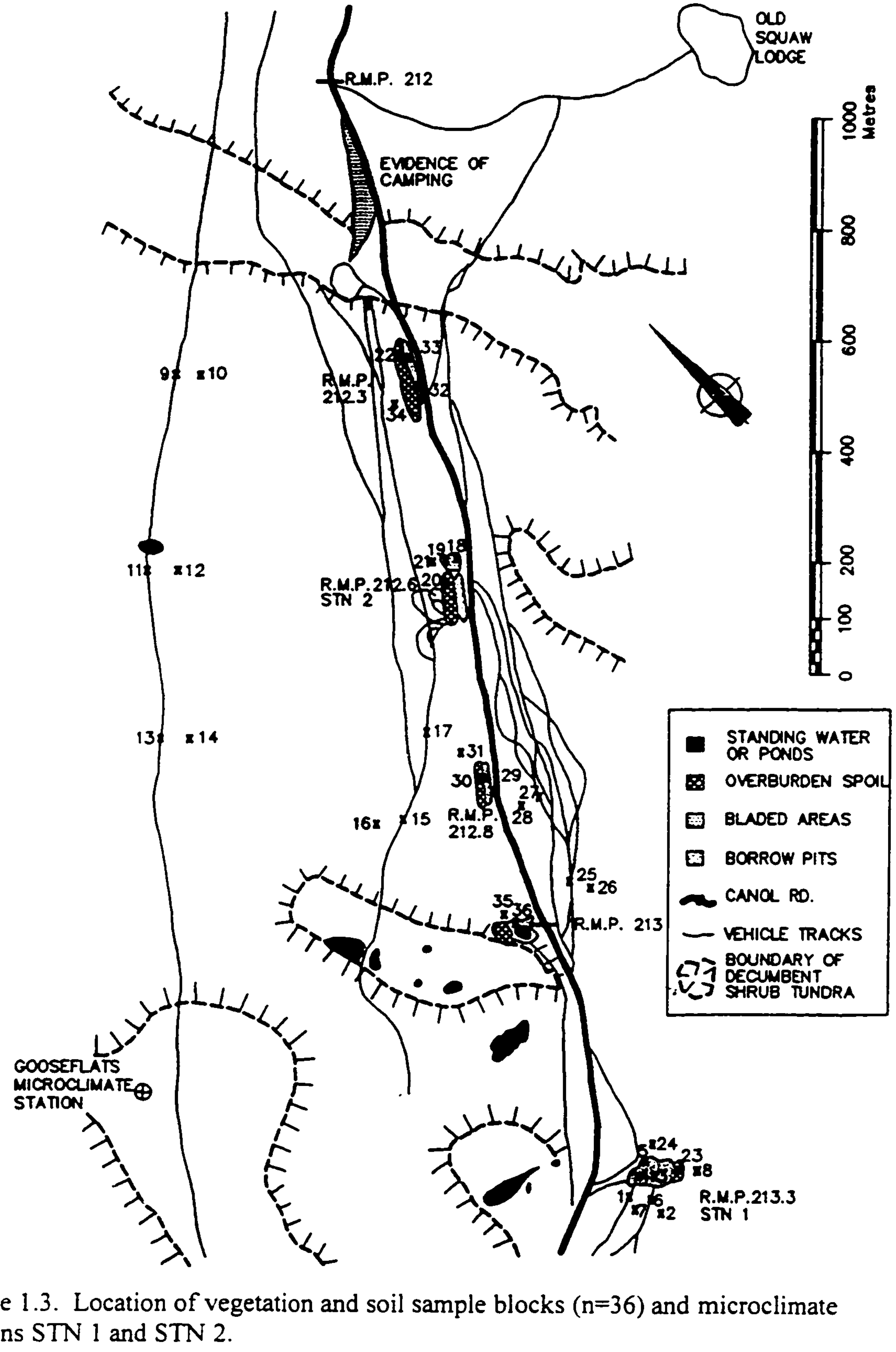

Figure 1.3. Location of vegetation and soil sample blocks (n=36) and microclimate stations STN 1 and STN 2.

Figure 1.4. Multiple vehicle track disturbance. Numerous tracked vehicle passes for pipeline and telephone line corridors are easily distinguished from the undisturbed tundra by the high density of tall woody shrubs. Located at Block 9 (fig. 1.3).

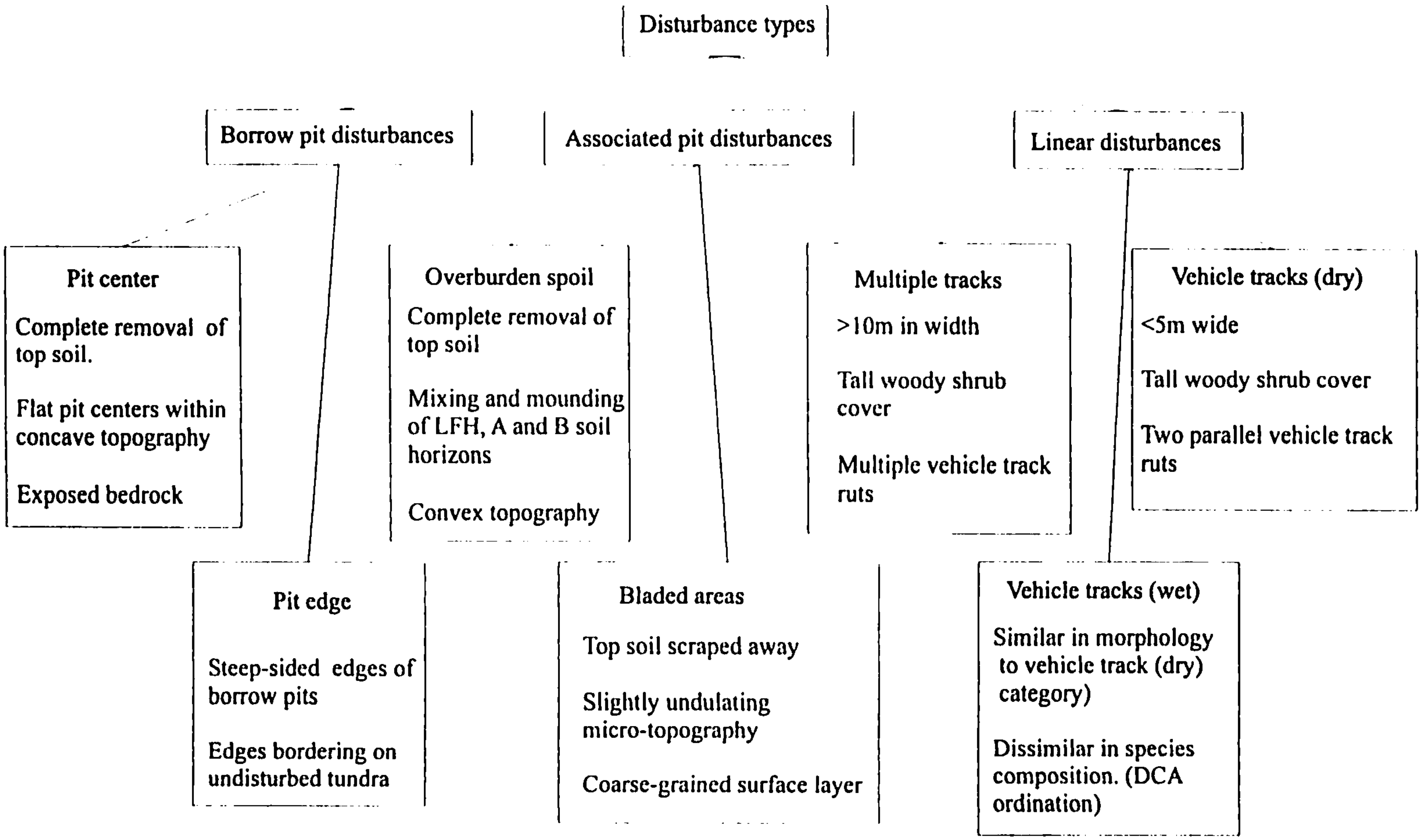

Figure 1.5. Description of the classification of disturbance types sampled in the Decumbent Shrub Tundra of the Mackenzie Mountain Barrens from R.M.P. 212-216.

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Chapter 2: Plant Community Analysis

Introduction

Subarctic plant communities characteristically have low species richness, and similar community types can be found throughout the Arctic. Recolonizing species are also small in number and common among various disturbance types, both natural and anthropogenic, and between widely separated geographical areas. Most recently, Forbes (1995) linked vegetation recovery in similar plants communities of Devon Is., Cornwallis Is., and Baffin Is. separated by almost 15 degrees of latitude. If links can be made along such wide spatial gradients in the High Arctic, recovery processes within one physiognomically-defined plant community such as the Decumbent Shrub Tundra should be linked. The objective of this chapter is to compare vegetation development on naturally revegetated disturbances and the undisturbed Decumbent Shrub Tundra found in the region of the Mackenzie Mountain Barrens, N.W.T.

The Decumbent Shrub Tundra was found in each ecosection of the CANOL study area (Kershaw 1983b; Kershaw 1984). This type of dwarf-shrub tundra has been denoted as 'typical tundra' (Chernov and Matveyeva 1979) and is characterized by the loss of many boreal species (Bliss and Matveyeva 1992). An attempt was made to sample the Decumbent Shrub Tundra exclusively because it represents typical subarctic vegetation. It occurs on well-drained gravelly substrates which was a common target for borrow pit construction along the CANOL. Borrow pits, vehicle tracks, overburden spoil piles and bladed areas that have undergone >50yrs of natural revegetation are the focus for comparison within this plant community.

Human activity has often resulted in a decrease in plant biomass and species' richness (Forbes 1993; Bliss and Matveyeva 1992; Borgegard 1990; Cargill-Bishop and Chapin 1989; Kershaw 1984; Kershaw 1983b; Babb and Bliss 1974). In most of these cases the change in composition is concurrent with the disturbance. However the long-term effect of tundra disturbance has been variously documented. Disturbances causing removal or killing of the surface cover such as gravel building pads, borrow pits, and trampling, display slow recovery and usually have low species' counts (Harper and Kershaw 1996; Forbes 1995; Forbes 1992; Borgegard 1990; Cargill-Bishop and Chapin 1989; Kershaw and Kershaw 1987; Kershaw 1984; Kershaw 1983b; Bayfield 1971). Disturbances that had higher species' richness were linear disturbances in which the substrate was simply compacted. This effect was seen more commonly in natural revegetation studies greater than 10yrs (Kershaw and Kershaw 1987; Kershaw 1984; Ebersole and Webber 1983; Kershaw 1983b; Bliss and Wein 1972). Various disturbance types found in the Decumbent Shrub Tundra may exhibit disimilarities in diversity.

Many anthropogenic disturbances do not return to their original predisturbance state (Ebersole and Webber 1983; Thorhaug 1980). Natural disturbance regimes have been observed in which the association composition and diversity is maintained by the disturbance itself. While anthropogenic disturbances typically do not show the cyclic nature of natural disturbance the processes involved should be transferable. Natural disturbance can manifest itself in many different forms and the resultant ecosystem is a function of the size, frequency or intensity of the initial disruption. Anthropogenic disturbance cannot always be classified in the same terms as natural disturbance for intensity and frequency, however, some models used widely in the description of natural disturbance recovery can be modified to include anthropogenic perturbations.

Rates of recovery among various disturbance types found in the Decumbent Shrub Tundra of the Mackenzie Mountain Barrens are expected to be significantly different. The existence of succession, as a directional progression of a plant community towards some stable endpoint has been questioned for arctic communities (Svoboda and Henry 1987). A non-equilibrium model of succession seems to be most appropriate in subarctic ecosystems. An example of this type of model is the intermediate disturbance hypothesis (Connell and Slayter 1977).

Intermediate Disturbance Hypothesis:

Currently the most widely accepted model for describing the process from disturbance resulting in an entirely bare surface to a stable plant community (in high diversity, tropical and temperate systems) is the intermediate disturbance hypothesis (fig. 1.1) (Chapter 1). This equilibrium hypothesis is driven by the balance between birth and death (Petaitis et al. 1989). In the Arctic there is a reduced flora, rates of immigration are reduced and environmental factors dictate that different species will be successful as early colonizers. The intermediate disturbance hypothesis is suitable for ecosystems with high diversity but needs to be tested in subarctic regions (Connell 1978).

Unconstrained Ordination:

Ecologists have developed many techniques to characterize the compositional similarity or dissimilarity of plant communities. Correspondence analysis (CA) is an indirect ordination technique which constructs hypothetical 'latent' environmental variables which give the best fit to the species' data (terBraak 1986). CA delimits the major pattern of variation in community composition and subsequently, environmental variables can be proposed to explain these variations. This technique has also been used in the geographic analysis of plant communities (Harper and Kershaw 1996; Forbes 1995; Forbes 1993).

Detrended Correspondence Analysis (DCA) is a modification of CA which generates the same information as CA but the data are plotted by segments to alleviate artificial cluster patterns created in CA output biplots. The 'arch' effect and the 'edge' or 'tongue' effect are cluster patterns in the output biplots which are partially alleviated by detrending. The 'arch' effect is a parabolic shape in the plotted species' data caused by the first axis of variation influencing the second axis of variation (terBraak 1986). The 'edge' effect or the 'tongue' effect (Michin 1987) is caused by unequal within-site variation. Since the variation in DCA is measured in standard deviation (S.D.) units, samples with smaller within-site variance occur at the edges of the cluster (terBraak 1986).

The output of DCA includes eigenvalues for four axes of variation. gradient lengths of the four axes in S.D. units and a separate biplot for species and for samples. Eigenvalues are importance indicators describing each axis of variation. They are values between 0-1 where a value of >0.5 is usually considered an important biological difference (Jongman, et. al. 1987). Gradient lengths are measured in S.D. units. terBraak (1986) estimated that a species will appear. reach an optimum and disappear within 4 S.D. units. One unit of S.D. separation on a biplot indicates at least a 50% variation in community composition (Forbes 1993: terBraak 1986). Biplots show both species and samples as separate graphs. Proximity of sample points indicates similarity in species' composition and proximity of species' points indicates associations between species and also to corresponding sample locations within the cluster diagram.

The primary objective of this analysis is to compare the long-term natural revegetation in different disturbance types associated with transport corridor (e.g. road. power line or pipeline) construction in low arctic tundra. Comparisons will be made between various taxonomic groups of plants to identify important early colonizers. Ordination will be used to classify the various plant associations occupying various disturbances. Finally, current successional models will be assessed in the context of natural revegetation in various low arctic tundra disturbances within the Decumbent Shrub Tundra.

Methods

Study Sites:

Control sites (n=36) were selected in areas of undisturbed tundra directly adjacent to the disturbance type being sampled (fig. 1.3). Specific site characteristics and the nearest disturbance blocks are listed in table 2.1. Disturbance sites were sampled only if the adjacent plant community resembled the Decumbent Shrub Tundra. Road, borrow pit access road and oil spill disturbance types as described by Kershaw (1984) were not included in the sampling due to recent redisturbance in the case of roads and absence of access roads and oil spills within the Decumbent Shrub Tundra.

Borrow pit disturbances fall into two categories: pit disturbances and associated pit disturbances. These categories were not similar in plant association composition but were grouped together because they were created during the same borrow pit construction process. Linear disturbances are created by the passage of wheeled traffic directly on the tundra surface (fig. 1.5).

Further subdivisions of the borrow pit disturbances resulted in pit (center) and pit (edge) classifications. The four (table 2.2; fig. 1.5) borrow pits were extensive excavations in bedrock all with steep-walled edges. Permanent and seasonal ponding of water was common, and areas of late-lying snow were present at each site. Pit center samples were located on the floor of the pits with relatively flat bottoms. Blocks for pit (edge) sites had 5m x 40m dimensions and ran along the steep-walled perimeters of the pits.

Associated pit disturbances surrounded the actual borrow pits and were subdivided into two distinct disturbance types: bladed areas and overburden spoil piles. Bladed areas were at the same level as the surrounding undisturbed tundra since the topsoil was scraped off to a shallow depth (table 2.2; fig. 1.5). Overburden spoil piles were formed by the removal and piling of soil at the edges of borrow pits. Sample sites were usually elongated, convex areas with fine-grained mixed substrate. Piles sometimes reached a height of 2m above the level of undisturbed tundra (table 2.2).

Vehicle tracks ranged in intensity from multiple to single tracks (table 2.2; fig. 1.5). These two categories were different in disturbance morphology with respect to width, number of tracks and evidence of telephone line construction. After ordination analysis a further subdivision of the single track disturbances was possible on the basis of species' composition. Single track (dry) disturbances were located in slightly higher more well-drained locations whereas the single track (wet) disturbances were distinguishable in the field by the presence of surface water and less well-drained substrates.

Field Methods:

Vegetation cover was determined using a block sample design (Harper and Kershaw 1996). Sample sites were chosen within visually homogenous vegetation to represent a particular disturbance type or control site within the Decumbent Shrub Tundra. Each block or site had an area of 200m^2 where the dimensions varied according to the shape of the disturbance type. Linear disturbances were 5m x 40m and borrow pit disturbances were square (20m x 20m). Percent cover of all vascular and non-vascular plants was assessed with 15 randomly located 0.25m x 0.25m quadrats within each block. Cover was estimated to the nearest 1% for cover less than 10% and to the nearest 5% for cover greater than 10%. Cover of bare mineral and litter in the quadrats was also recorded.

Provisional species' identifications of vascular plant species were made in the field according to Porsild and Cody (1980) and Hultén (1968). Lichen and bryophyte nomenclature followed Vitt et al. (1988). A sample collection was made for verification with the CANOL collection at the University of Alberta. Ecological samples of various taxa were verified by Linda Kershaw (vascular plants) and Dr. C. LaFarge-England (bryophytes) and Derek Johnson (some ecological lichen specimens). Voucher collections are located in the Department of Earth and Atmospheric Sciences, University of Alberta. A digital copy of the raw cover values is available through W. Davis or Dr. G.P. Kershaw at the University of Alberta, Edmonton.

Candidate sites were subjectively chosen by air photo analysis (as described in Chapter 1) to represent undisturbed Decumbent Shrub Tundra, borrow pit centers, borrow pit edges, overburden spoil, vehicle tracks of varying intensities and bladed areas. The final selection of sites in the field was based on three criteria: 1) representation of the disturbance type, 2) no evidence of anthropogenic redisturbance within the past 50yrs.

and 3) proximity of an area of undisturbed tundra representing the Decumbent Shrub Tundra plant community. In total there were 36 sample sites, 14 control or undisturbed Decumbent Shrub Tundra, 9 linear disturbances, 5 borrow pit centers, 2 borrow pit edges, 4 overburden spoil piles and 2 shallow bladed areas.

Analysis:

Average frequency (% of sample plots occupied by at least one rooted individual) and average cover was calculated for all species separately and for mineral and litter components. Means were also calculated for the plant groupings of bryophytes, lichens, forbs, woody plants, and *Lycopodium* and *Equisetum* species for all the disturbance categories as well as the undisturbed. Species with a cover of >1% or a frequency of >10% were considered 'common' and species less than the previous values of abundance are considered 'rare' (Harper and Kershaw 1996).

Throughout this thesis species' richness per unit area (per block) was used as a simple measure of species diversity. Other indices such as the Simpson's index (Simpson 1949) or the Shannon-Weaver's index (Shannon and Weaver 1949) combine both richness and evenness in the calculation. Such calculations use the proportions of all individuals in a sample that belong to a particular species (Barbour et. al. 1987). Thus communities with fewer species but greater evenness may be more diverse than communities with a greater number of species but with strong dominance by a single species. These indices are useful in plant communities with larger numbers of species. In communities such as the Decumbent Shrub Tundra where the total flora is small, species' richness can be an adequate measure of diversity.

Richness was calculated as number of species (Krebs 1978; Whittaker 1972) in each taxonomic group within the categories of undisturbed Decumbent Shrub Tundra, pit disturbances, pit center, pit edge, overburden spoil, linear disturbances, single tracks (wet) and (dry), multiple tracks and bladed areas. Most of these categories are the original subjectively chosen disturbance types except for the single tracks (wet) which were separated from the rest of the undisturbed sites and linear disturbances after interpretation of the DCA ordination.

Detrended correspondence analysis (DCA) was performed using the program CANOCO (terBraak 1987) using all 540 quadrats in the vegetation data set. There were 118 active species in the analysis (Appendix 1). DCA is a weighted averaging ordination technique which orders site and species' scores simultaneously (Palmer 1993; terBraak and Prentice 1988). The DCA was used initially to determine whether the selected treatment types were different in species' composition from each other and whether the 14 undisturbed sites varied among each other. Other computer programs that have been used for this purpose are TWINSPAN (Forbes 1995; Forbes 1993) and COMPCLUS (Kershaw 1983b). DCA was used because the sampling area encompassed only one vegetation type (Decumbent Shrub Tundra) which was previously classified using COMPCLUS (Kershaw 1983b).

Detrended correspondence analysis generates four eigenvalues which are latent hypothetical variables. Both species' and site scores are plotted along the first two axes of variation. Proximity and clustering may indicate similarity in species' composition.

Comparison to the Intermediate Disturbance Hypothesis:

Detrended correspondence analysis is an indirect method of determining variation within a plant community. The actual vegetation data are analyzed in the absence of environmental variables so that the variation can be interpreted by the researcher. Species' richness is another measure of the variability within the plant community and is used here to describe the change in species' diversity along a gradient of different disturbance intensities, magnitudes or frequencies. According to the intermediate disturbance hypothesis diversity in a plant community is at its maximum at intermediate levels of disturbance. If the variation in species' diversity between disturbance types represents a gradient from primary succession (borrow pits) to secondary succession processes (linear disturbances) then the primary DCA axis can be used as the measure of disturbance intensity. Using species' richness as a measure of species' diversity and indirect ordination as the primary source of variation in a plant community, the intensity of disturbances can be characterized.

Results

Undisturbed Decumbent Shrub Tundra:

The undisturbed low-arctic tundra sampled in the Mackenzie Mountain Barrens occupies an area of extensive active and relict patterned ground (non-sorted circles and stripes). The resultant plant community consisted of raised edges dominated by a continuous bryophyte mat interspersed with low center patches of bare ground. Mineral soil occurred in 30% of all control sample quadrats and accounted for 8% (table 2.3) of the cover in the Decumbent Shrub Tundra.

The total flora of the sampled undisturbed area was small at 125 species (table 2.4). Forbs were the largest taxonomic group when all occurrences were used in calculating species' richness (table 2.4). Species' richness of 'common' species was highest for bryophytes and lichens. Combined, these groups accounted for over half of the 'common' species of the undisturbed Decumbent Shrub Tundra (table 2.5).

Most important of the bryophytes are *Polytrichum juniperum* and *Dicranum elongatum*, which were dominant species on raised patterned ground edges in the Decumbent Shrub Tundra. The most important lichen species were *Stereocaulon paschale*, *Peltigera aphthosa* and *Cladina mitis* (table 2.3).

None of the species of tall shrub common on disturbances were prevalent in the undisturbed Decumbent Shrub Tundra. *Salix polaris*, occurred in 86% of all quadrats (table 2.3). It was the most frequently occurring species and provided the largest amount of cover. Tall shrub cover was rare in the Decumbent Shrub Tundra.

Comparison of disturbance types:

Borrow Pit Disturbances:

Borrow pit edges and centers each had different cover and species' composition. Borrow pit centers had a greater mineral cover and less litter than pit edges. The majority of cover in pit edge samples was provided by forbs (table 2.6).

Individual lichen species abundant in the pits were *Peltigera aphthosa, Panaria pezizoides, Stereocaulon* sp. and crustose lichens. Bryophytes were comparable in total species' richness to other disturbance types (table 2.5). Species of forb common to both pit (center) and pit (edge) (table 2.5) disturbances were *Minuartia rossii, Epilobium latifolium* and *Sibbaldia procumbens*. These species actually increased in abundance from the undisturbed where they were absent from the list of common species (table 2.3). Tall shrubs were absent in borrow pit disturbances, however the decumbent shrub *Salix polaris* still occurred in 28 to 29% frequency in pit disturbances (table 2.6).

Associated Pit Disturbances:

Overburden spoil and bladed areas were characterized by an increase in cover in comparison to the borrow pits and similar cover in comparison to undisturbed samples (table 2.7). Conversely, species' richness of all taxonomic groups decreased (table 2.4). The largest decrease in richness occurred in the lichen group within the overburden samples where the only frequently occurring species were *Peltigera aphthosa* and *Stereocaulon paschale* (table 2.5). *Salix polaris* was still considered 'common' in the associated pit disturbances but *Salix glauca, Salix pulchra* and *Salix planifolia* were also 'common' on the overburden spoil.

Linear Disturbances:

The DCA ordination allowed clear separation of another vehicle track category (single track (dry)). In the DCA cluster diagram these samples were clearly apart from the main cluster composed of single track (dry) and multiple tracks (fig. 2.1c). Single track (wet) were located within the study area at blocks 25 and 26 (fig. 1.3).

Total species' richness was highest in vehicle track samples (table 2.4). Conversely, the total richness of 'common' species was reduced for each type of vehicle track (table 2.5).

The same pattern of species' richness differences was observed within all taxonomic groups except lichens in the single track (wet) samples (table 2.5). For single track (dry) and multiple tracks, lichens, bryophytes and forbs increased in total species' richness compared to the undisturbed while those same groups decreased in richness when only 'common' species were considered. Single tracks (wet) displayed different total richness trends with increases in the forb group and absence of most lichen species (table 2.4). There were no 'common' species of lichen within single track (wet) samples (table 2.5; table 2.8)

Single tracks (wet) were different from other vehicle tracks in terms of the presence of bare mineral areas. Single track (dry) and multiple tracks had 33%-56% of all quadrats containing bare mineral soil indicating active or recently active patterned ground structures associated with non-sorted circles and stripes. Single track (wet) samples had 0% bare mineral occurrence and high litter cover values (table 2.8)

The presence of tall shrubs characterized all linear disturbances. *Salix planifolia* was the only 'common' tall shrub species (table 2.5). The decumbent shrub *Salix polaris* was still one of the most abundant species in vehicle tracks.

Unconstrained Ordination (Differences Between Disturbance Types):

All disturbance types displayed significant overlap in species' composition in the DCA ordination diagram. In order to clarify the scatter plot the 540 sample quadrats were separated into borrow pit (center) and (edge) (fig. 2.1a), overburden spoil and bladed areas (fig.2.1b), linear disturbances (fig. 2.1c) and undisturbed Decumbent Shrub Tundra (fig. 2.1d).

Differences between the main categories, borrow pit disturbances and linear disturbances were described by the primary axis of variation. The eigenvalue 0.771 (table 2.9) indicates significant difference in species' composition between samples along the horizontal axis of the DCA diagram (fig. 2.1). Differences among the linear disturbances are described mainly by the secondary axis of variation with a lower eigenvalue of 0.442 (table 2.9). Single tracks and multiple tracks were similar in species' composition, while a slight difference in species' composition was found in 2 samples taken from single tracks (wet).

Variation in species' composition was evident along the first and the second axis of variation within the pit and associated pit disturbance categories. Disturbances in this category ranged from borrow pits with almost no significant natural revegetation to overburden spoil with complete vegetation cover in most instances. Pit center and pit edge samples were separated along the vertical axis to a small degree whereas the overburden and bladed areas ranged along the horizontal axis indicating a more important difference (fig.2.1a,b,c).

The primary and secondary axes of variation in the DCA ordination reflected the large and small scale differences in species' composition among the disturbance types, respectively. The significant eigenvalue of the primary axis separates the major categories of disturbance between relatively poorly revegetated to well revegetated. The less important eigenvalue of the secondary axis separated similar disturbance types within the main categories. Pit (edge) and (center) disturbances varied along the secondary axis as did the single tracks (wet) and (dry).

Affinity for various taxonomic groups to various disturbance types was evident in some cases. The most marked affinity of the 6 taxonomic groups for a specific area were the lichens. The species' ranges in optima were almost exclusively clustered in the lower portion of the DCA ordination scatter plot (fig. 2.2f) which corresponds to areas occupied by pit (edge), pit (center) and a portion of the undisturbed sample cluster (fig. 2.1a,d). Tall shrubs *Salix pulchra*, *Salix planifolia* and *Salix glauca* were all located on the upper portion of the graph (fig. 2.1d). Bryophytes, graminoids and forbs as groups did not have any discernible patterns to their distribution (fig. 2.2a,c,e).

Comparison to Intermediate Disturbance Hypothesis:

When species' richness for each block was plotted against the primary DCA axis (fig. 2.3), the best fit curve was a 4th order polynomial with a correlation coefficient of 0.675. The second best fit was a rational function ($r=0.6511$) and the quadratic fit was third at $r=0.633$. The quadratic fit is the curve that most closely resembles the curve described in the intermediate disturbance hypothesis, however, the data set collected does not include samples from areas that remain at a mild level of disturbance.

Discussion

Undisturbed Decumbent Shrub Tundra:

The Decumbent Shrub Tundra was common in all ecosections along the North CANOL road (Kershaw 1983b). The *Salix polaris - Dactylina beringica* plant association was one of the three subcategories of the Decumbent Shrub Tundra as described by Kershaw (1984) and one of the notable features was the prevalence of *Salix polaris* often found in pure stands. Similar findings were seen in the results of this study with *Salix polaris* occurring in 86% of all sampled quadrats in the undisturbed. These low arctic communities are referred to as 'typical' sedge-dwarf shrub tundra and they are characterized by the loss of boreal species of shrubs such as *Salix alaxensis, S. planifolia* and *Betula glandulosa* and the prevalence of decumbent shrub species (Bliss and Matveyeva, 1992).

Pevious work done in the Taimyr peninsula on communities affected by extensive cryoturbation (Chernov and Matveyeva 1979) described a patterned ground structure consisting of vegetated hummocks and non vegetated low centers where low centers made up 1/3 of the surface cover. In this study similar results were found for the frequency of bare mineral substrate in the undisturbed samples (table 2.3). The patterned ground structure of vegetated raised edges and non-vegetated low centers of the Decumbent Shrub Tundra was comparable to other 'typical' tundra morphologies of the Subarctic.

The total flora of the Decumbent Shrub Tundra on the Mackenzie Mountain Barrens was small, species' richness was dominated by bryophyte taxa, one species of decumbent shrub was dominant and patterned ground accounted for 1/3 bare ground. These are all features representative of a 'common' vegetation zone not only of northwestern Canada but also displays characteristics of 'typical' tundra of the circumpolar low-arctic.

Differences Within Disturbance Types:

Borrow Pit Disturbances:

Borrow pit disturbances were different from other disturbance types because of the extraction of all topsoil materials, yet there were similarities in the vegetation structure. The fast growth of perennial forbs as compared to the slower growth of lichens and bryophytes accounts for their relative success as colonizers of borrow pit disturbances. The difference in plant cover between the pit edges and centers may be due to the proximity of the edges to a viable seed bank existing in the undisturbed tundra. Also fragments of vegetation from the steep edges of the pits can break off and reproduce vegetatively on the pit edges. The faster growing perennial herbs 'common' to the borrow pit edges should be more successful at establishing in steep loose substrate areas than slow growing lichens and bryophytes which do not develop rooting systems important in stabilizing surfaces.

Associated Pit Disturbances:

Both overburden spoil piles and bladed areas had a high prevalence of species of tall woody shrubs. The vegetation mat in both cases was disrupted but the topsoil layer was not removed. Topsoil contains most of the nutrients available to plants and any buried seed which may allow for natural revegetation processes to proceed quickly. Richness for lichens was different between overburden spoil and bladed areas. Nitrogen fixing species *Peltigera aphthosa* and *Stereocaulon paschale* were the only species able to colonize the overburden spoil whereas species 'common' in the undisturbed tundra were also 'common' in the bladed areas. Kershaw (1983b) noted that bladed areas were common in the construction of the pipeline and were scraped to a shallow depth often grazing the tops of hummocks and leaving low centers untouched. Such a technique would explain the presence of species of slow growing lichen in areas unaffected by the blading operation.

Linear Disturbances:

The DCA sample scores cluster diagram separated the vehicle track types along the vertical axis. Disturbances caused by more that one passage of tracked vehicles (multiple tracks) were more similar to the single pass disturbances in dry substrate (single track (dry)) than samples in wet substrate (single track (wet)) (fig. 2.1c). There was also a complete lack of 'common' species of lichen after 50yrs of natural revegetation. It may be that the wetter substrates are more susceptible to tracked vehicle disturbance. However since the number of lichen species found in blocks adjacent to the single track (wet) sites was less than the undisturbed it may be that these samples lie in an ecotone between the Decumbent Shrub Tundra and the wetter plant community of Sedge Meadow Tundra.

Differences Among Disturbances:

Species' Richness:

When the total flora of a plant community is small the number of potential colonizers of disturbance will also be small. This group would be expected to be made up of rare species. The comparison of species' richness values of 'common' species versus total richness helped in the evaluation of evenness. For the undisturbed Decumbent Shrub Tundra, richness values for 'common' species were higher than all disturbed sites. When rare species were taken into account vehicle track disturbances had higher richness values. This indicated that the undisturbed areas had a greater evenness component than the disturbed areas and that the species responsible for the increase in total richness of the vehicle tracks were rare species.

In the discussion of differences among disturbance types comparisons were made on the basis of differences between colonizing species. This group of species was separated into 5 taxonomic groups.

Bryophytes:

As latitude increases bryophytes become relatively more important in naturally occurring plant communities. In polar deserts, cryptogram species make up the majority of the flora whereas in the Subarctic other taxonomic groups account for more of the floristic richness (Russell 1990). As a group, bryophytes tend to be more successful in high latitude environments because of their perennial growth form, low nutrient requirements and the ability of some species to acclimatize to cold environmental conditions (Russell 1990; Longton 1988). The ability to acclimatize to cold conditions necessitates a low rate of photosynthesis thus growth and recolonization is slow (Bliss and Wein 1972). Once mosses become established it is typical for phanerophytes to begin recolonizing sites within the moss turf (Bliss and Svoboda 1984; Sohlberg and

Bliss 1984).

The overall species' richness of bryophytes was highest when all disturbances were combined (table 2.5), confirming the importance of mosses as colonizing species. Further analysis revealed that even in borrow pit disturbances where other taxa were almost completely absent, at the 'common' level the bryophyte flora was relatively rich (table 2.5). Among the common species were *Racometrium canescens* and *Polytrichum* ssp. Both of these species are common in revegetation sites in the Decumbent Shrub Tundra (Viereck 1966; Harper 1994; Harper and Kershaw 1996; Kershaw 1984; Kershaw 1983b). Kershaw noted that *Polytrichum* spp. were successful colonizers in disturbances along the CANOL pipeline and the Dempster Highway and were recorded as primary colonizers on hummock tops within oil spills (Kershaw and Kershaw 1986). *Racometrium canescens* is also a well-known colonizing species of exposed lava substrates in southern Iceland (Fridriksson 1975).

Species of *Polytrichum* in particular have been studied because of their apparent success as early successional species (Schofield 1971; Russell 1990). Because of their slow growth, mosses are considered poor competitors, however in the Decumbent Shrub Tundra harsh climatic conditions allowed bryophytes to become early successional species. In stressful conditions species of *Polytrichaceae* have been documented to acclimatize to their environments. *Polytrichum alpinum* has shown ability to photosynthesis before snow-melt thereby increasing the length of the growing season (Russell 1990). Coupled with perennial habit and the ability to modify physiological needs, bryophytes are effective colonizers in cold tundra environments. Further discussion of climatic conditions among disturbance types and within the undisturbed tundra follows in Chapter 3.

Lichens:

The impact of different disturbances on lichen cover and frequency was more severe than on bryophytes in the Decumbent Shrub Tundra. Reports on lichen regeneration agree that they are slow recolonizers (Bliss and Wein 1972; Ebersole 1985). Lichens that have the capability to fix nitrogen such as *Peltigera aphthosa*, *Solorina crocea* and *Stereocaulon paschale* recolonized borrow pits in the Decumbent Shrub Tundra (Longton 1988). The same pattern was observed in the Erect Shrub tundra (Harper and Kershaw 1996; Kershaw 1984)

In the case of pit (centers), pit (edges), overburden spoil and single tracks (wet), lichen species' diversity and abundance reflected high susceptibility to disturbance (table 2.5). Borrow pit and overburden samples involved the extraction and mixing of topsoil and destruction of the undisturbed vegetation. In this case lichen regeneration was too slow for significant cover to develop on bare substrates after 50yrs.

Lichens did show a preference for recolonization on bare borrow pit substrates. Even though richness values indicate lichens were few in number in the borrow pits the DCA cluster of species' samples showed lichens clustered in the areas occupied by the borrow pits and the undisturbed. Species of lichen occupying the borrow pit areas were species of crustose lichen (Csx1), all three *Stereocaulon* species (Stto, Stpa, Stal) and *Panaria pezizoides* (fig. 2.2f.).

Graminoids:

Graminoid species have been considered one of the most important taxonomic groups in revegetation because they are easy to sow and accumulate biomass quickly (Cargill-Bishop and Chapin 1989; Hernandez 1973; Bliss and Wein 1972). Most successful over the long-term (10-15yrs) are commercial species adapted to northern conditions (Younkin and Martens 1985) and thus graminoid species may be expected to be important recolonizers in the the Decumbent Shrub Tundra. However graminoids did not exhibit high relative abundance in either the naturally disturbed Decumbent Shrub Tundra or anthropogenic disturbances. Native graminoid species of the Decumbent Shrub Tundra would be adapted to harsh condition and would be expected to be successful colonizers, but if they are not prevalent in the undisturbed tundra it follows that they will not be more abundant after anthropogenic disturbance. This highlights the importance of specific sit characteristics in revegetation.

Forbs:

Based on individual autecology, forbs are the most diverse taxonomic group. Individual species *Minuartia rosii*, *Epilobium latifolium* and *Sibbaldia procumbens* were most important colonizers in the Borrow pit disturbances (table 2.4). Furthermore these three taxa did not occur 'commonly' in the undisturbed samples. Forbs, such as these three colonizers native to the tundra are usually perennial species, as opposed to annuals typically considered recolonizing species (Billings and Mooney 1968). The success of forbs in the severe borrow pit disturbances must be due to their relative fast growth in comparison to bryophytes. In the pit (edge) areas sloping topography creates unstable substrate which can only be colonized by fast-growing species.

Sibbaldia procumbens was one of the only species that increased in abundance on all disturbance types compared to the undisturbed tundra. This indicates that there are subtle differences between the natural disturbance regime of the Decumbent Shrub Tundra and anthropogenic disturbances caused by pipeline construction procedures. These differences may be described by abiotic factors which will be examined in Chapter 3.

Dwarf Shrubs and Tall Shrubs:

Salix polaris was the most commonly occurring plant species in the undisturbed and the disturbance samples in the Decumbent Shrub Tundra. Kershaw (1983b) found *Salix polaris* dominated the undisturbed stands and it had greater cover on all disturbance sites than in the controls. Consequently *S. polaris* was considered a successful colonizer. Conversely, tall shrub species such as *S. planifolia* were not 'common' species in the undisturbed tundra yet they had high cover in Linear and Associated pit disturbances.

These species are also successful colonizers of roadsides and other disturbances all along the CANOL (Kershaw and Kershaw 1987).

The reaction of tall willow shrubs to disturbances in low shrub tundra has been documented previously by Ebersole (1985) and Kershaw (1983b). The willows grow on raised, deeply disturbed areas with warmer soils and on vehicle tracks. Vehicle tracks are not raised but compaction often produces warmer soils even though they are a wetter environment with ponded and running water. Ebersole noted that the species prevalent on riparian (naturally disturbed) sites, were different from the willows prevalent on the raised disturbances. In the Decumbent Shrub Tundra the only willow species to increase in abundance on the vehicle tracks was *Salix planifolia* while overburden spoil piles and bladed areas had at least three types of tall willow species. Willow species in general seem to be good colonizers of disturbance but the individual species types show preferences to different disturbances.

Differences Among Disturbance Types Using Ordination:

Species' composition among disturbance types appeared to be markedly different in the field. The most obvious of these differences was the tall shrub growth in linear disturbances and overburden spoil piles which was obvious even under spring snow cover. Pit (centers) and (edges) were almost devoid of vegetation and were differentiated by physical characteristics. The comparison of total richness and richness of 'common' species revealed that only a few species were responsible for the observed dissimilarity among the disturbances (table 2.5). In the DCA, disturbance types were in close proximity in the sample scores plots because the majority of species found in each sample were similar. Only rare species are diagnostic of differences between disturbance types and those are not emphasized in correspondence analysis (terBraak, 1987).

The ordination diagrams show a high degree of overlap in species' composition yet the eigenvalues indicate significant change in species' composition from the extremes of the plots and differences among the anthropogenic disturbance plant associations. The important species indicating recovery between disturbances are few and are sometimes common species in the undisturbed tundra. Brady (1984) examined mining disturbances in subarctic tundra up to 80yrs old. He found that only a small number of native plants with the physiological, morphological and life history characteristics suitable for recolonization was small and that these species were normally found in the undisturbed areas since they are already adapted to harsh (disturbance) environments.

Comparison to the Intermediate Disturbance Hypothesis:

By comparing the results of the DCA analysis to the total species' richness a gradient can be described between the diversity in the borrow pit, linear disturbance and undisturbed plant associations. The first three best fit curves on the plot of the 1°DCA axis versus species' diversity were limited by the lack of data in samples of mildly disturbed Decumbent Shrub Tundra (fig. 2.3).

Undisturbed samples in this treatment occurred at similar levels of species' diversity to those on linear disturbances. The undisturbed Decumbent Shrub Tundra was naturally disrupted by extensive patterned ground. Natural disturbance patterns exposed smaller disturbances but disturbance occurs at more frequent intervals than anthropogenic disturbance where the initial disruption is large followed by >50yrs of inactivity. The results of this analysis suggested that the impact of the initial anthropogenic disturbance was equivalent to the frequent perturbations associated with cryoturbation. It is also possible that the linear disturbances recovered from the initial anthropogenic disturbances and natural redisturbance from cryoturbation.

Svoboda and Henry (1987) describe succession in high arctic marginal environments as the balance between the incident climatic conditions and the biological driving forces of succession seen in more moderate climates. They argue that high arctic communities are rarely self sustaining and the process of succession rarely develops to a stage where early pioneer species are replaced and a stable community develops. The curve generated in fig. 2.3 resembles in part the intermediate disturbance hypothesis but lacks information in the area where a stable plant community exists. Succession in the low arctic community the Decumbent Shrub Tundra was stagnating at the equivalent of an early successional community and furthermore this stage was similar to the stage of succession reached by vehicle tracks, and associated pit disturbances that resulted from pipeline construction.

Summary

The Undisturbed Decumbent Shrub Tundra sampled in the Mackenzie Mountain Barrens was a common biogeographic zone around the Low Arctic. The plant community was subject to a high degree of natural disturbance associated with the maintenance of patterned ground. The resultant plant community consisted of vegetated raised edges and low poorly vegetated centers.

The regional flora was small and thus so were the number of potential colonizers of anthropogenic disturbances. Taxonomic groups with the highest richness values in the revegetating areas were the bryophytes and the forbs. Graminoids, commonly considered important colonizing species in temperate climates, were relatively less important among early recolonizers after 50yrs. Lichens were particularly susceptible to disturbance and slow to reestablish.

Individual species may be important recolonizers because of physiological, morphological and life history characteristics even in a less diverse taxonomic group. The dominant plant in the undisturbed tundra was *Salix polaris* often forming pure stands. Few other dwarf shrubs are native to the area yet *S. polaris* was a 'common' colonizer in all types of disturbance. *S. polaris* was also found to be a successful colonizer 35 yrs post abandonment (Kershaw 1983a) thus revegetation may still be in a similar stage of succession 15yrs later. Tall shrubs are not 'common' in the undisturbed tundra but dominate in linear disturbances and associated pit disturbances. This group represented 'rare' taxa in all cases yet *S. planifolia* was a colonizer of all disturbance types.

One species of forb (*Sibbaldia procumbens*) also had high affinity for growth in all disturbance types in the Decumbent Shrub Tundra. It had a similar pattern of relative abundance to *Salix planifolia* where predisturbance occurrences were lower than the frequency calculated for all disturbance types.

Ordination techniques provide a method to compare the disimilar anthropogenic plant associations along a continuous successional gradient. Combining species' richness measurements with the ordination results of species' dispersion, plant succession appears in part to be following the pattern of the intermediate disturbance hypothesis (Connell 1978). Further measurements could be done within the undisturbed Decumbent Shrub Tundra to determine if diversity values representative of a stable plant community could be obtained. Specifically this could be accomplished with a gradient analysis taking into account the patterned ground structure of bare low centers and raised vegetated edges.

After approximately 50yrs of natural revegetation disturbances associated with the construction of the CANOL pipeline have recovered to varying degrees. Linear and associated pit disturbances supported a more diverse plant community similar to the undisturbed tundra. The borrow pit disturbances were still in the very early stages of natural revegetation processes. None of the disturbances have recovered to the state exactly equivalent to the pre-construction Decumbent Shrub Tundra.

Table 2.1. Undisturbed Decumbent Shrub Tundra sample site (control samples) characteristics. Disturbance blocks associated with the control sample were the samples taken immediately adjacent to the control. Exact locations of the sample sites is shown in fig. 1.3.

Block #	Disturbance block	Aspect	Slope	Site Characteristics
B2	B1(Vehicle track)	255	slight	10-25cm raised non-sorted circle edges
B7	B6(Vehicle track)	255	slight	raised non-sorted circle edges
B8	B5, B4, B3(Borrow pit)			
	B23(Overburden spoil)	100	slight	raised non-sorted circle edges
B10	B9(Multiple tracks)	40	slight	30cm raised non-sorted circle edges, standing water in hollows
B12	B11(Multiple tracks)	n/a	no slope	25cm raised non-sorted circle edges
B14	B14(Multiple tracks)	n/a	no slope	Bare substrate in bare circles, water saturated
B16	B15(Vehicle track)	n/a	no slope	25cm raised non-sorted circle edges
B21	B20(Overburden spoil), B18,B19(Bladed area)	n/a	no slope	15-20cm raised non-sorted circle edges
B24	B5, B4, B3(Borrow pits), B23(Overburden spoil)	100	slight	15cm raised non-sorted circle edges
B26	B25(Vehicle track (wet))	150	slight	25cm raised non-sorted circle edges
B28	B27(Vehicle track (wet))	150	slight	25cm raised non-sorted circle edges
B31	B29(Pit), B30(Overburden spoil)	n/a	no slope	10-15cm raised non-sorted circle edges
B34	B32, B30(Borrow pit)	33	slight	10-15cm raised non-sorted circle edges
B35	B36(Borrow pit)	180	slight	>25cm raised non-sorted circle edges with graminoid dominated tops.

Table 2.2 Site characteristics of disturbance sample blocks. R.M.P. is the road mile post of the CANOL No. 1 Pipeline corridor (East). Block # corresponds to sample site locations in fig. 1.3.

Block #	Disturbance type	Aspect	R.M.P.	Slope	Microscale topography
B1	Vehicle track (dry)	255°	214.6	slight	2 parallel +/-10cm ruts
B6	Vehicle track (dry)	255 °	214.6	slight	2 parallel +/-10-15cm ruts
B9	Multiple tracks	40 °	212.6	slight	multiple +/-10-20cm ruts
B11	Multiple tracks	40 °	213	slight	multiple +/-10-20cm ruts
B13	Multiple tracks	n/a	21.5	no slope	multiple +/-10-20cm ruts
B15	Vehicle track (dry)	160 °	213.8	slight	2 parallel 5cm track ruts
B17	Vehicle track (dry)	n/a	213.6	no slope	Criss-crossed +/-5-10cm rutting
B25	Vehicle track (wet)	150 °	213.8	slight	2 parallel ruts +/-50cm
B27	Vehicle track(wet)	150 °	213.6	slight	2 parallel ruts +/-25cm
B18	Bladed area	230 °	213.4	slight	Shale gravel, 5cm
B19	Bladed area	n/a	213.4	no slope	Shale gravel, 5m
B20	Overburden spoil	n/a	213.4	no slope	Fine grained substrate
B22	Overburden spoil	n/a	212.6	no slope	Fine grained well mixed substrate
B23	Overburden spoil	n/a	214.5	no slope	Patches of coarse grained gravel and fine grained mixed substrate
B30	Overburden spoil	n/a	213.9	no slope	Fine grained well mixed substrate
B29	Pit (center)	n/a	213.9	no slope	5-10cm gravel
B32	Pit (center)	303 °	212.6	slight	10-25cm boulders and finer gravel.
B33	Pit (center)	303 °	212.6	slight	10-25cm boulders and finer gravel.
B3	Pit (center)	n/a	214.5	no slope	Shale gravel and bedrock 5-10cm
B4	Pit (center)	n/a	214.5	no slope	Shale gravel and bedrock 5-10cm
B5	Pit (edge)	230°	214.5	extreme	Fine gravel,1-2cm
B36	Pit (edge)	150°	213.9	extreme	Fine gravel mounds at base grading to coarser material towards the top of the slope

Table 2.3 Percent frequency and cover for 'common' species in the undisturbed Decumbent Shrub tundra (>10% frequency and/or >1% cover).

Taxonomic group	Species	%Frequency	% Cover
	Mineral	30	8
	Litter	98	13
Bryophytes	*Brachythecium turgidum*	29	3.4
	Racomitrium canescens	18	1.2
	Aulacomnium palustre	10	1.0
	Conostomum tetragonum	22	2.6
	Dicranum elongatum	49	6.1
	Pleurozium schreberi	13	1.8
	Polytrichum piliferum	14	1.7
	Polytrichum juniperum	64	9.4
	Hepatics	10	0
Lichens	*Cladina* sp.	26	1.0
	Cladina mitis	37	2.1
	Cladonia cornuta	20	1.0
	Cladonia borealis	17	0
	Icmadophila ericetorum	19	1.0
	Cetraria islandica	13	1.0
	Cetraria ericitorum	29	1.0
	Nephroma arcticum	10	1.0
	Peltigera aphthosa	34	1.9
	Solorina crocea	18	1.0
	Stereocaulon paschale	42	1.8
	Dactylina arctica	26	1.0
	Panaria pezizoides	17	0
Graminoids	*Deschampsia brevifolia*	22	2.1
	Festuca altaica	20	1.4
	Luzula arcuata	24	1.0
	Carex filifolia	1.0	1.0
	Carex aquatilis	37	2.4
Forbs	*Antennaria monocephala*	36	1.6
	Artemisia arctica	73	7.0
	Petasites frigidus	21	1.0
	Anemone narcissiflora	43	2.5
	Ranunculus Eschscholtzii	11	0
	Polygonum viviparum	14	0
Dwarf shrubs	*Salix polaris*	86	11.9

Table. 2.4. Species richness (number of species per site within various disturbance types) for all occurrence including rare species (species with <10% frequency and/or <1% cover).

Taxonomic group	Undisturbed	Pit (center)	Pit (edge)	Overburden spoil	Bladed areas	Vehicle tracks (dry)	Multiple tracks	Vehicle tracks (wet)
Bryophytes	36	20	11	20	25	43	42	34
Lichens	34	10	15	8	28	36	29	4
Graminoids	14	6	5	7	2	12	17	20
Forbs	39	12	22	30	39	41	44	71
Dwarf shrub	2	3	2	3	2	11	4	4
Tall shrub	0	2	1	3	1	1	2	1
Fern allies	0	3	0	0	0	1	0	1
Total	125	55	55	168	97	133	137	133

Table 2.5. List of 'common' species (species with >10% frequency and/or >1% cover averaged per quadrat in each disturbance type) in each of the disturbance types sampled for each taxonomic group. Ordination species abbreviations are used, a full list appears in (Appendix 1)

Taxonomic group	Undisturbed	Pit (center)	Pit (edge)	Overburden spoil	Bladed areas	Vehicle tracks (dry)	Vehicle tracks (wet)	Multiple tracks
Bryophytes	Aupa Brtu Cote Diel Difl Plsc Poju Popi	Cote Diel Difl Poju Raca	Aupa Brri Brtu Raca	Brtu Cote Diel Difl Poju Popi Raca	Aupa Brtu Cote Diel Difl hepatics Poju Popi Raca	Cote Diel Difl Poju Raca	Aupa Brtu Cote Diel Difl Poju	Aupa Brtu Cote Diel Difl hepatics Plsc Poju Raca
Lichens	Clx1 Ceer Ceis Clbo Clco Clmi Daar Icer Near Pape Peap Stpa Socr		Csx2 Daar Mari Socr	Peap Stpa	Clbo Clco Icer Peap Socr Stal Stpa Stto	Clx1 Ceer Clbo Clsq Daar Icer Pape Peap Socr Stpa Thsu		Clx1 Ceer Clbo Daar Icer Pape Peap Socr Stpa Stto

Table 2.5. Cont'

Taxonomic group	Undisturbed	Pit (center)	Pit (edge)	Overburden spoil	Bladed areas	Vehicle tracks (dry)	Vehicle tracks (wet)	Multiple tracks
Graminoids	Caaq Debr Feal Luar		Alal Dece	Debr Feal Trsp	Debr Luar	Caaq Cami Debr Feal Lupa	Feal Poa sp	Caaq Cafi Cape Debr Luar
Forbs	Anmo Anna Arar Pefr Povi Raes	Miro	Cere	Arar Cear Elpa Epla Pefr Sipr Vewo	Anmo Arar Pefr Poac Raes Sipr Vewo	Anmo Pefr Povi Sipr	Anmo Anna Arar Llse Pefr Pesu Povi Raes Rhin Vewo	Anmo Anna Anri Arar Pefr Pesu Povi Rhin Sipr Vewo
Dwarf Shrubs	Sapo	Sapo		Sapo Sare	Sapo	Sapo	Vavi	Sapo
Tall shrubs				Sapl	Sapl	Sapl	Sapl	Sapl
Fern allies		Eqar						

Table 2.6. Percent frequency and cover for 'common' species in borrow pit disturbances (>10% frequency and/or >1% cover).

		% Frequency		% Cover	
Taxonomic group	Species	Pit center	Pit edge	Pit center	Pit edge
	Mineral	96	97	77	51
	Litter	63	60	4	9
Bryophytes	*Brachythecium* sp.	12	17	0	0
	Brachythecium turgidum	0	0	0.8	2.5
	Racomitrium canescens	51	10	2.4	0.3
	Aulacomnium palustre	0	0	0.0	1.0
	Conostomum tetragonum	47	30	6.3	3.1
	Dicranum elongatum	27	0	1.4	0.2
	Polytrichum juniperum	23	10	0	1
Lichens	Crustose lichens	36	27	0	0
	Peltigera aphthosa	0	13	0	1.0
	Stereocaulon paschale	12	33	0.5	1.2
	Stereocaulon tomentosum	12	0	1.0	0
	Panaria pezizoides	0	13	0	0
Graminoids	*Poa* spp.	7	0	0.4	1.0
	Deschampsia brevifolia	16	0	0.8	1.0
	Trisetum spicatum	0	17	0	1.0
	Agrostis latifolia	9	0	0	0
	Luzula arcuata	24	0	1.2	0
	Eriophorum vaginatum	0	10	0	0
	Carex aquatilis	4	0	0.2	2.0
Forbes	*Minuartia rossii*	11	13	0	0
	Antennaria monocephala	0	10	0	1.0
	Artemisia arctica	13	37	0.9	4.2
	Epilobium latifolium	12	13	1.0	1.0
	Petasites frigidus	1	3	0.1	1.4
	Anemone narcissiflora	0	0	0.0	1.3
	Sibbaldia procumbens	0	43	0.3	2.0
Dwarf shrubs	*Salix polaris*	29	23	0.7	3.8
	Salix reticulata	3	3	0.1	3.4
Fern allies	*Equisetum arvense*	17	0	1.2	0.0

Table 2.7. Percent frequency and cover for 'common' species in the associated pit disturbances (>10% frequency and/or >1% cover).

		% Frequency		% Cover	
Taxonomic group	Species	Overburden spoil	Bladed areas	Overburden spoil	Bladed areas
	Mineral	37	57	4	5
	Litter	98	97	12	10
Bryophytes	*Brachythecium turgidum*	33	23	7	5
	Racomitrium canescens	10	10	2	1
	Aulacomnium palustre	0	10	2	1
	Conostomum tetragonum	20	13	3	2
	Dicranum elongatum	18	37	3	3
	Pleurozium schreberi	8	3	3	2
	Polytrichum piliferum	10	20	2	1
	Polytrichum juniperum	25	33	5	5
	Hepatics	0	13	0	1
Lichens	*Cladina mitis*	0	3	0	1
	Cladonia cornuta	0	17	1	0
	Cladonia spp.	0	10	0	0
	Icmadophila ericitorum	0	13	1	0
	Peltigera aphthosa	20	33	1	1
	Solarina crocea	0	17	1	1
	Stereocaulon paschale	17	87	1	0
	Stereocaulon tomentosum	0	10	0	0
	Stereocaulon alpinum	0	10	0	0
Graminoids	*Deschampsia brevifolia*	43	47	2	2
	Festuca altaica	10	0	4	3
	Trisetum spicatum	18	0	0	0
	Luzula arcuata	0	10	1	0
	Eriophorum angustifolium	10	0	0	0
	Carex aquatilis	2	0	3	3

Table 2.7. Cont'

		% Frequency		% Cover	
Taxonomic group	Species	Overburden spoil	Bladed areas	Overburden spoil	Bladed areas
Forbs	*Draba longipes*	10	0	0	0
	Antennaria monocephala	3	17	0	1
	Artemisia arctica	27	60	3	7
	Petasites frigidus	47	37	7	4
	Epilobium angustifolium	45	7	7	0
	Epilobium latifolium	12	3	1	0
	Polemonium acutiflorum	0	20	0	1
	Ranunculus Eschscholtzii	3	10	0	0
	Sibbaldia procumbens	22	63	1	6
	Veronica Wormskjoldii	12	20	0	1
	Rhodiola rosea	5	3	0	0
	Polygonum viviparum	0	7	0	0
Dwarf shrubs	*Salix polaris*	15	17	1	1
	Salix reticulata	10	0	1	0
Shrubs	*Salix glauca*	7	0	0	0
	Salix pulchra	9	0	0	0
	Salix planifolia	46	40	6	4

Table 2.8. Percent frequency and cover for 'common' species in linear disturbances (>10% frequency and/or >1% cover).

Taxonomic group	Species	% Frequency			% Cover		
		Vehicle tracks (dry)	Vehicle tracks (wet)	Multi-tracks	Vehicle tracks (dry)	Vehicle track (wet)	Multi-tracks
	Mineral	33	0	56	5	0	7
	Litter	97	100	96	9	17	13
Bryophytes	*Brachythecium turgidum*	20	77	47	1	16	10
	Racomitrium canescens	37	20	44	2	2	3
	Aulacomnium palustre	0	33	22	0	3	3
	Tortula norvegica	10	0	0	0	0	0
	Conostomum, tetragonum	32	13	31	6	0	2
	Dicranum elongatum	38	23	22	4	3	2
	Pleurozium schreberi	30	0	0	9	1	1
	Polytrichum piliferum	40	20	0	4	1	0
	Polytrichum juniperum	52	23	71	7	2	5
	Hepatics	0	0	27	0	0	1
Lichens	*Cladina* sp.	17	0	18	0	0	0
	Cladina mitis	25	0	0	2	0	0
	Cladonia cornuta	10	0	20	0	0	1
	Thamnolia subuliformis	18	0	0	0	0	0
	Cladonia squamosa	17	0	0	0	0	0
	Cladonia borealis	38	10	24	0	0	0
	Icmadophila ericitorum	17	0	33	0	0	1
	Cetraria islandica	0	10	0	0	1	0
	Cetraria ericitorum	28	0	27	1	0	0
	Peltigera aphthosa	43	10	31	3	0	1
	Solorina crocea	22	0	16	0	0	0
	Stereocaulon paschale	58	0	36	2	0	1
	Dactylina arctica	17	0	16	1	0	0
	Panaria pezizoides	27	0	27	1	0	0

Table 2.8. Cont'.

Taxonomic group	Species	% Frequency			% Cover		
		Vehicle tracks (dry)	Vehicle tracks (wet)	Multi-tracks	Vehicle tracks (dry)	Vehicle track (wet)	Multi-tracks
Graminoids	*Poa* spp.	0	13	0	0	0	0
	Deschampsia brevifolia	27	40	31	2	3	3
	Festuca altaica	18	37	0	2	8	4
	Agrostis latifolia	0	20	0	0	1	0
	Luzula parviflora	13	0	0	1	0	0
	Luzula arcuata	0	0	38	0	0	1
	Carex microchaeta	13	0	20	1	0	0
	Carex filifolia	0	0	11	0	0	0
	Carex podocarpa	0	0	11	0	0	0
	Carex aquatilis	13	90	31	0	7	4
	Eriophorum angustifolium	0	10	0	0	0	0
Forbs	*Draba longipes*	0	10	0	0	0	0
	Antennaria monocephala	57	37	36	3	3	2
	Artemisia arctica	65	73	51	4	7	5
	Petasites frigidus	13	43	18	0	2	2
	Gentiana glauca	15	0	0	0	0	0
	Astragalus umbellatus	0	10	0	0	0	0
	Lloydia serotina	0	13	0	0	0	1
	Polemonium acutiflorum	0	10	0	0	1	1
	Anemone narcissiflora	30	23	13	2	2	1
	Anemone richardsonii	0	0	11	0	0	0
	Ranunculus Eschscholtzii	10	47	0	0	2	1
	Sibbaldia procumbens	33	0	42	2	0	1
	Lagostis Stelleri	0	20	0	0	1	0
	Pedicularis sudetica	15	13	22	1	1	1
	Veronica Wormskjoldii	0	37	24	0	1	0
	Rhodiola rosea	0	37	13	0	4	2
	Polygonum viviparum	13	63	38	0	2	2
Dwarf shrubs	*Vaccinium vitis-ideae*	0	13	0	0	0	0
	Salix polaris	87	60	76	11	5	7
	Salix reticulata	0	20	0	0	3	2
Shrubs	*Salix planifolia*	12	23	24	1	11	7

Table 2.9. Eigenvalues and variances for the first four ordination axes for the DCA analysis of the full vegetation data set.

Ordination Axes	1	2	3	4	Total inertia
Eigenvalues	0.711	0.442	0.34	0.278	11.256
Cumulative percentage variance of species data	6.3	10.3	13.3	15.7	

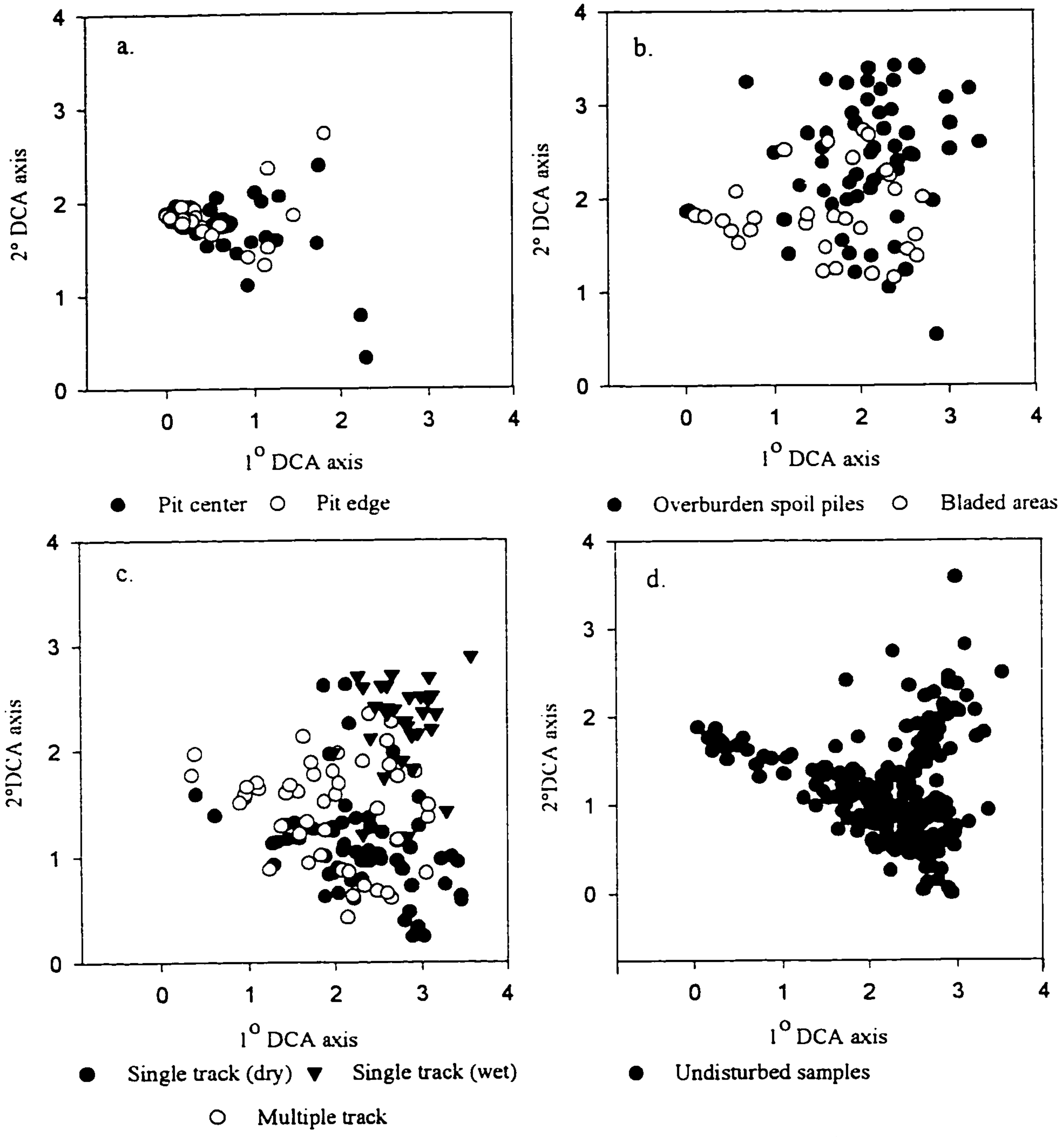

Figure 2.1. DCA ordination diagram for all sample scores. Disturbance types are separated into related groups for clarity a) borrow Pit disturbances, b) associated pit disturbances, c) linear disturbances, d) undisturbed samples. The primary and secondary ordination axes are used as the x and y axes respectively.

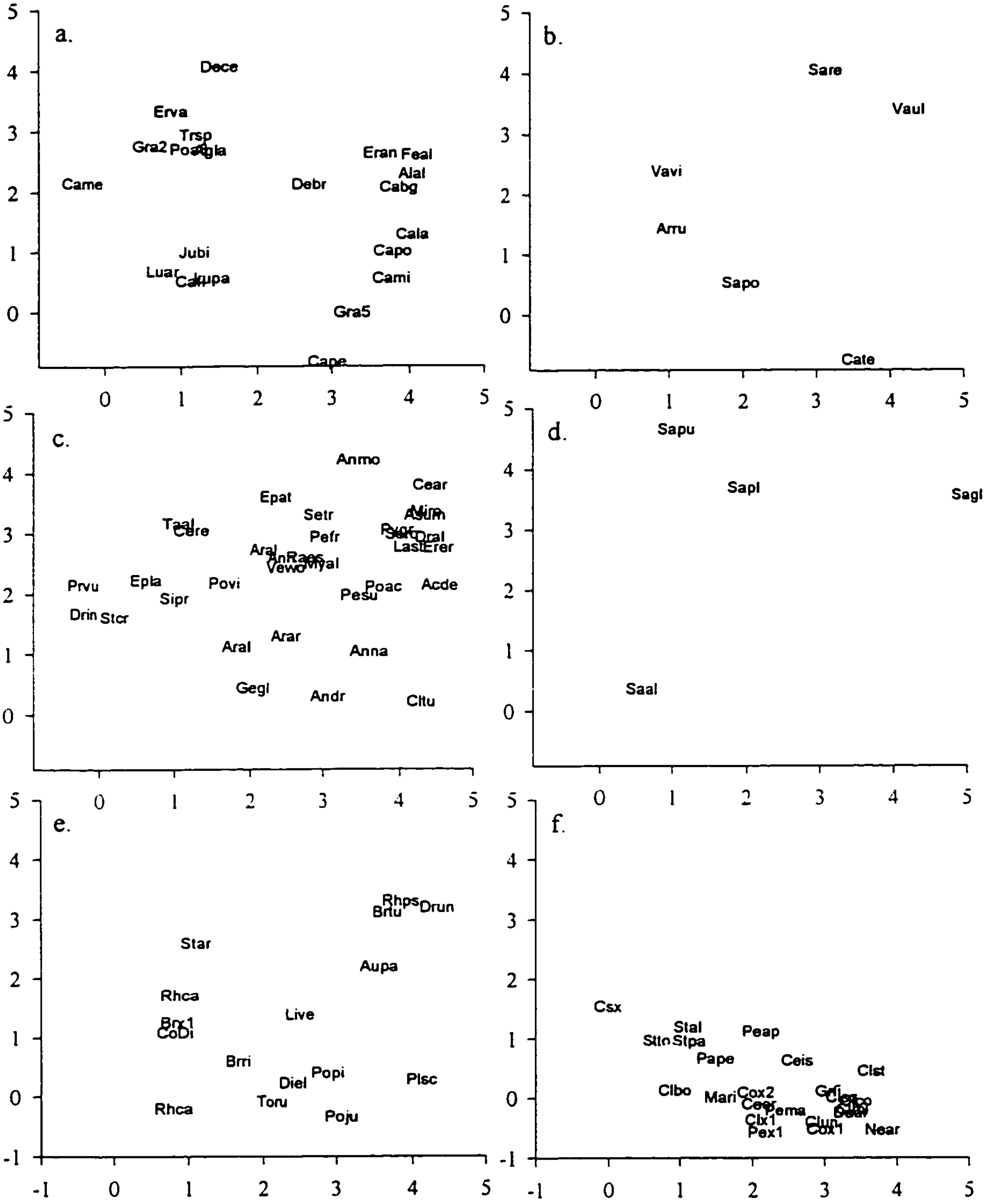

Figure 2.2. Species scores form the DCA ordination of vegetation data. Graph panes represent the 1° DCA axis versus the 2° DCA axis for each taxonomic group, a) graminoids, b) dwarf Shrubs, c) forbs, d) tall shrubs, e) bryophytes and f) lichens.

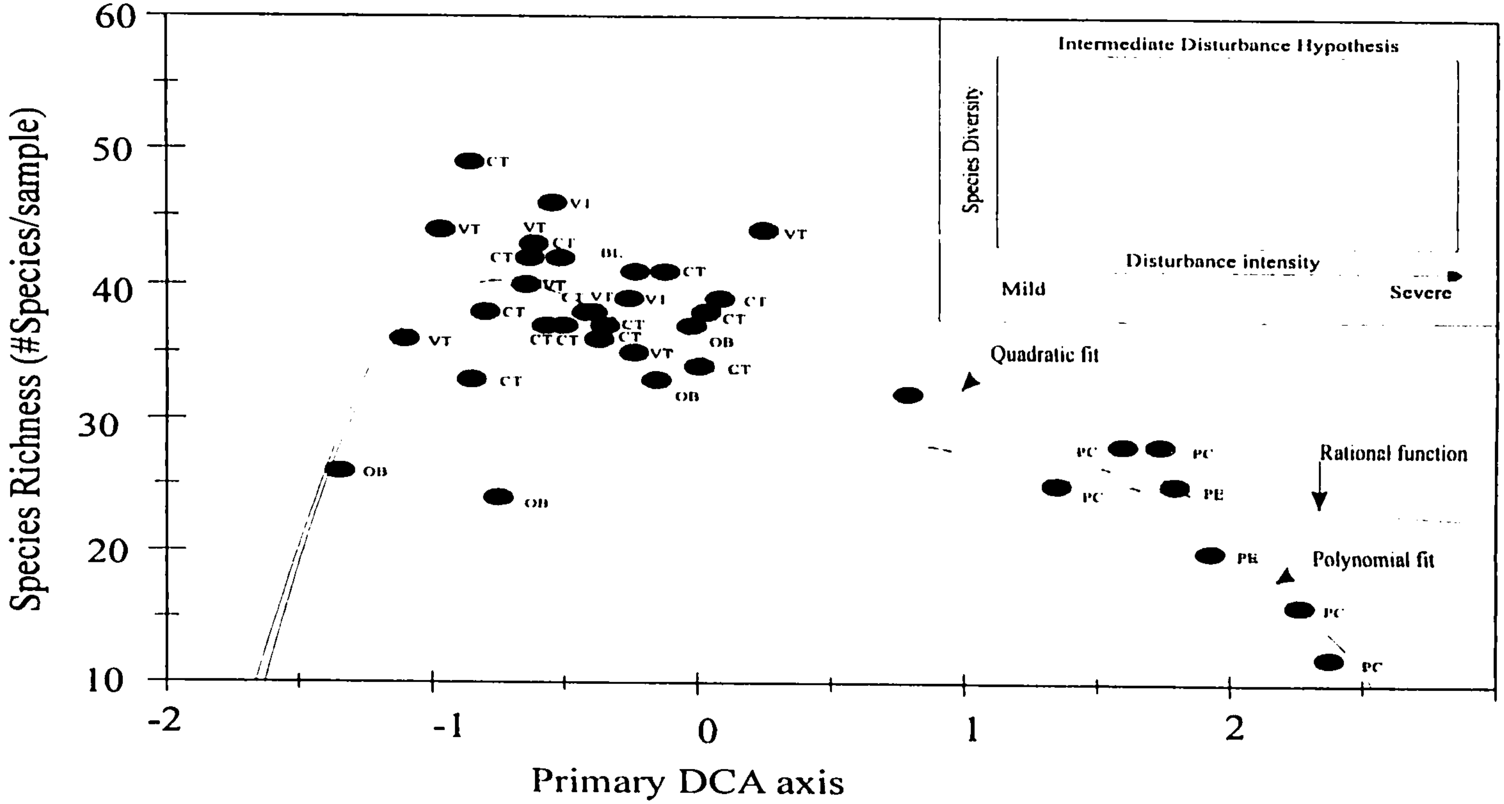

Figure 2.3. Primary DCA axis (sample scores) versus species richness (a measure of species diversity) at each sample site. Sample scores are points with text denoting the represented disturbance type, PC=pit center, PE=Pit edge, VT=Vehicle track, OB=Overburden spoil, BL=Bladed areas. The best fit curves are the polynomial function (r=0.67), the rational function (r=0.65) and the quadratic fit (r=0.63). The inset is an illustration of the Intermediate disturbance hypothesis relationship (Connell 1978).

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Chapter 3: Soil and Microclimate Analysis

Introduction

Subarctic tundra vegetation distribution is controlled by complex interactions between surface and subsurface conditions. Many abiotic factors affecting biotic characteristics can be evaluated through microclimate and soil measurements. Tundra vegetation characteristics change along relatively short microtopographical scales and these shifts can be reflected in subtle microclimatic and substrate variations. Likewise, disturbance to the natural plant communities resulting in a change in microtopography can be measured using the same variables.

Low soil temperature is known to be the main microclimatic factor influencing soil forming processes and the growth of plants in the Subarctic (Schimel et. al. 1996; Ebersole and Webber 1983; Babb and Bliss 1974; Bliss and Wein 1972). Soil temperature is highly related to many soil forming processes and it is invariably used in soil and microclimate analyses. Near surface temperature is commonly used as a parameter in energy budget analysis of natural communities of an entire growing season or annual cycle (Rouse 1984; Ng and Miller 1977; Weller and Holmgren 1973). Few attempts have been made to characterize the changes in microclimate due to anthropogenic disturbances (Harper and Kershaw 1997; Haag and Bliss 1973) and none have used a full growing season record for disturbances >50yrs in age.

In relationships to the overlying plant association, soil temperature is invariably a factor among other soil physical and chemical properties (Davey *et al.* 1992; Rouse 1984; Ng and Miller 1977; Weller and Holmgren 1973; Nakano and Brown 1972). It is often considered the most important soil characteristic and used as a proxy for biological activity in the soil. Warmer soil temperatures promote greater decomposition which in turn produce higher available nutrients (Dighton 1995; Ebersole and Webber 1983; Chapin, et. al. 1979).

Nitrogen (one component of the soil nutrient cycle) is usually the primary limiting factor to growth of tundra plants (Haag 1973). Slow decomposition due to cold soil temperatures severely limits the cycling of Nitrogen and its available forms NH_4 and NO_3 (Haag and Bliss 1973). Thus it is a key factor to be measured in natural plant revegetation.

The relationship of soil temperature and vegetation production is reversed in the case of low soil moisture. Moisture content is secondary to near-surface temperature in affecting the nutrient content of soil. It is estimated that if moisture is <20% it acts independently as a predictive factor of soil nutrient status (Haag 1973). Many studies examining soil nutrient cycles have been in wet to mesic plant communities (Kevan et al. 1995; Marion et al. 1989; Ebersole and Webber 1983; Marion and Miller 1982; Chapin and Shaver 1981; Chapin et. al. 1979).

The aim of this chapter is to classify various disturbance types associated with the CANOL pipeline corridor in the Decumbent Shrub Tundra based on the interrelationships of abiotic factors (microclimate and soil properties).

Methods

Study Site:

The same sample sites used for the vegetation cover assessment of the Decumbent Shrub Tundra (Chapter 2) were used for the analysis of abiotic factors (fig. 1.3). Soil factors were sampled at every vegetation sample block (n=36) and near-surface temperature was measured in a subset of these sample blocks representing all disturbance types (n=12).

The disturbance types compared in Chapter 2 for vegetation and Chapter 3 for abiotic factors fall into two main categories (fig. 1.5). Linear disturbances which include all vehicle tracks and borrow pit disturbances which include borrow pits, overburden spoil piles, and bladed areas. The variance within and among these groups was analyzed for each abiotic factor measured.

Variation within the undisturbed Decumbent Shrub Tundra was an important aspect of the comparison of abiotic factors. The variation was largely due to widespread patterned ground. The pattern consisted of low non-sorted, poorly vegetated circles with raised well-vegetated edges. Species' composition varied depending on the position along microtopographical gradients.

Raised edges were populated by species of *Polytrichum* while *Brachythecium turgidum* and *Aulacomnium palustre* occupied vegetated low centers (Chapter 2). In particular *Polytrichum* spp. provide the bulk of material (living and dead) for the organic and LFH layers on the tops of raised patterned ground edges.

Surficial deposits on the Mackenzie Mountain Barrens were predominantly unconsolidated glacial deposits. Underlying bedrock was Cambrian to Mississippian clastic sedimentary rock (shale, siltstone, chert, chert sandstone)(Douglas 1968).

Soils of the Mackenzie Mountain Barrens study area were Orthic Turbic Cryosols (upland tundra soils) (Canadian Soil Survey Committee 1987). These soils occurred in areas with extensive cryoturbation and patterned ground (fig. 3.1). The most prevalent patterned ground feature in the Decumbent Shrub Tundra were non-sorted circles, common in finer-grained media. Raised edges ranged from 10-25 cm in height and were approximately 1m apart (table 2.1). This type of microrelief was present in all undisturbed sample types but not all circles appeared to be active since some low center areas were covered with thin organic crusts and some lichen species (fig. 3.2).

Microclimate:

Two microclimate stations at Road Mile Post (R.M.P.) 213.3 (STN 1) and R.M.P. 212.6 (STN 2) (fig. 1.3)(table 3.1) were established before snowmelt to compile a continuous record of environmental variables associated with each type of disturbance within the study area (fig. 3.2). Each site had a series of mast sensors and a series of near-surface temperature sensors. Mast sensors measured relative humidity, air temperature, windspeed and direction and incoming shortwave radiation. The mast sensors were not used to collect data for comparison with disturbance types. Near-surface temperature sensors were type T copper constantan thermocouples with three leads of equal length (1m) soldered to the measurement end. The combination of three leads gave an average reading from three random locations within a disturbance type. Disturbance types measured at STN 1 were 2 vehicle tracks, 2 overburden spoil piles, 2 bladed areas and 1 undisturbed site (table 3.1).

The logger at STN 1 was located midway between the two masts so that sensors would be located within the undisturbed tundra and the pit center. Mast sensors only measured information in the undisturbed tundra and the pit center, near-surface temperatures were obtained for 2 vehicle tracks, 1 pit edge site and 1 pit center site. This station began recording on 15 June 1997. Sensors were placed before snowmelt to ensure measurement of an entire growing season. Necessary realinements due to snowmelt were done 7 July upon return to the field. The data gap and eventual logger failure was probably due to a lightning strike (table 3.1).

Only one mast was located at STN 2 on the north edge of the overburden spoil pile in order to reduce visibility from the road. Near-surface temperature profiles were obtained for 2 overburden spoil pile sites, 2 bladed area sites, 1 undisturbed site and 2 vehicle tracks. The LICOR pyranometer was not operational due to disturbance by ground squirrels (table 3.1).

The Goose Flats microclimate station was located within a palsa and peat plateau complex surrounded by the Decumbent Shrub Tundra within the boundaries of the study area (fig. 1.3). This station collected year-round data for the palsas (Kershaw unpublished data 1997). Incoming shortwave radiation (LICOR pyranometer) and windspeed (RM Young wind sentry) were taken from this station to replace missing data due to the logger and sensor failure (table 3.1)

Statistical Analysis:

All near-surface temperature sample sites were analyzed statistically to determine the variation within similar disturbance types and among disturbance types. In total 2 undisturbed sites, 1 pit center, 1 pit edge, 4 vehicle tracks, 2 overburden spoil piles and 2 bladed areas (table 3.1) were used in the analysis. Because of non-normal distributions the Kruskal Wallis One Way ANOVA followed by a non parametric multiple comparison test (Dunn's test) (Zar 1996) were used. All possible combinations were tested at a P=<0.05 level in order to determine whether similar samples in different locations were statistically similar (Zar 1996).

Near-surface minimum temperatures of the entire measurement period including all data gaps were plotted for both undisturbed sites and air temperature at STN 1 (table3.1) (fig. 3.3). The mean and minimum near-surface temperature were used to define the extent of the full growing season to determine a suitable period to compare the two logger sites. The last hard frost occurred on 30 June when the undisturbed near-surface temperature was -2.58°C at STN 2 and the air temperature and STN 1 was -0.69°C. The next hard frost occurred on 3 August where these three samples dropped below zero for a period of two days. Corresponding temperature drops in the mean and minimum temperatures were observed in all sample sites although not all sites reached <0°C values (fig. 3.3a,b).

The full growing season lasted from 1 July to 2 August 1996 but due to logger failure only the overlapping portion of the record was used. Both loggers were operational from 1 to 17 July (table 3.1). This shortened period represented typical conditions throughout the growing season (fig. 3.3a).

Mean Diurnal Fluctuations for the Growing Season:

Mean near-surface temperature measurements were calculated for each 2hr interval throughout the day for the overlapping growing season period. A plot of the mean daily temperature variation over a period gives information on differences between the hour when maximum and minimum temperatures are reached, the ranges of temperature fluctuations and the degree of variation at different times of day. These patterns of diurnal temperature fluctuations were compared among the disturbance types both graphically (fig. 3.4a,b,c,d) and statistically (table 3.2).

Degree Day Calculations:

Degree days are the cumulative number of degrees above or below a particular threshold over a given period. Degree days are useful in describing cold climates as in the ratio of degree days > 0°C (thawing degree days) versus the number <0°C(freezing degree days) (French and Slaymaker 1993). In agriculture the >5°C threshold is used for growing degree days where crop plant cellular tissue is not frozen and photosynthesis can occur. Arctic and alpine species can begin respiration and photosynthesis at temperatures near 0°C (Billings and Mooney 1968). Given uniform surface features, soil environment and parent material vegetation composition is controlled by temperature in northern latitudes. Vegetation composition varies depending on the thermal regime of an area because individual plant species have specific growing degree day requirements (Ecoregions Working Group 1989). For example species of subarctic conifers (*Picea. Pinus, Larix*) are limited to areas with growing degree day values above 600 (Sakai 1978).

Degree day calculations were made for each disturbance type using the average daily near-surface temperatures at the >0°C and the >5°C threshold levels for the overlapping growing season. The >0°C calculation is important because it is the threshold for arctic plants and patterned ground (controlled by freeze thaw regimes) is an important controlling process in the undisturbed Decumbent Shrub Tundra. The >5°C threshold is used to consider the potential for new species to colonize in disturbed areas because increased temperature and depths of thaw are required for germination (Billings and Mooney 1968).

General Climatological Patterns:

Total rain, relative humidity, shortwave radiation and windspeed were measured to provide mean values for the entire study area, because these measurements could not be made at each sample site they could not be used to compare disturbance types. Total daily rain was measured at STN 2 (fig. 3.5), mean daily relative humidity was measured at STN 1 (fig. 3.5a) while the mean daily incoming shortwave radiation and windspeed data from the Goose Flats palsa microclimate station (Kershaw unpublished data, 1996) (fig. 3.5b,c) were used to fill data gaps in the borrow pit stations due to sensor failure. The Goose Flats microclimate station was located within a palsa and peat plateau complex approximately 1.5 km west of borrow pit 1 (fig. 1.3). The data were assumed to be representative of the entire study site and provided comparison for the near-surface temperature data.

Soils

Field and Laboratory Analysis:

The same sample blocks used for the vegetation cover assessment (Chapter 2) were used for soil sampling. A full range of disturbances were instrumented for microclimate monitoring, however replication was limited to disturbances located close to the two microclimate stations. A full account of undisturbed and disturbed site plant associations was presented in Chapter 2.

Soil pits were dug to the depth of the rooting zone beside 3 randomly-located vegetation quadrats in each vegetation sample block. The pits were described *in situ* for color using a Munsell soil colour chart and layer thickness was measured. Soil samples from each identified horizon were tested for pH using litmus paper. weighed and air dried in the field prior to transport back to Edmonton for laboratory analysis. In some cases the top organic layer was not extensive enough to sample and was measured for thickness but omitted from the remainder of soil layer analyses.

At each soil pit an auger was used to drill a hole for the measurement of an instantaneous temperature profile. The hole was drilled to the maximum possible depth (large particle sizes within the substrate and the proximity of bedrock to the surface often prevented deep drilling) (fig. 3.6) and a temperature profile was measured at 5cm intervals from the surface to the maximum depth of the core hole. A temperature probe attached to a multimeter was mounted inside a hollow tube marked with 5cm intervals. Temperature was taken at each depth from the top to the bottom of the auger hole.

Laboratory analyses included the measurement of bulk density. volumetric water content, organic matter content, particle size analysis and partial nutrient analysis as described in (Kalra and Maynard 1991). Bulk density was measured using the core method with bulk density tins of known volume (kg m^{-3}) (Kalra and Maynard 1991). Water content of each soil layer was measured volumetrically and expressed as a percentage of water per wet soil weight. The loss on ignition (LOI) technique was used to determine organic matter content (Kalra and Maynard. 1991). Organic matter values represent a percentage of dry weight of the <2mm portion of soil.

Gravel particles (>2mm) were separated from dry samples by dry seiving. Remaining particle size analysis was completed using the Boyocous hydrometer method. (Kalra and Maynard 1991). Particle sizes were expressed as a percentage of dry weight.

Partial nutrient analyses involved measurement of Total N, and the NO_3 and NO_4 components. Surface layers for all blocks were used in this analysis as well as layers within the rooting zone for two sample undisturbed soil pits which had three horizons each. The undisturbed profiles were used to determine the variation among layers and the relative importance of surface layers.

A total of 67 samples were analysed for Total N, NO_3 and NO_4. For 39% of the samples the surface layers were mixed if the horizon designation was the same for all three pits per block. The remaining 61% were samples from single soil pits. Total N was determined using the Kjeldal digestion method and a colorimetric autoanalyzer. Net mineralizable nitrogen ($NO_3$and NO_4) was determined using a KCL extraction technique. Values are expressed in percent by weight of soil.

Because of the patterned ground structure of the undisturbed tundra the soil pits varied considerably in 'typical' morphology. Three samples from the undisturbed stands were chosen to represent these 'typical' profiles encountered in the undisturbed Decumbent Shrub Tundra. Of these pits all soil horizons were analyzed for NO_3, NH_4 and Total N in order to determine variations within layers of the rooting zone. Two of the selected soil pits had three distinct soil horizons (fig. 3.7) including, Oh, Ah, Bgy, Bt and Bh. The third soil pit was typical of some pits in which a surface moss mat was present, overlying a clay layer (fig. 3.8). In this case the clay layer was below the rooting zone but the overlying LFH mat was too thin to sample.

Soil Profiles (Depths of Thaw):

Soil profiles were obtained in order to measure the depth of the 0°C isotherm. Only two of the cores actually reached 0°C so the isotherm was inferred by extrapolating from the data obtained. The full temperature profiles suggest a logarithmic fit however it was not possible to fit a log curve to all the samples and the y-intercept (0°C isotherm) was difficult to calculate. A simple linear fit produced r values ranging from 0.80 to 0.97 for all core holes. The y-intercept on a plot of depth vs. temperature at each sample site represented the maximum depth of thaw. The comparison of this fit with the two pits in which the frost table was reached indicated that this method of extrapolation overestimates the depth of thaw by 10 to 15cm (fig. 3.9).

All control soil pit data were analyzed for each variable measured at the soil pits and in the laboratory analysis, by soil layer type (Om, Ah, Bgy, Bh, Bt, Bth) using one way ANOVA and the Tukey multiple comparison procedure ($P>0.05$) or the Kruskal Wallis ANOVA on ranks and the Dunn's nonparametric multiple comparison test ($P>0.05$). 'Typical' soil pits showing the undisturbed arrangement of all soil horizons were chosen to determine the relative importance of the surface layers because nutrient data was only available for a limited number of samples (fig. 3.10). Pearson's product moment correlation was used to determine the nature of the relationships between soil chemistry (NO_3, NH_4, Total N and pH) and soil physical properties of bulk density and volumetric moisture content (table 3.3).

Results

Microclimate:

Snowmelt and Growing Season Periods:

Two distinct periods during the 1996 field season were evident in the near-surface temperatures and all other supporting microclimate data. The early season which may have corresponded to the snowmelt period and the growing season for which a portion was available for comparison with both stations (STN 1 and STN 2). The early season lasted from 16 to 30 June and the growing season began after 30 June and ended 2 August (fig. 3.3). Determination of the growing season period and restrictions to that period due to logger failure are outlined in the microclimate methods section.

General Microclimate Characteristics of the Mackenzie Mountain Barrens:

Selected atmospheric parameters consistently exhibited a change after 30 June. Incoming radiation at Goose Flats weather station was higher during the early season. The shortwave radiation high corresponds with a period of no rain, low relative humidity during the early season period (fig. 3.5a). Windspeed, measured at the Goose Flats station were less variable during the early season than after 30 June (fig. 3.5c). Wind direction had 2 prevailing azimuths, south east (155°) and north east (65°) (fig. 3.11).

After the beginning of the growing season (30 June to the end of the record period) there was a trend of higher rainfall and relative humidity with two peaks (fig. 3.5a). This period of wet weather corresponds with cloudy skies and a more variable wind pattern (Fig 3.5 b, c).

Temperature Difference Calculation:

Temperature differences (ΔT=Mean disturbance temperature - Mean undisturbed temperature) were greatest before the beginning of the growing season (last hard frost event)(fig. 3.12a,b,c,d). This time period corresponded with the record of high incoming radiation and low precipitation during the early season (fig. 3.5a,b). Logger stations were installed before snowmelt was complete.

Positive values for ΔT indicated that disturbances were warmer than the control and negative values indicated disturbances were colder than the control. In general all ΔT for undisturbed STN 1 were >0°C but were <0°C for undisturbed STN 2.

Both pit (edge) and (center) had consistently high ΔT values for both undisturbed STN 1 and undisturbed STN 2 and they were the warmest disturbance types. The bladed area (edge) sample was thermally similar to the borrow pit disturbances.

The overburden spoil (center) sample was the only disturbance colder than undisturbed STN 1 however the bladed area (center) varied little from undisturbed STN 1. Vehicle tracks and overburden spoil (edges) were moderately warmer than undisturbed

STN 1. ΔT for disturbance types as compared to undisturbed STN 1 graded from coldest to warmest as follows 1) overburden spoil (center) 2) bladed area (center) 3) vehicle tracks 4) overburden spoil (edge) 5) bladed area (edge) 6) borrow pit samples.

Daily Mean, Minimum and Maximum Records:

Both mean and maximum records for the 2 undisturbed samples were significantly different (table 3.4). The difference between the mean temperatures was up to 9°C. Because of such obvious temperature differences the control sites were treated separately (fig. 3.13)

Vehicle tracks varied from each other in the extreme temperature ranges (maximum and minimum records). Mean record values were used for the two vehicle track samples at STN 2 and the two vehicle track samples at STN 1 because the maximum and minimum differences were only found between the tracks of separate microclimate stations (table 3.4; fig. 3.4). Since there were some similarities between the mean values of the samples taken at each microclimate station it was assumed that both stations were valid samples representative of the study area of Decumbent Shrub Tundra. The wide separation of the undisturbed samples was taken to represent the normal internal variation of near-surface temperature within this vegetation type.

Both overburden spoil and bladed area disturbances were significantly different, though the sample size was small in both cases (n=2)(table. 3.4). Most notable was the overburden spoil (center) sample site which had the smallest range in values of all monitored disturbance types. Sensors at the overburden spoil (edge) site may have experienced some change in position because of the sudden decrease in range near the end of the measurement period after julian day 190 (fig. 3.13d). These data were logged after the last maintenance check and it is impossible to determine the cause of possible disruption.

Degree Day Calculations:

Growing degree days varied little among disturbance types (table 3.5). The highest number of growing degree days occurred in the borrow pit and bladed area (edge) and the lowest number occurred in the overburden spoil (center) sample. Values obtained for the overlapping record season (18 June- 17 July) are underestimations of the full season calculations. Degree days for the shortened season represented approximately half of the degree days calculated for the undisturbed sample (STN 2) for the entire measurement period. There was no significant difference (one way ANOVA) between values obtained for degree days above 0°C and growing degree days above 5°C.

Mean Daily Diurnal Fluctuations:

Diurnal near-surface temperature means of vehicle tracks and bladed areas were intermediate to both undisturbed samples. The overburden spoil samples had different daily patterns where the overburden spoil (edge) ranged between the control samples (fig. 3.4a.) and the overburden spoil (center) had lower maximum temperatures and the smallest overall range (table.3.5). Borrow pit samples had similar maximum daily values to the undisturbed STN 2 sample and occurred at similar times during the day. The daily range of the borrow pits was less than the range of the undisturbed STN 2 (higher daily minimum temperatures) and the minimum temperatures occurred 2hrs after those of both undisturbed samples (table 3.5, fig. 3.4)

Soils (physical and chemical properties):

Soil Pit Morphology:

A maximum of 3 horizons were evident in the undisturbed sample pits (table 3.6).

Om or organic rich Ah horizons were present in the non-sorted circle raised edges underlain by Bh or Bth horizons which were included in the rooting zone. Bare mineral soil (By horizons) was present in the low centers of the non-sorted circles.

A discontinuous tephra layer was present in many samples composed of mixed and illuviated volcanic ash. The presence of a tephra layer within the pedon may also affect the plant community. Multiple comparison tests of the particle size distribution revealed that silt sized particles were significantly more important in the tephra layers ($p>0.05$). Tephra samples had evidence of mixing with gravel and mottling. These eolian deposits were denoted as Bgy, and provided strong evidence of current or relict cryoturbation (fig. 3.7).

Surface soil horizons in the borrow pit, overburden spoil and bladed areas were commonly mineral layers. Borrow pit (center) and (edge) were composed of unconsolidated parent material with little evidence of soil development 50yrs after being disturbed (Cp horizons)(fig. 3.6). Bladed areas maintained some original overburden material and in some cases thin organic horizons were present over the Cp layer. Overburden spoil was composed of mixed organic and A horizons. Such material supported a complete vegetation canopy but only displayed thin LFH development and no distinct horizons. Linear disturbances had a maximum of 2 surface horizons within the rooting zone. The depth of the rooting zone was comparable to that of the undisturbed and the typical characteristics of undisturbed soil horizons were still evident (table 3.6).

Soil Chemistry:

The three samples representing the ‘typical’ soil pits found in the undisturbed sample blocks displayed variation among soil horizons and in surface layers associated with the non-sorted circles (fig. 3.10). The surface layers also varied within the small geographical area of Decumbent Shrub Tundra investigated in this study.

In the 2 selected sample pits with three soil horizons it was evident that the surface layers contained the bulk of the available and mineralized N (fig. 3.10a,b,c). Well developed organic layers (Om particularly at the surface) were the most important sources of all the available N species. One soil pit was selected from an area with a well developed moss mat overlying a clay layer (fig. 3.10c). Roots did not penetrate into the clay layer (fig. 3.8) and nutrient analysis revealed no NO_3 and negligible amounts of NH_4 and Total N. Intracommunity variation ranged from areas of well developed organic mats and soil horizons to simple organic mats overlying a Bt layer and finally areas with bare mineral substrate.

Organic carbon was most highly correlated with Total N levels in the surface soil layer ($r=0.749$) (table 3.3). Moisture content was positively correlated with Total N and bulk density was negatively correlated. NO_3 and NH_4 were not highly correlated ($r=0.492$) however each species was highly correlated with Total N levels ($r=0.678$) for NO_3 and ($r=0.781$) for NH_4. Thus Total N was a good indicator of the levels of both species of available N.

Comparisons among disturbances explained most of the anthropogenic community variation however the variation within the surface layers of the control samples was still evident (table 3.3). Controls had the highest mineralized N status followed by vehicle tracks, bladed areas, overburden spoil and borrow pit disturbances . Notably, Total N values in the borrow pits were approximately 7x greater than the mean obtained for surface layers in control samples (table 3.3).

Depth of Thaw:

Results of the depth of thaw extrapolation analysis were only sufficient to determine broad trends and illustrate that the surface horizons (depth of rooting zone) were not affected by permafrost. Maximum calculated depth of thaw was 292cm in the Multiple track disturbances. Minimum calculated depth of thaw was 62cm in the pit disturbances. For all vehicle tracks, bladed areas, overburden spoil piles and undisturbed samples the range of values calculated was between 100 and 150cm whereas the borrow pit disturbances ranged from 60 to 100cm. On average the permafrost level was predicted to be within 2m of the surface on the Mackenzie Mountain Barrens. Standard deviation was highest for the undisturbed at 72cm where n=14 and lowest for the bladed areas at 1.41cm with n=2 (Fig 3.9).

Discussion

After more than 50 years, the effects of pipeline corridor construction were still acute in many areas. As well as plant community disruption (Chapter 2) soils were affected and microclimate of all disturbed areas differed from control stands. The degree to which the anthopogenic disturbances had returned to their original state was a combination of the condition of the original disturbance and the amount of soil development during the intervening time period. In the case of borrow pit, bladed area and overburden spoil disturbances it was assumed that the initial substrates were entirely barren of vegetation. Linear disturbances were more difficult to assess because the degree of initial disturbance was only quantified by aerial photography, ground photography and historical notes.

Early Season Abiotic Variation:

During the early season period ΔT for all disturbance types gradually decreased as the snowpack ablated, leaf flush began and depth of thaw increased. All of the disturbances sampled could be classified as either concave surfaces, convex surfaces or flat surfaces with a plant cover. Due to wind erosion and redeposition of snow the drifts accumulate on different areas of surface microtopography features such as those created by anthropogenic disturbances. Concavities tend to collect deep drifts of snow while convex topography has a thin snow cover on the windward side and deep drifts on the leeward side (Timoney and Kershaw 1992; Young et al. 1997). The presence of tall vegetation also causes drifts to occur especially in a zone of transition between low stature and higher stature plant cover (Kershaw 1995; Kershaw 1991).

Borrow pits are the warmest sites as compared to STN 1 during the early season (fig. 3.12). The windward edge of STN 1 was 2m high and the snow drifted to the level of the undisturbed tundra surface (fig. 3.14). The insulation provided by such a deep snowpack may be the cause of such warm early season near-surface temperatures compared to the undisturbed.

Linear disturbances were also warmer than the undisturbed tundra during the early season (fig. 3.12b). All vehicle tracks were distinguishable from the undisturbed tundra by the presence of species of tall woody shrubs (*Salix planifolia, Salix glauca, Salix pulchra, Salix alaxensis*)(fig. 3.15) which trap snow being redistributed by the wind. The insulating characteristics of a late-lying snowpack along linear disturbances was a possible cause of warmer near-surface temperatures observed there.

Convex disturbances such as the overburden spoil (center) and the bladed area (center) had much less difference in early season temperature compared to STN 1. In fact the highest feature (overburden spoil center)(fig. 3.16) was colder during the early season than control measurements at STN 1(fig. 3.12a). The tops of the convex disturbances would be subject to a high degree of wind erosion and possibly have less snow cover and insulation, thus the soils would be colder and remain so during the growing season.

Based on the location of drifts in the borrow pit at STN 1 and on the leeward side of the overburden spoil pile at STN 2 the prevailing winter winds may have been from a south east direction. A severe winter storm may also have been responsible for the deposition of a large drift that remained for the entire winter regardless of the prevailing winds. STN 2 was located on the leeward side of the overburden spoil pile at block #21 (fig. 1.3). This could have been the site of another late lying snowbank explaining the much warmer near-surface temperatures during the early season than all the disturbance types except for the overburden spoil (center).

Undisturbed Decumbent Shrub Tundra:

The underlying tundra community was also subject to a high degree of natural disturbance. The presence of discontinuous permafrost contributes to areas of cryoturbation, and long harsh winters with short cool growing seasons create an environment of frequent perturbations. Large-scale climatic events which occur at longer intervals also affect the natural community and the restoration of anthropogenic disturbances. The effects of these events may not be measurable over one 'typical' season but will manifest themselves over a long period in the rate of recovery of the ecosystem. A recent study of near-surface soil temperatures in Spitzbergen found the springmelt to be delayed by 1 month from the previous year (Mietus 1992). Such large-scale weather disruptions are common in the non-temperate environments of the Arctic and the Subarctic and they affect the plant communities for long periods.

The undisturbed sites varied significantly from each other in all measures of microclimate characteristics (maximum near-surface temperature, minimum near-surface temperature, mean near-surface temperature, and diurnal fluctuation regimes). Canonical correspondence analysis based on relative species' abundances did not indicate differences in the vegetation composition that could account for these differences among control sites (Chapter 2). Variations of the nutrient status and Organic carbon content of the two sites (undisturbed STN 1 and undisturbed STN 2) are negligible, small differences occurred in the moisture levels and %clay contents. The microclimatic variation between the two sites was not captured with the current vegetation or soil sampling procedure. The temperatures of STN 2 may represent the soil temperature profiles of active natural disturbance (patterned ground) thus for the purposes of discussion the temperature profile of STN 1 will be used. The range of characteristics of STN 1 and STN 2 demonstrate the high level of intracommunity variation already detailed in the plant community of the Decumbent Shrub Tundra (Chapter 2).

Linear Disturbances:

Linear disturbances varied less from the undisturbed (fig. 3.12a) because the original surface layers were left relatively intact. Soil physical properties of the vehicle tracks had returned to a state similar to the undisturbed tundra. Organic mats and horizon thicknesses were not compressed and the depth of the rooting zone was identical to the undisturbed (table 3.3). These effects have been observed to result from wheeled traffic in both summer and winter on tundra surfaces (Kevan *et al.* 1995; Forbes 1993; Babb and Bliss 1974). It has already been shown that vehicle tracks in the adjacent tundra community (Erect Deciduous Shrub Tundra) to the Mackenzie Mountain Barrens have recovered to a predisturbance state in terms of soil properties (Harper and Kershaw 1997; Harper 1994).

Previous research concerning soil near-surface temperatures and physical properties of vehicle tracks on arctic tundra agree that an overall warming of the soil occurs. In cases where the organic mat is damaged or removed an increase in albedo and improved drainage (Ebersole and Webber 1983; Kershaw 1983a; Haag and Bliss 1973) are factors. When the damage is a result of compaction the associated increase in bulk density is the important factor (Chapin and Shaver 1981). Associated with this increase in temperature is an increase in microbial decomposition and associated increase in nutrient levels as well as an increase in the depth of the active layer (Ebersole 1987; Kevan, et al. 1995; Hernandez 1973; Bliss and Wein 1972).

The nutrient status of all the vehicle tracks in the Decumbent Shrub Tundra was similar or less than that of the undisturbed tundra (table 3.3). Moisture content was highly positively correlated to the nutrient levels and bulk density was negatively correlated but neither of these values differed significantly from values for the control samples (table 3.3). This suggests that the vehicle track disturbances in this section of the CANOL pipeline corridor have recovered to a level indistinguishable from the Decumbent Shrub Tundra at the sampling intensity of this study. However the structure of the overlying plant community remained dissimilar in the most obvious case due to the proliferation of the tall woody shrubs *Salix planifolia*, *S. pulchra* and *S. glauca* (fig. 3.15) (Chapter 2).

Borrow Pit Disturbances:

As expected microclimate and soil properties of the borrow pits deviated most from the undisturbed tundra. Borrow pits displayed an increase in growing-season temperature associated with the removal of the entire organic layer and soil profile (fig. 3.13c) which was a pattern obvious in all sampled parameters.

The dry gravelly substrates have lower thermal conductivity and the removal of the topsoil layer decreased the albedo. The sensible heat received during the day is not conducted to great depths but is most important in the near-surface temperature range (-5cm), the low albedo allows this zone to warm more than undisturbed tundra. This could explain the 2hr time lag observed in the mean diurnal fluctuations (fig. 3.4b) (table 3.2).

The extrapolated depths of thaw values were the shallowest in the pit (center) (fig 3.9). This did not concur with the increase in maximum diurnal temperatures. however if the depth of thaw was compared from the level of the surrounding tundra (e.g. 2 m higher than the pit center surface) the overall depth of thaw increased.

Borrow pits had higher values for total N than any other disturbance type. Neither species of mineral N reflected the high values for total N as compared to the undisturbed areas (table 3.3). This dispersion would suggest that there was input of non mineralized nitrogen from the atmosphere. Since vegetation was basically absent from borrow pit disturbances, mineralization processes from vegetation and soil biota did not occur.

Overburden Spoil and Bladed Areas:

Associated pit disturbances were the most obviously different disturbance type in terms of plant community variation. Overburden spoil piles were characterized by growth of tall woody *Salix* ssp. (fig. 3.16) and an almost complete ground cover of graminoid species (fig. 3.17). A thick, shaded, insulating ground cover may be the cause of the damped temperature profiles of the overburden pile center sample (fig. 3.4a,d) (fig. 3.13a,d).

Overburden spoil and bladed areas were easily distinguished from the surrounding tundra by the presence of tall woody species. After fifty years the temperature profiles were still measurably higher than STN 1 undisturbed tundra. Increased microbial activity should account for a larger pool of available N supporting such prolific growth. However the nutrient status of all these disturbance types was somewhat reduced compared to the undisturbed tundra (table 3.3). Thus the nutrient balance appeared not to be the primary driving factor in determining the pattern of reestablishment of vegetation on disturbances.

The gradient of N levels ran from borrow pits (low levels) to undisturbed Decumbent Shrub Tundra (highest levels) (table 3.3). The intermediate levels measured in the associated pit disturbances were sufficient to support vigorous plant growth.

The undisturbed Decumbent Shrub Tundra evolved to its current state over thousands of years (Kershaw 1983b). All of the suitable substrates re occupied by a thick bryophyte mat or bare active patterned ground substrates making it difficult for plants to colonize. The higher nutrient levels of the undisturbed tundra as compared to the well vegetated disturbances may represent pooled nitrogen. Disturbances which were composed of some topsoil material with residual nutrient status provided good colonization sites for pioneer plants that did not usually exist in the undisturbed tundra. Nutrient status may be the primary limiting factor to tundra plant growth but competition for germination sites is the primary restriction to colonization.

Summary

Some pipeline corridor construction disturbances within the Decumbent Shrub Tundra in the Mackenzie Mountain Barrens have recovered naturally to a plant community similar to that of the adjacent undisturbed areas. In all cases however, the resultant plant community was visually distinguishable from the surrounding tundra. Less obvious soil and microclimate characteristics also varied.

A high degree of internal variation in the Decumbent Shrub Tundra particularly in near-surface temperature was evident from this analysis. Such variation was in large part a product of a natural disturbance regime and thus distinctions were made between the anthropogenically disturbed tundra and the naturally disturbed tundra.

Vehicle tracks were most similar to the undisturbed tundra. Overburden spoil and bladed area disturbances have also recovered to an ecologically functional unit. The plant associations were markedly different from the undisturbed tundra however evidence suggests that soil forming processes have begun. Borrow pits were still at the earliest stages of recovery and displayed the widest variation in all respects to the undisturbed tundra.

Table 3.1. Sensor locations at both microclimate stations and supplementary Gooseflats station. Output intervals are 2hr and daily for STN 1 and STN 2 and daily for Goose Flats, Overlapping gap free period = 16 June-18 July.

Met Station	Data logger	Disturbance	(*n*)	Microclimate parameter	Sensor models	Data gaps
STN 1 R.M.P.213.3	Cambell Scientific CR10	Undisturbed	1	Relative humidity	HMP35C	19 July-2 Aug. 7 Aug.-4 Sept.
				Air temperature (50cm)	HMP35C	"
				Wind speed	RM Young wind sentry (offset 0.2)	"
				Wind direction	RM Young wind sentry (offset 0.2)	"
				Near surface temperature (-5cm)	Type T copper/constantan thermocouple	"
		Pit center	1	Relative humidity	HMP35C	"
				Air temperature (50cm)	HMP35C	"
				Wind speed	RM Young wind sentry	"
				Near surface temperature (-5cm)	Type T copper/constantan thermocouple	"
		Pit edge	1	Near surface temperature (-5cm)	Type T copper/constantan thermocouple	"
		Vehicle tracks	2	Near surface temperature (-5cm)	Type T copper/constantan thermocouple	"
STN 2 R.M.P.212.6	Cambell Scientific CR10	Overburden spoil edge	1	Relative humidity	HMP35C probe	None
				Air temperature (50cm)	HMP35C probe	None
				Wind speed	RM Young wind sentry (offset 0.2)	None
				Wind direction	RM Young wind sentry (offset 0.2)	None
				Rainfall	TE525 tipping bucket	None
				Incoming radiation	LI-COR LI200S-L pyranometer	No record
				Near surface temperature (-5cm)	Type T copper/constantan thermocouple	None
		Overburden	1	Near surface temperature (-5cm)	Type T copper/constantan thermocouple	None
		Bladed areas	2	Near surface temperature (-5cm)	Type T copper/constantan thermocouple	None
		Vehicle tracks	2	Near surface temperature (-5cm)	Type T copper/constantan thermocouple	None
		Undisturbed	1	Near surface temperature (-5cm)	Type T copper/constantan thermocouple	None
Goose flats	Cambell Scientific CR10	Palsa complex		Wind speed	MET 1 (Offset 0.447)	None
				Incoming radiation	LI-COR LI200S-L pyranometer	None

Table 3.2. Description of range of mean diurnal near-surface temperature fluctuations at the daily minimum and daily maximum with the average time of occurrence. Values are calculated for the period 18 June to 17 July 1996. This table corresponds with fig. 3.4.

		Daily maximum values (°C)				Daily minimum values (°C)			
Disturbance type	Daily range (°C)	Maximum temperature	Time (hrs)	Range	SD	Minimum temperature	Time (hrs)	Range	SD
Borrow pit (center)	16.7	20.4	1600	14	3.5	3.7	400	6.7	1.8
Borrow pit (edge)	19.4	22.1	2000	14	3.8	2.7	600	6.2	1.5
Overburden spoil (center)	14.5	10.3	2000	5.8	1.2	0.5	600	5.3	1.5
Overburden spoil (edge)	18.7	19.9	1800	14.2	3.8	-1.7	600	8.7	2.7
Bladed area (center)	21.2	19.9	1600	14.1	3.4	0.1	600	7.1	2.1
Bladed area (edge)	18	21.9	2000	13.5	3.7	2.7	600	6.3	1.6
Vehicle track 1 (STN 1)	14	15.2	2000	8.4	2	0.7	800	6.5	1.6
Vehicle track 2 (STN 1)	9.8	19.2	1800	13.2	3.2	0.5	600	5.6	1.6
Vehicle track 1 (STN 2)	21.6	19.7	1800	14.3	3.5	-1.5	400	7	1.7
Vehicle track 2 (STN 2)	19.2	17.8	1200	17.2	4.1	-0.2	400	6.3	1.8
Undisturbed (STN 1)	19.8	14.2	1800	8.8	2.1	0.2	600	6.4	1.7
Undisturbed (STN 2)	25.5	25	2000	19.8	5.3	-0.5	400	7.4	2

Table 3.3. Mean soil parameter values and standard deviations for each disturbance category. Pearson's product moment correlation was used in comparing all measured soil variables with total N (Zar 1996).

	Undisturbed n=32		Borrow pits n=10		Bladed areas n=2		Overburden n=4		Vehicle tracks n=15		Correlation to Total N
Soil parameter	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	r value (n=62)
NO3(%weight)	5.09	20.40	9.21	4.62	0.77	0.77	8.87	13.80	2.48	3.02	0.678
NH4(%weight)	9.14	9.21	2.73	3.73	3.80	1.12	4.10	1.96	7.12	5.24	0.781
Total N(ppm)	0.58	0.54	4.31	3.01	0.19	0.09	0.22	0.12	0.41	0.30	1
PH	6.58	0.30	43.73	30.03	6.80	0.00	6.80	0.07	6.62	0.17	0.524
Moisture content	62.99	30.19	12.29	21.43	43.33	8.59	30.39	4.62	58.23	19.80	0.631
Bulk density	1.07	0.65	12.08	8.53	1.91	0.01	1.56	0.13	1.30	0.54	-0.787
%Carbon	17.26	17.56	4.09	1.18	8.51	3.10	6.50	1.50	12.34	7.60	0.749

Table 3.4. Results of Dunn's multiple comparison test for minimum, mean and maximum records. Comparisons are pairwise for each monitored disturbance location for the overlapping record period at both STN 1 and STN 2 stations. Reported results are comparisons within each disturbance group. Crossed cells indicated no difference between samples in a group. A letter (group code) is assigned to each sample within disturbance groups . Letters in each of the columns indicate pairs of samples that are significantly different from each other at $p>0.05$.

Disturbance location	Group code	Minimum near-surface temperatures	Mean near-surface temperatures	Maximum near-surface temperatures
Borrow pit (center)	a	✕	✕	✕
Borow pit (edge)	b			
Overburden spoil (center)	a	✕	b	b
Overburden spoil (edge)	b		a	a
Bladed area (center)	a	✕	b	✕
Bladed area (edge)	b		a	
Vehicle track 1 (STN 1)	a	d,c	✕	c
Vehicle track 2 (STN 2)	b	c		
Vehicle track 1 (STN 1)	c	b		a
Vehicle track 2 (STN 2)	d	a,b		
Undisturbed (STN 1)	a	✕	b	b
Undisturbed (STN 2)	b		a	a

Table 3.5. Degree days (≥ 0°C) and growing degree days (≥ 5°C) (Ecoregions working group 1989) for the overlapping measurement period (18 June to 17 July). Values were calculated from mean daily near-surface temperature records. There were no significant differences between the thawing degree days and the growing degree days at p>0.05. The degree days (>0°C and >5°C) at control site at STN 2 for the period 18 June to 29 Aug. are shown to evaluate the portion of the full growing season is represented by the overlapping season.

	Overlapping season		Full record season	
Disturbance type	Degree Days (>0°C)	Growing Degree Days (>5°C)	Degree Days (>0°C)	Growing Degree Days (>5°C)
Borrow pit (center)	325	325	n/a	n/a
Borrow pit (edge)	307	307		
Overburden spoil (center)	180	152	n/a	n/a
Overburden spoil (edge)	251	242		
Bladed area (center)	263	255	n/a	n/a
Bladed area (edge)	344	344		
Vehicle track 1 (STN 1)	247	242	n/a	n/a
Vehicle track 2 (STN 1)	260	256		
Vehicle track 1 (STN 2)	239	223		
Vehicle track 2 (STN 2)	217	198		
Undisturbed (STN 1)	233	212		
Undisturbed (STN 2)	305	302	625	560

Table 3.6. Selected soil pit characteristics within the rooting zone of each disturbance type

			Sample soil pits with an organic surface layer			Sample soil pits with a bare mineral surface layer	
Disturbance type	(*n*)	Maximum # layers	% Sample soil pits	Depth (cm)	Depth of rooting zone	% Sample soil pits	Depth of rooting zone
Undisturbed	42	3	76	2-15	19.5	21	8.2
Borrow pit (edge)	6	1	0	n/a	n/a	100	6.2
Borrow pit (center)	15	1	0	n/a	n/a	100	5.3
Bladed area	6	1	0	n/a	n/a	100	17.7
Overburden spoil	12	2	33	1-4	19	67	26
Vehicle track (multiple)	9	2	67	2-20	19.7	33	15
Vehicle track (Single, dry)	12	2	33	2-7	8.8	67	9
Vehicle track (Single, wet)	4	2	100	5-13	13.8	0	n/a

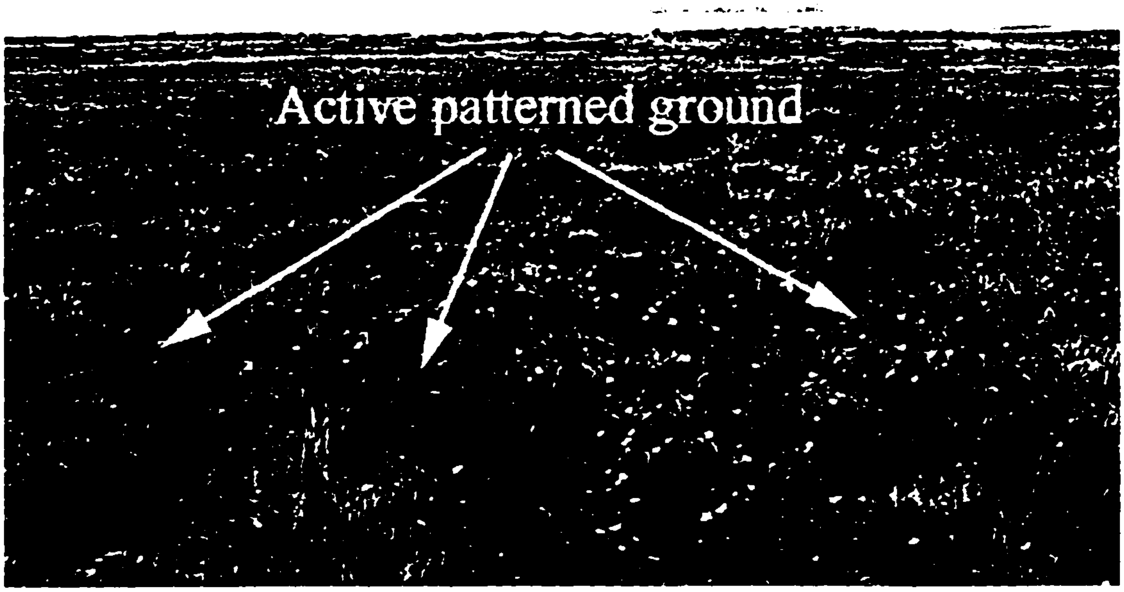

Figure 3.1. Patterned ground complex in the Decumbent Shrub Tundra. Arrows denote active patterned ground with no evidence of plant colonization. In this case non-sorted circles (rear of picture) grade into non-sorted stripes (foreground). Near road mile post 213, CANOL pipeline.

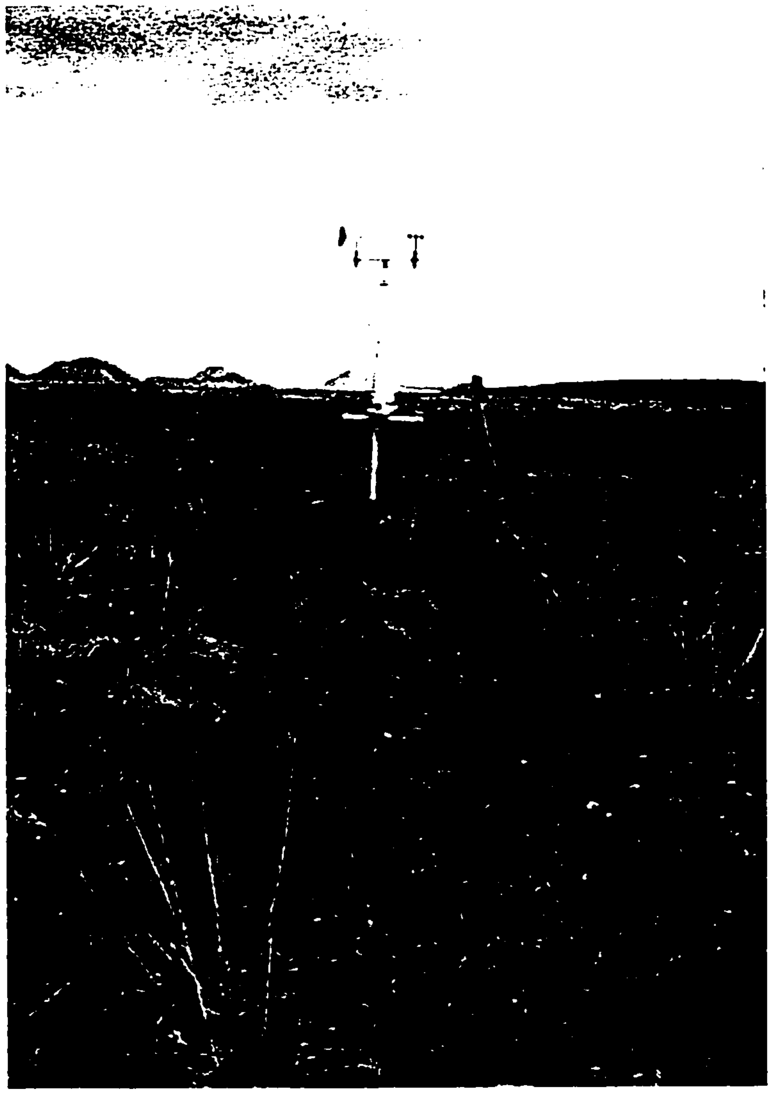

Figure 3.2. Microclimate mast in undisturbed area near STN 1. Well-vegetated patterned ground centers with low raised edges dominated by graminoid species.

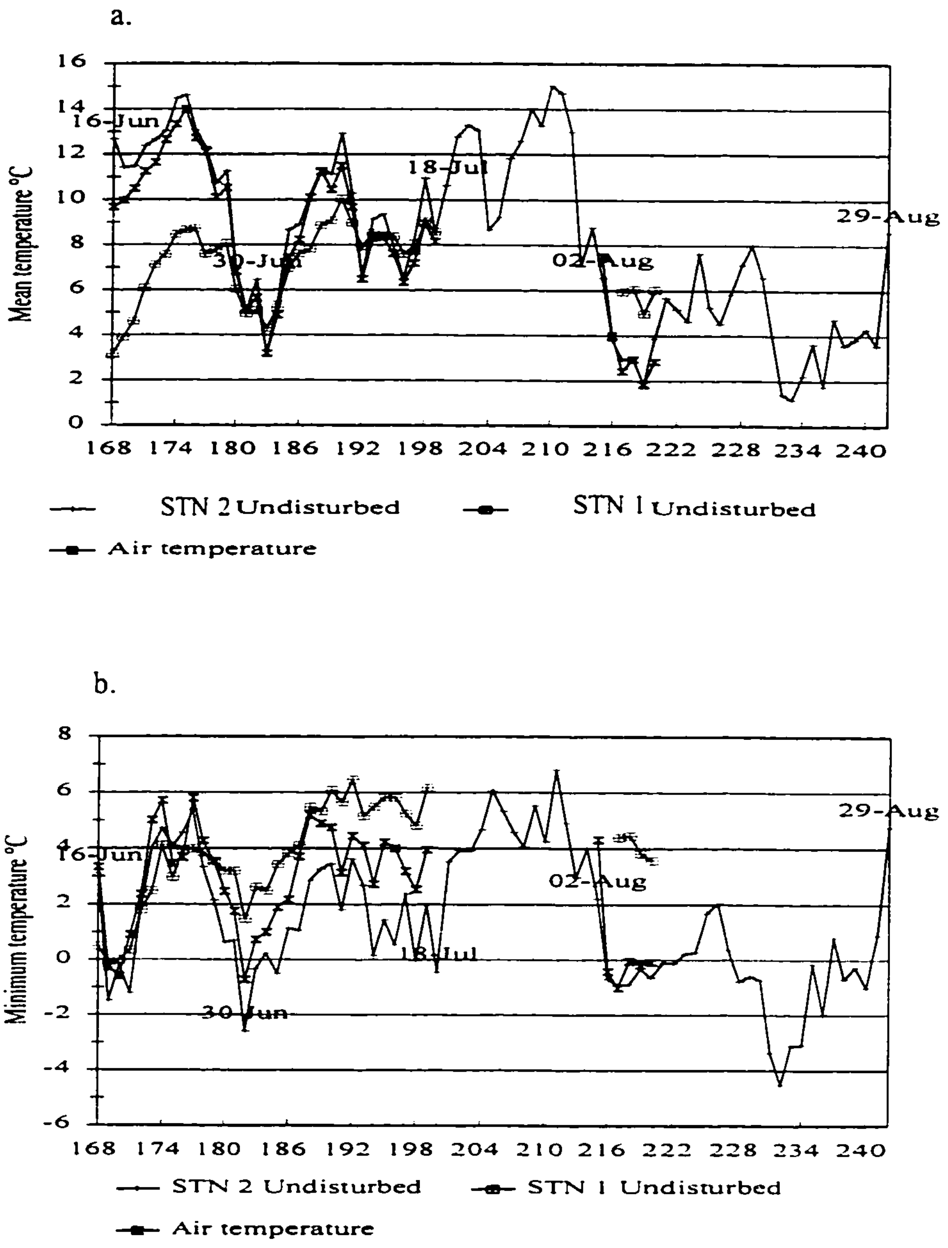

Figure 3.3. Full season temperature record (16 June to 29 Aug 1996) including all data gaps at STN 1. Graph a) is the mean near-surface temperature at STN 1 and STN 2 and air temperature at +50cm. Graph b) is the minimum near-surface temperature at STN 1 and STN 2 and air temperature at +50cm (the x-axis is the julian day).

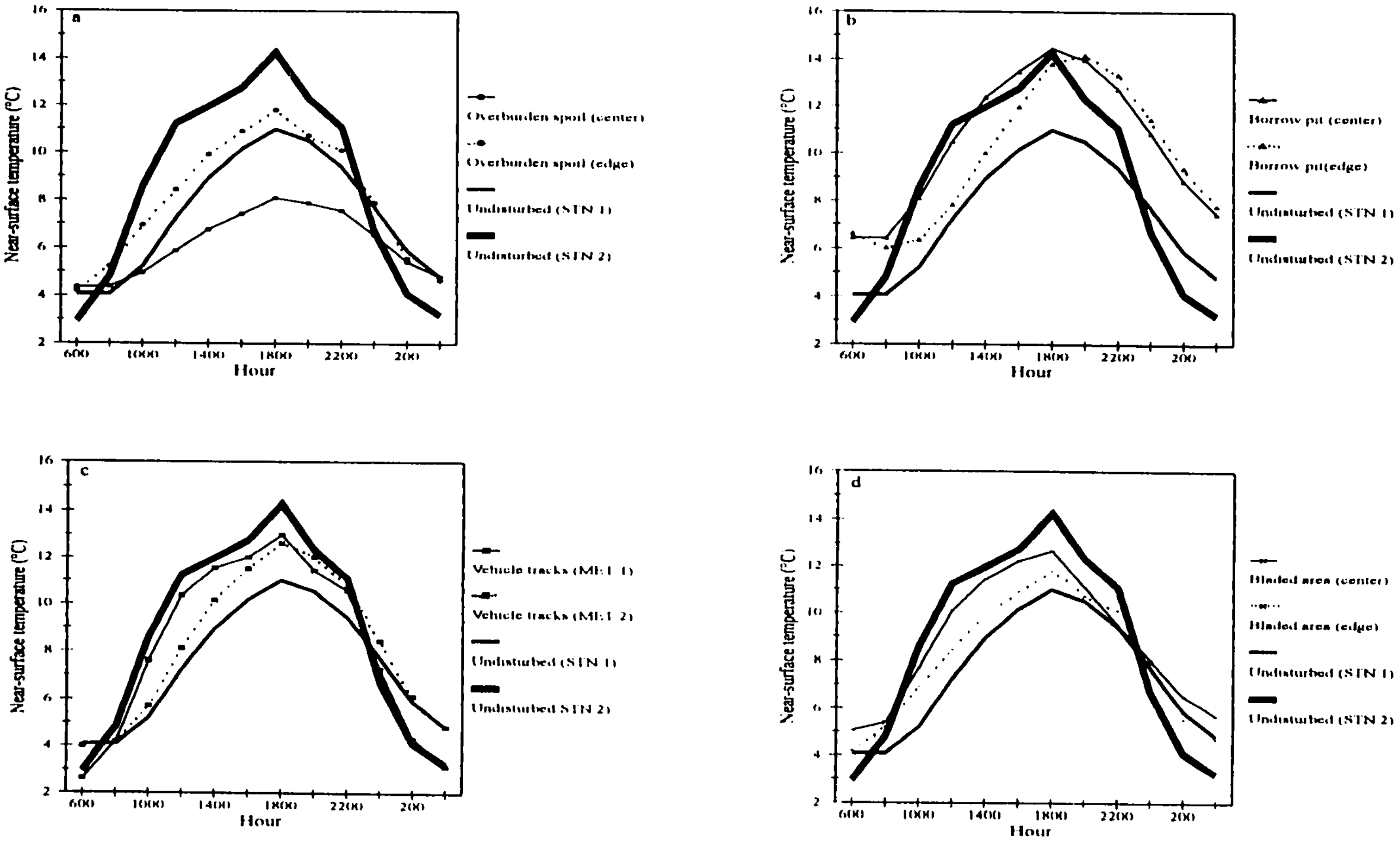

Figure 3.4. Mean diurnal near-surface temperature fluctuations for all disturbance types and both undisturbed samples. Graph panes are grouped as follows: a) overburden spoil, b) borrow pit disturbances, c) vehicle tracks, d) bladed areas. Calculations of mean temperatures for each 2hr period are made for the overlapping growing seasons at both microclimate sations (30 June to 17 July 1996).

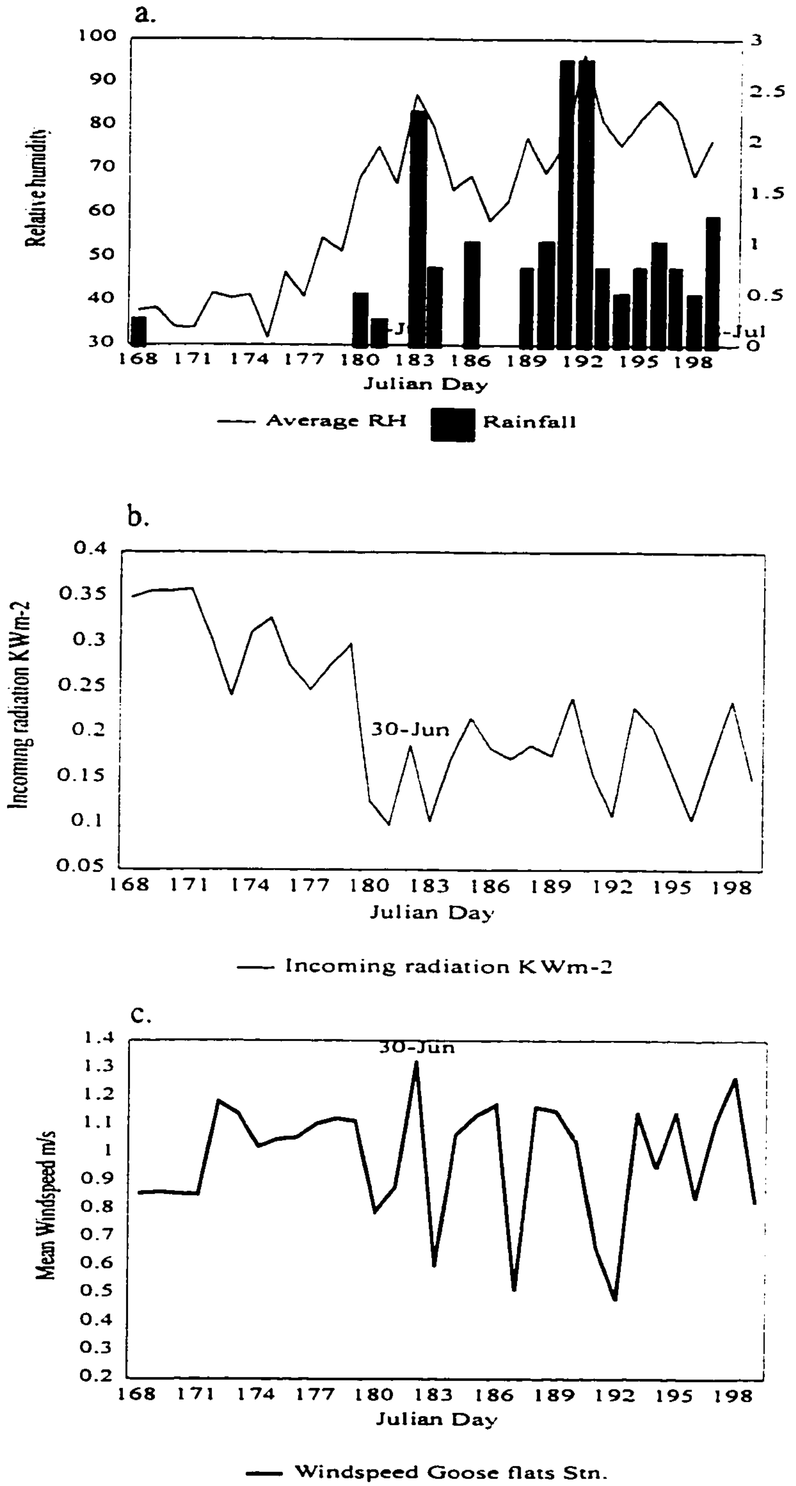

Figure 3.5. General microclimate conditions for the study area within the Decumbent Shrub Tundra for the entire measurement period (16 June to 28 Aug 1996). Graph pane a) is mean relative humidity and total rainfall at STN 2, b) is mean incoming shortwave radiation at Gooseflats microclimate station and c) is mean windspeed at Gooseflats.

Figure 3.6. Soil pit located in borrow pit disturbance type with shallow rooting zone (between 90 cm and 95 cm on tape) and coarse-grained substrate.

Figure 3.7. 'Typical' Undisturbed Decumbent Shrub Tundra soil profile. Raised circle edge with a thin LFH layer, Ah layer, light coloured Bgy with faint mottles and a Bth layer within the rooting zone. Depth of thaw is lower than the depth of the pit.

Figure 3.8. 'Typical' Decumbent Shrub Tundra layer. Thin LFH layer above the line is composed of mat-forming bryophyte species. Lower clay layer is beneath the line and the rooting zone.

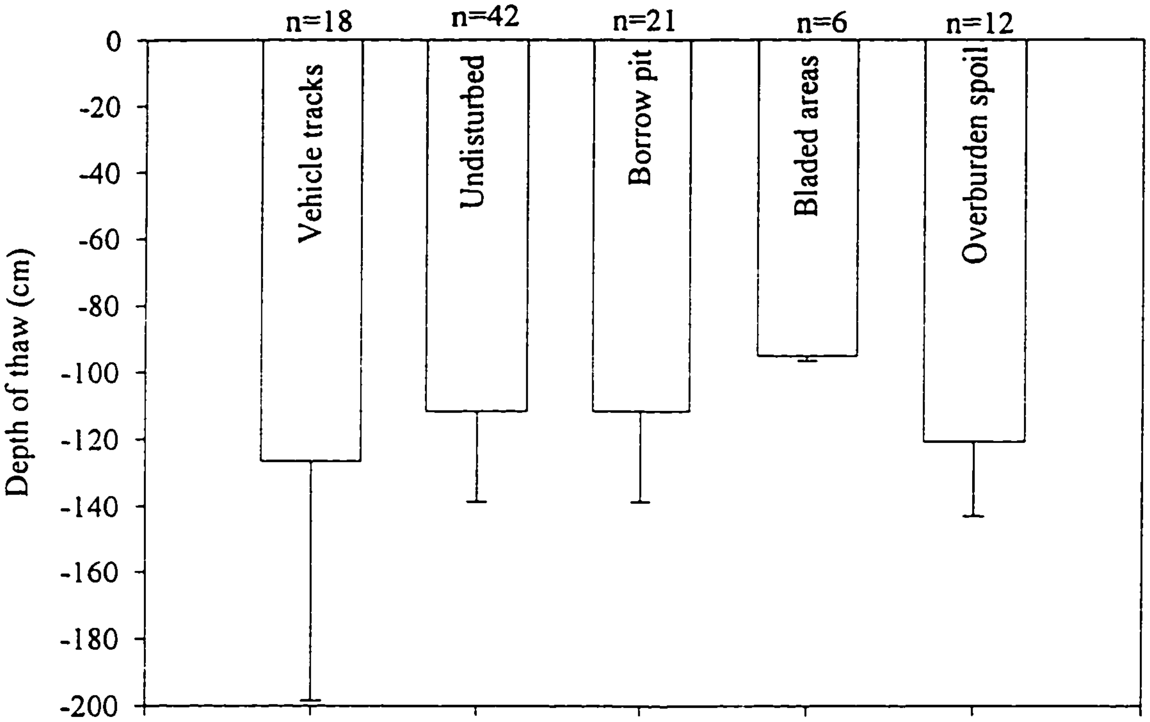

Figure 3.9. Mean extrapolated depths of thaw from soil profile readings on 2 Aug. 1996 with standard deviation error bars for each broad disturbance category. There is no significant difference between any of the disturbance types at $p<0.05$.

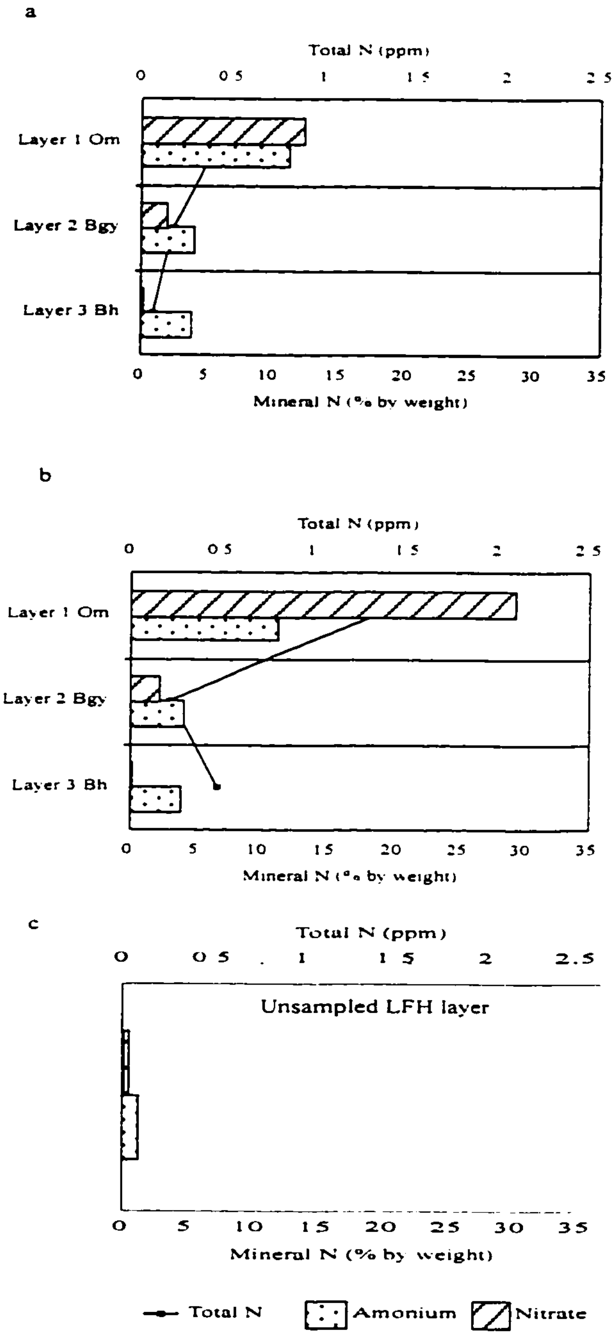

Figure 3.10. Three 'typical' soil pit samples from the undisturbed tundra showing the relationship of nutrient status to soil surface layers and subsurface layers. Panes a) and b) represent complete soil horizon development and pane c) is a third common soil pit type The third type had a continuous moss mat overlying a clay layer which did not support any rooted plants.

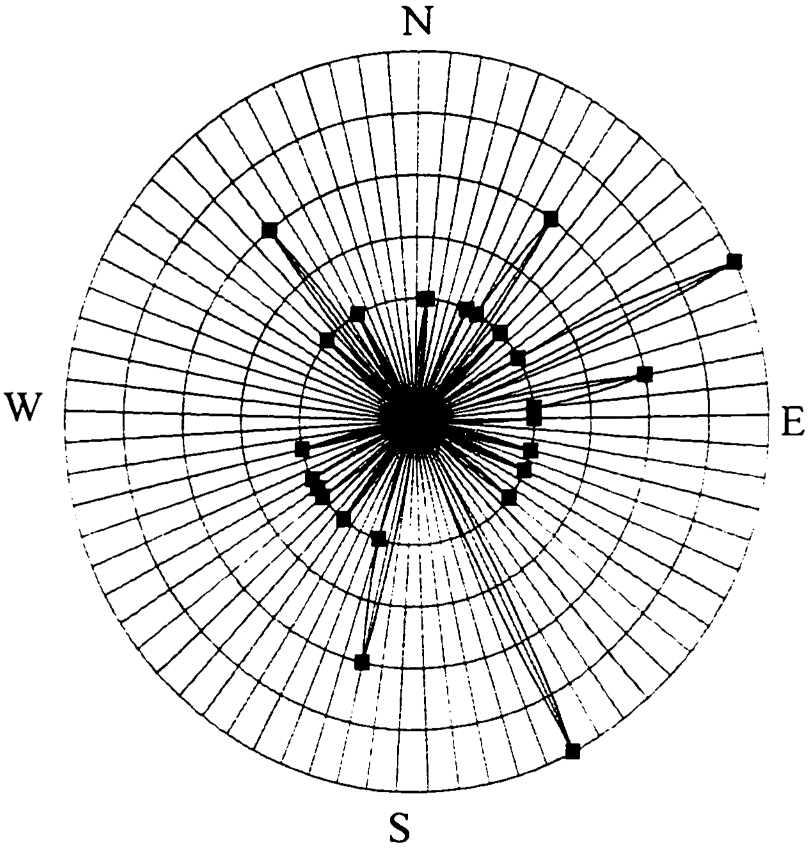

Figure 3.11. Wind rose diagram for the period of 16 June to 17 July at the STN 1 undisturbed location. An RM young wind vane was used (Table 3.1).

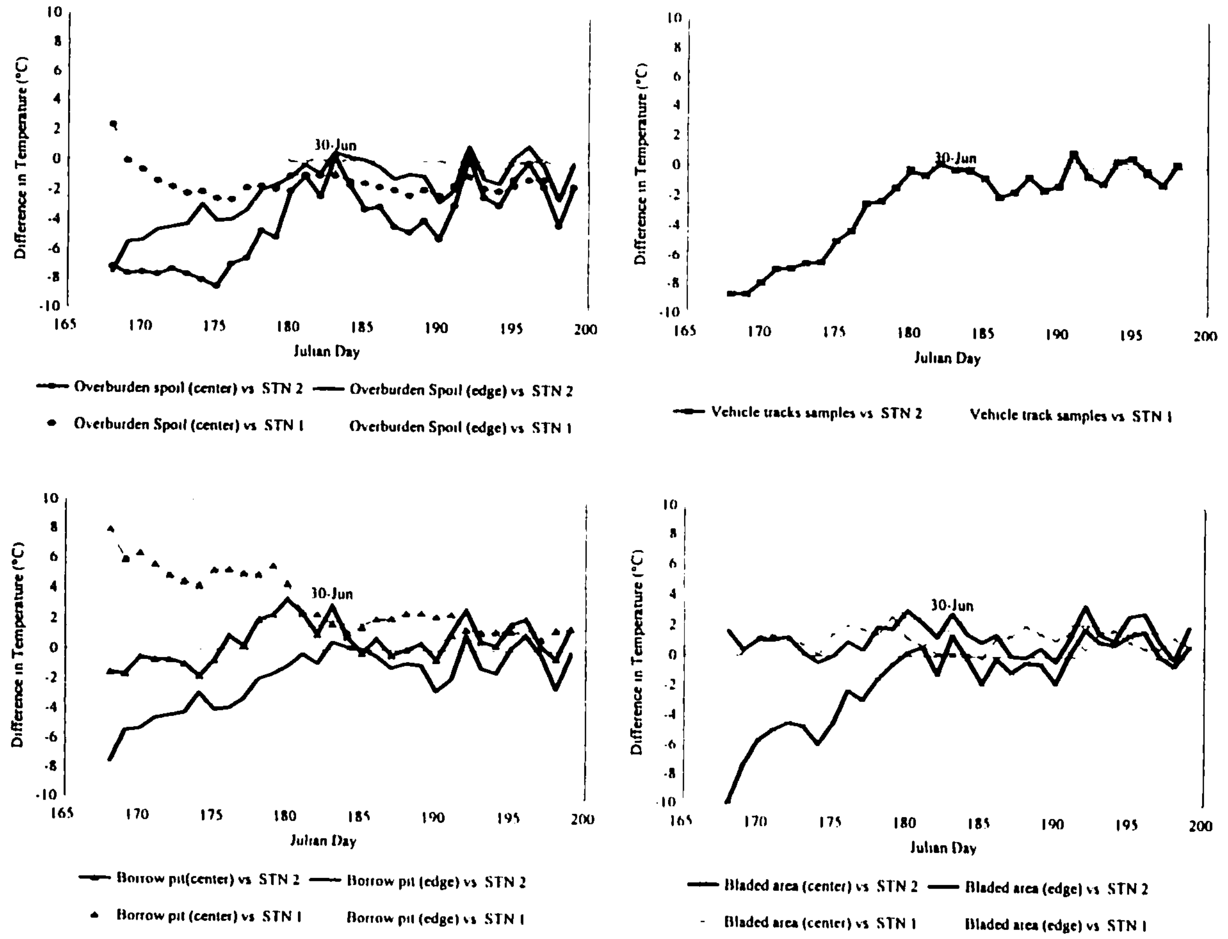

Figure 3.12. Temperature differences between disturbance types and both undisturbed samples. Positve values indicate that the disturbance is warmer than the undisturbed. Disturbances compared to STN 1 are indicated with a thin line and those compared to STN 2 are indicated with a thick line.

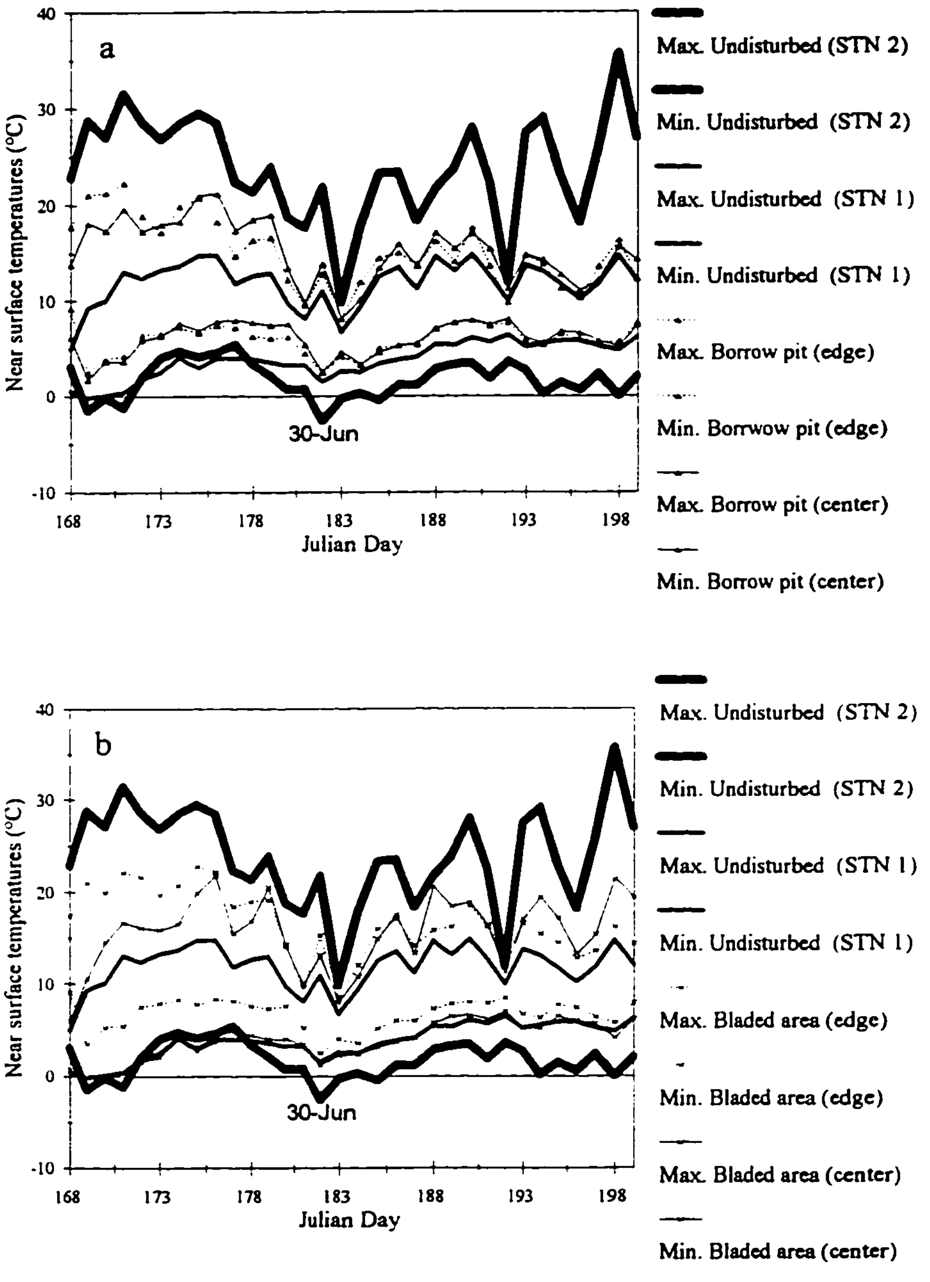

Figure 3.13. Maximum and minimum near-surface temperature records for the entire overlapping measurement period (16 June to 17 July). Panes a) and b) are overburden spoil samples and vehicle track samples respectively.

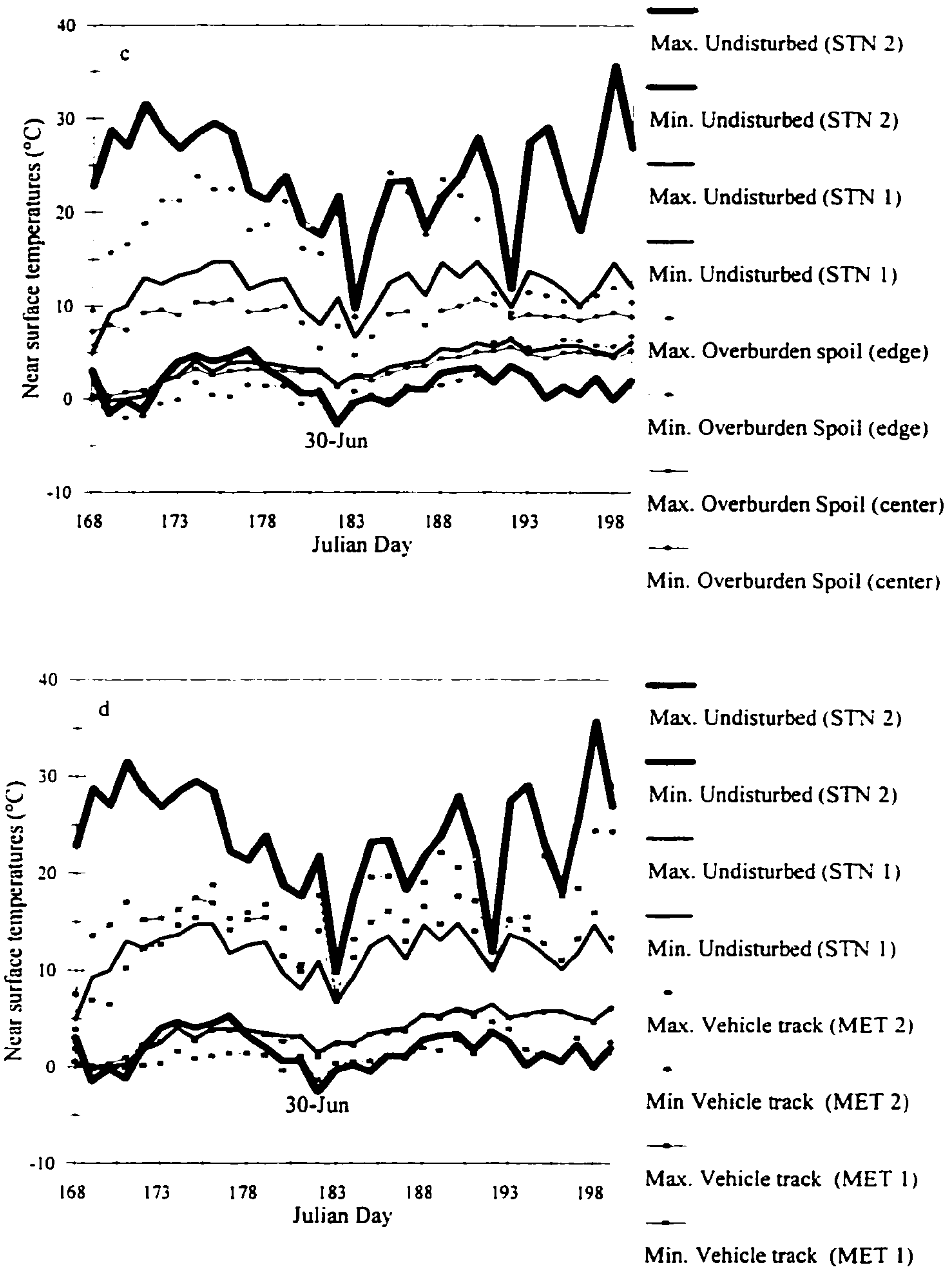

Figure 3.13 con't. Maximum and minimum near-surface temperature records for entire overlapping measurement period (16 June to 17 July). Panes c) and d) are borrow pit samples and bladed areas respectively

Figure 3.14. Snowpack accumulation in STN 1 borrow pit during snowmelt at the time of station installation. Depth of snow is approximately 2m (height of borrow pit sides).

Figure 3.15. Multiple vehicle track disturbance. Numerous tracked vehicle passes for pipeline and telephone line corridors are easily distinguished from the undisturbed tundra by the high density of tall woody shrubs.

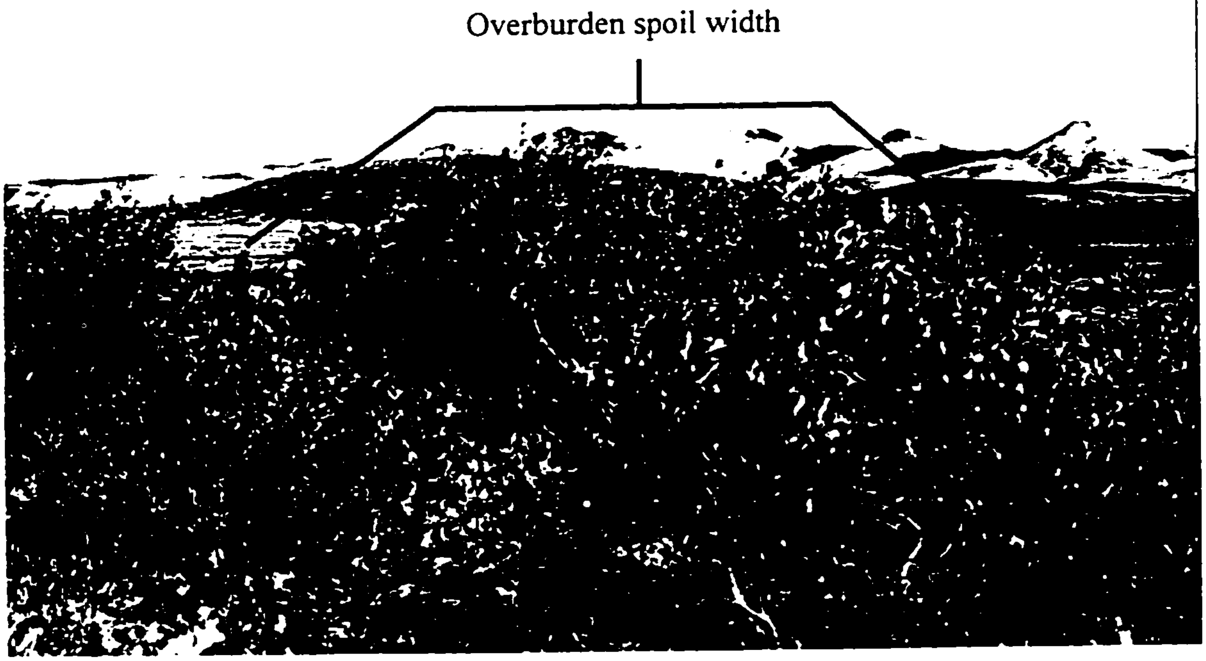

Figure 3.16. View along long axis of an overburden spoil pile. Prevalent high tall woody shrub cover in comparison to the Undisturbed Decumbent Shrub Tundra of Fig. 3.3.

Figure 3.17. Overburden spoil pile soil pit. Thick LFH layer and a small degree of soil horizon development (Ah) at the surface overlying homogenous 'spoil' material. Spoil material was bladed off the borrow pit prior to aggregate extraction.

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Chapter 4: Environmental Parameters and Species' Composition Synthesis

Introduction

Describing ecological characteristics of plant communities is complex due to the large number of interrelated environmental and biotic factors. Therefore, a common approach in ecological studies is to isolate specific components of a plant community, such as the abiotic or biotic factors, and to use statistical techniques to describe variations in these factors. This approach was used in Chapter 2 and Chapter 3, where abiotic and biotic components of the Decumbent Shrub Tundra in the Mackenzie Mountain Barrens were described separately.

In Chapter 2 indirect community analysis was performed on a large species'/samples data set, comparing the disturbance categories previously described. From this type of indirect gradient analysis hypothetical environmental variables are computed and subsequently causes for the species' dispersion are inferred by the researcher based on separate observations of environmental variables.

In Chapter 3, a full analysis of the measured environmental variables was carried out. Although these analyses were useful in describing variations in isolated components of the Decumbent Shrub Tundra community, an alternate technique is necessary to describe interrelations of abiotic and biotic factors and their combined effect on species' variations. Therefore, the main objective of this chapter is to combine the vegetation, soil and near-surface temperature data sets from the previous chapters to determine the most important abiotic factors in controlling the variation in plant communities found within disturbances associated with the CANOL pipeline construction.

The method of canonical correspondence analysis, (CCA) (terBraak, 1987), a direct ordination technique which allows for a graphical representation of species' variation along gradients of numerous environmental variables, will be used to accomplish this objective. Direct ordination maximizes the plant community variation in light of measured environmental variables (Jongman et. al. 1987), thus it is possible to determine the most important variables accounting for plant community variation. Furthermore, CCA gives information on the interrelationships among environmental variables. These interrelationships, calculated through ordination can be verified by comparison to indirect ordination of species' data and separate analysis of the abiotic factors.

Data Analysis Techniques (Direct and Indirect Ordination):

The indirect family of community ordination includes correspondence analysis (CA) and its modification, detrended correspondence analysis (DCA). In CA and DCA a theoretical environmental variable is constructed based on the observed species' distributions. Species' scores are calculated by a weighted averaging technique based on Gaussian unimodal response curves. The species' scores can be plotted in two dimensional space as the 'best fit' representation of actual species' distributions. The eigenvalues are measures of the importance of the constructed environmental variable on the species' distribution. Species' scores can be plotted on two axes which represent the hypothetical environmental variables in a biplot (Jongman *et al.* 1987).

The distribution of species' scores is explained using eigenvalues which represent hypothetical environmental variables calculated in DCA. The value of an eigenvalue (>0 and<1) indicates the importance of the hypothetical axis in defining the 'best fit' distribution of species' scores. Sample scores are weighted averages of the species' scores derived for each sample quadrat.

The output of these analyses include biplots of species' scores and their relative positions along hypothetical (calculated) environmental variables. The effects of environmental variables are inferred from the species' score distribution portrayed by the biplot. All analyses for this chapter were run using the program CANOCO (terBraak

1987).

Canonical correspondence analysis (CCA), a form of direct community ordination, is also a weighted averaging technique based on the unimodal Gaussian response curve (terBraak 1986). It is a modification of CA and DCA because the algorithm takes into account a set of measured environmental variables. This type of analysis has been successfully used when investigating the relationships between tundra vegetation and the environment (Harper and Kershaw 1996; Forbes, 1995 and 1993). It can also be used in conjunction with indirect methods such as DCA in order to understand the nature of the relationships between the environment and species' distribution (terBraak 1986).

CCA generates a number of products beyond the scope of DCA in order to interpret plant community variation with respect to measured environmental variables. The algorithm is based on the unimodal species' response curve but the ordination axes are restricted as linear combinations of the environmental variables. Because the axes are restricted in this manner the eigenvalues are expected to be smaller (terBraak 1987).

The species'-environment correlation is a multiple correlation calculation reflecting the correlation between sample scores as calculated from weighted averages of species' scores and sample scores as calculated from the linear combination of environmental variables (Jongman et al. 1987). In interpretation, these values are important in combination with the eigenvalues to determine the degree to which the actual species' variation is accounted for by the hypothetical axes derived in light of the environmental variables.

Inter-set correlations give the relative importance of each measured environmental variable to each ordination axis (ter Braak 1987). Inter-set correlations and a full correlation matrix between all measured variables (also supplied in the output) can be used to find interrelationships among environmental parameters (Jongman et.al 1987).

Output of CCA can be combined in a triplot with species' and sample scores arranged along the first two ordination axes (as for a DCA biplot). A third component is arrows representing environmental variables. The length of the arrow represents the relative importance of the variable. The direction of the arrow can be used to infer the species' correlations to that environmental variable. Species located within the quadrant of the graph in the direction of the arrow are positively correlated to that environmental variable. The arrow can be extrapolated in the opposite direction to determine which species are negatively correlated to that environmental variable. Relative position along the arrow is an indicator of the strength of the correlation between the environmental variable and the species. In other words arrows represent environmental gradients and species optima are located along that gradient in the ordination diagram. If a species' score does not fall directly on the line of the arrow the point is positioned by extending a line from the species' point perpendicular to the arrow line (terBraak 1987; terBraak 1986).

Ordination as a Disturbance Classification Tool:

Vegetation succession is a natural directional process in which plant species' composition changes (depending on individual species' autecology) as the environment changes. Such changes occur in an area over time, where different environments have different successional rates. The goal of correspondence analysis is to define the variation in a plant community with derived and real environmental variables. If one of the environmental variables is time then plant succession can be analyzed. This has been done over a six year period for plant succession processes on a rising seashore. Environmental variables used were elevation and year of sampling (Cramer and Hytteborn 1987). If the succession period is so slow that sampling cannot be done in a reasonable amount of time a temporal gradient can be introduced using geographic features that can be reliably dated. The assumption in these cases is that a process occurring at a known rate is exposing barren substrate. Svoboda and Henry (1987) and Viereck (1966) used glacier forelands and Bliss (1977) used raised beach ridges.

For linear disturbances in the Mackenzie Mountain Barrens the exact vegetation composition at the time of disturbance was not known for all disturbance types. Sampling done in 1977 (Kershaw 1983) provided too few samples for comparison to data collected for this thesis, thus it was not possible to introduce time as a variable in describing succession on these disturbances. The borrow pit disturbances were assumed to be entirely devoid of vegetation at the time of construction and thus represented the rate of primary succession in the Decumbent Shrub Tundra. In chapter 2 indirect ordination was used to link the processes of succession occurring in both the linear and borrow pit disturbances along a gradient. Direct gradient analysis can be used to determine which environmental variables are responsible for the variation in resultant anthropogenic plant associations

In a previous study of the Erect Deciduous Shrub Tundra, Harper and Kershaw (1997) showed that soil temperature was the most important measured environmental variable accounting for variation within disturbance types. Gradients described by the derived axes were due in part to regional differences in plant associations, dividing the study area into east and west zones. Within these zones significant variation was observed among disturbance types.

In the current study regional effects were not a factor. The plant community sampled was located within a smaller geographical area and the effect of regional variation was not pronounced in the indirect gradient analysis (Chapter 2). Direct gradient analysis using a set of measured environmental variables may define important environmental variables in natural long-term succession processes within various degrees of disturbance intensities and show differences between neighboring plant communities.

Methods

Two subsets to the full vegetation relative abundance data set were collected during the field season of 1996. Relative abundance data for individual plant species was collected using 15 quadrats per sample site (n=36) (vegetation data set sampling methods Chapter 2). Soil parameters were measured at 3 randomly-selected vegetation quadrats per sample site (n=36) (soil data set sampling methods Chapter 3). Near-surface temperature was measured throughout the growing season at selected sample sites representing all disturbance types (n=12) (near-surface temperature data set e.g. microclimate sampling methods Chapter 3).

Soil Data Set:

Soil parameters used as environmental variables for the soil data set were pH, NO_3 levels, NH_4 levels, total nitrogen, bulk density, moisture content, depth of organic layer, % carbon content and gravel, sand, silt and clay composition as reported on in Chapter 3. All of the soil parameters are specific to each individual vegetation quadrat measured. The data were used for surface layers only.

A DCA was performed on the soil data set without the environmental variables. The DCA biplot of the relative species' abundance of the three vegetation quadrats associated with the soil pits was used to evaluate results of the DCA analysis using the full vegetation data set. Eigenvalues of the primary axis were also compared to direct gradient analysis to evaluate the amount of variance accounted for by the measured environmental variables. All ordinations were done using the computer program CANOCO (ter Braak 1987).

Because CCA axes are constrained by measured environmental variables the eigenvalues are generally smaller than those of DCA analyses (Jongman et al. 1987). Combinations of direct and indirect gradient analysis can be used to determine what the sources of the species' variation are (ter Braak 1986). If the two solutions do not differ much then the measured environmental variables account for most of the species' distribution. If the solutions differ but the species'/environment correlations are high then the variation will not be from obvious sources (Jongman et al. 1987).

CCA and CA was performed on the soil data set. All measured environmental variables were used in order to determine how much community variation was accounted for by the measured variables. Species'/sample/environmental variable triplots were generated with 94 active species, 108 active samples and 12 environmental variables. No data transformations were made and the default scaling option was accepted.

Near-Surface Temperature Data Set:

A separate analysis was done with the near-surface temperature data and the same soils environmental data. The three leads of the thermocouple wires in sensored sample sites were placed next to the three soil pit quadrats. The single near-surface temperature value for that sample was considered to be the average for the three soil sampling pit locations. The average near-surface temperature value was used for all three quadrats in each block samples near STN 1 and STN 2.

A CCA was performed with the near-surface temperature data set using the same protocol listed for the soil data set CCA. The species'/samples/environmental variables triplot was generated with 66 active species and 33 active samples. Near-surface temperature was added to the list of environmental variables (n=13). Care was taken in the interpretation of the correlation coefficients for Total N since the inflation factor for that variable was 27.00. Large inflation factors (>20) indicate that the variable is almost perfectly correlated with other variables and the correlation coefficients will be unstable (terBraak, 1987) .

Results

Direct and Indirect Ordination Techniques:

The eigenvalue of the primary DCA axis for the soil data set was high at 0.718 and the other 3 axes were 0.445, 0.323 and 0.254 (table 4.1). The samples scatter diagram (fig. 4.1) had considerable overlap of similar disturbance type samples as observed in Chapter 2 (fig. 2.1).

The difference between the eigenvalue of the primary axis of the DCA versus the CCA of the soil data set was 0.381 which was large considering eigenvalues of <0.2 are not considered important (terBraak 1987). The species'/environment correlations were also high for all 4 axes in the CCA (table 4.2).

In the scatter plot of sample scores for the soil data set, pit (center), pit (edge) samples were clustered together. Undisturbed, vehicle track (dry) and multiple tracks form another large group. Vehicle tracks (wet) and overburden spoil were individually clustered (fig. 4.1)

Eigenvalues for the CCA of the soil data set were much smaller than the DCA eigenvalues. A corresponding reduction in the percent variance (of species' distributions) accounted for this difference (table 4.1). Some reduction was expected due to technical differences in the analysis (Michin 1987; terBraak 1986). Such a large difference would also indicate that the measured environmental variables did not account for most of the plant community variation. However species'-environment correlations for the CCA were all >0.6, the cumulative percent variance of the species'-environment relationship for all four axes was 62.7% and the Monte Carlo test indicated significance of the first axis in explaining the species' variance, thus the measured environmental variables must have accounted for much of the 'best fit' species' distribution but the relationships among the environmental variables were complex (terBraak, 1986).

Direct Ordination of the Soil Data Set:

Species'-environment correlations were 0.738, 0.685, 0.698 and 0.666 for the first four axes respectively and 62.7% of the variance associated with the weighted averages of species with respect to the measured environmental variables was accounted for by these axes (table 4.2). Furthermore the results of the Monte Carlo permutation test indicated that the primary axis was significantly related to the species' distribution, indicating the variation associated with the differences between natural and anthropogenic plant communities was explained by the measured variables.

Gravel content was the most important variable associated with the first extracted axis of variation in the CCA as indicated by the inter-set correlation of 645 (table 4.2). The most important measured variable for the subsequent axes were nitrate, total N and organic layer thickness for axes 2 to 4 respectively (table 4.2).

Species'-environment correlations were >0.6 for all axes extracted by the CCA (table 4.2). Groupings of variables were established using correlations among actual measured environmental variables. The groupings are shown in tables 4.2 and 4.3 by the bold characters indicating positive correlations. Total N, ammonium, nitrate, organic layer thickness and moisture content were positively correlated. Bulk density and gravel content were positively correlated (table 4.3).

Direct Ordination of the Near-Surface Temperature Data Set:

For the near-surface temperature data set the eigenvalues were somewhat higher than for the soil data set. Species' environment correlations were near-perfect for each of the ordination axes with a total cumulative percent variance of 62.1% with the addition of near-surface soil temperature to the list of environmental variables (table 4.5). The results of the Monte Carlo permutation test indicated that the primary eigenvalue was significant in describing the species' variance.

Gravel content had the highest positive inter-set correlation followed by soil temperature for the primary ordination axis (table 4.5). The highest inter-set correlations for subsequent axes were for clay content, % carbon content and organic layer thickness for axes 2, 3 and 4 respectively.

Correlations among measured environmental variables displayed consistent groupings to ones calculated for the soils data set. NH_4, NO_3, organic layer thickness and moisture content were highly positively correlated as a group. Near-surface soil temperature was not highly correlated to any other environmental variable measured.

Discussion

Comparison of Direct and Indirect Ordination Techniques:

Using DCA for the soil data set reinforced the results of the DCA performed on the vegetation data set in Chapter 2 (Fig 2.1). Disturbance types differentiated in the field overlapped but the groups with the largest spatial separation on the scatter plot were similar in the comparisons of the vegetation and soil data sets. The reduction in sample size did not severely alter the species' distribution patterns at this level of analysis and comparisons are made on this assumption.

Groupings Among Environmental Variables:

The comparison of the DCA and the CCA indicated that the relationship between the species' distribution and the measured environmental variables was a complex rather than simple cause and effect relationship. The environmental variables used in this analysis were highly interrelated as noted in Chapter 3.

Inter-set correlations were instructive in explaining the species' distributions on all calculated axes and were easily described based on lengths and directions of arrows on the triplot (fig. 4.2). Environmental variables in the group associated with nitrogen contents were all correlated with vehicle track disturbances and undisturbed tundra which were both vegetated disturbances.

Gravel content and its correlates formed a soil texture group of variables which were all important in borrow pit disturbances (fig. 4.2). This group was the most important in describing community variation because the gradient from non-vegetated pits to vegetated disturbances was larger than the gradients seen in community composition within the vegetated disturbances. From a reclamation standpoint the importance of the soil texture variables highlights the importance of the replacement of topsoil material on disturbed areas of the Decumbent Shrub Tundra.

Overburden spoil pile samples fell intermediate to the borrow pits and the other vegetated disturbances. Overburden spoil was a disturbance with full vegetation cover, however the construction process involved the destruction of the surface vegetation. The overburden spoil provided an example of how a plant community will develop if the overburden is simply replaced without attention to preserving soil horizon structure.

Near-Surface Temperature:

The high eigenvalues and near-perfect species'-environment correlations indicated that the addition of near-surface temperature allowed for the calculated axes to represent more of the species' distribution (e.g. near-surface temperature explained the residual variation). Gravel content remained the most important factor on the primary axis but was followed by near-surface temperature (table 4.5). In the triplot the same groupings of soil texture variables associated with the borrow pit samples were seen. The nutrient cycle variables were associated with the intact vegetation mat samples (fig. 4.3). Since Near-surface temperature did not have high correlations with other environmental variables it was not considered to be a part of either the nutrient or the soil texture groups of variables observed in both data sets.

It was difficult to draw definite conclusions based on the triplot of fig. 4.3. While environmental variables in general were similarly correlated in both the soil data set and the near-surface temperature data set the level of vegetation sampling obviously did not produce results similar to any other direct or indirect method used. Near-surface temperatures may be an important factor in monitoring the recovery of disturbances but limitations were imposed due to the low levels of replication in the continuous temperature records.

Summary

Correspondence analysis helped in the evaluation of differences between anthropogenic disturbances at all levels of sampling (within the vegetation, soil and near-surface temperature data sets). A combination of direct and indirect methods indicated that the measured environmental variables accounted for much of this variation but there were complex relationships among the variables.

Measured environmental variables associated with soil texture were most important in all direct analyses followed by nutrient quality variables in the soil data set. Near-surface temperature accounted for the remaining variation but was still secondary to soil texture as a predictor of community composition. The degree of natural succession in the Decumbent Shrub Tundra can be predicted by measuring soil texture variables.

Table 4.1. Comparison of eigenvalues and variances of DCA and CCA ordinations for the soil data set

	Soil data set DCA			
Ordination Axes	1	2	3	4
Eigenvalues	0.718	0.445	0.323	0.254
Cumulative percentage varinance of species data	8.5	13.7	17.5	20.5
	Soil data set CCA			
Eigenvalues	0.337	0.178	0.138	0.114
Cumulative percentage varinance of species data	4.0	6.1	7.7	9.1

Table 4.2. Interset correlations (multiplier 1000) for each measured environmental variable, eigenvalues , species-environment correlations, percent variances of species data and species-environment relations for the CCA of the soil data set.

Ordination axis	1	2	3	4
Nitrate	-275	332*	104	10
Amonium	-347	95	175	155
Total nitrogen	-476	55	283*	83
Depth of organic layer	-465	44	-63	381*
pH	305	150	-84	52
Moisture content	-621	12	252	-47
Bulk density	525	-30	-144	-179
Gravel	645 *	4	171	173
Clay	395	-226	-333	-196
Silt	307	-443	-111	-30
Sand	186	-279	-214	-90
%Carbon content	-510	78	176	100
Eigenvalues	0.337	0.178	0.138	0.114
Species-environment correlations	0.738	0.685	0.698	0.666
Cumulative percent variance of species data	4.0	6.1	7.7	9.1
Cumulative percent variance of species-environment relationship	27.5	42.1	53.3	62.7

*indicates the highest positive interset correlations at each ordination axis.

Table 4.3 Correlation matrix of measured environmental variables calculated in the CCA analysis of the soil data set. Positive correlations are indicated in bold lettering.

	Nitrate	Amonium	Total N	Organic thickness	pH	Moisture	Bulk Density	Gravel	Clay	Silt	Sand	%Carbon
Nitrate	1.0000											
Amonium	**0.4801**	1.0000										
Total nitrogen	**0.6647**	**0.8298**	1.0000									
Organic thickness	**0.3813**	**0.5463**	**0.6121**	1.0000								
pH	-0.3079	-0.4846	-0.5057	-0.5380	1.0000							
Moisture	**0.4525**	**0.4314**	**0.6775**	**0.5216**	-0.4492	1.0000						
Bulk density	-0.4486	-0.6717	-0.7757	-0.6176	**0.4955**	-0.6181	1.0000					
Gravel	-0.3311	-0.4559	-0.5299	-0.4525	**0.3585**	-0.6490	**0.4954**	1.0000				
Clay	-0.4979	-0.6146	-0.6613	-0.4908	**0.2397**	-0.4641	**0.5683**	**0.3636**	1.0000			
Silt	-0.4687	-0.5148	-0.5092	-0.3876	**0.2152**	-0.2962	**0.4029**	**0.2675**	**0.5874**	1.0000		
Sand	-0.4221	-0.5008	-0.5653	-0.4286	**0.2402**	-0.3290	**0.5371**	**0.2282**	**0.5889**	**0.2850**	1.0000	
%Carbon	**0.5855**	**0.7042**	**0.8285**	**0.6496**	-0.5278	0.6546	-0.7610	-0.5172	-0.6946	-0.5639	-0.5930	1.0000

Table 4.4 Correlation of measured environmental variables calculated in the CCA analysis of the near-surface temperature data set (smaller data set including the same variables as above with the addition of near-surface temperature). Positive correlations are denoted by bold lettering.

	Nitrate	Amonium	Total N	Organic thickness	pH	Moisture	Bulk Density	Gravel	Clay	Silt	Sand	Carbon	Surface temperature
Nitrate	1.0000												
Amonium	**0.7677**	1.0000											
Total nitrogen	**0.7755**	**0.8359**	1.0000										
Organic thickness	**0.2499**	**0.5076**	**0.7184**	1.0000									
pH	-0.5738	-0.4176	-0.5138	-0.4054	1.0000								
Moisture	**0.6068**	**0.7668**	**0.8468**	**0.6776**	-0.5113	1.0000							
Bulk density	-0.4583	-0.6472	-0.7069	-0.5880	**0.3336**	-0.6301	1.0000						
Gravel	-0.4487	-0.5818	-0.5003	-0.3732	**0.4280**	-0.7025	**0.3632**	1.0000					
Clay	-0.1743	-0.1302	-0.2464	-0.3075	**0.1947**	-0.3867	**0.3346**	**0.1776**	1.0000				
Silt	**0.2668**	**0.1355**	**0.3476**	**0.2433**	**0.0639**	-0.0511	-0.0362	**0.3297**	**0.1462**	1.0000			
Sand	-0.0336	0.0771	-0.1168	-0.1432	**0.0196**	**0.1648**	**0.0479**	-0.4005	-0.0344	-0.3897	1.0000		
%Carbon	**0.7196**	**0.8008**	**0.9166**	**0.6531**	-0.5330	**0.8891**	-0.6826	-0.5710	-0.2286	**0.1685**	-0.0258	1.0000	
Near-surface temperature	-0.2148	-0.2611	-0.0534	**0.0498**	**0.2080**	-0.2558	**0.1474**	**0.4878**	**0.0644**	**0.4519**	-0.4945	-0.1435	1.0000

Table 4.5. Interset correlations (multiplier 1000) for each measured environmental variable, eigenvalues , species-environment correlations, percent variances of species data and species-environment relations for the CCA of the near-surface temperature data set

Ordination axis	1	2	3	4
Nitrate	24	-121	92	143
Amonium	-309	-196	-27	90
Total Nitrogen	-233	-361	114	414
Depth of Organic layer	-389	-331	32	548*
pH	176	186	-171	53
Moisture content	-614	-383	41	226
Bulk density	163	418	209	-384
Gravel	684 *	7	233	-29
Clay	168	453 *	338	-103
Silt	474	-262	285	349
Sand	-535	6	-285	-231
%Carbon content	-422	-343	306*	310
Near-surface temperature	522	-426	238	26
Eigenvalues	0.669	0.423	0.364	0.276
Species-environment correlations	0.971	0.904	0.940	0.886
Cummulative percent variance of species data	12.0	19.6	26.1	31.1
Cummulative percent variance of species-environment relationship	24.0	39.2	52.2	62.1

*indicates the highest positive interset correlations at each ordination axis.

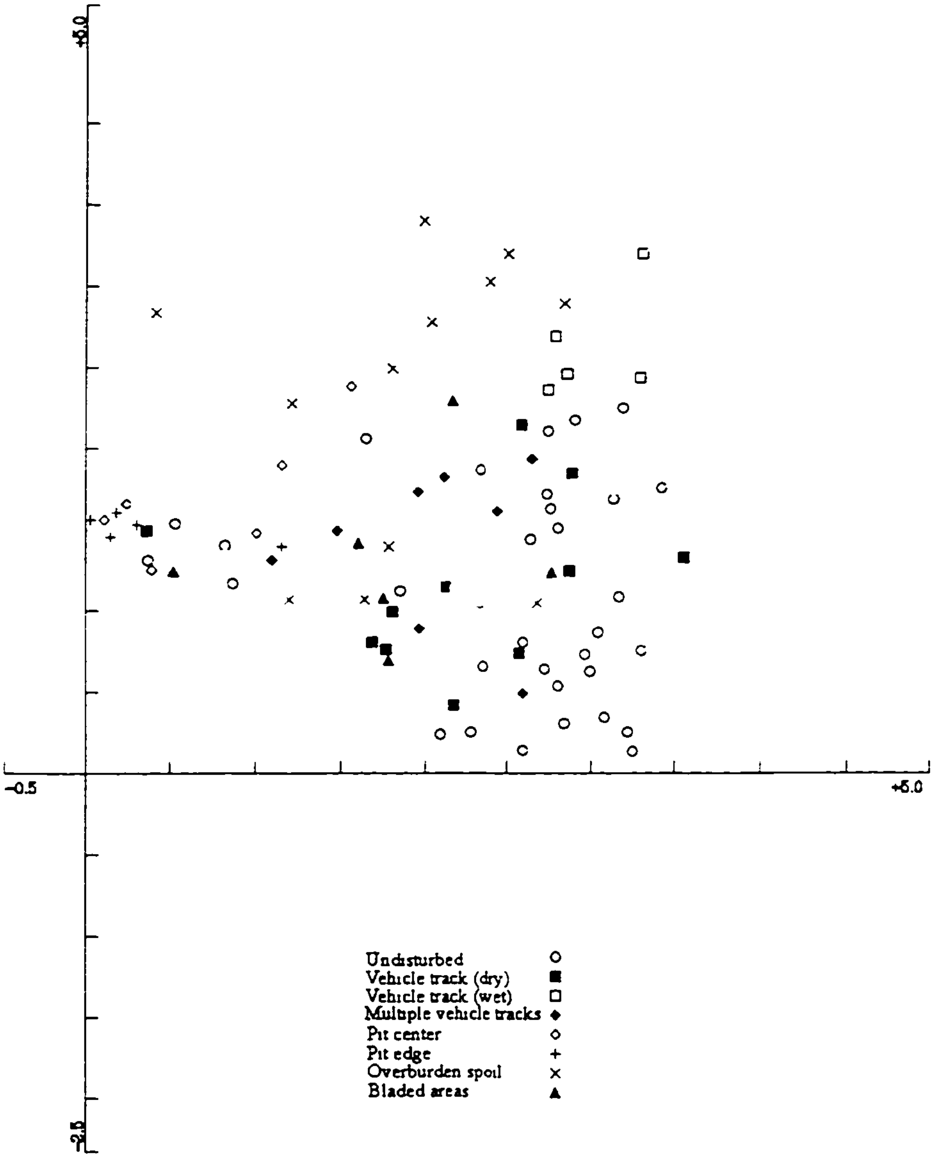

Figure 4.1. DCA scatter diagram of sample scores for the Soil data set

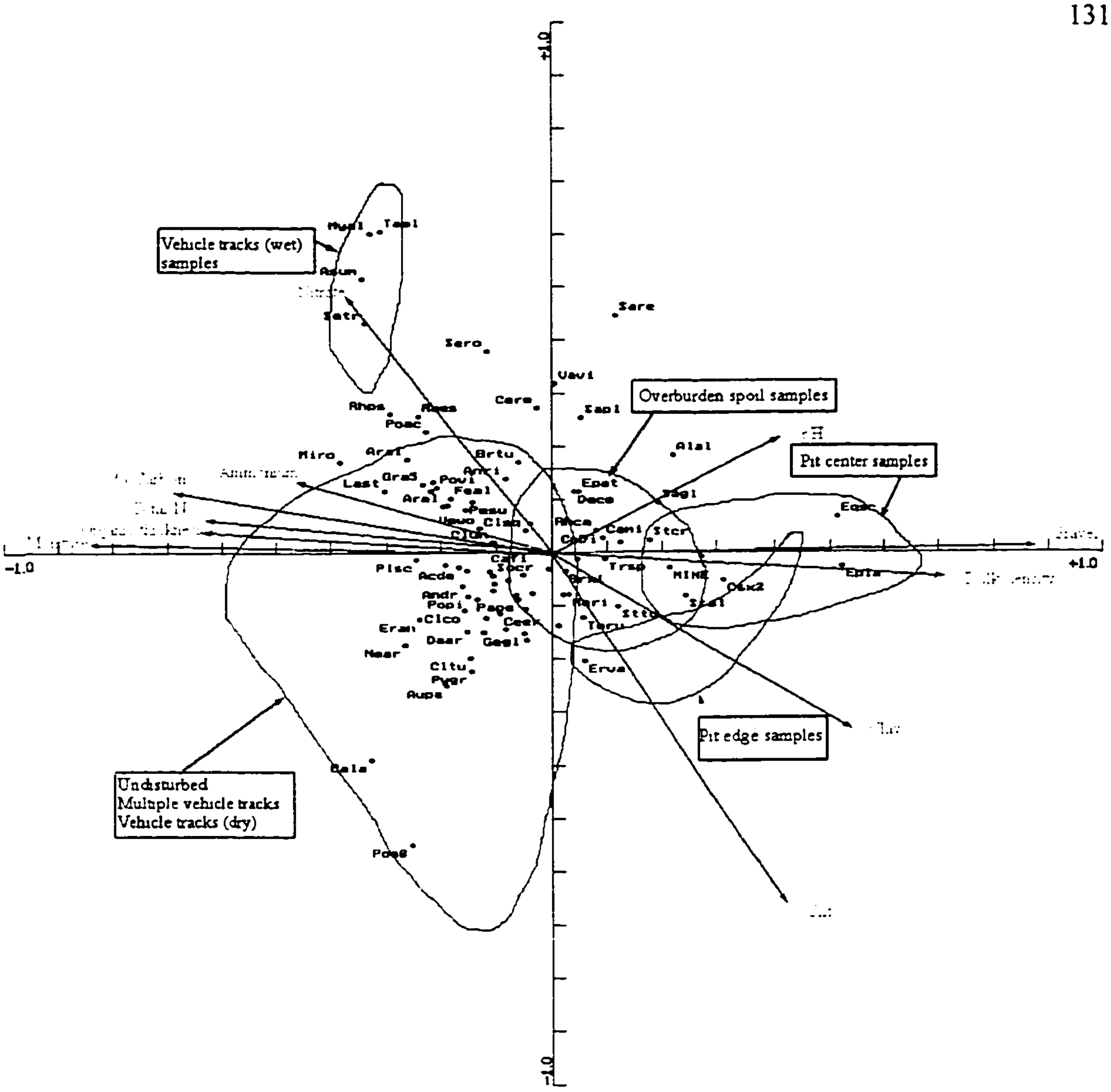

Figure 4.2. Triplot with species scores (points and abbreviated species name), sample scores (zones in which samples are scattered are outlined) and environmental variables (represented by arrows) for the soil data set.

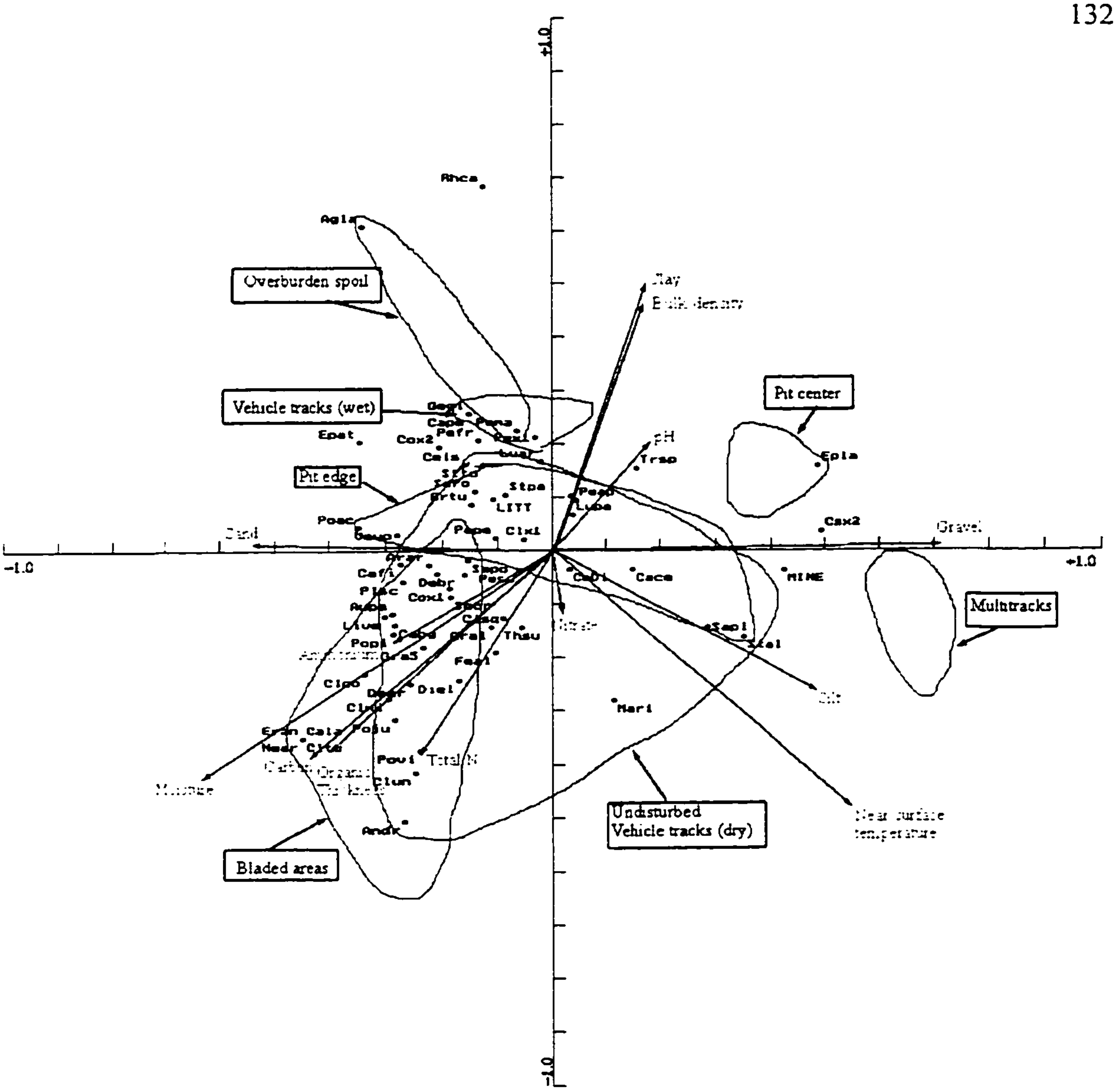

Figure 4.3. Triplot with species scores (points and abbreviated species name), sample scores (zones in which samples are scattered are outlined) and environmental variables (represented by arrows) for the near-surface temperature data set.

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Chapter 5: Conclusions

1) Natural and Anthropogenic Plant Associations

The Decumbent Shrub Tundra:

The Decumbent Shrub Tundra was previously-defined by Kershaw (1984, 1983). It is a common subarctic plant community similar to other documented types (Chernov and Matveyeva 1979; Bliss 1977). The total flora was small, consisting of plant species capable of existing within a naturally-disturbed environment. Species of bryophytes accounted for most of the species' richness and the dominant woody plant was *Salix polaris* which often occurred in pure stands. The natural perturbation regime was caused by cryoturbation in the form of non-sorted circles and stripes. Vegetation composition differed along the gradient from raised circle edges to low centers which was the cause of much of the observed inter-community variation.

Anthropogenic Disturbances from the Pipeline Construction:

Disturbances ranged from poorly vegetated borrow pits to 100% plant cover in vehicle tracks and overburden spoil. After more than 50yrs of natural revegetation borrow pits remained in early stages of revegetation whereas the other sampled disturbance types appeared to have developed functional plant associations equivalent to the natural undisturbed tundra. There were still compositional differences between the resulting anthropogenic plant associations of linear disturbances which were most noticeable by the presence of tall woody shrub species not common in the undisturbed tundra (e.g. *Salix planifolia*, *S. glauca*, *S. alexensis* and *S. pulchra*).

Indirect ordination was used successfully to classify disturbances based on plant association structure. Similar associations were obtained to those of Harper and Kershaw

(1996) in which the same method was used. Disturbance types described in the field could be classified in ordination diagrams and further disturbance type subdivisions were made such as (wet) and (dry) vehicle tracks.

Colonizing Species:

Species present in the undisturbed tundra were adapted to conditions of recurring natural perturbation and thus had characteristics of successful colonizers in anthropogenic disturbances. All species found in the disturbance samples were also found in the undisturbed samples however there were a few that colonized all disturbances but were considered rare in the undisturbed tundra. In the Decumbent Shrub Tundra these species were *Sibbaldia procumbens* and *Salix planifolia* and were important because they increased in abundance on all disturbance types from borrow pits to vehicle tracks. Another successful colonizer was *Salix polaris* which was common in the natural community. Similar results were found by Kershaw and Kershaw (1987) 15yrs prior to this study.

Succession:

Species' richness and the sample scores derived from the indirect ordinations were used to compare the gradient observed in the sampled anthropogenic disturbances to a successional model (intermediate disturbance hypothesis) (Connell 1978). Samples ranged along a successional gradient from severe (borrow pit samples) to intermediate (linear disturbances and undisturbed tundra). This analysis linked the primary and secondary succession processes described by Kershaw (1983) and Harper and Kershaw (1996) and revealed that the undisturbed tundra was at an intermediate level of perturbation due to edaphic disturbances resulting from cryoturbation.

2) Soil Development and Microclimate

Differences Among Disturbance Types:

A comprehensive microclimate record was obtained from before snowmelt to mid growing season. Microclimate (near-surface temperature) differences between all disturbance types existed for an early season snowmelt period and a representative portion of the growing season. In the early season microclimatic differences among disturbance types were accentuated. In general, disturbances were warmer than the undisturbed tundra with the exception of one overburden spoil sample with convex topography. This result was consistent with other disturbance temperature analyses in the Subarctic (Harper and Kershaw 1997; Forbes 1993; Ebersole and Webber 1983; Haag and Bliss 1973).

Variation among disturbances was also evident in the nitrogen status and the associated soil physical properties of moisture content and bulk density. Borrow pits displayed evidence of accumulating atmospheric N as indicated by elevated total N values. The lack of plant cover or soil development in these disturbances explains the low levels of mineral N in comparison to high total N levels. Vehicle tracks and undisturbed samples seemed to be functionally similar in nutrient status and no difference was observed in soil physical properties.

As with the results of the vegetation analysis a high degree of internal variation was observed in the undisturbed samples. The two microclimate samples were significantly different in all treatments of near-surface temperature values (mean seasonal temperatures, mean diurnal fluctuations, and degree day totals). The vegetation sampling method could not explain the difference between these two samples.

3) Direct Ordination: Synthesis of Vegetation Distribution and Environmental Variables:

Employing direct ordination procedures (Chapter 4) it was determined that the set of measured environmental variables accounted for the majority of the measured species' distributions, particularly with the addition of the near-surface temperature values. The combination of direct and indirect ordination helped define which environmental variables were associated. Groupings were in general, soil texture variables, N content variables and soil temperature. These groups were consistent with correlations derived in Chapter 3 and as a product of CCA.

In all direct ordinations the soil texture variables and in particular gravel content, were the most important variables in defining species' distribution. The widest range in species' distribution was between the borrow pits and the linear disturbances where the most obvious difference was a lack of topsoil material in the borrow pits. For successful revegetation of these disturbances the most important process was the replacement of finer textured topsoil material as was present in all other disturbance types.

Research Implications:

Reclamation is a relatively new field of study and the boundaries and definitions are still being defined as research moves forward. The reason for this is partially due to the high degree of site specificity in reclamation projects. Reclamation is usually carried out a short time after construction site abandonment and once regulations are met, sites are rarely revisited. If more is learned about the natural revegetation leading to the development of functional plant communities then initial site alterations can be done to maximize the effectiveness of natural processes over the long term.

This study can be used to test how succession processes vary among different plant community types. The previous study by Harper (1994) in the neighboring plant community (Erect Deciduous Shrub Tundra) has been expanded to the Decumbent Shrub Tundra in this research and can provide information for reclamation projects in these common subarctic tundra community types.

Future Research Suggestions:

Throughout this study a high degree of inter-community variation was always present. The block sample design was used to avoid error due to pseudoreplication while allowing a degree of subjectivity in sample site selection and for comparison with the study by Harper (1994). In the Decumbent Shrub Tundra the inter-community variation was largely due to patterned ground features which are regular recurring features. In order to more effectively describe this variation the sample design could be set up along transects in the undisturbed tundra.

The block sample design was modified in this study by allowing the dimensions of the block to change to fit the shape of the disturbance being sampled. This was done to avoid sampling areas of undisturbed tundra as though they were part of the disturbance and consequently biasing the plant abundance measurements. Even though blocks only covered the width of a given vehicle track, random quadrats could fall in the track centers which may have been less disturbed than the actual track ruts. It would be advisable to use a method where track ruts and track centers could be distinguished in the final analysis and this may be as simple as distinguishing between quadrats at the time of field measurements.

In this thesis the nutrient sampling was limited to nitrogen analysis of surface layers. Such a preliminary survey was necessary to determine how various nitrogen components of the soil are related and if there is significant variation among the disturbance types and within the undisturbed Decumbent Shrub Tundra. Future research would include more detailed analysis of effects of depth on nutrient content and an examination of soil biota.

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Appendix 1. Full species' list and four letter abbreviations used in ordinations.

MINE	Mineral
LITT	Litter
	Bryophytes
Aupa	*Aulacomnium palustre* (Hedw.)
Brri	*Brachythecium rivulare* B.S.G.
Brtu	*Brachythecium turgidum*
Brx1	*Brachythecium sp.*
CoDi	*Conostomum tetragonum* (Hedw.) Lindb.
Diel	*Dicranum elongatum*
Drun	*Drepanocladus uncinatus* (Hedw.) Warnst.
Live	Hepatics
Plsc	*Pleurozium schreberi* (Brid.) Mitt.
Poju	*Polytrichum juniperinum* Hedw.
Popi	*Polytrichum piliferum* Hedw.
Rhca	*Racomitrium canescens* (Hedw.) Brid.
Rhps	*Rhizomnium pseudopunctatum*
Toru	*Tortula norvegica* (Web.) Lindb.
	Lichens
Ceer	*Cetraria ericetorum* Opiz.
Cehe	*Cetraria hepatizon* (Ach.) Vain.
Ceis	*Cetraria islandica* (L.) Ach.
Clbe	*Cladonia bellidiflora* (Ach.) Schaer.
Clbo	*Cladonia borealis*
Clco	*Cladonia cornuta* (L.) Hoffm.
Clcu	*Cladonia cucullata*
Clmi	*Cladina mitis* (Sandst.) Hustich
Clsq	*Cladonia squamosa* (Scop.) Hoffm.
Clst	*Cladina stellaris* (Opiz) Brodo
Clun	*Cladonia uncialis* (L.) Wigg.
Clx1	Cladina sp.
Csx1	Crustose lichen species
Daar	*Dactylina arctica* (Hook.) Nyl.
Icer	*Icmadophila ericitorum* (L.) Zahlbr.
Mari	*Masonhalea richardsonii*
Near	*Nephroma arcticum* (L.) Torss.
Pape	*Pannaria pezizoides* (G. Web.) Trev.
Peap	*Peltigera aphthosa* (L.) Willd.
Pema	*Peltigera malacea* (Ach.) Funck

Socr	*Solorina crocea* (L.) Ach.
Stal	*Stereocaulon alpinum* Funck
Stpa	*Stereocaulon paschale* (L.) Hoffm.
Stto	*Stereocaulon tomentosum* Fr.
Thsu	*Thamnolia subuliformis* (Ehrh.) W.Culb
	Graminoids
Agla	*Agrostis latifolia*
Alal	*Alopecurus alpinus* J.E. Smith
Caaq	*Carex atrofusca* Schk.
Cabg	*Carex aquatilis* Wahlenb. var. *stans* (Drej.)Boot
Cafi	*Carex filifolia* Nutt.
Cala	*Carex lachenalii* Schk.
Came	*Carex membranacea* Hook.
Cami	*Carex microchaeta* Holm.
Cape	*Carex petricosa* Dew.
Capo	*Carex podocarpa* R. Br.
Dece	*Deshampsia caespitosa* (L.) Beauv.
Eran	*Eriophorum angustifolium* Honck.
Erva	*Eriophorum vaginatum* L.
Feal	*Festuca altaica* Trin.
Debr	*Deshampsia brevifolia* R. Br.
Jubi	*Juncus biglumis* L.
Juca	*Juncus casteneus* Smith
Luar	*Luzula arcuata* (Wahlenb.) Sw.
Lupa	*Luzula parviflora* (Ehrh.) Desv.
Poa8	*Poa* sp
Trsp	*Trisetum spicatum* (L.) Richt.
	Forbs
Acde	*Aconitum delphinifolium* DC
Andr	*Anemone Drummondii* Wats.
Anmo	*Antennaria monocephala* DC
Anna	*Anemone narcissiflora* L.
Anri	*Anemone Richardsonii* Hook.
Aral	*Arnica alpinum* (L.) Olin ssp. *tomentosa* (J.M. Macoun) Maguire
Arar	*Artemisia arctica* Less.spp. *arctica*
Arle	*Arnica Lessingii* Greene
Asum	*Astragalus umbellatus* Bunge
Cear	*Cerastium arvense*
Cere	*Cerastium regelii*
Cltu	*Claytonia tuberosa* Pall.
Dral	*Draba albertina* Greene

Drin	*Dryas integrifolia* M. Vahl
Epan	*Epilobium anagallidifolium* Lam.
Epat	*Epilobium angustifolium* L.
Epla	*Epilobium latifolium* L.
Erer	*Erigeron eriocephalus* J. Vahl
Gear	*Gentiana arctophila* Griseb.
Gegl	*Gentiana glauca* Pall.
Last	*Lagostis Stelleri* (Cham. and Schlecht.) Rupr.
Llse	*Lloydia serotina* (L.) Rchb.
Miro	*Minuartia Rossii* (R.Br.) House
Myal	*Myosostis alpestris* Schm. spp. *asiatica* Vestergr.
Pefr	*Petasites frigidus* (L.) Fries
Pesu	*Pedicularis sudetica* Willd.
Poac	*Polemonium acutiflorum* Willd.
Povi	*Polygonum viviparum* L.
Prvu	*Prunela vulgaris*
Pygr	*Pyrola grandiflora* Radius
Raes	*Ranunculus Eschscholtzii* Schlecht
Ruar	*Rumex arcticus* Trautv.
Sace	*Saxifraga cernua* L.
Satr	*Saxifraga tricuspidata* Rottb.
Selu	*Senecio lugens* Richards
Sero	*Rhodiola rosea ssp. integrifolia*
Setr	*Senecio triangularis* Hook
Sipr	*Sibbaldia procumbens* L.
Somu	*Solidago multiradiata* Ait.
Stcr	*Stellaria crassipes* Hult.
Taal	*Taraxacum alaskanum* Rydb.
Vewo	*Veronica Wormskjodii* Roem. and Schult.
	Dwarf shrubs
Arru	*Arctostaphylos rubra* Rehd. and Wils.
Cate	*Cassiope tetragona* (L.) D.Don ssp. *tetragona*
Epni	*Empetrum nigrum* L. ssp. *hermaphroditum* (Lge.) Böcher
Kapo	*Kalmia polifolia* Wang
Vaul	*Vaccinium uliginosum* L. s. lat.
Vavi	*Vaccinium Vitis-ideae* L. var. *minus* Lodd.
	Tall shrubs
Begl	*Betula glandulosa* Michx.
Saal	*Salix alaxensis* (Anderss.) Cov.
Sagl	*Salix glauca* L. s. lat.
Sapl	*Salix planifolia* Pursh

Sapo	*Salix polaris* Wahlenb. ssp. *pseudopolaris* (Flod.) Hult.
Sapu	*Salix pulchra* Cham.
Sare	*Salix reticulata* L.
	Fern Allies
Eqar	*Equisetum arvense* L.
Eqsc	*Equisetum scirpoides* Michx.
Lyse	*Lycopodium Selago* L.
Lyal	*Lycopodium alpinum* L.

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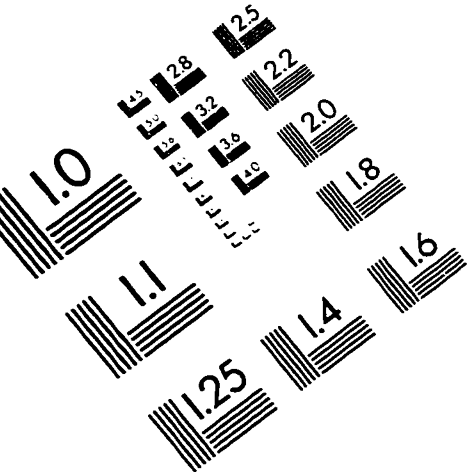

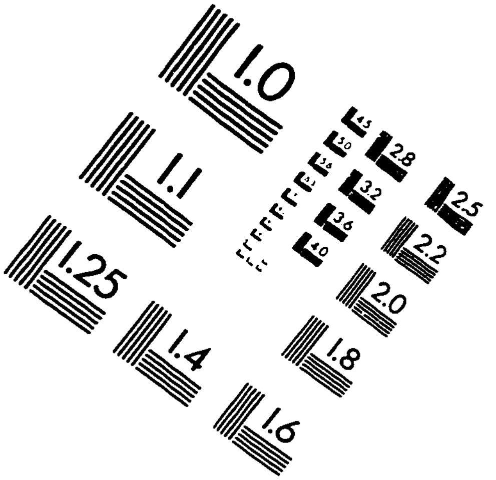

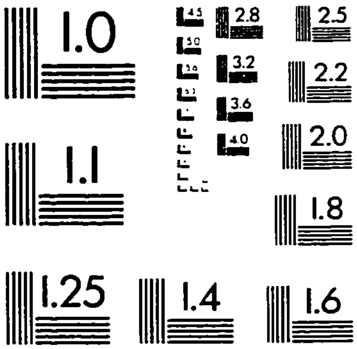

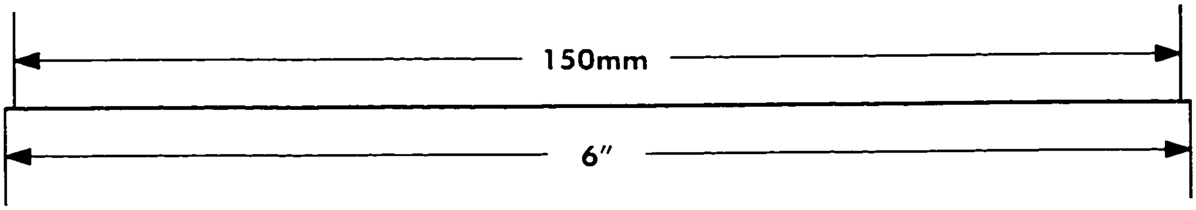

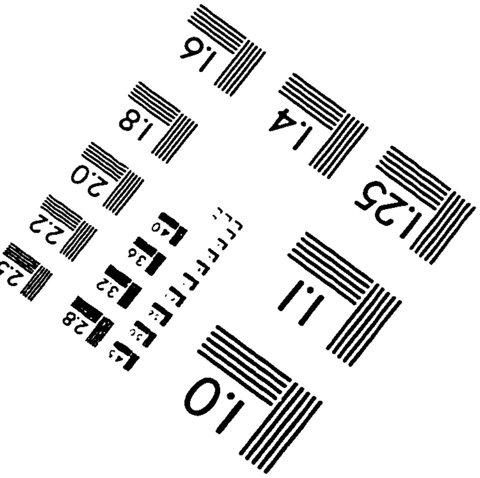

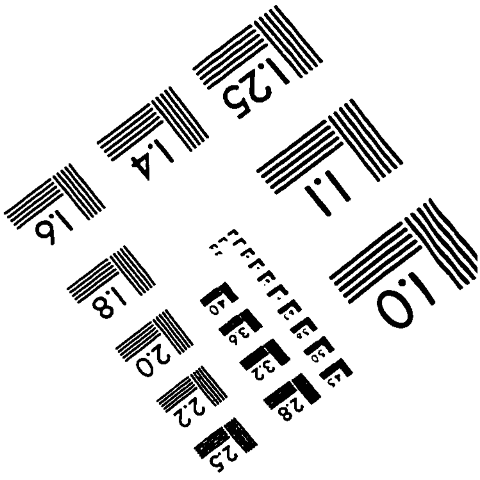

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