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THIRTY YEARS OF RECOVERY FROM VEHICLE DISTURBANCE
IN ALASKAN ARCTIC TUNDRA.

presented by

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has been accepted towards fulfillment
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THIRTY YEARS OF RECOVERY FROM VEHICLE DISTURBANCE IN ALASKAN ARCTIC TUNDRA.

By

Steven P. Rewa

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ABSTRACT

THIRTY YEARS OF RECOVERY FROM VEHICLE DISTURBANCE IN ALASKAN ARCTIC TUNDRA.

By

Steven P. Rewa

Recently, off-road travel over tundra has increased markedly around Barrow, Alaska. Different types of vegetation respond differently to vehicle traffic and the effects on vegetation may remain for many years with site moisture appearing to be a major determinant of resilience. This study, examining the recovery of 30-year-old vehicle disturbances, supports the hypothesis that wet sites recover more rapidly than dry sites. Evidence is presented that suggests that sites of intermediate moisture are slowest to recover as a result of only moderate resistance to disturbance and moderate resilience.

Lingering physical effects of vehicle disturbance may be manifested as differences in microtopography, soil moisture and depth of thawed soil. A comparison of the vegetation in impacted and non-impacted terrain using principal components analysis showed that impacted areas had less variation in the recovered plant cover than the controls. This suggests, on the assumption that recovery towards an advanced functional state leads to a divergence in cover type, that impacted areas are still at early stages of succession. Sites of moderate moisture show the most difference between control and impact. This is further supported by the absence of species from impacted areas that are present in the controls, which is most obvious in areas of moderate site moisture. Species richness data also demonstrates spread of the disturbance beyond the initial impact.

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CHAPTER 1

1 Introduction

1.1 Aims and Objectives

Off-road vehicle (ORV) use has been widespread throughout the history of exploration and expansion over the North Slope of Alaska. When the tundra is subjected to ORV use it is easily and immediately marred and is often slow to recover, yet today several former vehicle trails are difficult to trace. This study takes advantage of an opportunity to examine the recovery of former tundra trails and to re-sample some previous experiments that examined the effects of vehicle disturbances.

Noble (1996) details a set of 4 necessary resources for quality management of landscapes. They are;

- Information on current land use practices,
- Information on alternative land use practices,
- Ability to predict consequences of particular practices, and
- A methodology for implementing appropriate land uses.

This study concentrates on the first and third resources above. The aim of this study is to document the extent to which an Alaskan Arctic tundra system is able to recover from vehicle disturbance after extended periods of time. This requires collection of data pertaining to the current land use practices in the Arctic. For the purposes of this study, the alternative land use practice would be non-use, or preservation. Data on lingering impacts from past disturbances that were left to natural recovery, would aid in the ability to predict outcomes of both continued use and non-use. If residual effects of ORV traffic are present even after a few decades, then it is likely that disturbance effects are longer lasting than previously expected. If this is the case, further consideration needs to go into the extent to which ORVs are used.

Information on land use goes hand-in-hand with information on land cover. Variations in use within a cover type will likely have varying impacts. Likewise, similar uses in different land cover types will also have varying impacts. Therefore, another important consideration of this study is the relative impact endured by different vegetation types, concentrating on the part played by moisture level of the areas in question.

This study addresses the lingering effects of off-road vehicles after approximately 30 years of recovery, and how the moisture regime of a site affects its recovery rate. Specifically, the lingering effects caused by tracked vehicles called Weasels and Low-Pressure Tire vehicles called Rolligons will be examined (refer to section 1.2.1).

1.2 Background

Off-road vehicle (ORV) traffic has been extensive and necessary in Arctic regions. With a lack of widespread roadway networks, transportation has been relatively costly and inefficient, particularly in summer (Rickard and Brown 1974; Brown 1976; Walker *et al.* 1977). It is estimated that by 1977 the most widespread cause of surface disturbance was use of tracked vehicles (Van Cleve 1977; Milchunas, *et al.* 2000). The same is true today. Transport of heavy equipment is limited to barge traffic and air freight both of which are extremely reliant on good weather conditions. Traditional methods of ground transport, such as the automobile, are simply not possible during large portions of the year since many rural locations in the Arctic have no roadway system. Automobiles are used within villages that have local road systems, but, in general, these villages are isolated from each other (Brown 1976).

In winter, it is often possible to travel by automobile over ice roads composed of densely packed snow and ice. The ice of the roads can be augmented by the addition of water sprayed by tanker trucks. Ice roads produce little or no disturbance on tundra (Van Cleve 1977), but in certain cases they have caused crushing or shearing of the shrub vegetation under the snow (Haag 1973; Rickard & Brown 1974). These ice roads are not without their difficulties. They are often hazardous as traction is limited and a slip off the road leaves very little chance to retrieve the vehicle making it a permanent fixture on the landscape. Like air and barge traffic, ice roads can only be used under appropriate weather conditions since the stability of the road depends greatly on the temperature and the consistency of the snow pack (Adam & Hernandez 1977). For these reasons, ice roads cannot replace more damaging forms of off-road vehicle traffic.

Off-road vehicles are used to a great extent in the daily lives of both the native Inupiat people as well as non-native settlers. The single-person, four-wheeled, all terrain vehicle has become a widely used tool in a subsistence lifestyle for traffic across tundra in search of game. In winter, the snowmobile is widely used as a replacement for the traditional dog sled for hunting expeditions, and for daily travel between villages (Rickard & Brown 1974). These practices are widely adopted in the local communities.

In addition to the transportation needs of the local inhabitants, industry relies on transport of heavy equipment and personnel for increasing development. Because of the lack of expansive roadways, the construction related to development of the land for purposes of oil drilling and urban expansion necessitates off-road traffic. Gravel foundations for drilling pads and roadway expansion require heavy machinery to travel across areas of tundra and these cause a great deal of disturbance to tundra systems. As oil fields become abandoned it has been mandated that these gravel pads be removed to allow the tundra to recover. These removals may require the continued use of ORVs. An alternative method of gravel removal utilizes the roads that are to be removed. Gravel could be removed from the extreme ends of the roads and hauled back toward the road source while using the roads for traffic rather than driving off onto the tundra.

During the early development of the Prudhoe Bay oil field, trains of sleds, called tractor trains were hauled over the tundra by bulldozers (Klein 1970). These occasionally operated in the snow free season, but were mostly a winter phenomenon. They have left an indelible mark on the tundra.

Regulations related to ORV use have changed over the course of the years. Initially, there were few regulations and one common practice was to remove the thawed soil layer by blading to provide a smooth, solid track (Rickard & Brown 1974). It was by this method that the previously mentioned tractor trains were able to travel during the summer months. Regulations are an issue in other Arctic regions as well. In Siberia, ORV use has been outlawed since 1989, but the laws are often broken (Khitun 1997).

1.3 Natural vs. Anthropogenic Disturbance In Tundra Systems

When considering disturbance it is often important to distinguish natural effects from anthropogenic effects. Many consider natural effects to be part of a disturbance regime that the ecosystem has adapted to recover from. Changes from the natural disturbance regimes can have a dramatic effect on plant diversity or other properties of a landscape (Pearson 1994). As a result, many consider anthropogenic effects to be more serious, since they are not a natural occurrence and the recovery mechanisms may not be present in the ecosystem. On the other hand, many see no difference at all between the two types.

Many of the human-induced disturbances to Alaskan Arctic tundra are related to vehicle traffic, both on and off roadways. Roadway construction brings with it a host of disturbances. A great deal of tundra has been destroyed in order to lay the gravel for the roads themselves. The Trans-Alaska Pipeline and associated road systems required the disturbance of approximately 12,000 ha of land. Other problems with roads include oil and diesel fuel spills related to vehicle traffic. In these cases, trampling and other problems of clean up operations adversely affect the tundra as well (Bliss 1983). One of the main secondary problems associated with roads is the accumulation of dust on adjacent tundra. Accumulation of dust leads to changes in pH and nutrient levels of the soil. A great deal of the dominant bryophyte species that occur in more acidic tundra, such as *Sphagnum sp.*, are strongly affected by the increased pH levels resulting from deposition of calcareous road dust (Walker & Everett 1987; Leadley *et al.* 1996). Dust can also accumulate in the stomata of plants blocking gas exchange and seriously inhibiting production (Auerbach *et al.* 1997).

Another significant effect of dust accumulation is the drastic change of the thermal regime. The Dalton Highway is considered to be one of the most energy related disturbances on the Alaskan North Slope (Leadley *et al.* 1996). Dust accumulation on the surface of the snow pack causes a reduction in surface albedo, which results in a warming of the snow pack and an earlier spring melt. Since the snow pack acts as an insulating layer, the soil and vegetation mat are exposed to the cold early on in the season. The dust also acts as an insulating layer in the summer time. On top of the dust effects, there can be increased insulation due to a significant snow drifting effect related to the presence of the road. These forces together cause drastic changes in active layer depth (Auerbach *et al.* 1997).

One issue dealing with human-induced disturbance is the idea of cumulative impacts. Cumulative impacts result from a combination of direct disturbance effects. As roadways increase, the areas immediately adjacent to them are affected by the disturbance in ways that are relatively predictable. However, as these areas become more common other effects become apparent. Roadways may impede drainage leading to drying or flooding of communities. As the unaffected patches become smaller and farther apart, the effects on wildlife become more apparent. Edge-sensitive species become scarce and migration corridors become more important. It has also been shown that many animals are frightened off by increased traffic causing abandonment of their territory (Bliss 1983).

1.4 U.S. Army Corps of Engineers – Cold Regions Research and Engineering Laboratory

Following World War II, there was an increased interest in military activity in the northern regions. Much like commercial industry, the military had serious concern for the transport of equipment, supplies and people. It was thought that future conflicts could arise over northern territories. The U.S. Army Corps of Engineers – Cold Regions Research and Engineering Laboratory (CRREL) was set up to examine the plausibility of travel in Arctic and other cold regions. Of particular interest in the 1970s was the development of air-cushion vehicles (ACV) for transport in arctic regions.

It was thought that ACVs would be ideal for Arctic travel considering the level nature of the landscape and the ability of ACVs to travel from land to water with little difficulty (Abele & Brown 1977). Researchers at CRREL were also concerned with the amount of damage that would be sustained by the tundra as a result of traffic by ACVs. For this purpose, a U.S. Coast Guard SK-5 ACV was driven multiple times over the tundra near Barrow, Alaska in 1971 to document impact (Figure 1).

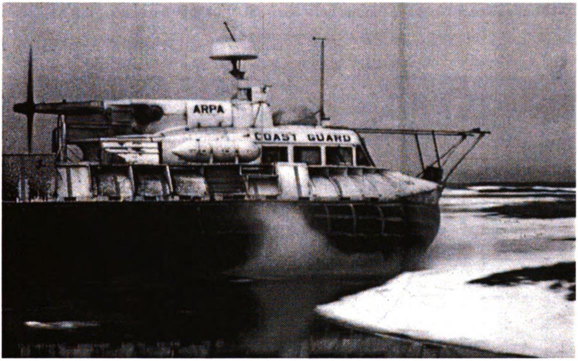

Figure 1: Coast Guard SK-5 Air Cushion Vehicle used by CRREL. Photograph by Atwood ca. 1971

The traditional method of off-road travel at the time used tracked vehicles. Therefore, an M-29 Weasel was run concurrently with the SK-5 ACV for comparison of the two vehicle types (Figure 2). At this same time, the Rolligon, a low-pressure tire vehicle, began to see more widespread use for off-road traffic. In 1974, a Rolligon was tested alongside the test tracks previously made by the SK-5 and the Weasel (Figure 3). These Rolligons were further tested in 1976 near Lonely, Alaska (Abele *et al.* 1977; Abele *et al.* 1978) and at the Prudhoe Bay oil field (Walker *et al.* 1977). These sites were revisited during this study, 30 years later, to assess residual impact on the landscape. According to studies by Abele and Brown (1977), the SK-5 hovercraft performed well over tundra surfaces, however, it did not see widespread use following these tests. The lack of mass production for hovercraft and its relatively high operational cost ($0.31 metric $ton^{-1}km^{-1}$ compared with $0.19 for fixed wing aircraft and $0.02 for ships in 1974)

Figure 2: Naval Arctic Research Laboratory M-29 Weasel. Photography by J. Brown, ca. 1965

Figure 3: A Rolligon, a low pressure tire vehicle. Photograph by Atwood, ca. 1974.

contributed to a decline in its use. Though no specific information on the operating costs of the M-29 Weasel or the Rolligon were available, Rolligons were estimated to have an even higher operational cost than the SK-5, but were cheaper and easier to construct. In 1977, Rolligons were used almost exclusively as the means of off-road travel for the Prudhoe Bay oil field (Walker *et al.* 1977).

1.5 Definitions Of Disturbance, Recovery, Resistance, And Resilience

The definitions of disturbance, recovery, resistance, and resilience are a matter of some debate in the scientific community. Scientists in various fields define disturbance based on relevance to their particular discipline. A disturbance is often defined by whether it is natural or anthropogenic. Many view disturbance as a phase along a successional pathway rather than an "unnatural occurrence." Some would view hurricane damage as a large-scale disturbance while others view it as a natural part of the ecosystem that does not really affect the long-term equilibrium of a system (Paine *et al.* 1998).

In this study, I define disturbance as a change in vegetation or underlying substrate caused by an external factor (Walker 1996). This definition encompasses all forms of disturbance, whether natural or anthropogenic. I define recovery as a return to the original ecosystem condition and function (Racine & Ahlstrand 1991). Areas that are not immediately impacted, but are located near an impact may still feel the effects of the disturbance and can therefore also be considered disturbed. In this study, I use the term "impact" to refer to the areas directly crossed by the vehicle. The terms "non-impacted" and "control" are used interchangeably and refer to any areas that were not directly driven over. I define resistance as the ability of an ecosystem to withstand disturbance and remain stable (Wardle *et al.* 2000). Resilience is defined as the rate at which an ecosystem is able to rebound and recover from a disturbance (Seybold *et al.* 1999). Resilience is the main issue in this study. Two major questions are addressed. Are Alaskan Arctic tundra systems resilient enough to recover fully from vehicle disturbance within 30 years? How does resilience differ between areas of differing site moisture?

1.6 Ecological Scale And Disturbance

Scale is an important factor in assessing the overall impact of a disturbance and the recovery rate associated with that disturbance (Pearson 1994). Three scales must be considered when evaluating a disturbance. Spatial scales are perhaps the easiest to consider because of their physical nature. Also of importance are temporal scales, which are of particular importance when considering the resilience or recovery rate of a system. Finally, it is important to consider the organizational scale at which the extent of disturbance and recovery is determined. For example, does a disturbance affect individuals or populations, or will it affect whole ecosystems?

1.6.1 Spatial Scale

The dependence of plant biodiversity upon spatial scales is well documented. One fairly prominent example is that of species area curves. Plot size can have a large effect on the ability to detect associations between species (Kilburn 1966; Crawley & Harral 2001). The same is true in tundra systems as they pertain to disturbance recovery (Forbes & Sumina 1999). When colonization becomes necessary, the speed at which an area recovers is determined, in large part, by its distance to surviving patches of similar vegetation (Romme *et al.* 1998). This is particularly true in areas with a poor viable seed bank where dispersal and vegetative growth are necessary.

The spatial scale of the disturbance is important in determining the severity of the impact on the ecosystem. Kevan *et al.* (1995) found strong evidence of lingering impact of off-road vehicle traffic in high Arctic sites, but state that the impact was localized around the vehicle tracks. In their case, the initial impact was limited to tractor treads of approximately 42cm width. The current study deals with similar types of impacts.

1.6.2 Temporal Scale

When considering the extent of disturbance, it is important to consider the temporal scale, as well as the spatial. A 30-year-long disturbance seems long lasting in terms of a human lifetime, but it would be very short lived when one considers it on a geological time scale. A disturbance that occurs at a single point in time would be very important to an annual plant that depends upon a single season to propagate. To a large clonal organism that reproduces vegetatively over many years, a single disturbance may be only a minor setback.

The temporal scale dictates the severity of a disturbance by placing importance on the longevity of the disturbance effects. A widespread disturbance whose effects are only present for a year may not be considered as important or as serious as a disturbance with a smaller spatial scale with residual effects after 20 years (Milchunas *et al.* 2000). This idea suggests a trade off between spatial extent and longevity of disturbance that can be difficult to choose between. The choice can only be made after careful analysis of the values of the public. One would like to preserve as much undisturbed area as possible and would, therefore, lean toward a smaller spatial extent. Theoretically, as small long-term disturbances become more frequent, they become cumulative and initially undisturbed areas become affected. It then becomes difficult to maintain undisturbed areas in which case a widespread, but short-lived, disturbance may be favored. It is, therefore, important to know how long a disturbance can be expected to last in order to accurately assess the impacts likely to result from any management options. Studies such as this thesis are useful for determining recovery rates.

1.6.3 Organizational Scale

The level of ecological organization at which a disturbance affects an area is important for considering the overall impact of a disturbance. For instance, the clipping of a leaf is a serious disturbance at the plant level or possibly even the population level.

However, at the level of the community and on up to the biosphere level, the clipping of a leaf is not likely to have high importance. A serious, population-wide disturbance, on the other hand, can effect interactions at the community level. As these community-level disturbances become large and frequent enough, it can be a serious impact over the whole biome.

Kevan *et al.* (1995) demonstrate that there is a significant, but highly localized, effect on soil invertebrates due to off-road vehicle traffic after 20 years. Although localized, the changes may become cumulative as the impacts become more frequent. Eventually these differences may affect the nutrients of the soil and forage for animals at higher levels of the food chain. This is a case of a localized impact causing changes to ecosystem processes.

1.7 Tundra Ecology

The ecology of the tundra is such that its behavior in response to impact is unique. The annual average temperature in the Arctic is less than zero degrees Celsius (Brown *et al.* 1980). As a result of the low temperatures, a layer of permafrost that never thaws lies below the surface. During the summer, the thawed layer of soil at the surface is the only portion available to plants for root growth and nutrient uptake. This thawed zone is referred to as the "active layer."

The layer of permafrost that underlies the tundra is impermeable to water, causing poor drainage. Because the average temperature is near freezing for much of the year, the soil, which is generally high in moisture, often succumbs to disturbance caused by the expansion and contraction of the water contained within the soil as it repeatedly freezes and thaws. This phenomenon is referred to as the "freeze-thaw cycle." As the water contained within the soil freezes its volume increases, and the soil is forced up and outward. This process is known as "frost heave." If the effect is localized within an area of about 1.0 m^2, it results in a structure called a "frost boil," which resembles a patch of bare, cracked soil. On a larger scale, or in cases where this occurs on a steep slope, the cracked soil resulting from thermal contraction collapses and breaks off in large clumps. This process, referred to as "thermokarst," often causes large-scale disturbances and leaves large patches of exposed soil whose thermal regime is drastically altered and it disrupts the previously existing plant communities.

Unlike permafrost, which is frozen soil, ice also exists in pure form as long veins that crisscross under the soil surface. These ice veins are generally triangular in cross section and are referred to as "ice wedges". As these ice wedges expand, they create trenches and troughs in the tundra surface. These troughs increase in size as water runs into them accentuating the freeze-thaw cycle that forms them. Because these ice wedges are plentiful and extend for long distances, the tundra often takes on a reticulate appearance and is considered to be "polygonized tundra" or "patterned ground"(see Figure 4).

Most of the natural disturbances mentioned above, such as thermokarst and patterned ground development, result from the thermal properties of the soil. Off-road vehicle traffic can affect these thermal properties and can compound the effects of the freeze thaw cycles, possibly causing these natural disturbances to become more frequent and more severe.

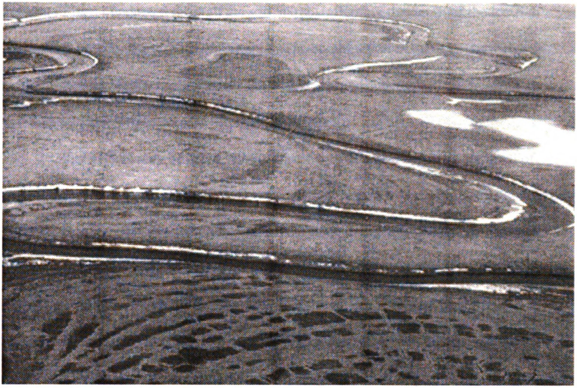

Figure 4: Typical polygon tundra with meandering streams.

1.8 Recovery of Tundra Following Off-road Vehicle Use

Tundra systems can be easily impacted by off-road traffic (Gersper & Challinor 1975). The traffic signature (the visible impact of the traffic) is generally the most obvious effect. Signature effects range from being purely esthetic, to a physical disruption of the ground surface, such as the removal of the vegetation. Along the gradient between these two extremes lie effects such as change in surface albedo, heat content of the soil, and ice content of the soil (Kevan *et al.* 1995). Because the soils of tundra systems generally have high moisture contents they are easily compressed by the weight of many ORVs during the summer months. These ORVs generally leave distinct ruts (Brown 1976). Pressure by ORV traffic can also affect the thermal regime of the soil caused by changing the surface albedo or by compacting the soil which can change the amount of heat conducted through the soil thereby affecting the depth of the ice-rich permafrost layer that underlies tundra soils. The combination of these two effects can lead to a trenching effect as the tracks fill with water and succumb to the freeze thaw cycle (Abele and Brown 1977).

Other effects may be more subtle. Traffic by ORVs can lead to a removal of standing dead vegetation or compression of dead vegetation into the soil causing a "green belt" effect where the affected area looks greener due to the removal of brown, dead vegetation (Rickard & Brown 1974). Additionally, the compression of dead matter into the soil system can accelerate decomposition and lead to an increase in nutrient availability and a true increase in greenness. These forces can affect plant succession in a number of ways. With the removal of the dead vegetation, space previously occupied by leaf litter may become available for plants to spread out. Increased sun exposure may lead to an increase in the vigor of shade intolerant species. Because the standing dead vegetation acts as an insulating layer, its removal would cause soil temperatures to be more extreme, possibly causing frost heave, allowing disturbance adapted species to colonize in the newly exposed soil.

Anthropogenic and natural disturbances are often similar in the ways in which recovery takes place. Species that occur the most in sites recovering from human-induced activities are those that would inhabit naturally disturbed areas such as riverbanks (Auerbach *et al.* 1997). Generally, pioneer species take over once the natural dominant species have been removed due to disturbance.

Historically, one of the largest and most important sources of anthropogenic surface disturbance has been the use of off-road vehicles (ORV) for oil exploration and development in the Arctic (Abele *et al.* 1977). For example, vehicle trails associated with Petroleum Reserve No. 4 have remained detectable 20 to 30 years after disturbance and roadways constructed in wet terrain can often require decades to revegetate (Van Cleve 1977). Disturbances like these can, therefore, be considered long lasting and potentially serious.

A fairly obvious result of vehicle disturbance on tundra is the depression of the ground surface resulting in increased bulk density, lower soil moisture, and lower soil aeration (Van Cleve 1977). It has been shown that a reduction in microtopography in tundra, which often results from vehicle disturbance, causes a reduction in species richness (Forbes 1992; Auerbach *et al.* 1997). Increased active layer thickness has been shown to cause an increase in plant productivity (Van Cleve 1977), possibly changing the plant community. It is also believed that these effects on the soil may be accentuated over time before they become ameliorated (Gersper & Challinor 1975).

The available seed bank is also affected by the alteration of the topography and microtopography of a site. Because much of the seed rain is wind bourn, depressions often collect seeds while hills may act as barriers. Higher densities of seeds and seedlings are often found in depressions (Grulke & Bliss 1983). Vehicular disturbances that change the topography of the sites would also change the distribution of seedlings impacting succession and other community level plant interactions.

1.8.1 Problems of Assessing Recovery From Vehicle Disturbance on Tundra Systems

There are several problems with assessing vehicle disturbance and recovery of tundra systems. The extent to which an area has been disturbed can be difficult to discern since the effects of a disturbance are not always visually obvious. Impacts on the thermal regime and moisture content may go unnoticed before causing serious problems. The effects of disturbances in tundra systems also tend to spread beyond the original boundaries of the disturbance due to heat conductance and changes in water content or water holding capacity, affecting areas adjacent to the initial impact.

The idea of disturbance is somewhat confused because landscapes and vegetation types are continuously changing and disturbance can often be looked at as a phase along the natural gradient rather than a unique event that is detrimental to the system. The idea of recovery is similarly confused. Defining recovery based on the condition of the landscape can be problematic based on the degree to which succession has occurred in neighboring regions. If recovery occurs over long periods of time, return to the original state of the landscape would leave the community lagging successionally. The community may require a great deal of time to catch up again from the lag and residual effects of the disturbance would be present, even if they are not very noticeable. In regions of high spatial heterogeneity, comparing an area to a neighboring region in order to assess recovery can be difficult. In effect, we may attempt to judge recovery based on a community that would naturally be different due to differing successional pathways of its particular region.

1.8.2 Differential Response of Communities to Disturbance

Both the resistance and resilience of the tundra surface depend on several factors. The climate and environment of the region, the topography and microtopography of the landscape and the season of the year all play strong roles in the extent of disturbance. Soil conditions such as bulk density, permafrost, and moisture content have a strong effect on resistance and resilience (Slaughter *et al.* 1990; Pearson 1994; Khitun 1997).

Soil moisture can be one of the most important factors determining the productivity of an Arctic system (Leadley *et al.* 1996). The various amounts of saturation in the soils lead to different communities ranging from dry heaths dominated by ericaceous shrubs to aquatic communities dominated by sedges, grasses or forbs. The various growth forms dominating is these diverse moisture regimes will have quite different responses to impact and, as such, will have different successional trajectories and different recovery rates.

Moisture plays a role in the thermal regime of a community, but plays a large part in the nutrient availability. Chapin *et al.* (1988) found that in areas where water was being channeled and collected, the productivity of vascular plants was higher than normal. This was attributed to the increased flow of nitrogen owing to the presence of moving water. This situation may be analogous to vehicle tracks like those found in the sites investigated in this study. Artificially increased productivity in this way could lead to different communities and, therefore, greatly hinder recovery to a pre-disturbance community.

Various authors have proposed differing hypotheses relating the recovery rates of landscapes to their moisture levels. Walker *et al.* (1977) found in their study of Rolligon damage in the Prudhoe Bay area that the wettest sites were the most easily impacted and they concluded that the dry sites would be the quickest to recover. Ebersole (1985) hypothesized, based on his observations and those of Hernandez (1973), that it would be the drier sites with lower resilience that would take the longest amount of recovery time to be identical to the undisturbed landscape. A synthesis conducted by Forbes *et al.* (2001) of studies concerning 20-75 year old disturbances showed similar results. Gersper and Challinor (1975) have shown that the greatest amount of physical change due to off-road vehicles occurred in the wet soils while the dry soils showed a greater change in color. They found soil compaction to be important and noted that the wettest and driest areas had higher initial bulk densities and that the magnitude of change was actually greatest in areas of intermediate moisture regime. Similar results were noted by Abele and Brown (1977).

1.9 The Study Focus

This study capitalizes on the opportunity to examine the recovery of a number of 20-40 year old vehicle trails in the vicinity of Barrow, Alaska. For example, trails left by Brown and Johnson (1965), Pitelka (Peterson 1978), and Abele and Brown (1977).

For these trails, no detailed quantitative measures of initial impact on vegetation or environment by the vehicles was recorded, although some photographic evidence exists and some personal interviews were possible with witnesses, such as Dr. Jerry Brown and Dr. Kim Peterson. Thus, this thesis relates primarily to recovery after a long time interval and allows interpretation of system resilience to be made. Only inferences can be made about initial impact and resistance to impact.

Because off-road vehicle traffic has been so extensive in the past and continues in some areas, long lasting effects become more important. If effects of the disturbance remain for 30 years or more, it is likely that in many areas, the frequency of disturbance is too high to allow adequate recovery time. In this case, management practices may need to be modified to further protect these areas. In order to document the extent to which the tundra is able to recover, this study examines historic vehicle disturbances of known age and duration.

The various trails examined in this study have been made over a number of terrain types and vegetation types. The literature documents and general observations suggest that different communities respond differently to disturbances. Many of the disturbances that frequently affect the tundra are related to the thermal properties of the soil. These thermal properties are modulated, in part, by the moisture content of the soil. Vehicle disturbances affect these thermal properties differently based on these soil properties. This study aims at testing the general hypothesis emerging from the earlier work of Hernandez (1973), Walker *et al.* (1977), Ebersole (1985) and Forbes et al. (2001) that drier sites have less resilience than wet sites.

CHAPTER 2

2 Methods

2.1 Site Descriptions

The study area is in northernmost Alaska in the vicinity of the City of Barrow. Barrow is situated in the littoral zone of the Arctic coastal plain (Figure 5). The climate is heavily influenced by the presence of the Arctic Ocean, which creates a more moderated climate. Mean July temperature is about 3.7°C. The annual mean temperature is approximately –12.6°C. The region annually receives about 124.1 mm of precipitation (Brown *et al.* 1980).

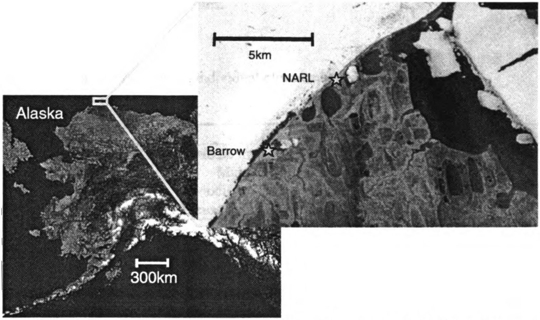

Figure 5: The location of the study area, the City of Barrow and the National Arctic Research Laboratory (NARL).

The Arctic coastal plain is a relatively flat landscape with low amounts of large-scale relief. The terrain is generally quite wet with thousands of oriented thaw lakes and ponds, as well as meandering streams. At a smaller scale, there is a great deal of variation in microtopography with ice wedges forming a reticulate pattern of troughs delineating polygons on the surface (Figure 4). The underlying soil of the coastal plain is frozen year round and the depth of the active layer is often no more than 1.0m (Gersper & Challinor 1975). Specific details for the individual sites are given in the following section.

2.1.1 Site 1 – Pitelka's Weasel trail

The test sites vary in location, moisture regimes, and vegetation types. In many cases, the vehicle causing the disturbance and the age of that disturbance also differ. The major differences between the sites are outlined below and also listed in Table 1. See Figure 6 for the locations of the sites.

Table 1: List of study sites with individual plot numbers and descriptions of disturbances.

Site Name	Disturbance Description	Plots
1. Pitelka's Trail	Periodic traffic by *M-29 Weasel c. 1955-1964	1-5
2. CRREL Test Site	Multiple passes by **Rolligon 1974	6-11
3. Oldest CRREL Trail	Periodic traffic by *M-29 Weasel c. 1962-1963	12-22
4. Youngest CRREL Trail	Periodic traffic by *M-29 Weasel c. 1963-1964	23-39

*Small tracked vehicle
**Large low-pressure tire vehicle

The vegetation of this site ranges from dry, polygonized tundra at the northeast end to a more wet meadow community at the southwest end. In the dryer areas, the dominant vascular species are *Eriophorum angustifolium*, *Eriophorum scheuchzeri*, and *Dupontia fischeri*. Dryer areas also have an abundance of *Luzula confusa*, while the wetter areas contain an abundance *Arctophila fulva*. The dominant bryophytes are *Calliergon sp.* and *Polytrichum juniperinum*. Many lichens are present including *Dactylina arctica* and *Cetraria islandica*. A complete species list for this site (Table A-1) is given in Appendix A.

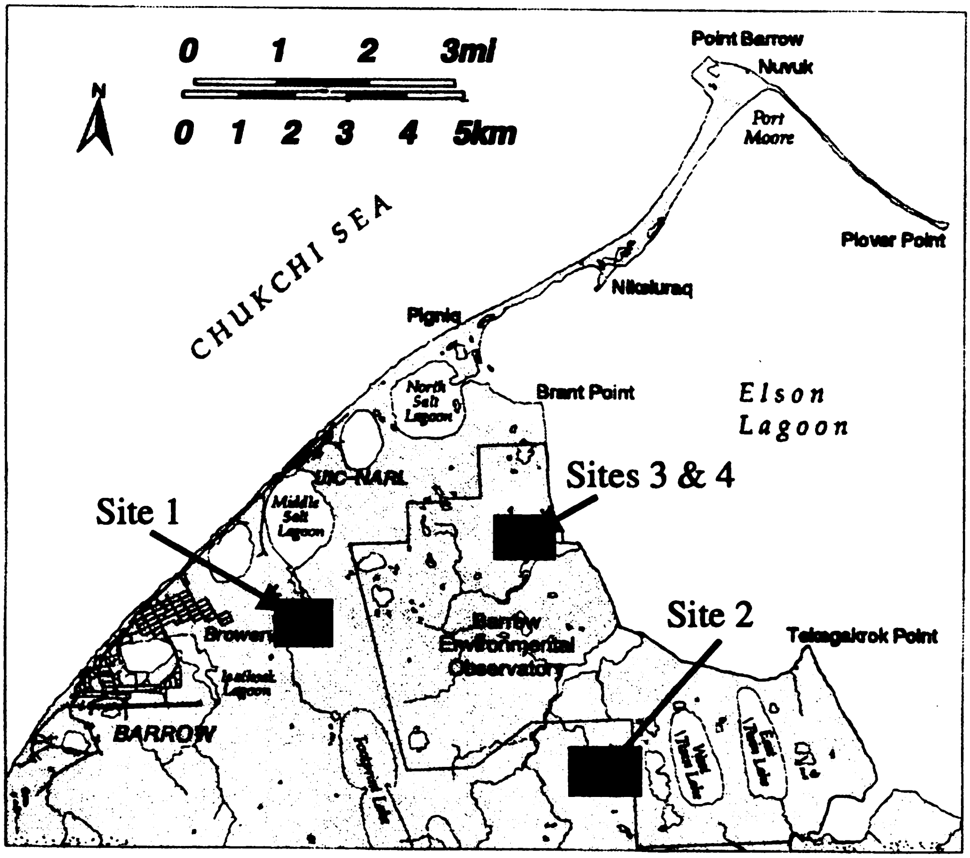

Figure 6: Location of sites of observation and experiment.

Within the site is a trail that was used 4 or 5 times per year as a route by scientists to check on experiments *via* Weasels. Frank Pitelka first used the track in 1955, and use of the track was stopped in 1964 following the creation of a gravel road located nearby the experiments. The track was later studied by Peterson (1978), who described five 5m by 20cm quadrats across the track and one control off the track. Figure 7 shows Pitelka's trail along with a Weasel trail used by the International Biological Programme (IBP). The IBP trail was relocated during this study, but not examined. A ground photograph of the IBP power-line trail is shown in Figure 8.

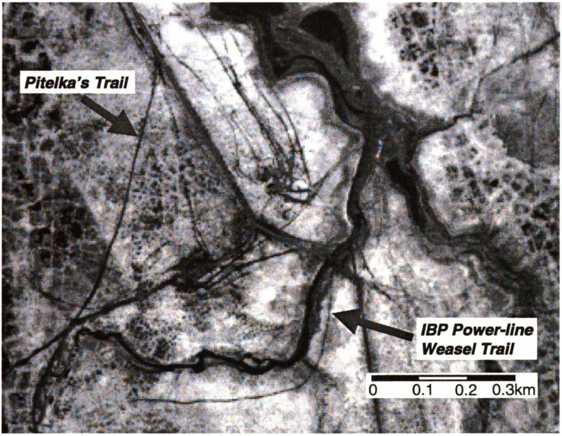

Figure 7: Aerial photograph of Site 1, including Pitelka's Trail and the IBP Power-line trail (1965).

Figure 8: The IBP Power-line Weasel trail. Photograph by Webber, 1971.

2.1.2 Site 2 – CRREL Test Track

The site is situated in a drained lake basin and is considered a wet meadow community. Site 2 was the most species-poor site in the study, containing only four species of vascular plants: *Eriophorum scheuchzeri*, *Eriophorum angustifolium*, *Dupontia fischeri*, and *Saxifraga cernua*. Bryophytes were more prevalent at this site and were dominated by *Sphagnum sp.*, *Calliergon sp.*, *Mnium sp.*, and *Polytrichum juniperinum*. The only common lichen at this site was *Peltigera sp*. A complete species list for this site (Table A-2) is given in Appendix A.

Within the site are several vehicle tracks of differing intensities made by different vehicles. Of particular interest is a track left by 15 passes of a Rolligon causing complete destruction of the vegetation mat (Abele *et al.* 1974). See Figures 9 and 10.

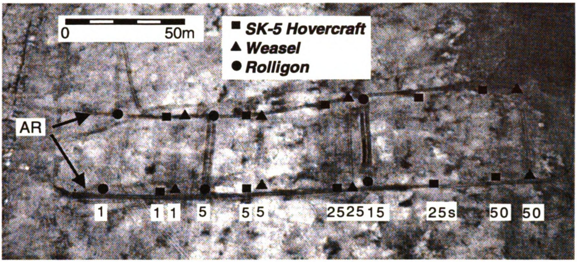

Figure 9: Aerial photograph of Site 2, the CRREL test site, taken in 1975. Horizontal trails are access roads (AR). Actual test tracks run vertical between points. Some are not readily visible in this photograph. Numbers indicate the number of passes made over that track. The designation 25s indicates a track of 25 passes at a slower speed.

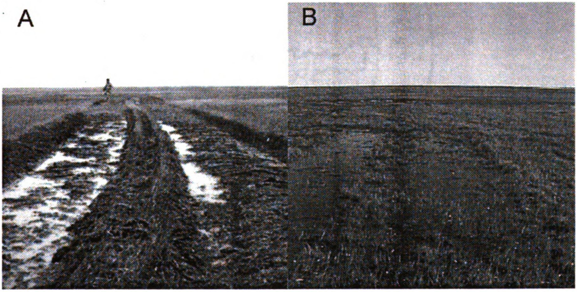

Figure 10: **(A)** The 15-pass Rolligon track at the CRREL test site in 1975 (photo by Atwood). **(B)** The 15-pass Rolligon track at the CRREL test site in 2001 (photo by Rewa). See person (in 10A) for scale.

2.1.3 Sites 3 & 4 – CRREL Weasel road

These sites cross a ridge and represent a gradient from weakly polygonized tundra in the wet basin to strongly polygonized tundra on the dry ridge top (Figure 11). At Site 3, the dominant vascular plants are *Salix rotundifolia, Arctagrostis latifolia, Luzula confusa, Luzula arctica* and *Alopecurus alpinus*. The diversity of bryophytes and lichens at these sites is higher than at the previous two sites. The dominant bryophytes at Site 3 are *Pohlia nutans, Tomenthypnum nitens, Calliergon sp., Drepanocladus brevifolius*, and *Polytrichum juniperinum*. Dominant lichens include *Cetraria islandica, Thamnolia subuliformis, Dactylina arctica*, and *Ochrolechia frigida*. A complete species list for this site (Table A-3) is given in Appendix A.

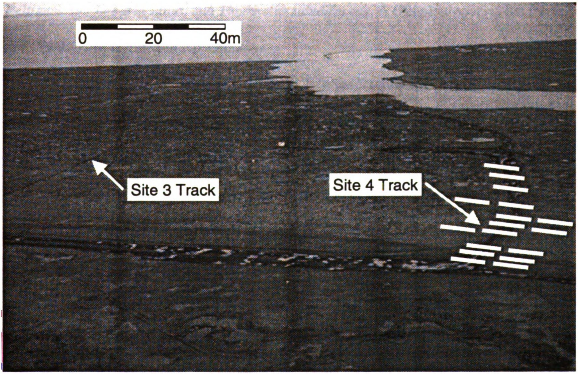

Figure 11: Aerial view of Sites 3 and 4 taken in 1964. Bars indicate locations of plots at site 4.

Site 4 ranges from a wet meadow community at its lowest point to a dry ridge at its highest. The dominant vascular plants in the wet meadow are *Poa arctica, Eriophorum scheuchzeri, Dupontia fischeri, Carex aquatilis,* and *Saxifraga cernua*. Dominant bryophytes include *Campylium stellatum, Pohlia nutans, Drepanocladus brevifolius,* and *Calliergon sp*. Common lichens include *Peltigera sp., Cetraria islandica,* and *Lobaria linita.*

In the dryer areas of Site 4, the dominant vascular plant species are *P. arctic, Salix rotundifolia, Alopecurus alpinus, Arctagrostis latifolia,* and *Petasites frigida*. Dominant bryophytes include *Pohlia nutans, Warnstorfia exannulata, Polytrichum juniperinum, Calliergon sp*., and *Campylium stellatum*. Common lichens include *Dactylina arctica, Peltigera sp., Lobaria linita,* and *Thamnolia subuliformis*. A complete species list for this site (Table A-4) is given in Appendix A.

Like Pitelka's trail, these tracks served as Weasel roads for CRREL scientists conducting cryopedological studies. The older trail, hereafter known as Site 3, was used in the summers of 1962 and 63 when it was abandoned due to overuse. A new trail, Site 4, was then adopted in 1963 and used through the end of the study in 1964 (Brown & Johnson 1965). Therefore, the disturbance at Site 4 is slightly more recent and more severe than that at Site 3. The Site 3 trail is more or less confined to a single set of tracks, while at Site 4, two and sometimes three sets of tracks are discernable. This necessitated the use of entirely no-impact control plots rather than the use of the ends of plots as controls. The plot design is presented in section 2.2.

2.2 Plot Layout

The plots were set up in a 2x10m grid by placing bamboo rods at 0.5m intervals along the length and width of the plot (Figure 12). Each plot contained 105 sample points to be used in point-based measurements such as microtopography and active layer sampling, and 80 subplots for sampling done on an area basis such as percent cover of vegetation. The plots were oriented perpendicular to and centered on the track (Figure 13).

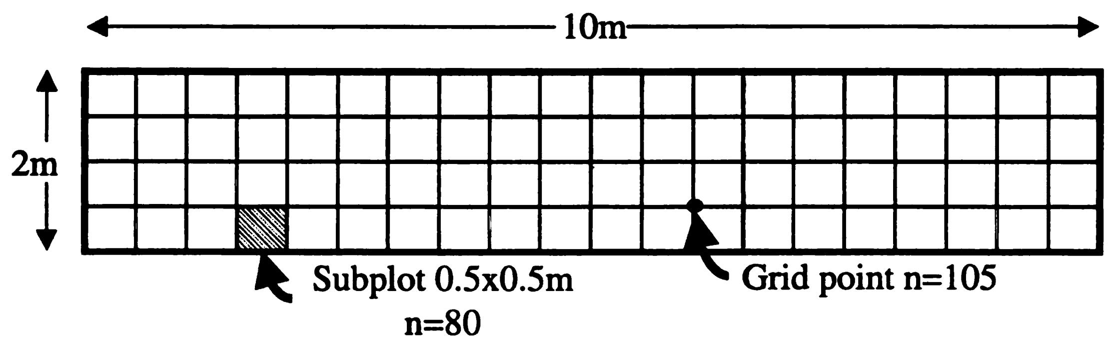

Figure 12: The sampling layout, indicating subplots and grid points.

Each plot was intended to include its own control by including sample points from non-impacted areas near the ends of the plots. As mentioned above, this was not practical in some particularly disturbed plots. In these circumstances, additional control plots were set up in nearby adjacent tundra that was considered representative of the appropriate undisturbed community. Plots were established at each of the 4 sites. Wherever possible, 3 replicate plots were established over as many vegetation types as were present, for a total of 39 plots. The primary benefit from this sample design was the ability to sample in increments of increasing distance away from the initial impact.

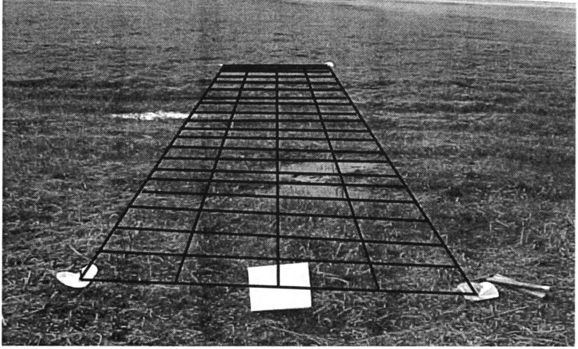

Figure 13: Plot 30 at site 4 with lines drawn to indicate 0.5 x 0.5m subplots.

2.3 Microtopography

Surface depression caused by vehicle traffic was assessed by measurements of microtopography using a telescopic level. The height of the ground surface at each point within the plot was recorded to the nearest cm above or below the average height of the plot, to determine spatial distribution of the topography within the plot.

2.4 Active Layer Depth

Measurements of active layer were taken to the nearest cm below the ground surface by thrusting a 1cm diameter metal rod into the earth at the grid points. This was done 4 times over the course of the summer at approximately 10-day intervals in order to determine seasonal variation. The dates of sampling were chosen in order to coincide with similar measurements recorded for the Circumpolar Active Layer Measurement

(CALM) project. The dates sampled included July 13 and 23, and August 2 and 12. An initial sampling was also conducted at Site 2 only on June 28.

In plots located over vehicle tracks, comparisons were made on an individual plot basis. The average thaw depth for non-impacted areas within the plot was compared with the average thaw depth for the impacted areas. In addition, all of the thaw depths taken throughout the whole study were analyzed together to test for the effects of time and site interactions with the thaw depth.

2.5 Soil Moisture Content, Bulk Density and pH

Measurements of soil moisture were taken for impacted plots by collecting a known volume of soil using 325ml soil cans. Three random soil samples were collected from areas under tracks, outside of tracks and between tracks. Wet weights were measured. Soil was dried overnight using a drying oven and dry weights were then measured and compared to wet weights. All weight measurements were recorded to the nearest 0.1g. The dry weights were also used to calculate the bulk density of the soil in order to compare soil compaction. A small amount of wet soil from each sample was used to determine the soil pH.

2.6 Vegetation Data

Percent cover of all vascular plants, as well as the dominant lichen and bryophyte species, was determined by visual estimation for the individual subplots (n=80). The measurements were conducted during the peak of the growing season to ensure maximum percent cover for the season. Estimation of percent cover of surface water and bare soil was also conducted at this time. Plants were identified to the species level whenever possible. In all cases, the plants were identified to the genus level. These groupings were considered species for purposes of species richness analysis and are hereafter referred to as such. The species and groupings used in the analyses are listed in appendix A and taxonomy matches that used in Webber (1978).

The plant cover data were converted to relative cover and relative frequency within the subplots. The variation in the relative cover data was examined using ordination by Principal Components Analysis (PCA) (McCune & Mefford 1995). Each plot was separated into two groups comprised of control and impacted subplots. These subplots were then arranged by the PCA in an n-dimensional hyperspace based on the similarities of their vegetation. All the variation is collected along the n axes of the hyperspace. Subplots with similar vegetation will be arranged near each other. The ordination was conducted once for all plots in the study and again using only those plots from which soil moisture data were recorded. For those plots with associated soil moisture data, separate ordinations were conducted for control and impacted subplots.

Correlations of the ordination axes with the microtopography, active layer depth, soil moisture, pH, and amounts of surface water and bare soil were calculated to estimate the relationships between the environmental factors and the variation in the vegetation. Ordinations for the individual sites were also conducted to determine if differences between impact and control are more or less pronounced at the site level than the whole study level. The individual site ordinations also indicate if different environmental factors are important at different sites.

Classification of the plots based on the relative cover data was done at the whole study level by cluster analysis using Euclidean distance measures and Ward's group linkage method (McCune & Mefford 1995). This was done for all plots and again for only those where soil moisture was measured. Additionally, a classification of the sites was conducted based on the environmental factors rather than the vegetation data

2.7 Species Diversity

The vegetation data were used to calculate species richness for each treatment within each site from which soil moisture data were collected. Because the impacted terrain was represented by fewer samples than the non-impacted terrain, it was possible that different species diversity in the impacted areas could be attributed to a smaller sample area. Species area curves were constructed for each site based on the vegetation data. These species area curves were created using PC-Ord (ver. 4.0) and calculated using the Sorenson method. They represent the mean number of species present in random selections from the total of a given number of subplots. This mean value is used to estimate the expected number of species for a given area. Up to 500 different random selections are used to generate these means. In cases when there are not 500 different random combinations of the appropriate number of subplots, all combinations of subplots are used. A range of one standard deviation about the mean is also included.

These species area curves were also used to investigate a possible change in species richness relative to the distance from the impact. All subplots within a single plot whose distance from the edge of impact were equal, were grouped together and their combined species richness was calculated. An analysis of variance was conducted using the general linear models procedure in SAS (ver. 8.0) to determine if there was a significant effect of distance from impact on species richness. Pair-wise comparisons were conducted between the richnesses of the different distance classes using Tukey's test. Additionally, species area curves were constructed for each distance class to indicate the number of species that are likely to be present in a given area a specific distance away from the impact.

CHAPTER 3

3 Results

3.1 Microtopography

Differences in microtopography between impacted and non-impacted areas within each of the 25 plots containing tracks were determined by comparison of means using t-tests. Each plot contained 105 sample points allowing 103 degrees of freedom. Microtopography differences were found in 20 of 25 plots indicating that the track ruts are still present along most of the trails considered in this study. Four of the plots with the least significant difference between impacted and non-impacted states (plots 6, 23, 24, and 25) are located in wet meadow communities. The fifth such plot (plot 22) was from a mesic community at the very end of the track at Site 3 where the disturbance was likely less severe. Even in this case the difference was nearly significant (t_{calc}=1.976, t_{crit}=1.984, α=0.05).

3.2 Active Layer Depth

Differences between thaw depth of impacted and non-impacted areas within a plot were determined by comparison of means using t-tests. Each plot contained 105 sample points allowing 103 degrees of freedom. Out of the 25 comparisons made, 22 plots showed significant differences between impacted and non-impacted subplots on at least one sampling date. Seven plots showed significant differences between the two conditions at all sampling dates. Plots with the most significant differences were those where track depressions have lead to ponding. The plots with the least significant differences between impacted and non-impacted areas were typically those that were uniformly wet.

Using the average thaw depth within a plot as a single data point, a comparison between whole plots containing disturbances and undisturbed plots within a particular moisture regime was made for each site. This was done with the wet meadow and dry slope plots at Sites 2 through 4. Site 1 was not used due to a lack of undisturbed plots. These comparisons were made for each of the 4 sampling dates, as well as the first test sampling at Site 2 on June 28. The thaw depth of disturbed plots was significantly deeper in 5 of the 17 comparisons made. In no comparison was the thaw significantly shallower for disturbed plots. None of these comparisons done at Site 3 showed significant differences between plots containing disturbed terrain and those that did not. The wet meadow plots at Sites 2 and 4 showed the most significant differences on the July 23rd sampling date (Site 2: $T_{calc} = 3.803$, $T_{crit} = 2.132$; Site 4: $T_{calc} = 2.608$, $T_{crit} = 2.132$), while Site 2 also showed significant differences on the August 12th sampling date ($T_{calc} = 2.771$, $T_{crit} = 2.132$) The dry heath plots at Site 4 showed the most significant differences at the plot level and steadily increased in significance until the last sampling on August 12th (August 2: $T_{calc} = 4.342$, $T_{crit} = 2.132$; August 12: $T_{calc} = 6.500$, $T_{crit} = 2.132$). See Table 2 for statistics of the comparisons.

All of the data from the 4 complete sampling dates were analyzed together using a repeated measures model using SAS (ver. 8.0) to look at the effect of time on the thaw depth progression and to compare the differences in the effect over the different sites. All of the tests for fixed effects showed significance in the study ($p < 0.0005$). The Kolmogorov-Smirnov, Cramer-Von Mises, and Anderson-Darling tests for normality showed that the data were significantly different from normal (p values <0.01, <0.005 and <0.005, respectively). It should be noted that with data sets as large as this the statistical power alone will often lead to problems with normality tests. Therefore, the results of the test will be reported here.

Table 2: Differences between disturbed and non-disturbed terrain at individual sites for each sampling date. Degrees of freedom and t statistics are given with an indication of significance.

Site	Moisture	Date	dof	t_{calc}	t_{crit}	Significant
2	wet meadow	06/28/01	4	0.3072	2.132	No
2	wet meadow	07/13/01	4	0.2708	2.132	No
2	wet meadow	07/23/01	4	3.8034	2.132	Yes
2	wet meadow	08/02/01	4	1.9796	2.132	No
2	wet meadow	08/12/01	4	2.7710	2.132	Yes
3	dry slope	07/13/01	4	0.0319	2.132	No
3	dry slope	07/23/01	4	1.5368	2.132	No
3	dry slope	08/02/01	4	1.1190	2.132	No
3	dry slope	08/12/01	4	0.6637	2.132	No
4	dry slope	07/13/01	4	0.0720	2.132	No
4	dry slope	07/23/01	4	1.7430	2.132	No
4	dry slope	08/02/01	4	4.3427	2.132	Yes
4	dry slope	08/12/01	4	6.5002	2.132	Yes
4	wet meadow	07/13/01	4	0.5661	2.132	No
4	wet meadow	07/23/01	4	2.6082	2.132	Yes
4	wet meadow	08/02/01	4	1.0715	2.132	No
4	wet meadow	08/12/01	4	0.5401	2.132	No

Sample date had the highest F statistic (4046.74) of any effect on thaw depth measurement. The condition of the terrain, disturbed or undisturbed, had the second highest F statistic of 161.86. The lowest F statistic (5.94) was for the effect of the site on thaw depth, but this was still highly significant (p<0.0005). The interactions between site and condition, date and condition, and date and site were all highly significant as well. See Table 3 for degrees of freedom and statistics.

Table 3: F statistics for variables related to thaw depth including numerator and denominator degrees of freedom.

Effect	Num DF	Den DF	F Value	Pr > F
Site	3	4052	5.94	0.0005
Cond	1	4052	161.86	<0.0001
Site*Cond	3	4052	23.73	<0.0001
Date	3	12000	4046.74	<0.0001
Date*Cond	3	12000	82.2	<0.0001
Date*Site	9	12000	97.95	<0,0001

Because the initial test indicated that there were significant differences between the thaw depths of sites and dates, and interactions between the effects, separate statistical tests were run for each site on each sampling date to further examine these differences. Again the data were significantly different from normal (Kolmogorov-Smirnov, Cramer-Von Mises, and Anderson-Darling p values: <0.01, <0.005 and <0.005, respectively). Wet sites behaved differently than dry sites throughout the study. Site 2, the wettest site, did not show a significant difference in thaw depth between impacted and non-impacted points until the last sampling on August 12th. Site 4, which has many wet plots as well, did not show a significant difference between impacted and non-impacted points until the second sampling on July 23rd. The difference at both of these sites seems to increase throughout the summer until reaching significance. Sites 1 and 3, which are the driest sites, showed significant differences from the beginning, and the differences seem to be unaffected by date of sampling over the course of the study period. The difference at Site 3 seems to begin to decline at the last sampling and the differences are likely to disappear beyond the end of the sampling period. It is interesting to note that the most significant differences are found at Site 1, which is intermediate in moisture when compared to the other sites. See Table 4 for statistics.

Table 4: Statistics for thaw depth comparisons between impacted and non-impacted grid points for each site on each sampling date.

Site	Date	Num DF	Den DF	F Statistic	p value	Significance
1	7/13/01	1	519	71.90	<0.0001	Yes
1	7/23/01	1	519	122.38	<0.0001	Yes
1	8/2/01	1	519	122.25	<0.0001	Yes
1	8/12/01	1	519	127.22	<0.0001	Yes
2	7/13/01	1	623	0.00	0.9793	No
2	7/23/01	1	623	0.02	0.8967	No
2	8/2/01	1	623	0.33	0.5645	No
2	8/12/01	1	623	4.83	0.0283	Yes
3	7/13/01	1	1143	25.29	<0.0001	Yes
3	7/23/01	1	1143	23.36	<0.0001	Yes
3	8/2/01	1	1143	21.15	<0.0001	Yes
3	8/12/01	1	1143	13.87	0.0002	Yes
4	7/13/01	1	1767	0.06	0.8127	No
4	7/23/01	1	1767	52.20	<0.0001	Yes
4	8/2/01	1	1767	51.15	<0.0001	Yes
4	8/12/01	1	1767	39.62	<0.0001	Yes

3.3 Soil Moisture Content

A comparison was conducted for the whole study area of the percent soil moisture for impacted areas, areas outside of tracks, and areas between tracks of each plot for which these data are available. These data were analyzed in SAS (ver. 8.0). Again, the data were non-normally distributed (Kolmogorov-Smirnov, Cramer-Von Mises, and Anderson-Darling p values: <0.01, <0.005 and <0.005, respectively), but the results are interesting. There was a significant difference between the soil moisture of each site (numerator degrees of freedom (df) =3, denominator df=170, p value <0.0001). However, the effect of the position of the samples relative to the tracks was not significant (numerator df =2, denominator df=170, p value =0.6596). The interaction between site and position was also insignificant (numerator df =6, denominator df=170, p value =0.8641), suggesting that the differences in soil moisture between positions would not be significant regardless of the site.

This was confirmed by analyses of the data for each site separately. Even at Site 1 where there was the greatest difference in surface water content between impacted and non-impacted areas, there was no significant difference in soil moisture content (p=0.1746). The differences at the remaining sites were not nearly so close to significant (Site 2: p=0.9223, Site 3: p=0.9335, Site 4: p=0.9375).

A simple linear regression was run to test the effect of soil moisture on thaw depth using the average thaw depth in meters on 8/12/01 (y) and percent soil moisture (x) for impacted and non-impacted areas of the plots. The analysis of variance showed a weak, but highly significant, trend (p<0.0001). As the soil moisture content increased, the thaw depth decreased. The equation for the trend is $y=-.0031x + 0.5498$, with an r^2 value of 0.2679.

3.4 Soil Compaction

In addition to the soil moisture, a comparison was conducted for the whole study area of the soil compaction for impacted areas, areas outside of tracks, and areas between tracks of each plot for which these data were available. Soil bulk density was used for this comparison. The data were also non-normally distributed (Kolmogorov-Smirnov, Cramer-Von Mises, and Anderson-Darling p values: <0.01, <0.005 and <0.005, respectively), and the results are similar to those from the soil moisture data. There was a significant difference between the soil bulk densities of each site (numerator degrees of freedom (df) =3, denominator df=170, p value <0.0001). The effect of the position of the samples relative to the tracks was not significant (numerator df =2, denominator df=170, p value =0.5943). The interaction between site and position was also insignificant (numerator df =6, denominator df=170, p value =0.9613), suggesting that the differences in soil moisture between positions would not be significant regardless of the site.

3.5 Ordination

The following results are based on principal components analysis (PCA) of the relative plant cover data. Graphing the PCA of the relative cover of all species in all subplots demonstrates a greater variation within the control subplots than the impacted subplots. Axis 1 of the ordination captured 16.9% of the variation and was most closely correlated with average percent of bare soil (r^2=0.379). Axis 2 captured 8.1% of the variation and was most closely correlated with the average active layer depth on August 12 (r^2=0.116). Axis 3 captured 7.1% of the variation and was most closely correlated with active layer depth on August 2 (r^2=0.061). Correlations with soil moisture and pH were not conducted for this ordination (Figure 14).

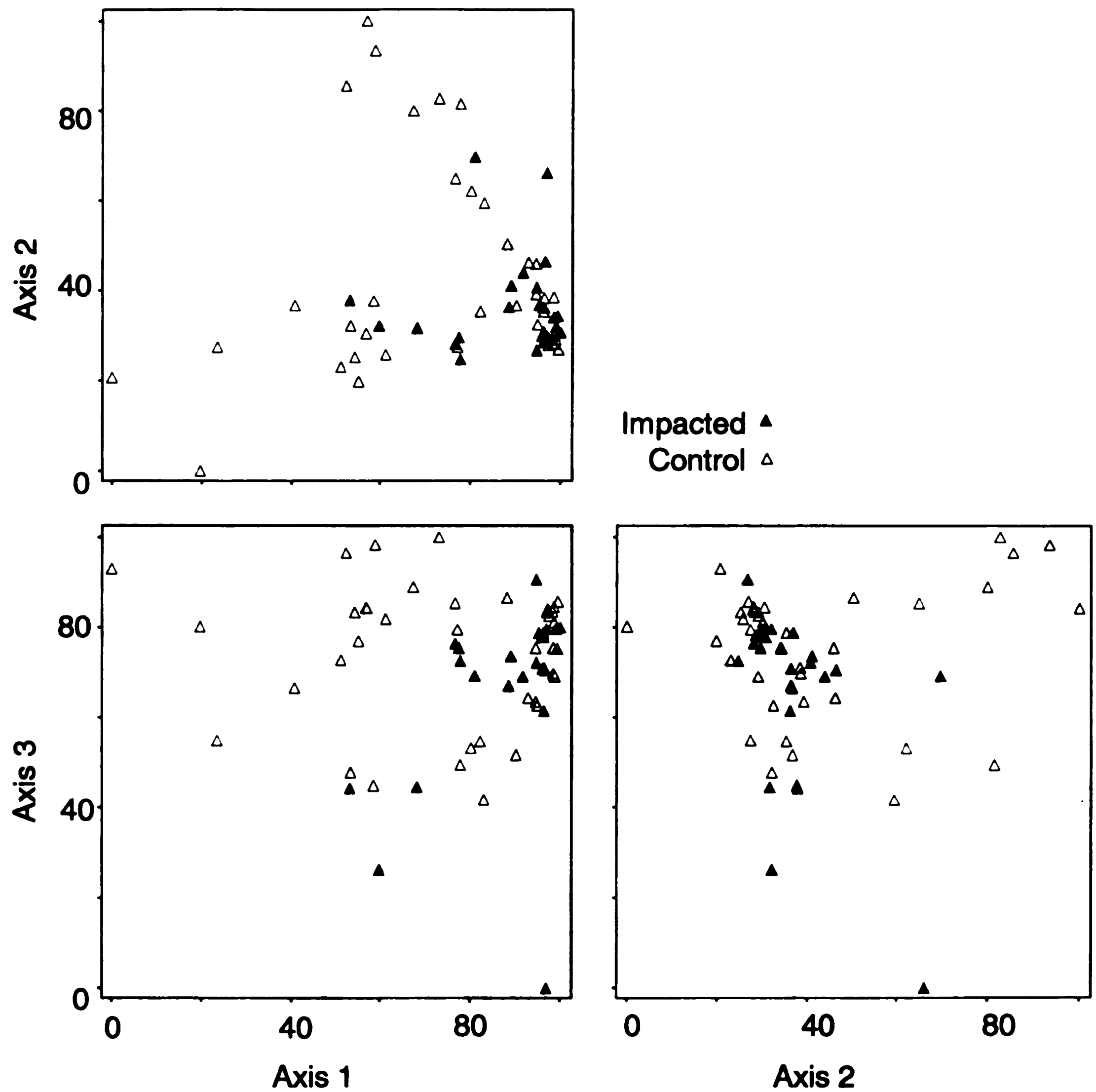

Figure 14: Results of the PCA for all plots in the study.

The results of the PCA for plots with moisture data show a greater variation in the control subplots than is present in the impacted subplots (Figure 15). Axis 1 of the ordination corresponds most closely with percent of bare soil ($r^2 = 0.371$), axis 2 with average soil pH ($r^2 = 0.111$), and axis 3 with late season thaw depth ($r^2 = 0.243$). Percent soil moisture has a lower correlation with these axes (r^2=0.244, 0.002, 0.182, respectively). Axis 1 captured 17.9% of the variation, axis 2 captured 9.0%, and axis 3 captured 7.5%. The cumulative variance captured by these three axes is 34.4%.

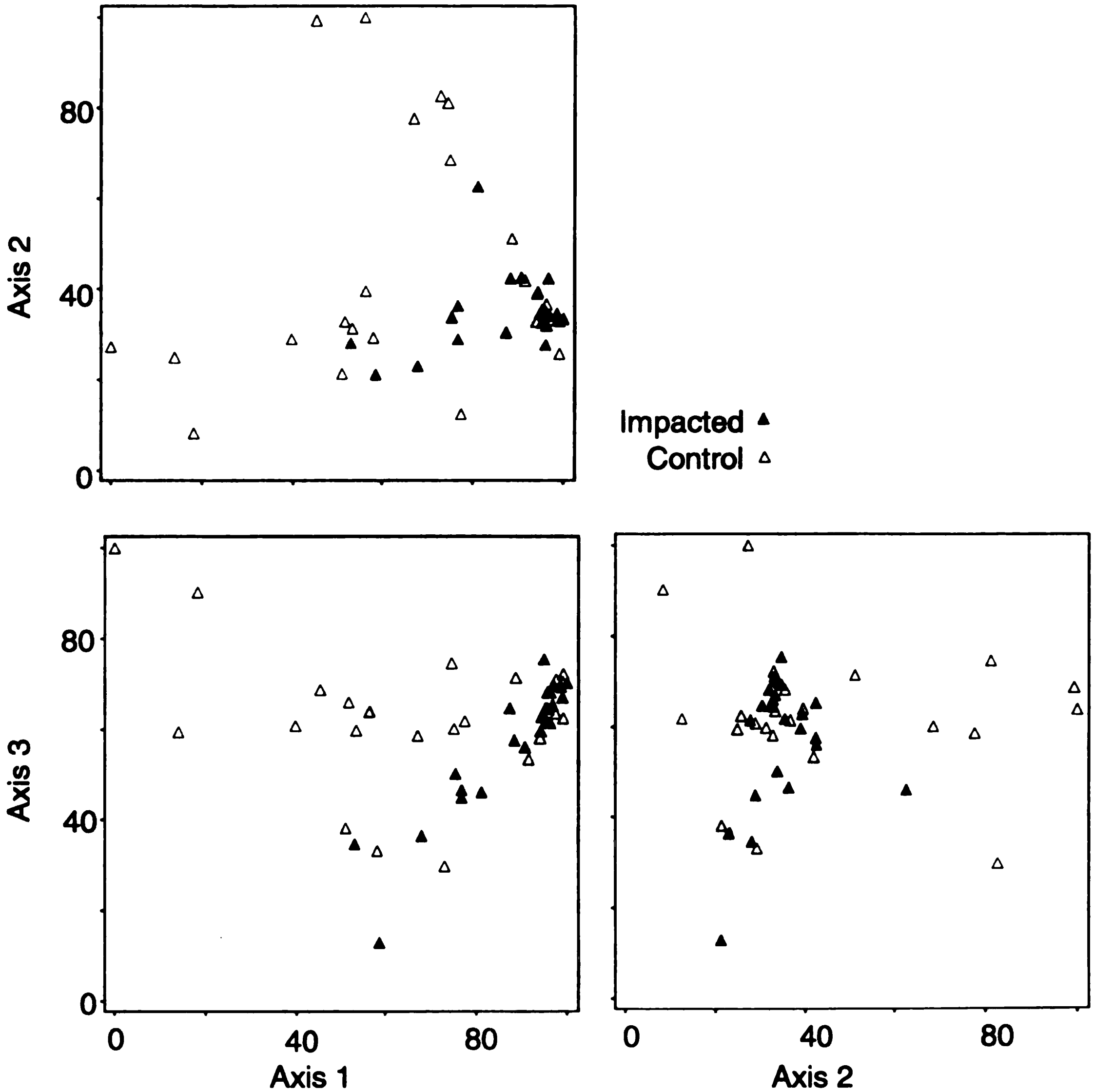

Figure 15: Results of the PCA for those plots for which soil moisture data were collected.

Separate PCAs were conducted for the control and impacted subplots using those plots from which soil moisture data were collected. The impacted subplots show slightly higher correlations with the environmental variables than do the controls. Axis 1 of the ordination for the controls corresponds most closely with early season thaw ($r^2 = 0.576$), axis 2 with average soil pH ($r^2 = 0.172$), and axis 3 with soil moisture content ($r^2 = 0.244$). Percent soil moisture has correlations with the first two axes of $r^2=0.342$ and 0.004, respectively. Axis 1 captured 19.4% of the variation, followed by axis 2 with 11.4%, and axis 3 with 8.4% (Figure 16). The cumulative variance explained by these three axes is 39.3%.

Axis 1 of the ordination for impacted subplots corresponds most closely with late season thaw ($r^2 = 0.625$), axis 2 with thaw depth on week 2 ($r^2 = 0.309$), and axis 3 with early season thaw depth ($r^2 = 0.243$). Percent soil moisture has correlation with these axes of $r^2=0.161$, 0.041, 0.098, respectively). Axis 1 collected 25.3% of the variation, followed by axis 2 with 10.2%, and axis 3 with 9.5% (Figure 17). The cumulative variance captured by these three axes is 45.0%.

The individual sites showed varying patterns in the ordination results. Separate Principal Components Analyses were conducted based on relative plant cover data to identify which factors were potentially controlling in the different sites. These ordinations only deal with data collected from plots where soil moisture data is available.

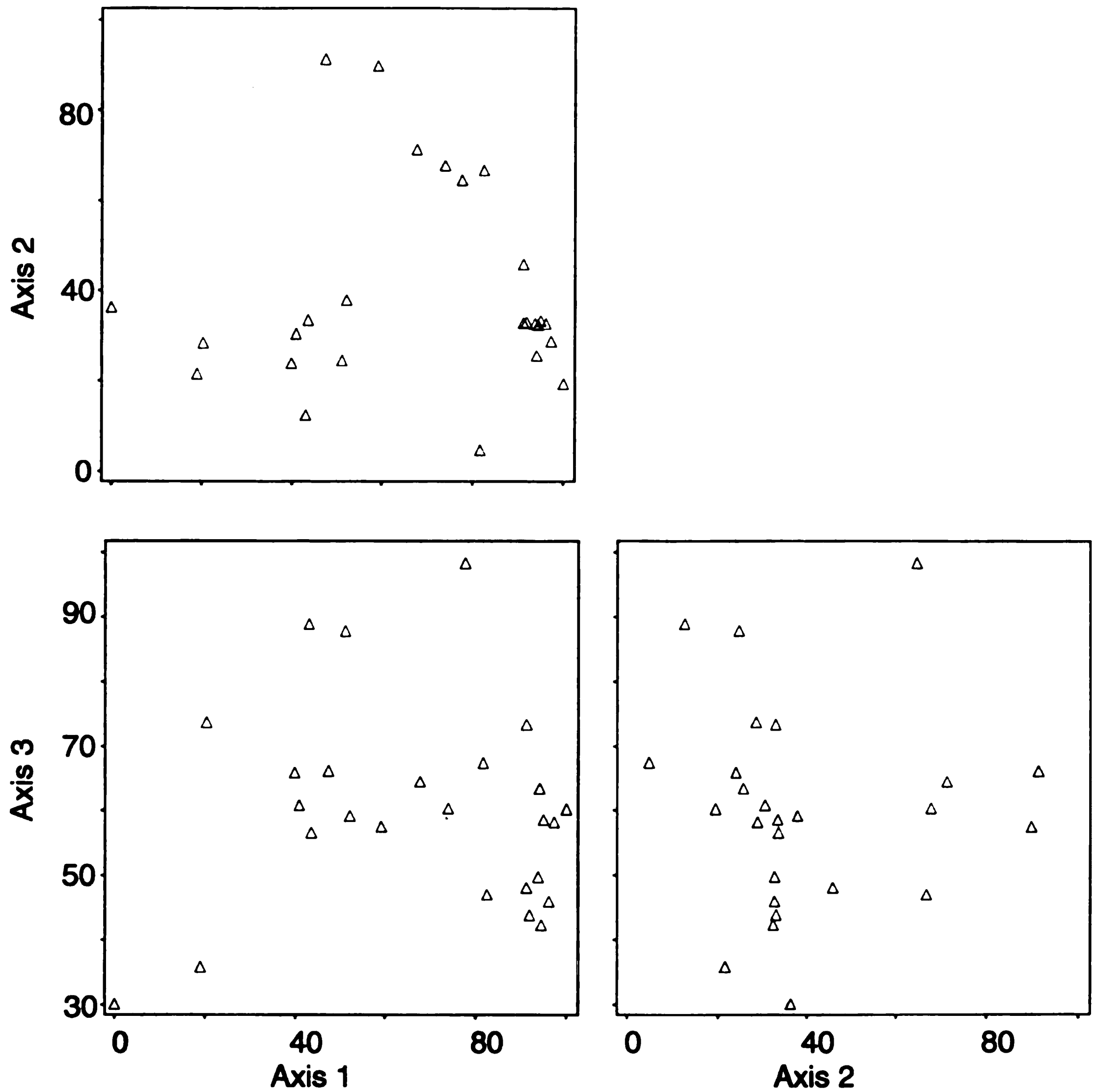

Figure 16: PCA results for control subplots from which soil moisture data were collected.

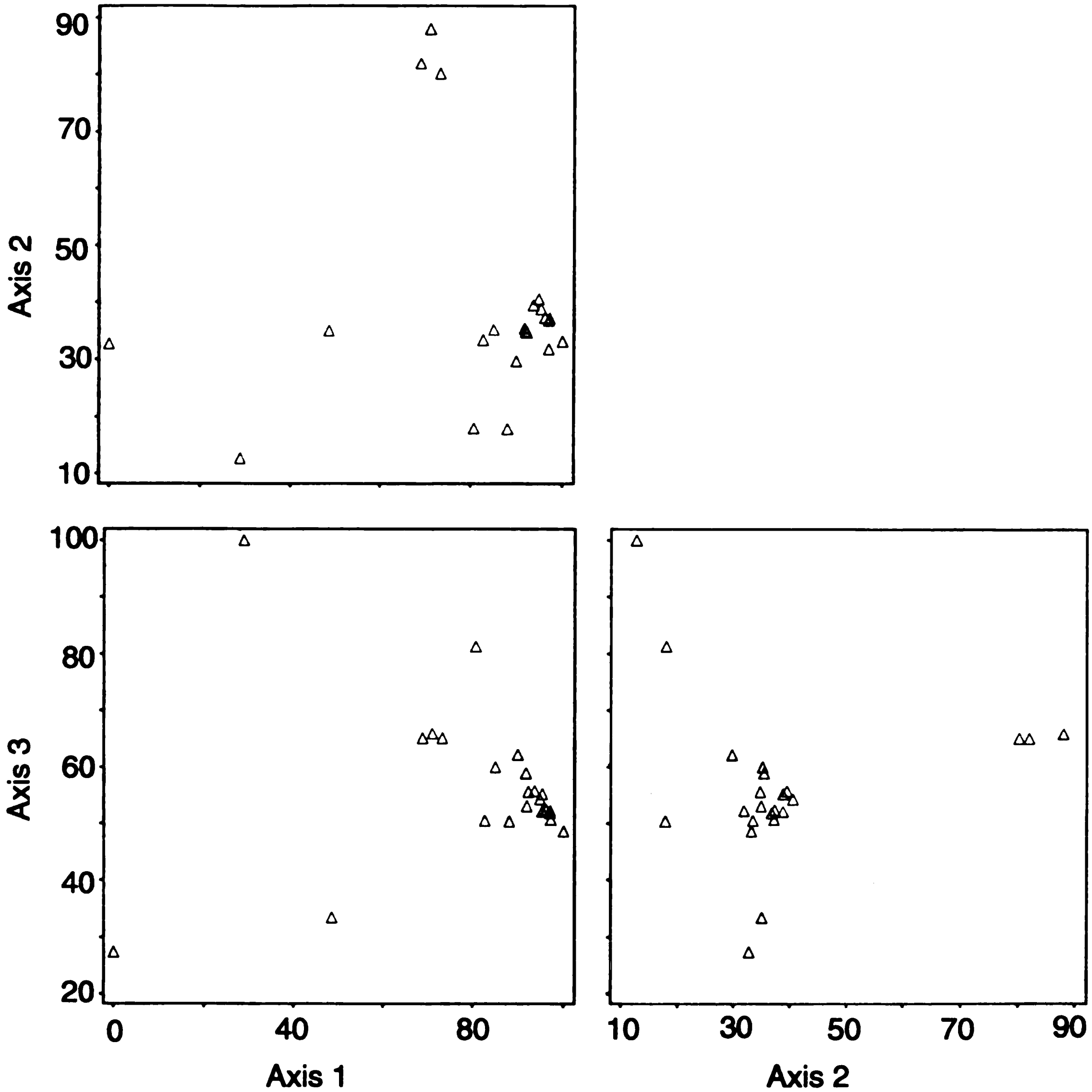

Figure 17: PCA results for impacted subplots from which soil moisture data were collected.

3.5.1 Site 1

Axis 1 of the ordination for Site 1 captured 41.1% of the variation in the relative plant cover data and corresponds most closely with average soil pH ($r^2 = 0.437$). Axis 2 captured 27.5% of the variation and correlates most closely with the average percent of surface water in the plot ($r^2 = 0.342$). Axis 3 captured an additional 11.9 % of the variation and correlates well with the average microtopographic height of the plots (r^2 = 0.829). Percent soil moisture has correlation with these axes of r^2=0.040, 0.080, and 0.020, respectively (Figure 18). The first 3 axes explain a total of 80.5% of the variation.

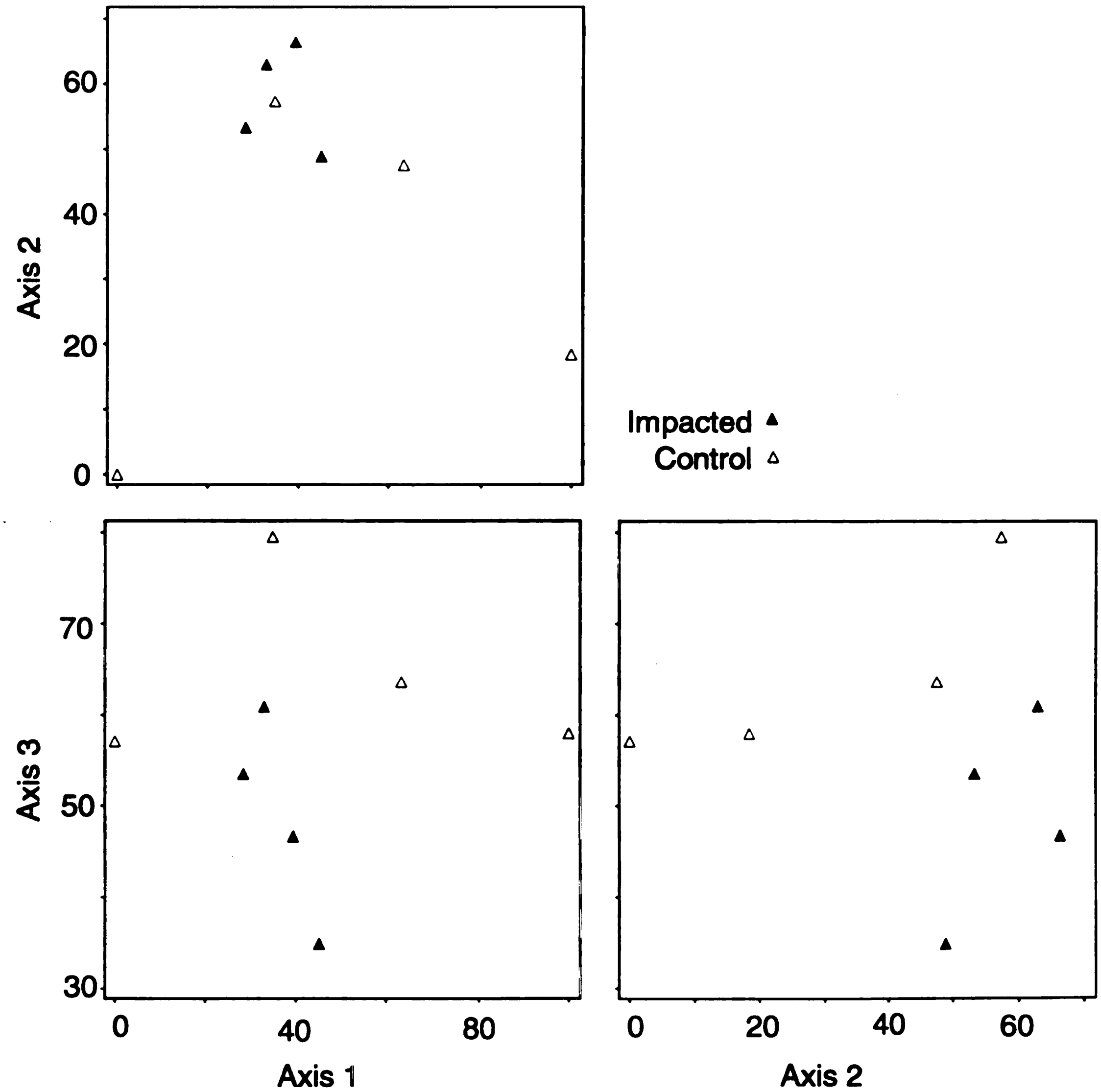

Figure 18: PCA results for plots at Site 1 from which soil moisture data were collected.

3.5.2 Site 2

Axis 1 of the ordination for Site 2 captured 44.5% of the variation in the relative plant cover data and has its highest correlation with the average percent of surface water in the plot ($r^2 = 0.719$). Axis 2 captured 32.3% of the variation and correlates most closely with the average soil pH ($r^2 = 0.613$). Axis 3 captured 11.4% of the variation and correlates best with the average active layer depth on July 23 ($r^2 = 0.419$). Percent soil moisture has correlation with these axes of r^2=0.315, 0.097, and 0.119, respectively (Figure 19). The first 3 axes captured a total of 88.2% of the variation.

3.5.3 Site 3

Axis 1 of the ordination for Site 3 captured 23.8% of the variation in the relative plant cover data and corresponds most closely with the average microtopographic height of the plots ($r^2 = 0.626$). Axis 2 captured 21.6% of the variation and correlates most closely with the active layer depth on August 12 ($r^2 = 0.695$). Axis 3 captured 12.1 % of the variation and has its highest correlation with the average percent of bare soil ($r^2 = 0.207$). Percent soil moisture has correlation with these axes of r^2=0.046, 0.027, and 0.136, respectively (Figure 20). The first 3 axes capture a total of 57.6% of the variation.

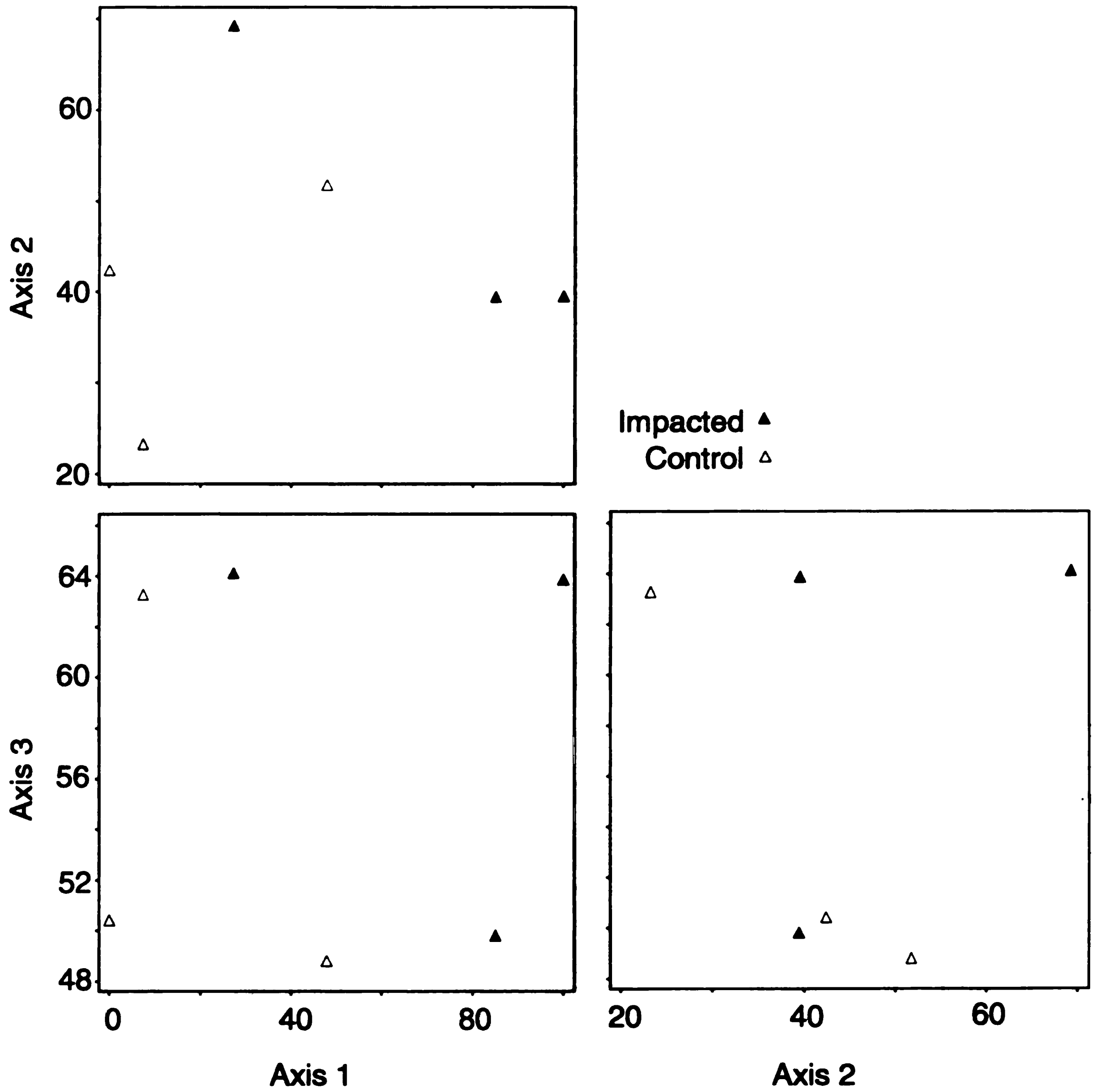

Figure 19: PCA results for plots at Site 2 from which soil moisture data were collected.

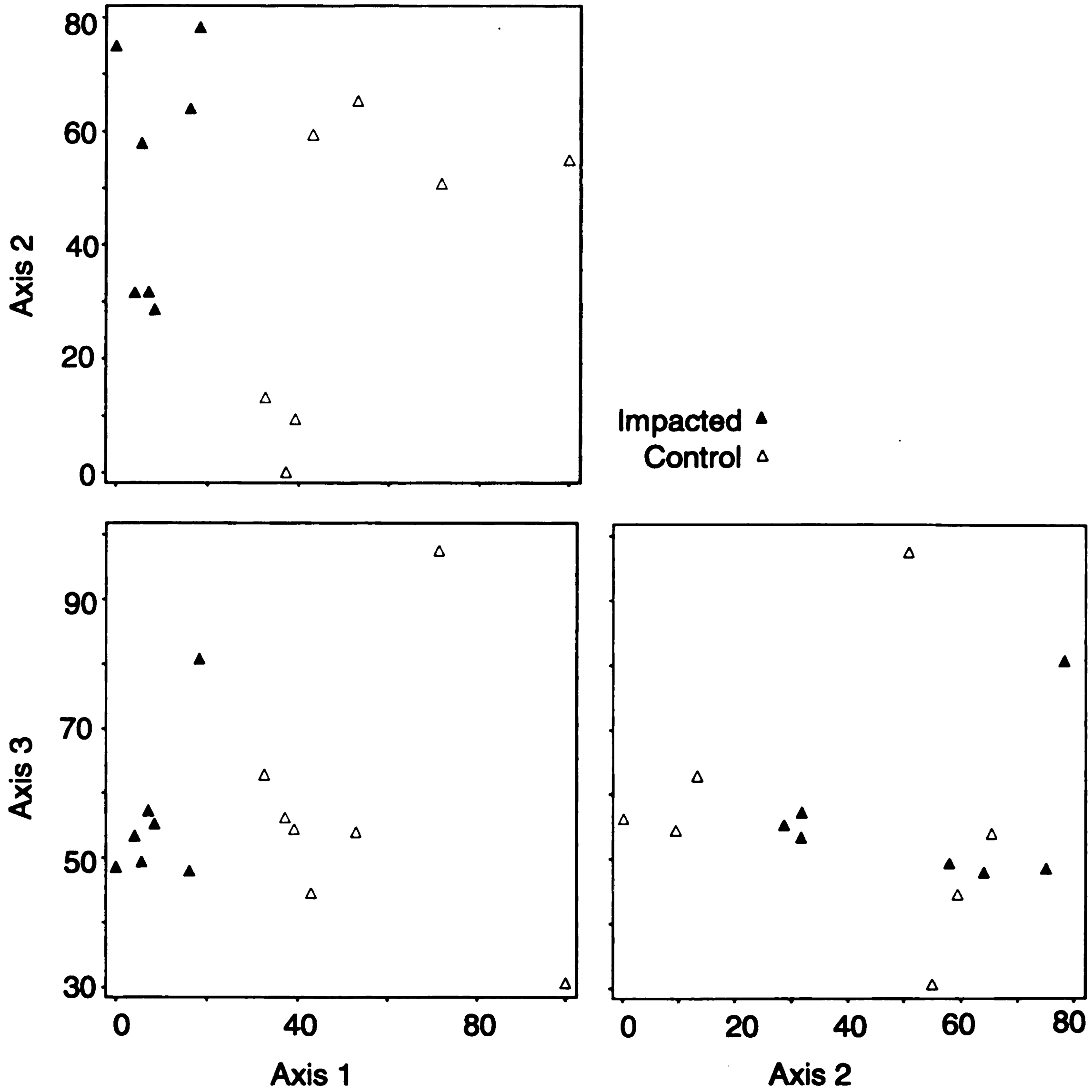

Figure 20: PCA results for plots at Site 3 from which soil moisture data were collected.

3.5.4 Site 4

Axis 1 of the ordination for Site 4 collected 25.6% of the variation in the relative plant cover data and has its highest correlation with the average thaw depth on July 13 (r^2 = 0.387). Axis 2 collected 13.0% of the variation and also correlates most closely with the average thaw depth on July 13, though the correlation is weaker than for axis 1 (r^2 =

0.077). Axis 3 captured 11.1% of the variation and correlates best with the average active layer depth on August 12 ($r^2 = 0.576$). Percent soil moisture has correlation with these axes of r^2=0.088, 0.047, and 0.021, respectively (Figure 21). The first 3 axes explain a total of 49.7% of the variation.

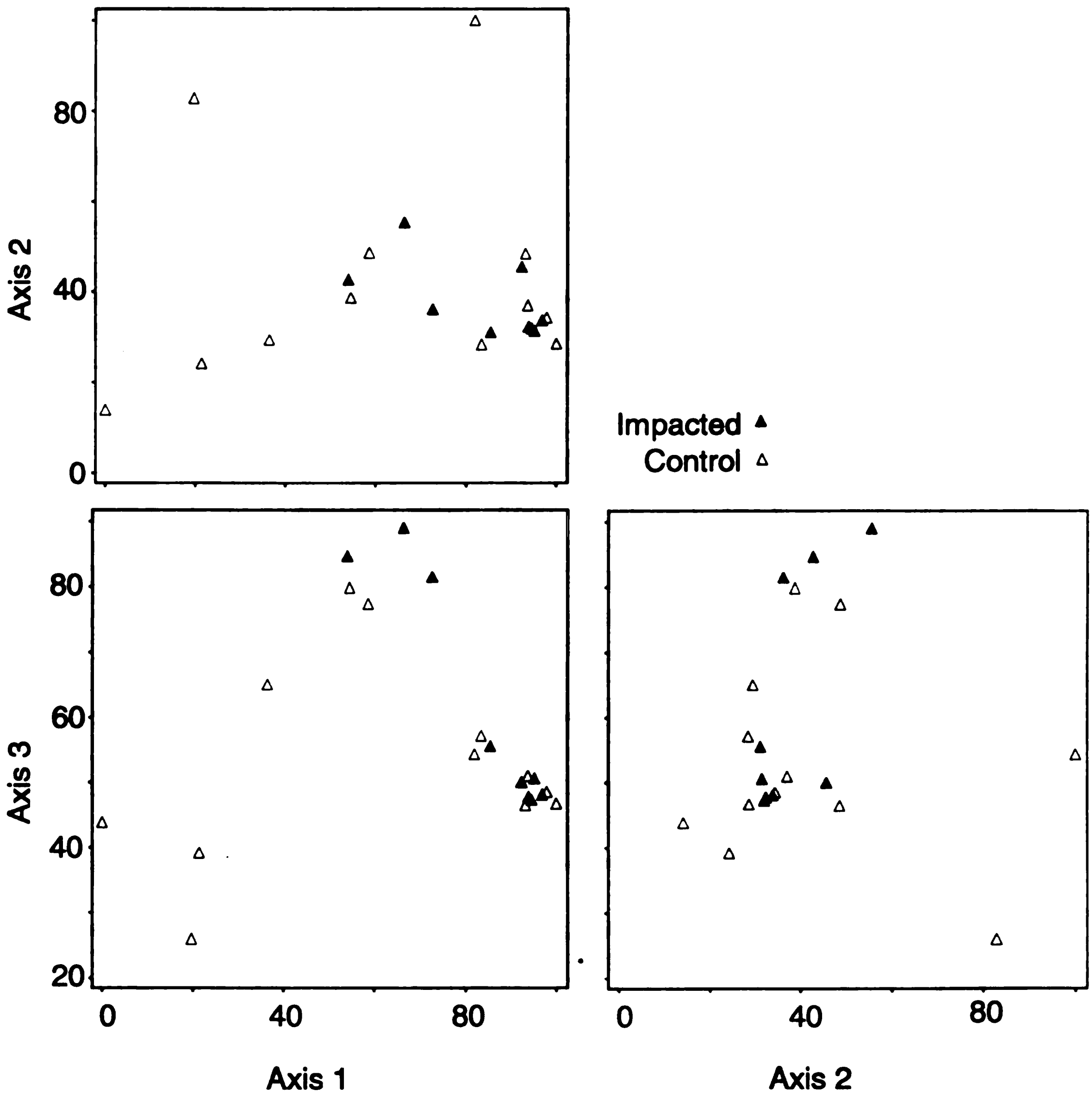

Figure 21: PCA results for plots at Site 4 from which soil moisture data were collected.

3.6 Classification

The statistical classification of the sites based on the relative cover of plants within the plots separated the plots into three fairly distinct groups. For purposes of the classifications each plot is separated into its control impacted subplots, designated by their plot number followed by 01 or 02, respectively. For example, the impacted portion of plot 5 is designated 0502. For the most part, nearby sites are grouped together in the classification. All of the plots at Site 2 are separated into a group by themselves, along with three of the plots at Site 1. The second and third groups are more closely related to each other than to the first. One of these groups is made up almost entirely of dry slope plots from Sites 3 and 4 and includes no plots from Sites 1 or 2. The last group is more variable and contains most of the plots from Site 1, as well as most of the plots from Sites 3 and 4 that were not located on the dry slope. Figure 22 shows these relationships and also includes a subjective classification into groups that roughly correspond to "wet", "dry" and "moist" tundra. This subjective classification was done using simple observation in the field during the establishment of the plots. Although these two classifications are fairly consistent, plots 23 to 28 at Site 4 were not placed in the same group by the statistical classifier compared to the subjective method. Also interesting is the separation of the impacted portion of plot 4, designated 0402, from its non-impacted counterpart 0401.

In a similar classification using vegetation cover data from only the plots where soil moisture data were available, the plots separate naturally into two groups subjectively designated "wet" and "dry" (Figure 23). There is a small group that corresponds most closely to the "moist" group from the full study classification, but it

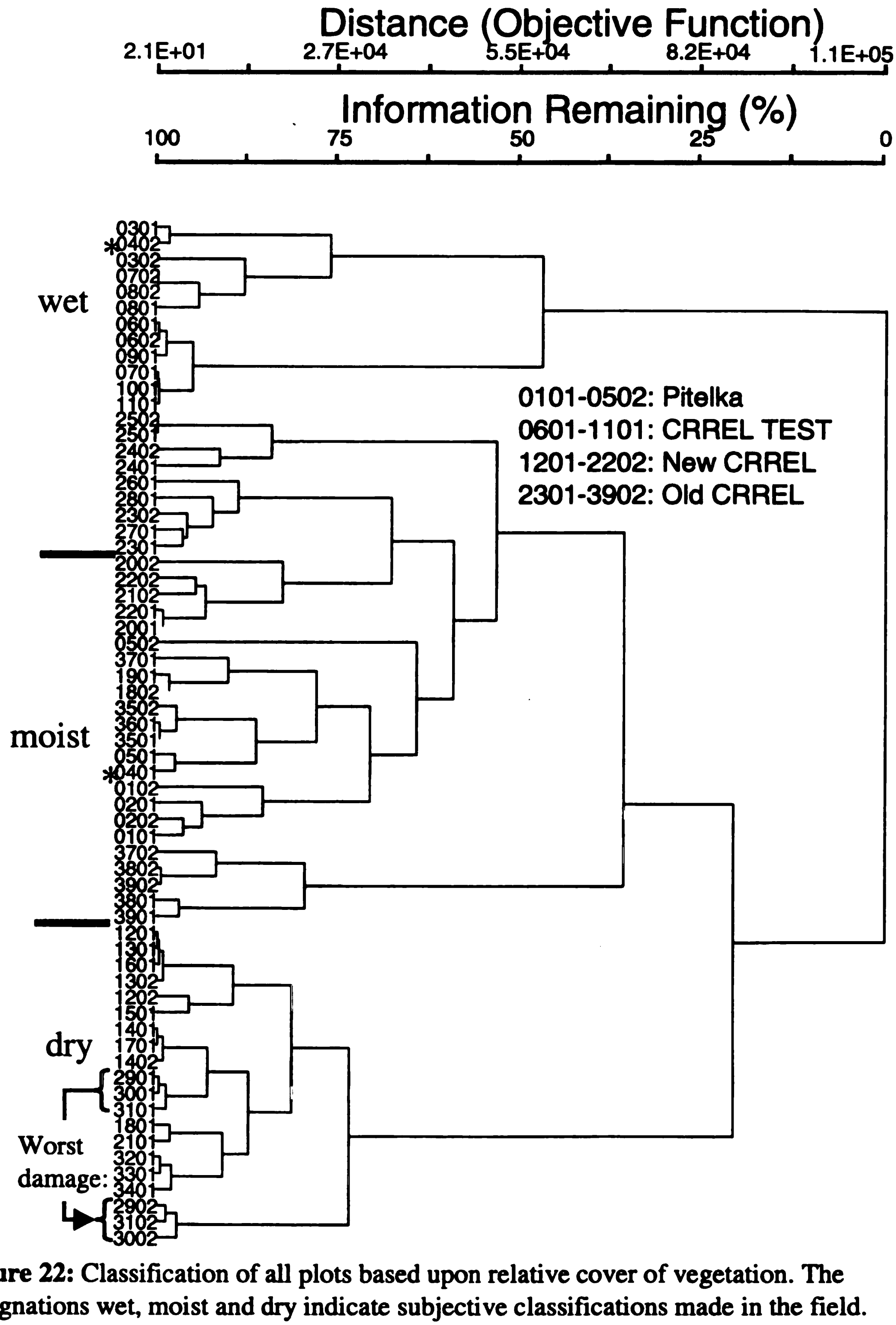

Figure 22: Classification of all plots based upon relative cover of vegetation. The designations wet, moist and dry indicate subjective classifications made in the field. Plots 0401 and 0402 (indicated by asterisks) are corresponding damaged and undamaged plots which are separated by the greatest distance possible in the classification.

contains only plots 37 through 39. These plots are located on an elevated flat just above the dry slope at Site 4. Because of the small size of this group it may be more useful to consider them a part of the dry classification to which they are most closely related.

The plots that were subjectively designated "wet" and "dry" during the initial site setup, are again in distinct groups much as they were in the whole-study classification. Those plots that had been designated "moist" are distributed fairly evenly into both the "wet" and "dry" groups in this second statistical classification, rather than being in their own group as they were in the full-study classification. Some relationships are closer in this second classification and others are farther away. The two parts of plot 4, which had the lowest possible similarity in the first classification, are fairly closely related in this second one. Conversely, although still all within the same major grouping, the plots of Site 2 are nearly as closely related in this classification as they were in the first.

The plots for which there was moisture data available were also classified based on their environmental characteristics rather than their vegetation composition. Again, two major groups were formed (Figure 24). The major environmental factor determining the clusters appears to be soil moisture. Within the major groupings, percent surface water seems to dictate the sub-groupings. In this case, the plots from Sites 1 and 2 made up the majority of the entries in the first group and within the group these two sites were separated quite distinctly. Plot 2402 was the only plot within this group that was not found at Sites 1 or 2. Similarly, plot 0302 was the only plot in the second group that isn't located at Sites 3 or 4. These two plots had the least possible similarity with their non-impacted counterparts, which classified as expected. Unlike Sites 1 and 2, Sites 3 and 4 are not distinct from one another within the major grouping to which they belong.

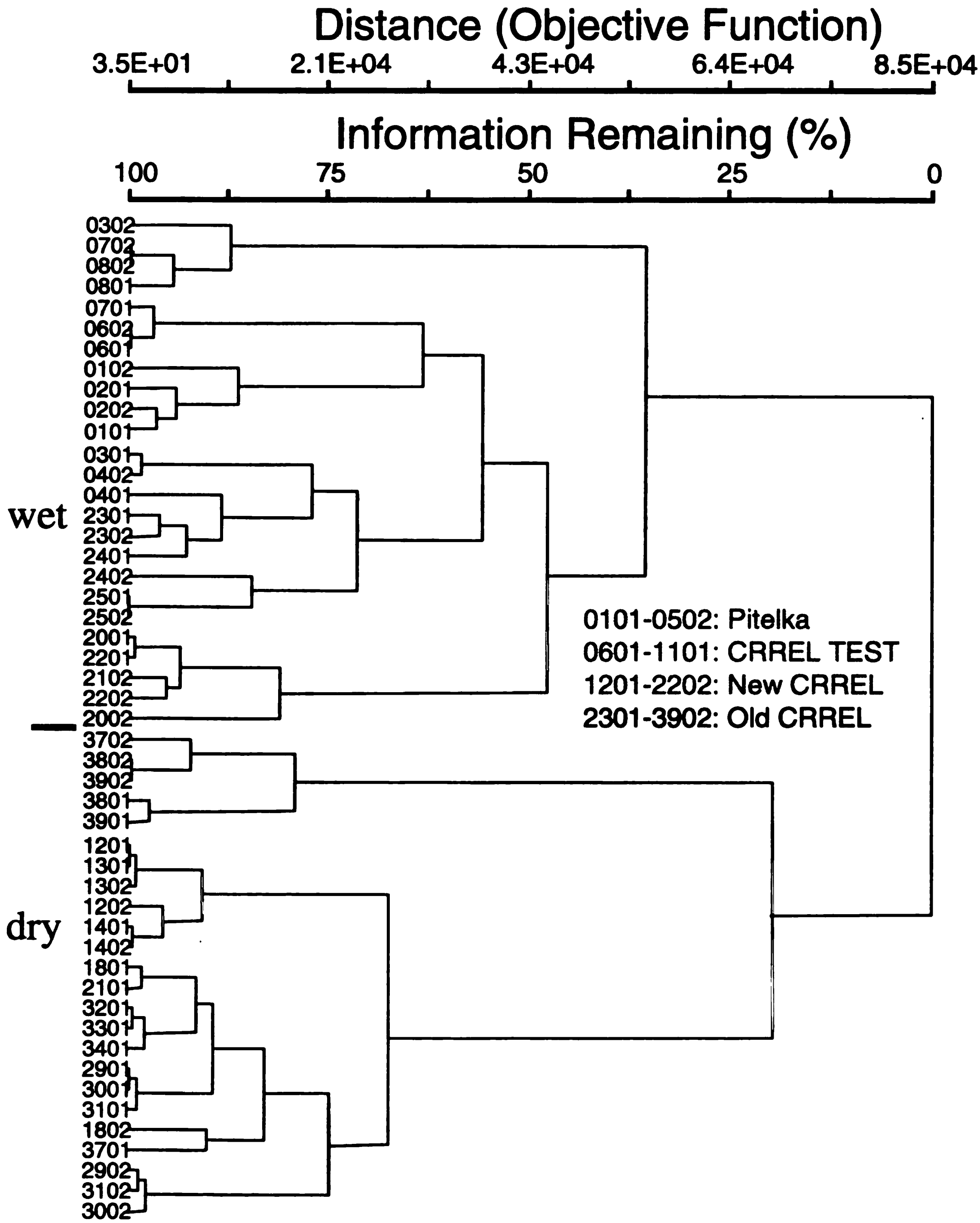

Figure 23: Classification of all plots from which soil moisture data was taken. The plots are classified into two major groups which can be subjectively called wet and dry.

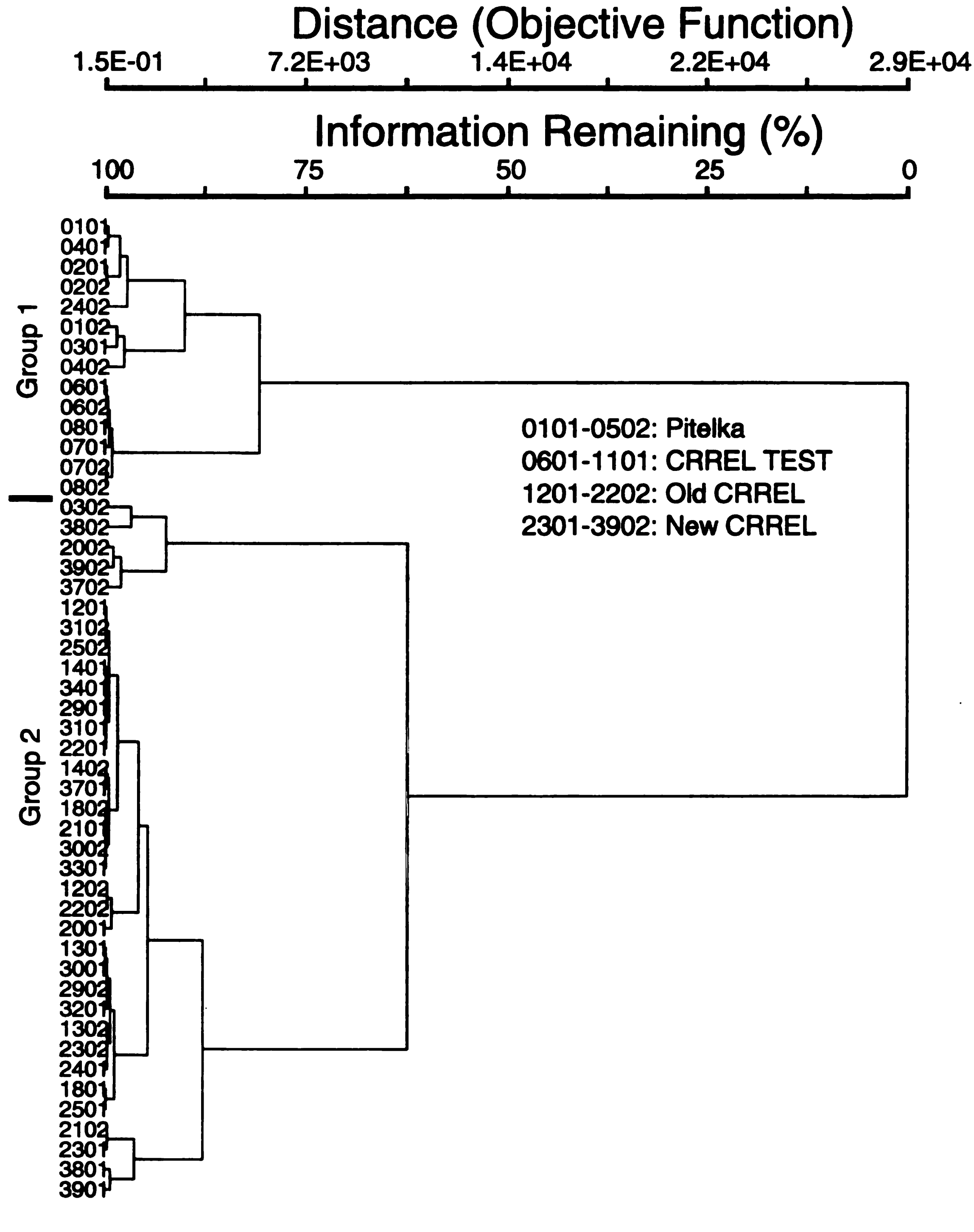

Figure 24: Classification based on environmental variables of all plots from which soil moisture data was taken. The plots are classified into two major groups that generally separate Pitelka's trail and the CRREL test trail from the old and new CRREL trails.

3.7 Species Losses

Over the whole study site there were species which do not occur in impacted subplots, but which are present in the corresponding non-impacted areas. 70 different species were encountered in soil moisture plots throughout the study. Only 58 were found in both impacted and non-impacted areas. Of the rest, 11 species were only found in non-impacted subplots, and one species, ***Bryum cyclophyllum***, which was not found in any non-impacted subplot, was found in one impacted subplot. Species area curves were used to determine if these losses were simply due to a smaller sample area and relatively rare species. 278 subplots were impacted and contained 59 species. 278 subplots sampled at random from the 2078 total subplots for generation of the species area curves had a mean number of species of approximately 64. Graphs of the species area curve with the standard deviation about the mean are shown in Figure 25.

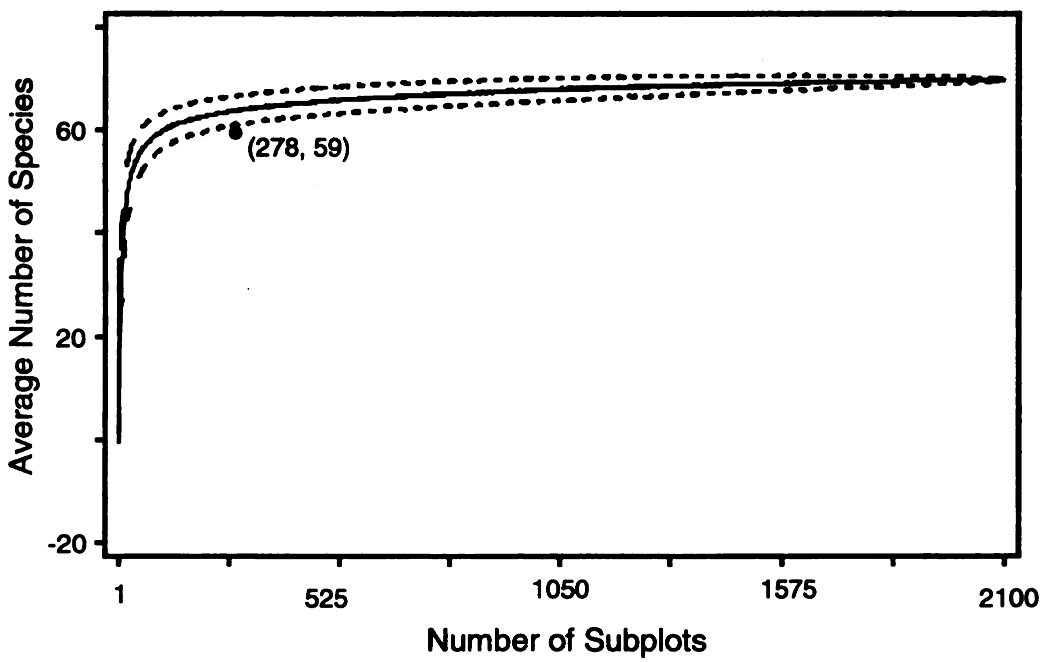

Figure 25: Species-area curve for all plots from which soil moisture data was taken. The coordinate listed indicates the species richness for the damaged subplots of the study. The hashed lines indicate 1 standard deviation about the mean.

The species losses in the impacted areas were not uniform across the study. The 4 sites had different diversities and the effects of the disturbance were more or less pronounced.

At Site 1, Pitelka's trail, there was a total of 36 impacted subplots containing 17 species. 36 subplots sampled at random from the 320 total subplots for generation of the species area curves had a mean number of species of approximately 28. Graphs of the species area curve with the standard deviation about the mean are shown in Figure 26.

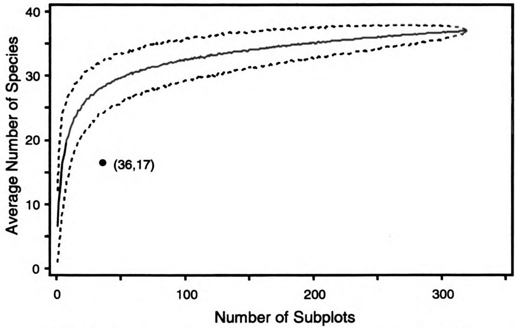

Figure 26: Species-area curve for all plots at site 1, from which soil moisture data was taken. The coordinate listed indicates the species richness for the damaged subplots. The hashed lines indicate 1 standard deviation about the mean.

At Site 2, the CRREL test site, there was a total of 52 impacted subplots containing 10 species. 52 subplots sampled at random from the 240 total subplots for generation of the species area curves had a mean number of species of approximately 11. Although the impacted subplots contained one fewer species, this was still within the expected range of species richness. Graphs of the species area curve with the standard deviation about the mean are shown in Figure 27.

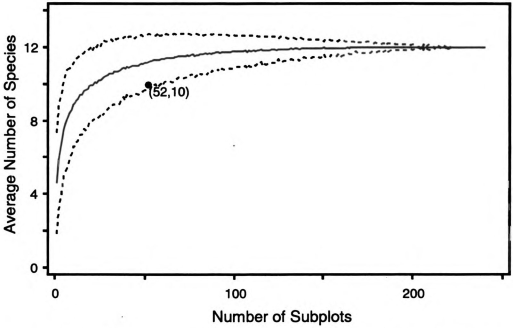

Figure 27: Species-area curve for all plots at site 2, from which soil moisture data was taken. The coordinate listed indicates the species richness for the damaged subplots. The hashed lines indicate 1 standard deviation about the mean.

At Site 3, the oldest of the CRREL trails, there was a total of 64 impacted subplots containing 38 species. 64 subplots sampled at random from the 560 total subplots for generation of the species area curves had a mean number of species of approximately 48. Graphs of the species area curve with the standard deviation about the mean are shown in Figure 28.

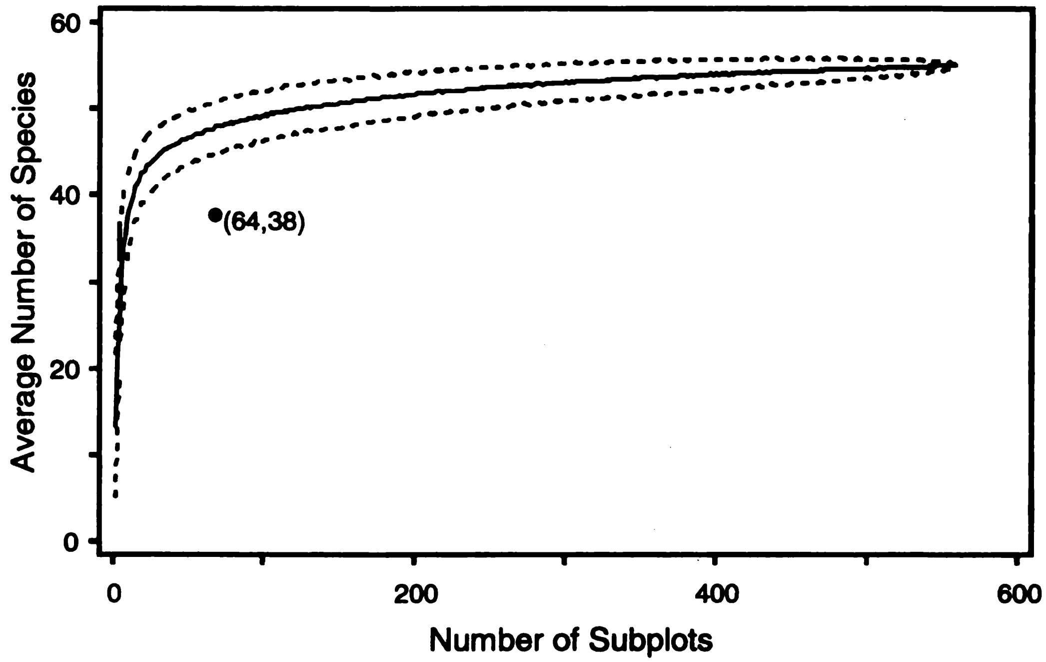

Figure 28: Species-area curve for all plots at site 3, from which soil moisture data was taken. The coordinate listed indicates the species richness for the damaged subplots. The hashed lines indicate 1 standard deviation about the mean.

At Site 4, the younger of the CRREL trails, there was a total of 126 impacted subplots containing 53 species. 126 subplots sampled at random from the 958 total subplots for generation of the species area curves had a mean number of species of approximately 58. Graphs of the species area curve with the standard deviation about the mean are shown in Figure 29.

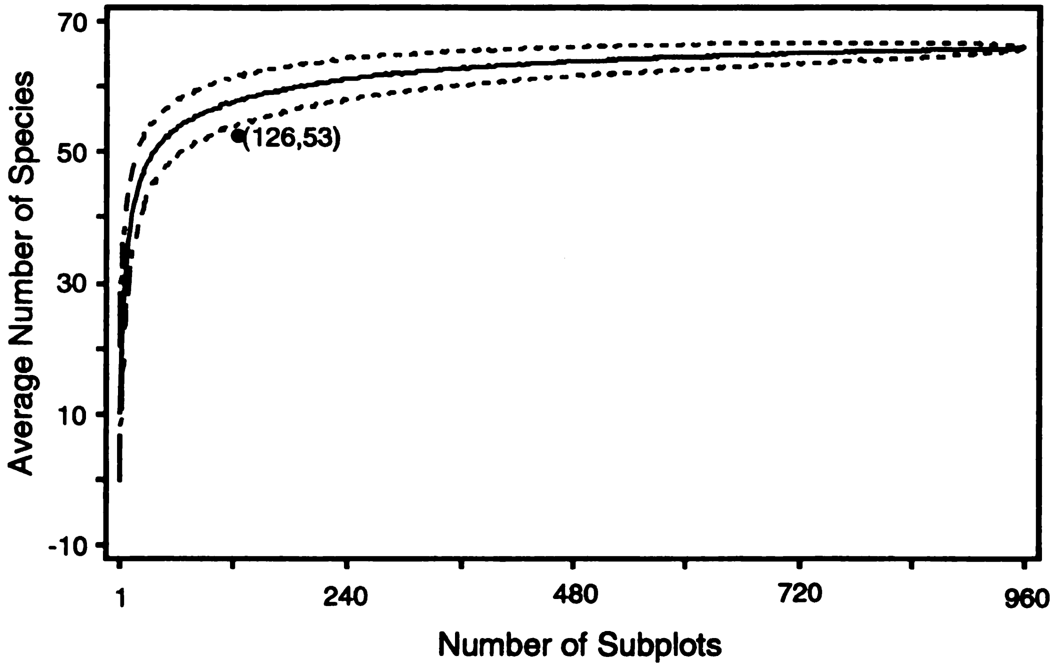

Figure 29: Species-area curve for all plots at site 4, from which soil moisture data was taken. The coordinate listed indicates the species richness for the damaged subplots. The hashed lines indicate 1 standard deviation about the mean.

In the examination of species richness based on the distance from the impact there is considerable overlap in the standard deviation about the mean of the curves, indicating that the species richness at any given distance will be fairly similar to that of any other distance. In both the whole-study case and the cases of the individual sites, the impacted subplots and the subplots between tracks that did not experience a physical impact, consistently have the lowest species richness. The species richness generally increases with distance away from the impact (Figures 30-34). One exception occurred at Site 4 where the lowest species richness was found at the three greatest distances away from the impact (Figure 34).

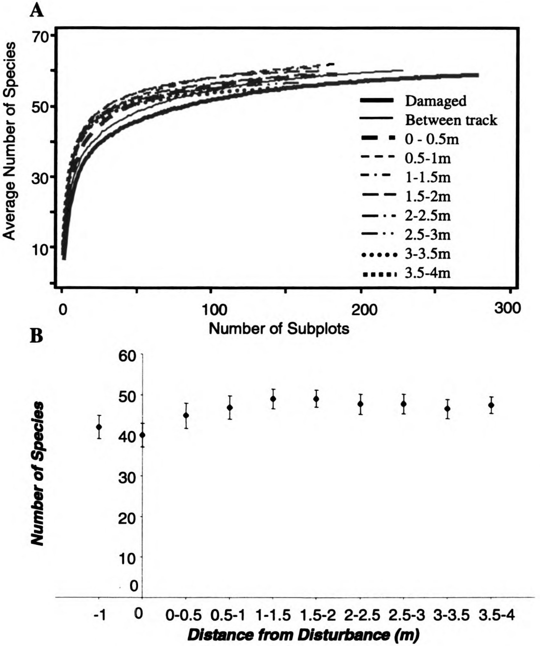

Figure 30: **(A)** Species richness at a given distance from impact over the whole study. **(B)** Mean species richness of 26 randomly chosen grid cells at a given distance from impact over the whole study. A value of 26 grid cells was chosen to approximate the inflection point of the species area curve for the impacted subplots. A negative distance indicates subplots found between tracks. Error bars represent one standard deviation about the mean.

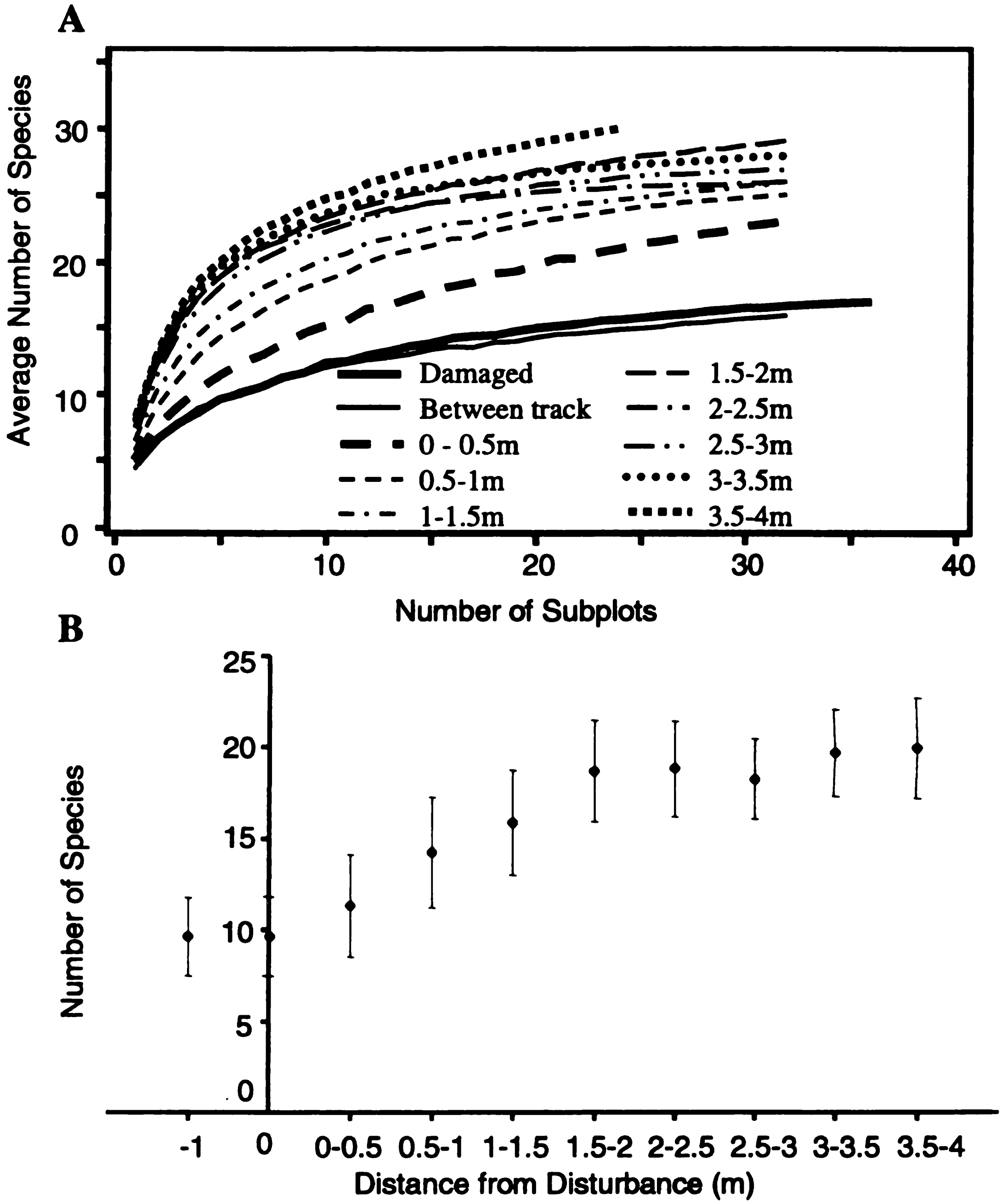

Figure 31: (A) Species richness at a given distance from impact for Site 1. (B) Mean species richness of 5 randomly chosen grid cells at a given distance from impact for site 1. A value of 5 grid cells was chosen to include the inflection points of the species area curves for all distances from the impact. A negative distance indicates subplots found between tracks. Error bars represent one standard deviation about the mean.

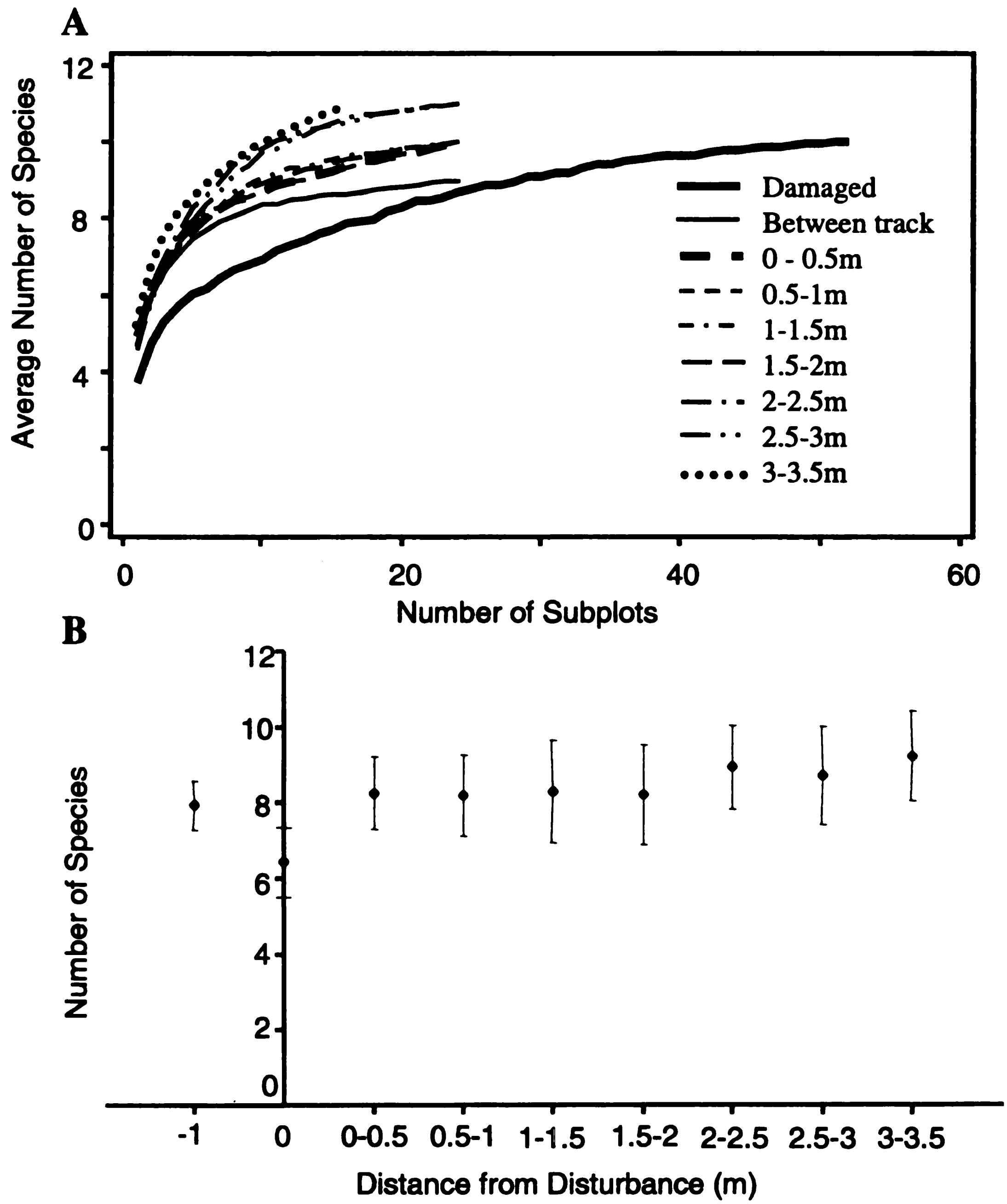

Figure 32: (A) Species richness at a given distance from impact for Site 2. **(B)** Mean species richness of 7 randomly chosen grid cells at a given distance from impact at site 2. A value of 7 grid cells was chosen to include the inflection points of the species area curves for all distances from the impact. A negative distance indicates subplots found between tracks. Error bars represent one standard deviation about the mean.

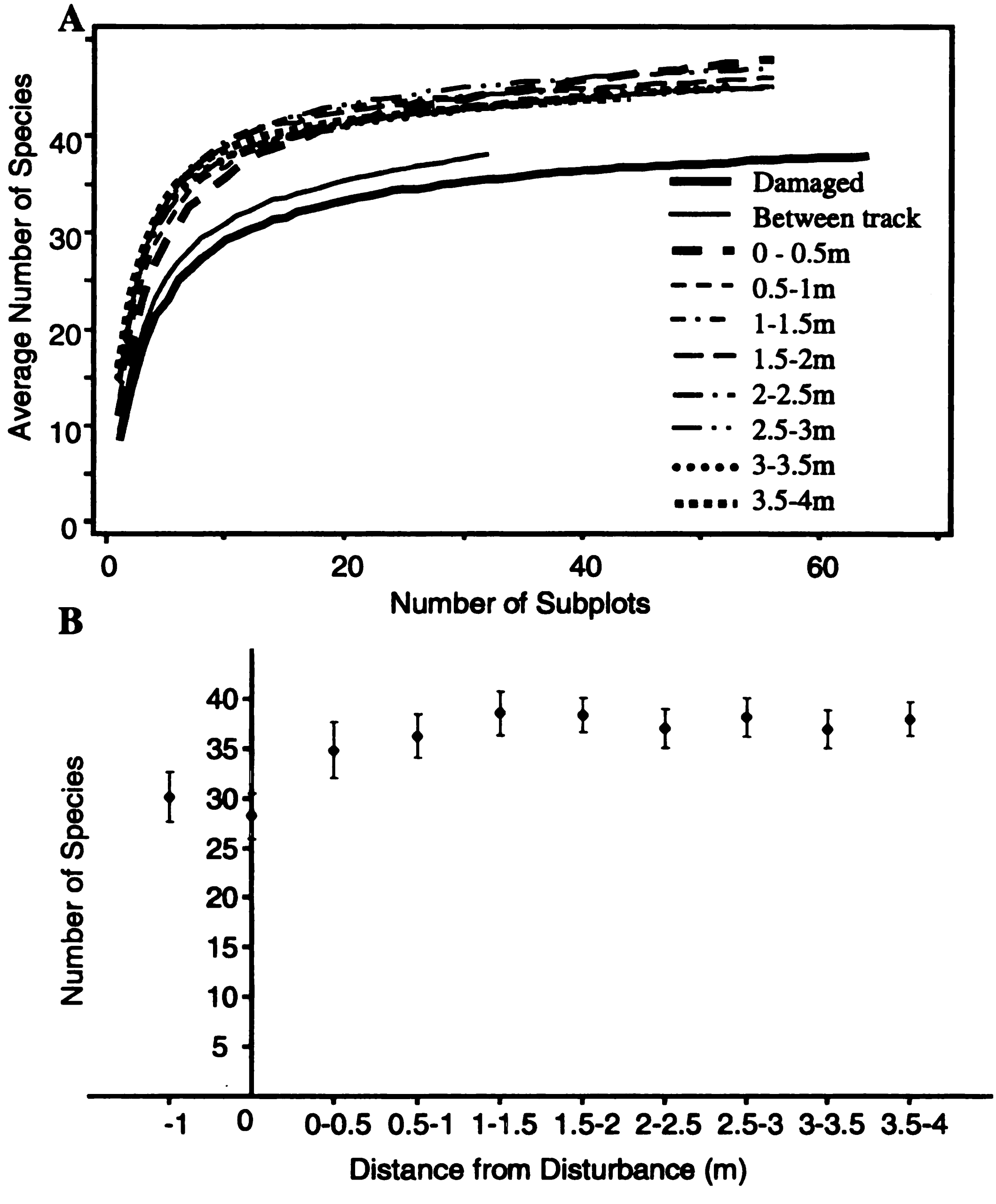

Figure 33: (A) Species richness at a given distance from impact at Site 3. (B) Mean species richness of 9 randomly chosen grid cells at a given distance from impact at site 3. A value of 9 grid cells was chosen to include the inflection points for the species area curves at each distance from the impact. A negative distance indicates subplots found between tracks. Error bars represent one standard deviation about the mean.

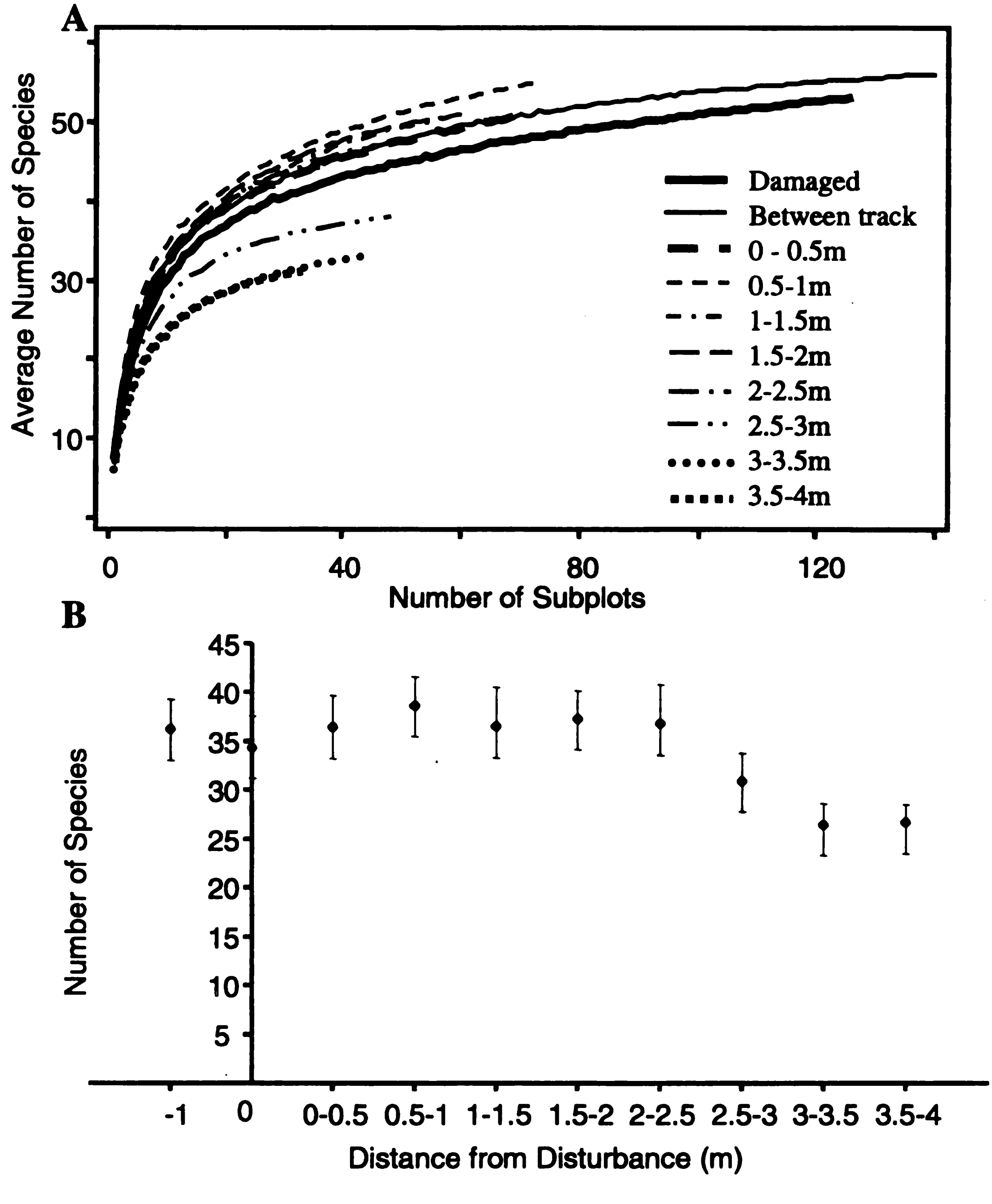

Figure 34: **(A)** Species richness at a given distance from impact at Site 4. **(B)** Mean species richness of 15 randomly chosen grid cells at a given distance from impact at site 4. A value of 15 grid cells was chosen to include the inflection points for the species area curves at each distance from the impact. A negative distance indicates subplots found between tracks. Error bars represent one standard deviation about the mean.

The results of the analysis of variance that tested for the effects of distance from impact on species richness and the comparisons made with Tukey's test vary between sites. At Site 1, there was a significant effect of distance class on richness ($p=0.002$, error df=27, $\alpha=0.05$). The species richness of the impacted subplots and the subplots located between the tracks was significantly lower than the species richness of all the other distance classes. Areas between 1.5 and 2m away from the impact and areas between 3 and 3.5 meters from impact had significantly higher species richness than all other distance classes (see Table 5).

Table 5: Comparison of species richness for Site 1, based on distance from impact. Significance class indicates which classes are significantly different from each other. Distance classes that share a letter are not significantly different. For example, a is significantly different from b, but ab is significantly different from neither a nor b.

Distance Class (m)	Upper 95% CI	Lower 95% CI	Significance Class
between	3.54	10.96	a
impacted	4.54	11.96	a
0-0.5	7.04	14.46	ab
0.5-1	8.79	16.21	ab
1-1.5	10.79	18.21	ab
1.5-2	12.79	20.21	b
2-2.5	11.04	18.46	ab
2.5-3	11.79	19.21	ab
3-3.5	14.29	21.71	b

At Site 2 there was no significant effect of distance on species richness ($p=0.811$, error df=16, $\alpha=0.05$). The pair-wise comparisons showed that no distance class had significantly different species richness from another (see Table 6).

Table 6: Comparison of species richness for Site 2, based on distance from impact. Significance class indicates which classes are significantly different from each other. Distance classes that share a letter are not significantly different. For example, a is significantly different from b, but ab is significantly different from neither a nor b.

Distance Class (m)	Upper 95% CI	Lower 95% CI	Significance Class
between	5.43	9.90	a
impacted	4.43	8.90	a
0-0.5	5.43	9.90	a
0.5-1	5.10	9.57	a
1-1.5	4.43	8.90	a
1.5-2	6.10	10.57	a
2-2.5	6.43	10.90	a
2.5-3	6.10	10.57	a

At Site 3, there was a significant effect of distance class on richness ($p<0.001$, error df=54, $\alpha=0.05$). The species richness of the subplots located between the tracks was significantly lower than the species richness of all the other non-impacted subplots. The species richness of the impacted subplots was not significantly different from either the areas between tracks or the areas immediately adjacent to the impact. It was, however, significantly lower than that of all other distance classes. All of the distance classes beyond 0.5 meters away from the disturbance had species richnesses significantly higher than that of the impacted subplots. The species richness of the area between 2.5 and 3 meters away from impact is also significantly higher than that of the areas immediately adjacent to the impact (see Table 7).

At Site 4 there was no significant effect of distance on species richness ($p=0.993$, error df=48, $\alpha=0.05$). The pair-wise comparisons showed that no distance class had significantly different species richness from another (see Table 8).

Table 7: Comparison of species richness for Site 3, based on distance from impact. Significance class indicates which classes are significantly different from each other. Distance classes that share a letter are not significantly different. For example, a is significantly different from b, but ab is significantly different from neither a nor b.

Distance Class (m)	Upper 95% CI	Lower 95% CI	Significance Class
between	12.49	18.65	a
impacted	15.78	21.93	ab
0-0.5	20.21	26.36	bc
0.5-1	23.35	29.51	cd
1-1.5	24.78	30.93	cd
1.5-2	25.78	31.93	cd
2-2.5	24.92	31.08	cd
2.5-3	26.64	32.79	d
3-3.5	23.92	30.08	cd

Table 8: Comparison of species richness for Site 4, based on distance from impact. Significance class indicates which classes are significantly different from each other. Distance classes that share a letter are not significantly different. For example, a is significantly different from b, but ab is significantly different from neither a nor b.

Distance Class (m)	Upper 95% CI	Lower 95% CI	Significance Class
between	12.07	25.93	a
impacted	11.18	25.04	a
0-0.5	10.96	24.82	a
0.5-1	13.41	27.26	a
1-1.5	10.52	24.37	a
1.5-2	12.07	25.93	a

CHAPTER 4

4 Discussion

4.1 Effects Of Terrain Damage

Signatures of vehicle trails are still present after 30 years or more of natural recovery. There are differences in the appearance of the trails, the thermal regime of the soil and in the plant communities themselves. Because there is a significant difference in the topography of the plots, there is a possibility that drainage and moisture levels within the tracks and adjacent areas of tundra also differ. This could have an effect on the plant community in these areas in the long run (Pearson 1994).

It should be noted that the differences, although statistically significant are not large. Because the landscape inherently has a large degree of microscale heterogeneity, the degree to which this difference will be ecologically significant is determined, in large part, by the characteristics of the site. On a dry slope where the soil is well drained, the depressions caused by vehicle traffic will not likely affect the surface or soil moisture levels. Similarly, in wet meadow areas that are typically submerged for a large part of the growing season, the change in the depth of standing water caused by off-road traffic is not likely to have an effect on the plants.

There can be ecologically significant differences in areas of moderate drainage. At Pitelka's trail, Site 1, the depression of the ground due to vehicle tracks has led to ponds forming in several locations. The plant communities in these ponds are drastically different from those outside the ponds. The result is small patches of wet meadow-like communities within an area dominated by lichen-heath type plants. This site is the most polygonized of the four sites and so we may expect to see different plants within polygon troughs, but the difference between a trough community and a polygon center community typical of the site, is not as distinct as the differences seen between the impacted and non-impacted areas found here. It is likely that the succession to a wet community is accentuated a great deal by the microtopographic differences caused by the off-road traffic at this site.

There seems to be no difference between the impacted and non-impacted areas in terms of soil moisture and soil compaction. This is encouraging because it suggests that the soil environment has recovered to the point where the root systems of the plants will not be affected by their location in relation to the tracks. There are, of course, other differences in the soil. No nutrient analyses were done in this study. If differences were observed in the nutrient levels of the soil it would be important for the recovery of the plants.

Though soil moisture and compaction were similar between impacted and non-impacted areas, one soil property, which differed significantly, was the extent to which the soil was able to thaw. In the most drastic case, an increase in active layer thickness allows plant roots to grow deeper and have access to more nutrients. This has the potential to effect plant vigor leading to larger, more robust plants with higher fitness. The effects would likely differ between species and the competition between species would be affected. Over the long-term, successional pathways could be changed by effects like this. The case presented here is an extreme one, but may not be terribly unrealistic given that the differences in thaw depth between impacted and non-impacted terrain are still significant after as much as 40 years of natural recovery. Long-term exposure to altered conditions can be an important driver of community change. Increased microbial activity in a thicker active layer over such a long period of time could greatly affect the nutrient levels in the soil. There is concern that carbon dioxide flux from the soil would be altered as well by these types of conditions.

Other evidence for successional change is found in the vegetation ordinations. The graphs of the Principal Components Analysis (PCA) of the vegetation data for the whole study demonstrate a greater variation in the relative cover of non-impacted subplots than that of impacted subplots. A possible explanation for this is that the disturbance caused by the vehicles has reset succession back to some baseline in the impacted plots.

If one considers that succession is not unidirectional, it is logical to think that undisturbed areas will diverge in their vegetation communities within the range of those communities able to cope with the particular environmental restraints present. This divergence would be based on the chance arrival of species and the fortunes of those species in dealing with the microenvironment of the place where the propagules end up.

If a vehicle drives over the tundra causing the destruction of the plant base, the rarer species, or even just the slow growing species, the succession in that particular spot would be reset to a base of ruderal species or in many cases the faster growing clonal plants in the surrounding undisturbed areas. These baseline communities would be more similar to each other than would be the undisturbed communities that have diverged from each other unhindered by the damage caused by the disturbance. Possible results would be lags in succession and likely changes in the direction of the successional pathways leading to different communities than would otherwise be present. The magnitude of the change would be related to the severity of the impact.

It is the intent of this study to test some hypotheses about the controlling factors involved in the recovery of tundra from disturbance, and to generate some others. The author's initial thoughts were that the moisture of the soil would have a strong impact on the resistance to damage and possibly also on the resilience of the system. Several other environmental factors were also examined to get a better feel for the total picture rather than to look at one variable, however important it may be. Interestingly enough, the PCA results suggest that many of these other variables may be more closely related to the distribution of the vegetation than the variable of primary interest. It is important to consider that many of the variables examined in this study may be fairly strongly correlated to each other.

The variable that correlated most highly with the ordination axes, in both the whole-study ordination, and the ordination using only those plots from which soil moisture data were collected, was the amount of bare soil present in the plot. Bare soil was fairly rare in this study and nearly all subplots had a total relative plant cover of 100%. The presence of bare soil is often representative of a continuously disturbed site, such as a frost boil or a grazing site. This suggests that the vegetation present in a plot containing bare soil may be similar to that found in a site disturbed by vehicles. Consider that the bare soil condition was only found in plots located on the dry ridge at Sites 3 and 4. It is possible that the similarities of plant communities found in areas with bare soil are based on the well-drained soils as much as on the actual presence of bare soil.

Another of the variables most highly correlated with the ordination axes was the depth of the active layer. As stated earlier, there were significant differences in the active layer depth between impacted and non-impacted areas. Because the active layer is significantly affected by disturbance and is implicated as a possible controlling factor for the vegetation, this demonstrates a considerable link between disturbance and vegetation cover that continues beyond the initial impact. It should be noted, however, that correlation does not imply causality.

Another variable that is potentially important is the average soil pH of the plot. The soil pH was collected along with the soil moisture data and as such it is only available for the plots from which soil moisture data were taken. In the ordination for these specific plots, soil pH was most highly correlated with the second ordination axis. This suggests that the pH controls to a degree the vegetation present in a location. Therefore, knowing the pH of the soil in an area could give an indication of the likely species to invade in a newly disturbed patch. In turn, knowing the growth rates and colonization rates of these plants may give an indication of the speed in which an area is likely to recover.

The soil pH recorded in this study ranged from 5 to slightly above 7, indicating that the site is primarily weakly acidic. It would have been interesting to also test areas of alkaline soil. However, this is an uncommon condition in the study area and, therefore, poses a difficulty in finding comparable vehicle trails on alkaline sites.

Although soil moisture had lower correlations with the ordination axes than other variables, it still bears consideration. It should be kept in mind that the variables that have higher correlations typically are themselves correlated with available soil moisture. As previously mentioned, bare soil is found in predominantly drier areas. Data collected in this study, as well as the general observation, shows that, near Barrow, Alaska, sites with high soil moisture content typically have shallower thaw depths than areas of dry soil

(Komarkova & Webber 1980). It appears that the factors which directly affect the vegetation present in a plot are affected themselves by the amount of soil moisture present in a site.

Looking at the ordinations for the individual sites tells a slightly different story. Generally, the ordination axes explain a greater amount of the variation in the data and the variables correlate better with the axes. This is likely due to the smaller amount of variation contained within an individual site compared to the whole study.

One of the differences seen in these ordinations is that, at the level of the individual site, the effect of the amount of bare soil is overshadowed by the other variables that may have a higher site-specific effect. There was no bare soil present at either Sites 1 or 2. At Site 3, bare soil had the highest correlation with axis 3 of the PCA rather than axis 1 as it did in the whole study PCA. At Site 4, other variables had higher correlations with all three of the primary ordination axes.

At the wetter sites, the first two axes were most correlated with average pH of the soil and the average amount of standing water present in the plot. The average pH correlation is no surprise considering that it had the highest correlation with axis 2 in the whole study moisture ordination. Average amount of surface water did not figure prominently in the whole study ordinations but in these individual sites, particularly Site 2, it does. Axis 1 of the PCA for Site 1 captured nearly 45% of the variation in the data, which is the highest of any axis in any of the ordinations carried out in this study. The correlation between this axis and the amount of standing water present is the highest of any variable with any axis in this study (r^2=0.719).

At the drier sites, active layer depth was more important than at the wet sites. All three primary axes at Site 4 had their highest correlations with thaw depth. This is also the case for axis 3 of Site 2 and axis 2 of Site 3.

At Site 3 the highest correlation with axis 1 was with the average microtopographic height of the plots. The average microtopographic height is best thought of as an indication of the difference in height of non-impacted areas and the corresponding impacted areas, since all points were recorded as height above a baseline. If wheel ruts were present from traffic, the impacted portion of the plots would be lower on average. The PCA of Site 3 separates the plots distinctly into a group of impacted subplots and another of non-impacted subplots indicating that there is different vegetation present at lower areas than at higher areas. Microtopography is also most closely correlated with axis 3 at Site 1. In wetter areas such as Site 1, microtopography is often the cause of differences in the amount of surface water present, which is also quite important at Site 1. It should be noted that at Site 1 the depressions caused by Weasel traffic have since become ponds in which species are found that are not present within other parts of the site.

One interesting point is the lack of a strong correlation of any of the environmental variables with the second axis in the whole-study PCA of the vegetation data. The highest correlation with this axis in the ordinations of either the whole-study or of those plots with moisture data was r^2=0.116. This is weak in comparison to the other axes. None of the environmental variables recorded in this seem to adequately explain this large portion of the variation in data. In further studies of this kind, nutrient availability should also be considered. This study focuses on the physical impact of off-road vehicle disturbance, but if there is also a chemical impact, it may go a long way to explaining the differences observed in this study.

Perhaps the most striking evidence of lingering disturbance from vehicle traffic comes from the loss of species from impacted subplots that are present in the surrounding area. There is a possible bias involved in comparing the species richness of the impacted and non-impacted areas within a plot. A great deal more area was sampled in the non-impacted areas surrounding the tracks and so it is more likely to encounter rare species in the non-impacted parts of the plot. In an attempt to remove this bias, a variation of the species area curve was used. A typical species area curve estimates the number of species that one would likely encounter in a plot of given size based on the total number of available species in the area. It is assumed that the species are distributed randomly throughout the area. If the species were, in fact, randomly distributed throughout the landscape, one would be just as likely to find rare species on an impacted area as a non-impacted one. Therefore, a designated area of impacted ground should yield the same species richness as the same area of un-impacted ground randomly chosen. If, on the other hand, randomly chosen, un-impacted areas yield more or fewer species than the same area of impacted land, it can be concluded that the species are not randomly distributed and any loss or gain could be attributed to the presence of the disturbance.

A species area curve of this sort was generated using the data from all plots for which soil moisture data were collected. There were a total of 70 species in this data set, only 59 of which were found in the impacted areas. If the distribution of species were random, there should be approximately 64 species present in the impacted area. Fifty-nine species is more than one standard deviation below the mean value of 64, which indicates that the species distribution is not random throughout the landscape and that the loss of species richness in the impacted areas is indeed related to the disturbance. Negative effects of the vehicle disturbance are, therefore, still present after 25 to nearly 40 years of recovery.

Information from these species area curves is interesting in another light and supports the hypothesis of this study that the recovery rate varies based upon the moisture of the sites. The results of the species area curves generated for the individual sites all show a reduction in species in the impacted areas over the non-impacted. However, at Site 2, the CRREL test site, the number of species present falls well within one standard deviation of the mean species richness showing that the species loss is not significant. This is the wettest of the three sites and is expected to have the highest resilience of all the sites.

The species loss at Site 4 is greater than one standard deviation from the mean, indicating a significant loss of species. It is, however, close to being within the acceptable range. This site combines some of the wettest plots and some of the driest plots. Site 3 has a similar community composition to the drier portions of Site 4. At Site 3, the species richness is well below the acceptable range about the mean. Because Site 3 has had approximately 2 years longer to recover from a similarly sever impact, it could be expected that Site 3's species richness would be closer to the mean than at Site 4, but this is not the case. This is probably due to the increased resilience of the wetter plots at Site 4.

Site 1 demonstrates the greatest difference between the species richness of the impacted subplots and the mean random species richness. This site experienced the most infrequent and lightest disturbances of any of the four, though over a longer duration. Even considering the longer time span over which the trail was used, the number of passes over this particular trail is likely to be fewer than was the case at Sites 3 or 4. Some of the test tracks at Site 2 which had recovered to the point where they were not able to be located for this study were documented to have had a greater number of passes than was estimated for Pitelka's trail. Though possibly having the least impact and the greatest recovery time of the four sites, Site 1 shows the greatest contrast between the species richness of it's impacted subplots and the predicted species richness of a randomly selected area within the site.

Site 1 had soil moisture levels intermediate between Site 2 on the high end of the spectrum and Sites 3 and 4 at the low end. It appears that Site 1 suffers from the reduced resistance commonly found at wet sites, as well as the reduced resilience commonly found at dry sites. This site is, therefore, easily impacted and slow to recover.

4.2 Importance of Scale

It is important to consider the scale of the disturbance to make predictions about the severity of the impact over longer time scales. The disturbances considered in this study are relatively small in size and short in duration of impact. On a typical Weasel trail considered in this study, none of the impacted points were more than one or two meters away from non-impacted areas. In rare cases where the disturbance was more severe, the distance to non-impacted areas could be as much as three or four meters, but would not likely be more. Considering the clonal nature of many of the plants found in the study sites, it could be expected that the root systems of many of the plants cross the boundary between impacted and non-impacted terrain and would dampen the effects of the impacted condition. Recovery can be expected to progress fairly quickly in this case.

The vehicles used to make the trails examined in this study were, for the most part, confined to established trails and only used a few times in a season. In cases where drivers of off-road vehicles don't adhere to limitations like these, we can expect disturbance over a broader area. The farther a disturbed area is from the nearest pristine tundra, the longer it is likely to take for recovery to proceed. Likewise, the more frequent the disturbance, the higher the degree of dissimilarity to the undisturbed tundra and the longer recovery can be expected to take.

In the examination of species diversity in an area, the scale of the study plays several roles. This particular study measured the diversity at several points to generate an estimate of the stand diversity for the study sites in question. It is necessary to consider this in a study of this sort since diversity at these two scales is not likely to respond similarly to a disturbance. For example, Chaneton and Facelli (1991) found that in response to flooding in Argentinean grasslands, the patch diversity behaved differently from stand diversity. Their study also examined the effects of grazing in combination with flooding and they found that the relationship between the effect of flooding on patch and stand diversities was not consistent or predictable between the grazing treatments. Therefore, it is necessary to consider the scale at which a disturbance is affecting an area in order to make the appropriate measurements to detect it. This is directly applicable to studies like this where the disturbed area is influenced by vehicle disturbance, grazing by animals and other tundra-specific disturbances such as thermokarst processes.

In this case, if we treat an entire site as a stand and the disturbance as a patch then we are at a loss to calculate changes in diversity without a pre-disturbance measurement of stand diversity, though we can compare the disturbed patch to an undisturbed patch and examine the patch diversity. When considering a disturbance and its undisturbed counterpart as distinct stands from each other and individual subplots as patches, it is possible to detect a reduction in diversity at this smaller scale due to disturbance and relate it back to the whole diversity of a vehicle track or the surrounding undisturbed land.

4.3 Relative Damage Of Each Vehicle

Of the three vehicles examined in the initial CRREL study, the M-29 Weasel is the one which has made the majority of the tracks identified and examined in this study. This is a good reflection of the trend in off-road vehicles from 1955 to 1975. This particular vehicle no longer sees use on the tundra. There are a few similar tracked vehicles still present in Barrow, but these are rarely, if ever, used. Nearly all large, off-road vehicle traffic is conducted using Rolligons.

The Rolligon is a large, low-pressure tire vehicle that was designed for use on fragile surfaces and has since replaced the M-29 Weasel as the primary mode of large off-road vehicle traffic. What is perhaps ironic is that the Rolligon is not as gentle on the landscape as was the Weasel. The initial result of the Second CRREL study run at Site 2 by Abele and Atwood (1976) indicated that in wet meadow tundra, 15 passes of a Rolligon was as devastating, if not more so, than 50 passes of a Weasel. There are a number of Rolligons of various sizes and types currently in use in Barrow and at the Prudhoe Bay oil field.

The vehicle that had the best test results was the SK-5 hovercraft. After 4 years of recovery, the track signature was nearly invisible to the eye and Abele and Atwood (1976) had reported an almost complete recovery. Although the SK-5 performed very well in the tests, it was deemed unusable for off-road transport. Hovercrafts are very difficult to maneuver over tundra and are not practical for carrying large loads.

4.4 Signature Spread

An interesting phenomenon in the recovery of terrain from disturbance is the effect of the disturbance on adjacent areas that were not impacted. These adjacent areas were unaffected by the direct disturbance, but secondary effects spreading from the impacted areas to their non-impacted neighbors begin after the initial disturbance has ended. Changes in drainage or heat conductivity of adjacent soil will have lingering effects on non-impacted terrain as long as the signature of the initial impact remains. In this way, the disturbance is likely to extend to areas not initially impacted and possibly even degrade further before recovery takes place.

The species richness data gathered from subplots at set distances from the impact demonstrates evidence for this. Though not directly impacted by the wheel or track of a vehicle, the areas caught between the ruts had nearly as low species richness as the impacted areas. Likewise, the areas immediately outside of the ruts have low species richness compared to subplots that are a greater distance away. This suggests degradation in areas that were not physically impacted by the initial disturbance.

Again it is important to consider the scale of examination for comparisons of this kind. In this particular case, the subplots were a set width of 0.5 m. This scale is fine enough to register the differences in richness as distance increases and seems to be appropriate. It also makes sense because the wheel ruts themselves are generally on a similar scale ranging from 0.3 – 2.0 m. If the subplot size were even 1m wide instead of 0.5m, it is likely that any differences would be masked by including areas that are beyond the signature spread with areas within it.

Signature spread can be a problem in studies like this one that seek to locate disturbances left by others in the past, which were, in most cases, not well documented since it was not the focus of the activity that caused them. It becomes more difficult to distinguish the actual boundaries of the initial impact from the signature spread and leaves it to the judgment of the investigator to determine what should be included in the study. The ideal way to conduct a study of this nature would be to set up the disturbance and immediately mark off any boundaries in a fairly permanent manner for study in the long term.

4.5 Functional Recovery and Continuous Succession

The effects of many vehicle disturbances are still present on the tundra, including, but certainly not limited to, those which are the subject of this study. However, the results are positive in some aspects. The vegetation has returned to areas from which it had been totally removed as a result of vehicle disturbance. In cases such as Pitelka's trail, Site 1, the vegetation that has colonized the impacted terrain is different from the initial community present. This appears to be a case where a new equilibrium has been formed with the soil environment so that it is unlikely that the impacted area will ever return to initial conditions. This can be considered a functional recovery since a different, but healthy, community is in place as a result of the disturbance. Peterson felt during his study in 1975 that this particular area would never be more than a patch of bare ground and was impressed at the amount of recovery at the time of this study (Peterson, K.M. *personal communication*).

It should also be considered that because succession is always ongoing, it is likely that the communities found on formerly disturbed areas will never match identically with their undisturbed counterparts. Succession may have advanced the recovery of the community to the point where it mirrors its pre-disturbance condition, but the neighboring undisturbed communities have not been static during those years of recovery and might therefore have diverged. The disturbed community will either lag behind the undisturbed community or change successional pathways.

4.6 Summary And Conclusions

The initial general hypothesis of this study is that site moisture plays a strong role in the resistance and resilience of the tundra vegetation to damage by vehicles. The prevailing literature supports the notion that wet sites recover quickly due to a high resilience and dry sites recover slowly but have high resistance to impact. This study conforms to the general hypothesis, however, a finding of this study, for this region and for these types of disturbances, is that landscapes with intermediate moisture levels, appear to show the most residual effect between impacted and non-impacted areas after 30 years. This may be a result of the combined effects of having a lower resistance than dry sites and lower resilience than wet sites. It is impossible to speak directly about recovery rate since there is no real quantitative data to describe the initial conditions after impact. We are able to determine similarity to the undisturbed condition, but the degree of similarity is a combination of resistance and resilience and we can not separate these two factors without knowledge of the initial impact. However, the photographic and anecdotal evidence suggests enough about the initial impacts that we can make inferences about them even if they can not be directly measured.

The vegetation ordinations indicate that it is not generally the soil moisture that dictates the variation in the vegetation. Generally, thaw depth, the amount of bare soil, and soil pH correlate more closely with the ordination axes indicating that they may be controlling factors in the variation in vegetation in the areas. However, these effects are often related to the soil moisture and standing water at a site, and are in keeping with the observations of Webber (1978) that the direct controls of vegetation at Barrow are site relief and water drainage.

The strongest evidence for moisture controlling the recovery of vegetation at a site is demonstrated by the losses of species in impacted subplots. At the wettest site, there is not a significant loss of species in the impacted subplots. At the driest sites there are fewer species in the impacted subplots than in the non-impacted subplots, but the differences are not as pronounced as they are at the intermediate moisture site where less than half of the species are present within impacted subplots.

Additionally, there is evidence that the disturbance has spread beyond the initial impact of the vehicle traffic. The species richness increases as the distance from the initial impact increases demonstrating that the areas adjacent to, but not immediately impacted by the vehicles have suffered a subsequent decline in species richness. The landscape has suffered further degradation prior to any recovery and the lingering effects of the impact are present after 30 years even on terrain that was not initially impacted. This secondary expansion of species loss has not been previously recognized.

Residual effects of off-road vehicle traffic are still evident at the study sites after 30 years. Differences in microtopography are still present allowing for identification of the tracks. Active layer depth and vegetation composition of impacted areas still differ from their non-impacted counterparts. Nevertheless, considerable plant community function has been restored. The impacted areas have been re-colonized by the native plants and almost no bare soil remains where the vegetation had been completely removed by the disturbance. At a glance, the plant communities within the immediately impacted subplots resemble those that were not impacted.

Most ongoing disturbances will likely require more than 30 years to recover depending on the type of terrain. It is certain that some effects of disturbance will never wholly be eliminated. Future off-road vehicle traffic should be kept to a minimum to protect past disturbances from further damage and aid in their functional recovery, as well as to prevent the development of new disturbances. Regulations are already in place in many areas for the protection of the systems, but more attention should be paid to their enforcement. It is important that the public considers the ramifications of continued off-road vehicle use and avoids it when possible.

In cases where off-road vehicle use is unavoidable, the extent and duration of the traffic should be considered before locations for trails are chosen and permits granted. Trails which will be used only a very few times should be made over dry ground where resistance is high enough to withstand the disturbance. Trails to be used repeatedly would be best created over wet areas unless the terrain will not support the weight of the vehicle. The impact will be more severe, but the increased resilience of the area will allow for quicker recovery. Areas of intermediate moisture should be avoided whenever possible as they are easily impacted and very slow to recover.

APPENDIX A

SPECIES LISTS

Table A-1: Species list for Site 1 including the groupings used for analyses of vegetation data in cases where the species could not be identified with certainty.

Species Name	Type
Unknown Algae	Algae
Bryocaulon divergens (Ach.) Kärnefelt	Lichen
Cetraria cucullata	Lichen
Cetraria islandica (L.) Ach.	Lichen
Cladina mitis (Sandst.) Hustich	Lichen
Cladonia sp	Lichen
Dactylina arctica (Richardson) Nyl.	Lichen
Lobaria linita (Ach.) Rabenh.	Lichen
Masonhalea richardsonii (Hook.) Kärnefelt	Lichen
Peltigera sp	Lichen
Pseudophebe pubescens	Lichen
Sphaerophorus globosus (Hudson) Vainio	Lichen
Thamnolia subuliformis (Ehrh.) Culb.	Lichen
Unidentified leafy liverwort	Liverwort
Aulacomnium turgidum (Wahlenb.) Schwaegr.	Moss
Calliergon sp	Moss
Campylium stellatum (Hedw.) C. Jens.	Moss
Drepanocladus brevifolius (Lindb.) Warnst.	Moss
Mnium sp	Moss
Polytrichum juniperinum Hedw.	Moss
Sphagnum sp	Moss
Unidentified bryophyte	Moss
Alopecurus alpinus Sm.	Vascular
Arctophila fulva (Trin.) Anderss.	Vascular
Carex aquatilis Wahlenb.	Vascular
Dupontia fischeri R.Br.	Vascular
Eriophorum angustifolium Honck.	Vascular
Eriophorum scheuchzeri Hoppe	Vascular
Juncus biglumis L.	Vascular
Luzula arctica Blytt	Vascular
Luzula confusa Lindeb.	Vascular
Pedicularis kanei Durand	Vascular
Petasites frigidus (L.) Franch.	Vascular
Poa arctica R.Br.	Vascular
Potentilla hyparctica Malte	Vascular
Ranunculus nivalis L.	Vascular
Salix rotundifolia Trautv.	Vascular

Table A-1: Continued.

Species Name	Type
Saxifraga cernua L.	Vascular
Saxifraga hirculus L.	Vascular
Stellaria laeta Richards.	Vascular

Table A-2: Species list for Site 2 including the groupings used for analyses of vegetation data in cases where the species could not be identified with certainty.

Species Name	Type
Bryocaulon divergens (Ach.) Kärnefelt	Lichen
Peltigera sp	Lichen
Unidentified leafy liverwort	Liverwort
Aulacomnium turgidum (Wahlenb.) Schwaegr.	Moss
Calliergon sp	Moss
Drepanocladus brevifolius (Lindb.) Warnst.	Moss
Mnium sp	Moss
Polytrichum juniperinum Hedw.	Moss
Sphagnum sp	Moss
Dupontia fischeri R.Br.	Vascular
Eriophorum angustifolium Honck.	Vascular
Eriophorum scheuchzeri Hoppe	Vascular
Saxifraga cernua L.	Vascular

Table A-3: Species list for Site 3 including the groupings used for analyses of vegetation data in cases where the species could not be identified with certainty.

Species Name	Type
Unidentified Algae	Algae
Bryocaulon divergens (Ach.) Kärnefelt	Lichen
Cetraria cucullata	Lichen
Cetraria islandica (L.) Ach.	Lichen
Cladina mitis (Sandst.) Hustich	Lichen
Cladonia sp	Lichen
Unidentified Crustose lichen	Lichen
Dactylina arctica (Richardson) Nyl.	Lichen
Hypogymnia austerodes (Nyl.) Raes.	Lichen
Lobaria linita (Ach.) Rabenh.	Lichen
Masonhalea richardsonii (Hook.) Kärnefelt	Lichen
Ochrolechia frigida (Sw.) Lynge	Lichen
Peltigera sp	Lichen
Pseudophebe pubescens	Lichen
Psoroma hypnorum (Vahl) S. Gray	Lichen
Solorina crocea (L.) Ach.	Lichen

Table A-3: Continued.

Species Name	Type
Sphaerophorus globosus (Hudson) Vainio	Lichen
Stereocaulon cf. alpinum Laurer ex Funck	Lichen
Thamnolia subuliformis (Ehrh.) Culb.	Lichen
Unidentified lichen	Lichen
Aulacomnium turgidum (Wahlenb.) Schwaegr.	Moss
Calliergon sp	Moss
Campylium stellatum (Hedw.) C. Jens.	Moss
Dicranum elongatum Schleich. ex Schwaegr.	Moss
Drepanocladus brevifolius (Lindb.) Warnst.	Moss
Mnium sp	Moss
Pohlia nutans (Hedw.) Lindb.	Moss
Polytrichum juniperinum Hedw.	Moss
Racomitrium lanuginosum (Hedw.) Brid.	Moss
Sphagnum sp	Moss
Tomentypnum nitens (Hedw.) Loeske	Moss
Unidentified bryophyte	Moss
Alopecurus alpinus Sm.	Vascular
Arctagrostis latifolia (R.Br.) Griseb.	Vascular
Cardamine pratensis L.	Vascular
Carex aquatilis Wahlenb.	Vascular
Cochlearia officinalis L.	Vascular
Dupontia fischeri R.Br.	Vascular
Eriophorum angustifolium Honck.	Vascular
Eriophorum scheuchzeri Hoppe	Vascular
Luzula arctica Blytt	Vascular
Luzula confusa Lindeb.	Vascular
Pedicularis lanei Durand	Vascular
Petasites frigidus (L.) Franch.	Vascular
Poa arctica R.Br.	Vascular
Potentilla hyparctica Malte	Vascular
Ranunculus nivalis L.	Vascular
Ranunculus pygmaeus Wahlenb.	Vascular
Salix phlebophylla Anderss.	Vascular
Salix rotundifolia Trautv.	Vascular
Saxifraga cernua L.	Vascular
Saxifraga foliolosa R.Br.	Vascular
Saxifraga hirculus L.	Vascular
Saxifraga punctata L.	Vascular
Stellaria laeta Richards.	Vascular
Unknown vascular plant	Vascular

Table A-4: Species list for Site 4 including the groupings used for analyses of vegetation data in cases where the species could not be identified with certainty.

Species Name	Type
Unknown Algae	Algae
Bryocaulon divergens (Ach.) Kärnefelt	Lichen
Cetraria cucullata	Lichen
Cetraria islandica (L.) Ach.	Lichen
Cladonia cf. gracilis (L.) Willd.	Lichen
Cladonia sp	Lichen
Dactylina arctica (Richardson) Nyl.	Lichen
Hypogymnia austerodes (Nyl.) Raes.	Lichen
Lobaria linita (Ach.) Rabenh.	Lichen
Masonhalea richardsonii (Hook.) Kärnefelt	Lichen
Ochrolechia frigida (Sw.) Lynge	Lichen
Parmelia sp	Lichen
Peltigera sp	Lichen
Pseudophebe pubescens	Lichen
Psoroma hypnorum (Vahl) S. Gray	Lichen
Solorina crocea (L.) Ach.	Lichen
Sphaerophorus globosus (Hudson) Vainio	Lichen
Stereocaulon cf. alpinum Laurer ex Funck	Lichen
Thamnolia subuliformis (Ehrh.) Culb.	Lichen
Unidentified lichen	Lichen
Unidentified leafy liverwort	Liverwort
Aulacomnium turgidum (Wahlenb.) Schwaegr.	Moss
Brachythecium turgidum (Hartm.) Kindb.	Moss
Bryum cyclophyllum (Schwaegr.) BSG	Moss
Calliergon sp	Moss
Campylium stellatum (Hedw.) C. Jens.	Moss
Dicranum elongatum Schleich. ex Schwaegr.	Moss
Drepanocladus brevifolius (Lindb.) Warnst.	Moss
Mnium sp	Moss
Pohlia nutans (Hedw.) Lindb.	Moss
Polytrichum juniperinum Hedw.	Moss
Racomitrium lanuginosum (Hedw.) Brid.	Moss
Sphagnum sp	Moss
Tomentypnum nitens (Hedw.) Loeske	Moss
Unidentified bryophyte	Moss
Warnstorfia exannulata (Schimp. in B.S.G.) Loeske	Moss
Alopecurus alpinus Sm.	Vascular
Arctagrostis latifolia (R.Br.) Griseb.	Vascular
Arctophila fulva (Trin.) Anderss.	Vascular
Cardamine pratensis L.	Vascular
Carex aquatilis Wahlenb.	Vascular
Cochlearia officinalis L.	Vascular
Draba pseudopilosa	Vascular
Dupontia fischeri R.Br.	Vascular

Table A-4: Continued.

Species Name	Type
Eriophorum angustifolium Honck.	Vascular
Eriophorum scheuchzeri Hoppe	Vascular
Juncus biglumis L.	Vascular
Luzula arctica Blytt	Vascular
Luzula confusa Lindeb.	Vascular
Oxyria digyna (L.) Hill	Vascular
Papaver hultenii Knaben	Vascular
Pedicularis kanei Durand	Vascular
Petasites frigidus (L.) Franch.	Vascular
Poa arctica R.Br.	Vascular
Potentilla hyparctica Malte	Vascular
Ranunculus nivalis L.	Vascular
Ranunculus pygmaeus Wahlenb.	Vascular
Salix ovalifolia Trautv.	Vascular
Salix phlebophylla Anderss.	Vascular
Salix pulchra Cham.	Vascular
Salix rotundifolia Trautv.	Vascular
Saxifraga cernua L.	Vascular
Saxifraga foliolosa R.Br.	Vascular
Saxifraga hieracifolia Waldst. & Kit.	Vascular
Saxifraga hirculus L.	Vascular
Saxifraga punctata L.	Vascular
Senecio atropurpureus (Ledeb.) Fedtsch.	Vascular
Stellaria humifusa Rottb.	Vascular
Stellaria laeta Richards.	Vascular

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