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Tundra Travel Modeling Project

Alaska Department of Natural Resources,
Division of Mining, Land and Water
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EXECUTIVE SUMMARY

This project is intended to provide natural resource managers with objective, quantitative data to assist decision making regarding cross country tundra travel typically associated with hydrocarbon exploration and development on the North Slope of the Alaskan arctic. The analyses contained herein make no recommendations concerning the environmental conditions when such travel is appropriate. That determination is an issue of policy balancing left to the discretion of land managers. These analyses employed data generated by the first ever standardized, controlled field trials, with base line data, to empirically investigate the effects of winter tundra travel in Alaska.

The project found interaction relationships among ground hardness, snow depth, and snow slab thickness with various types of exploration vehicles which affected the subsequent active layer depth, soil moisture, and vegetation productivity in various tundra communities. These results are not inconsistent with anecdotal field observations and the few available published articles in the scientific literature. Statistically significant differences in depth of active layer, soil moisture at a 15 cm depth, soil temperature at a 15 cm depth and the absorption of photosynthetically active radiation were found among treatment cells and among treatment types. In addition to descriptive analyses, four models were constructed to address physical soil properties. For the purposes of this study, DNR assumes that changes in the abiotic factors of active layer depth and soil moisture drive alteration in tundra vegetation structure and composition.

Two models, one predicting change in the depth of active layer and a second predicting change in soil moisture were created for the wet graminid/moist sedge shrub communities of the coastal plain. Two more models for change in depth of active layer and soil moisture were constructed for the tussock tundra communities which dominate more rolling terrain typically found in the foothills. In addition to the four models, this report discusses the limited potential management utility in using soil temperature, the amount of photosynthetically active radiation absorbed by plants, and changes in micro-topography as tools for the identification of disturbance in the field.

Because of the lack of variability in snow depth cover throughout the period of field experimentation, these models were unable to thoroughly investigate the interaction role

between snow depth and disturbance. Therefore, these models can only be employed after a minimum threshold snow depth of 15 cm has been attained in wet sedge environments and 23 cm in tussock tundra.

The amount of change in disturbance indicators associated with the treatments was found to be greater in tussock tundra than in wet/moist sedge tundra. However, the over all level of change in both community types was generally less than expected. The project found that in the wet sedge tundra, characteristic of the coastal plain, ground hardness and snow slab thickness were the most important environmental ameliorators of disturbance regarding active layer depth and soil moisture. In tussock tundra, only snow cover appeared to play an important role in ameliorating the level of change in active layer depth and soil moisture as a result of treatment. Once certain minimum thresholds for ground hardness, snow slab thickness, and snow depth are attained, it appears that little or no additive effect is realized regarding increased resistance to disturbance in the tundra communities studied.

The project recommends that further monitoring of the plots continue to determine if the changes detected within the study sites increase or decrease over time. If unanticipated change occurs, the model should be altered to take into account new information. In addition, the project recommends that a rigorous program of in-field monitoring of cross tundra travel activity be instituted to verify if disturbance changes materialize consistent with model predictions. Finally, the project recommends DNR institute an adaptive management approach, anticipating an iterative process as new data is collected and the model is improved.

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I. INTRODUCTION AND PURPOSE

A. Introduction

On Alaska's North Slope, the oil and gas industry requires off-road travel across the tundra during winter for seismic exploration, to build ice roads for exploratory drilling, for construction activity, and for routine maintenance of remote infrastructure. The Department of Natural Resources (DNR) authorizes travel across the tundra on state land, which includes the Prudhoe Bay Area and most of the surrounding areas being developed and explored.

DNR authorizes winter travel across the tundra after it determines that the tundra is sufficiently frozen and protected by ample snow cover so that the travel will not have major environmental effects. The length of the winter work season imposes a profound limitation on exploration activity and has declined markedly over the past 30 years along a pronounced downward trend. The number of days between the opening and closing of the tundra for exploration activity has decreased from over two hundred days in 1970, to only about one hundred days in 2003 as a result of progressively later opening (see Figure 1). The degree to which this trend can be attributed to climate change or to changing management strategies cannot easily be discerned.

The reduction in season length is not symmetrically distributed between a later beginning of the season and an earlier end of the season. Rather, most of the shortening of the winter work season occurs as a result of a later onset of winter. According to Alaska Department of Natural Resources data, the opening of tundra travel, (to start the winter work window), is now 85 days later than in the 1970's, while the closure of tundra travel, (ending the winter work window), is now 15 days earlier than in the 1970's (Appendix A). This pattern is consistent with available scientific literature observing a significantly later freeze up of the active layer in autumn (Romanovsky, Sergueev, and Osterkamp 2003) and a slightly earlier disappearance of snow from the tundra in spring (Foster 1989). Therefore, this project concentrates on a model to predict the disturbance consequences of tundra opening, beginning the winter work window, in order to gain maximum benefits from the effort.

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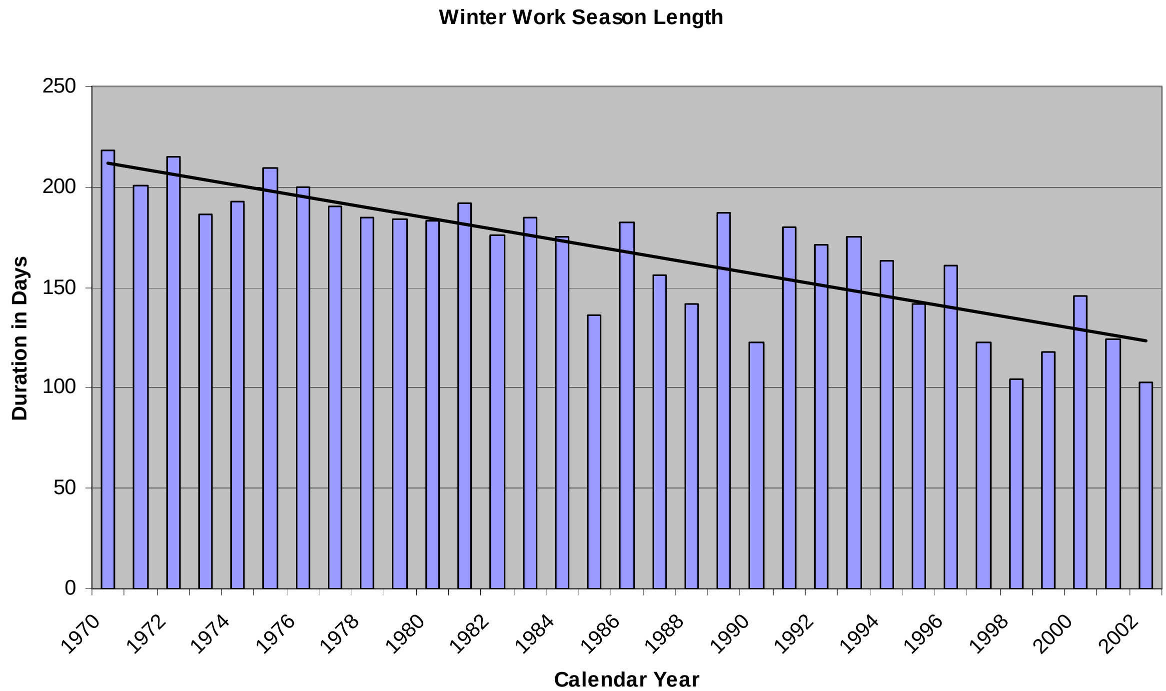
Figure 1. Length of winter work season from 1970-2002.



Land managers need a thorough understanding of the ecological disturbance effects generated by winter tundra travel to ensure the effectiveness of long-term resource management decisions. However, both the National Research Council (NRC) and the Arctic Research Commission (ARC) recently reported a paucity of studies investigating the impact of winter cross-country travel on tundra ecosystems. (NRC 2003; ARC 2003). Noting that data do not now exist describing the effects of overland exploration activity on tundra under varying snow and soil conditions, the NRC stated that, "Studies are needed to determine the amount of snow and the frost penetration required to adequately protect the tundra from the effects of seismic exploration." (NRC 2003). The NRC then commented that "The current regulations governing minimum snow depth and frost penetration to allow [exploration] activities on the tundra are not based on research." Seconding this opinion, the ARC emphatically called for immediate quantitative field investigations to address such issues. (ARC 2003).

This DNR modeling project represents a scientific research attempt to integrate (1) real time environmental variables such as snow depth and ground hardness (at time of disturbance), with (2) controlled and standardized experimental field treatments of

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known type and intensity, with (3) base line ecological characteristics, to (4) identify disturbance associated with winter travel on arctic tundra under different conditions. Because DNR does not currently take into account the interactive effect of varying snow characteristics and ground frost penetration depths (Hazen 1997), the project develops models designed to describe the integration of these variables and thereby enhance DNR decision making.

Understanding the properties of frozen ground and snow is essential to prevent environmental disturbance and costly damage to the oil and gas infrastructure. The need for such knowledge is particularly great today as increased exploration and development is expected on the North Slope as the search for gas reserves accelerate (NRC 2003). Improved information regarding anthropogenic disturbance of tundra ecosystems, directly and indirectly associated with resource exploitation, is a critical emerging need (Forbes 1992), especially in light of the debate concerning the effects of winter vehicular travel and the sensitivity of tundra under the current information vacuum (Kevan et. al. 1995).

The purpose of the study is to provide DNR with objective and quantitative information to understand the extent of environmental change associated with different management choices regarding the timing of tundra opening. With this understanding, DNR can design approaches that may minimize disturbance while facilitating exploration. This project is a response to the findings of the National Research Council and the U.S. Arctic Research Commission.

B. Description of Tundra Travel and Oil/Gas Exploration

Oil and gas production industries require off road travel across the tundra in winter to accomplish three distinct tasks: (1) seismic exploration activity; (2) ice road construction for exploratory drilling; and (3) routine maintenance of infrastructure such as pipelines. Without the opportunity to travel across the tundra, the exploration for oil and gas resources in the Alaska arctic would come to a halt.

The most extensive use of off-road tundra travel over the past ten years has been for what is called 3D seismic exploration. The National Research Council report describes seismic activity in detail. It is a survey using sound waves that travel underground and

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bounce off various geological formations creating an image from the echo, which can then be mapped and evaluated for hydrocarbon potential. Seismic camps involve a variety of vehicles, sleds, and activities that travel across the winter snow as a slow moving city on sleds, housing up to 100 workers.

A set of microphones (geophones) connected by miles of cable, are laid out on the surface of the ground in a rectilinear grid of parallel lines, often spaced about 0.25 miles apart. These lines receive the echo. Rubber tracked vehicles called Tucker Snowcats are most often used for this phase of the operation. After an area has been set out, another group of tracked vehicles, called vibrators, travel in parallel lines perpendicular to the receiver lines, forming the grid. Vibrators are very heavy and often move in tandem to generate coordinated sound waves. The vibrator lines are termed source lines. Once an area has been surveyed, the Tuckers are sent back down the lines to retrieve the receivers. The process continues to repeat itself in an adjacent area until the entire survey is complete. Each line can measure over six miles long at a time, and a single winter survey project can cover over 300 square miles.

Supporting the survey is a whole community with workshops, kitchen facilities, dormitories, laboratories, power generation plants, and sewage facilities built upon huge sleds and pulled by steel tracked D-7 dozers and rubber tracked Challengers. During the period 1990 to 2001, an estimated 16,000 miles of seismic lines were traveled across the tundra (NRC 2003).

After seismic surveys have been completed, the next phase of exploration involves drilling test wells. Because of the size and weight of drill rigs and needs for continual traffic to maintain logistical support for the operations, ice roads are constructed to access and maintain the drilling operations. Ice road use, and the potential environmental disturbance that may accrue from them are not the subject of this study. However, ice road construction does require a level of off-road tundra travel to build.

Ice road construction first requires that the snow be packed down to form a firm bed and assist in the penetration of cold deep into the ground. Then, water is broadcast over the packed snow trail to freeze in a solid layer. The process is repeated several times and the ice smoothed between broadcasts to build up a road to the required thickness.

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Once the road is built, all traffic occurs on the ice roadway. During the winter of 2001-2002, over 250 miles of ice road were built.

Maintenance crews take advantage of winter conditions to travel across tundra for repair of infrastructure in remote locations. Crews and equipment generally travel to work sites in a Tucker or a Challenger.

C. History of DNR Tundra Travel Management

DNR regulation of tundra travel has evolved over the past 30 years. While the Department has increased its sophistication over that time, it has relied, for the most part, upon subjective standards and an anecdotal sampling system to predict tundra resistance to disturbance. (A comprehensive history describing DNR tundra travel management on the North Slope was prepared for the agency in 2004 and is included as Appendix D of this report.) At first, managers used their general familiarity with the North Slope to estimate when weather conditions were such that adequate frost depth and snow cover would be present to prevent tundra damage. Under this system, the tundra was generally “opened” for cross country travel and exploration if it appeared that at least 6 inches of ground cover snow was found and the ground was determined to be hard to a depth of at least 12 inches. This ad hoc approach, adopted in the 1970’s without the benefit of prior scientific investigation, appears to provide a high degree of tundra protection during oil exploration, although occasional severe tundra disturbance has been documented (Felix and Raynolds 1989a,b).

Ground frost was estimated by driving a metal rod into the ground with a sledge hammer and by boring holes into lake ice. By 1995, measurement of ground hardness was accomplished with a slide hammer that was physically pounded into the ground by personnel.

In response to a need for a more objective and quantitative approach towards tundra travel management, DNR initiated a number of reforms starting in the year 2002. The first reforms standardized measurement techniques. DNR created 30 permanent measurement stations in 2002. These stations serve as the locations for measuring snow depth and ground hardness on a periodic basis starting in November of each year. Ten of these 30 sampling locations are distributed along a 100 mile north-south transect

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from Deadhorse to Slope Mountain along the Dalton Highway at approximately 10 mile increments. The remaining sampling locations are distributed within the oil field complex spanning approximately 40 miles from east to west (Figure 2).

A second reform divided state lands on the arctic North Slope into four geographically distinct management subunits (named Tundra Opening Areas, or TOA's). The TOA's replaced the earlier practice that considered the entire North Slope as a single ecological region. Relying on topo-climatic differences as well considering infrastructure and administrative concerns, the North Slope is separated into an Upper Foothills TOA, Lower Foothills TOA, East Coastal TOA, and West Coastal TOA (Figure 2). The division between the Coastal and Lower Foothills TOA follows the Alaska Coastal Zone Management administrative boundary that approximates the maritime temperature influenced ecological boundary, which extends about 50 miles inland from the Arctic Ocean. The demarcation between Upper Foothills TOA and Lower Foothills TOA approximates the 500 foot contour, which follows another climo-topo-edaphic boundary (Spetzman 1959). Each TOA is managed as an independent unit.

Another reform redesigned the slide hammer probe for measuring ground hardness. Previous slide hammers required DNR staff to exert energy to pound a 9/16 inch diameter probe into the ground. In addition to the variation in measurement attributable to personnel strength and fatigue, each hammer employed was slightly different in weight and drop distance. In 2003 the slide hammer was redesigned. It is now a true "drop" hammer with standard drop weight and drop distance, employing no assistance from the operator. Each new drop hammer uses a 3/8 inch diameter probe for easier penetration into the ground. Variability in measurement due to the individual operator and equipment has been eliminated. The new drop hammer was field tested in January of 2003 and calibrated to assist with comparison to prior data sets.

Despite these improvements, DNR still lacks scientific information linking snow and ground hardness characteristics with tundra resistance to disturbance by vehicles traveling off road. This modeling project represents an effort to provide necessary information, and thereby improve DNR management of the North Slope environment regarding tundra travel.

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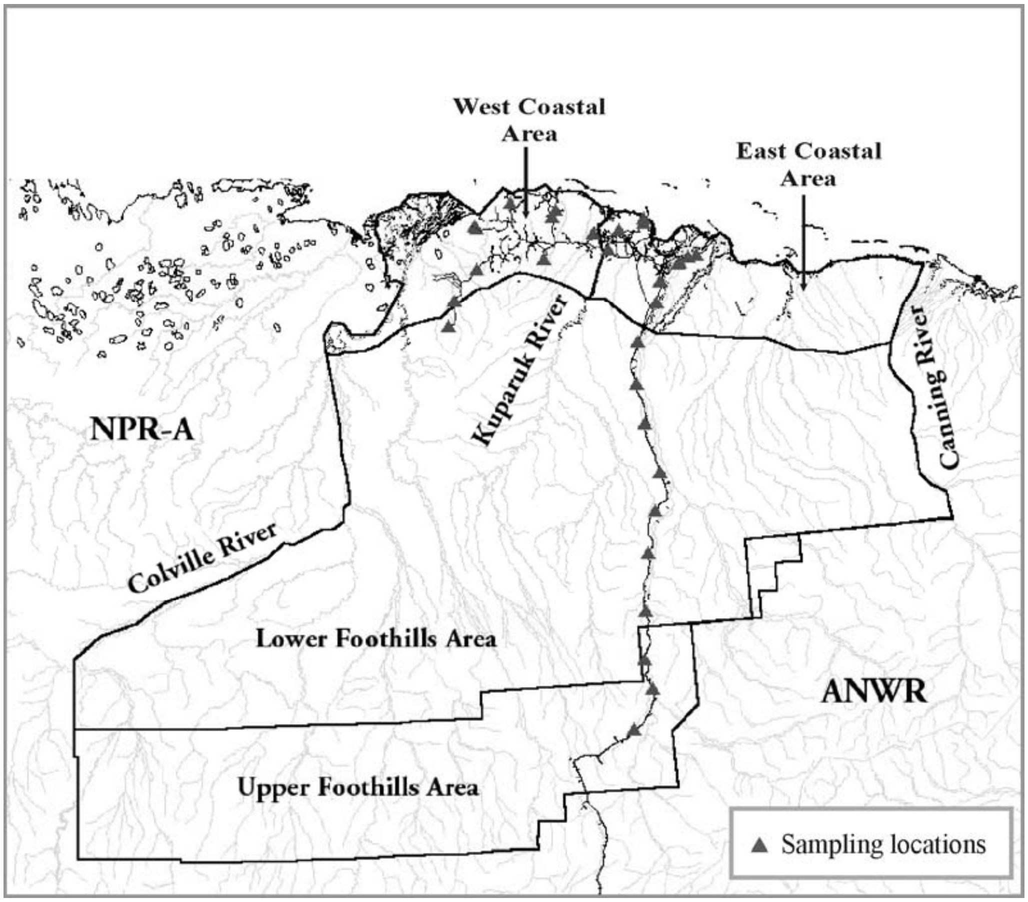
Figure 2: Tundra Opening Areas and Snow and Ground Sampling Stations



D. Description of Alaska North Slope – General

Alaska's arctic North Slope covers an area of 89,000 square miles (about the size of the state of Minnesota). The North Slope can be divided into three general geographic areas: (1) Brooks Range; (2) Foothills; and (3) Coastal Plain (Gallant et al 1995; Walker and Acevdeo 1987). The southern boundary of the North Slope is formed by the Brooks Range. North of these mountains is a 50-75 mile wide band of rounded hills and broad valleys. Between the Arctic Ocean and the foothills, lies a nearly level plain varying in width, ranging from 100 miles in the west to less than 12 miles wide in the east. The North Slope is sparsely populated with about 8,000 residents, approximately 70% of whom are Alaska Native peoples of Inupiat descent (NRC 2003).

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1. Climate

The Brooks Range is steeply sloped and heavily dissected with deep gorges. South of the continental divide, separating those waters that flow north to the arctic and those which flow into the Bering Sea via the Yukon River system, the mountains exhibit the continental climate of the interior boreal forest. North of the divide, the mountains are dominated by vegetation characteristic of arctic tundra. Mean annual temperature is approximately –6 degrees Celsius with about 375 mm of precipitation, 60% of which occurs as rain during the growing season (Mull and Adams 1989). An average year accumulates approximately 4000 cumulative freezing degree-days, punctuated by a 110 day growing season (Mull and Adams 1989). Since little or no hydrocarbon exploration is expected in this region, the modeling project does not address travel in these rugged mountains.

The Foothills lie just north of the Brooks Range and vary in width from over 125 miles wide in the west to just 10 miles wide before tapering out, east of the Canning River in the Arctic National Wildlife Refuge. They vary in elevation from 1000 m in the south at the base of the mountains, to about 160 m in the north, forming a low border with the coastal plain. Irregular buttes, bluffs, and east-west trending ridges characterize the southern margin of the Foothills. The northern foothills are also dominated by east-west trending ridges, but are lower, broader, and more rounded. Mean annual temperature in the Foothills is –9 degrees Celsius with a 120 day growing season; an average year accumulates nearly 5,500 freezing degree-days (Mull and Adams 1989). A little over 210 mm of precipitation falls over the foothills, evenly divided between winter snow and summer rain.

The Coastal Plain is heavily influenced by the maritime margin and the adjacent ice cap on the Arctic Ocean. This broad, flat, wetland plain has a mean annual temperature of only –11 degrees Celsius and only a 100 day growing season (Mull and Adams 1989). Maximum annual cumulative freezing degree days can reach 8,000 (Brewer 1958). Total precipitation is typically less than 200 mm, the majority of which is in the form of snowfall.

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2. Ground Characteristics

a. Permafrost

The entirety of both the North Slope coastal plain and foothills are underlain with continuous permafrost (Brown 1997). Permafrost is most commonly defined as that ground which remains continuously frozen for at least two consecutive years (NRC 2003, ARC 2003); though some researchers have defined it as requiring much longer periods in a frozen state (Lunardini 1995). Permafrost is generally regarded as being comprised of four main constituents that interact, affecting its mechanical properties: (1) solid mineral or organic grains; (2) ice; (3) liquid water; and (4) gases (Ladanyi 1985).

The Prudhoe Bay area is known to have anomalously deep permafrost compared to the rest of the North Slope, with a maximum depth of about 650 m (Lachenbruch et. al. 1982). The great depth of Prudhoe Bay area permafrost is attributed in part to the high thermal conductivity of the fine grained, silicious parent material (Lachenbruch et. al. 1982). It is believed that the permafrost in Alaska began to form about 2.5 million years ago, and has undergone periods of warming and cooling during that time (Osterkamp and Gosink 1991).

Temperatures in the uppermost portion of permafrost, typically the top 20 m, fluctuate with annual seasonal variation, warming in summer and getting colder in winter, though remaining always below freezing (Romanovsky, Sergueev, and Osterkamp 2003; Williams and Smith 1989; Brewer 1958). The point in the permafrost profile at which there is no seasonally affected temperature change is called the level of “zero annual amplitude” (Burn and Smith 1988). Permafrost temperatures are often at their coldest at this point. On the North Slope, the minimum permafrost temperature ranges between –8 and –11 degrees Celsius (Osterkamp 1988; Lachenbruch et. al. 1982; Brewer 1958). The bottom of permafrost (maximum depth) is determined by heat flow escaping upward from the earth’s interior and interacting with the long term climate effects cooling the ground from the surface down (Williams and Smith 1989). Overtime, permafrost temperatures fluctuate in response to long-term climate trends. It appears that the temperature of permafrost in Alaska has been warming slightly during the past 100 years (Romanovsky, Sergueev and Osterkamp 2003; Osterkamp and Gosink 1991).
While it may appear incongruous, permafrost contains substantial quantities of liquid water locked within the particle and ice matrix (Hinkel et. al. 1996; Smith 1985). Indeed,

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volumetric liquid water can reach 20% at near 0 degrees Celsius, dropping to about 5% at –12 degrees (Romanovsky and Osterkamp 2000). Liquid water in frozen permafrost exists as both strongly bound films to mineral particles and weakly bound in soil pore spaces (Ladanyi 1985). The finer grained the soil and the warmer the temperature of the permafrost, the more liquid water will be present in the permafrost (Williams and Smith 1989).

The varying amounts of liquid water within permafrost have profound consequences on the characteristics of the frozen ground. Liquid water can retard temperature change in permafrost during seasonal fluctuation in early winter through latent heat (Romanovsky and Osterkamp 2000); and alter the mechanical strength of the permafrost (Williams and Smith 1989). As a result of the presence of liquid water in frozen ground, one may encounter slight mud streaking on equipment penetrating into permafrost, even though the ground is thoroughly frozen.

While permafrost obstructs the downward percolation of surface water into the ground, contributing to the abundant standing water characteristic of tundra environments (Lachenbruch et. al. 1982), the liquid water fraction within the permafrost is capable of movement through the frozen ground (Hinkel et. al. 1996; Smith 1985). The movement of liquid water in frozen ground allows for the formation of ice aggregation creating lenses of pure ice and expanding the volume of frozen soil significantly (Williams and Smith 1989). Ice segregation and differential frost heave contribute to the unique landforms found in the arctic.

The mechanical strength of frozen ground surpasses the sum of independent strengths for ice and unfrozen soil combined (Williams and Smith 1989). The rather remarkable strength is the product of four factors: (1) pore ice strength; (2) soil inter-particle friction; (3) adhesion ice bond resistance to dilation; and (4) the synergistic strengthening between soil and ice matrix (Ladanyi 1985). Affecting these four factors are soil grain size and temperature. The finer the soil grain the stronger the permafrost; and the warmer the temperature of the ground, the more liquid water is present in the frozen soil, and thus the weaker the permafrost (Williams and Smith 1989). Strength of frozen ground, such as permafrost, increases quickly as the temperature drops from 0 to –10 degrees Celsius (Ogata et. al. 1982). After a temperature of –10 is reached, the rate of

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increasing strength drops off precipitously (Williams and Smith 1989). Permafrost also increases in strength with increasing ice content, up to a certain point, after which higher ice contents can generate brittleness and lead to failure.

Two very different strength types are present in frozen ground: resistance to deformation and resistance to shear failure (Williams and Smith 1989). Resistance to deformation and compression (ductile failure) is weakest between –2 and 0 degrees Celsius (Joshi and Wijeweera 1990). At temperatures below –10 degrees, shear failure may be more common due to the tendencies of frozen ground to become brittle with cold temperatures (Davis 2001; Joshi and Wijeweera 1990).

b. Ice

In addition to abnormally deep permafrost, the segregated ice content in the permafrost is inordinately high in the region of state lands on the North Slope between the Canning and Colville Rivers (Hazen 1997). Segregated ice is often referred to as excess ice, because the volume of ice present exceeds the volume within the soil pore spaces had the ground not been frozen. This excess ice can constitute almost 50% of the total volume of permafrost (Williams and Smith 1989). It is the movement of liquid water through the pore spaces of frozen ground along a thermal and hydrostatic gradient that creates segregated ice formations (Williams and Smith 1989). Once an ice lens is established, liquid water is removed from adjacent frozen ground pores and water flows up through the soil to replenish the vacated pores, thus fostering continued growth of the segregated ice (Henry 2000).

Intrusive ice is quite different from segregated ice. Intrusive ice forms when water percolates downward into frost cracks in the permafrost to form vertical wedges. Ice wedges can constitute 10% of total permafrost volume in the top three meters (Davis 2001). In sum, there are three primary forms of ice found in permafrost: (1) massive ice, which is water frozen within the pore spaces of the soil; (2) segregated ice that forms horizontal lenses as the result of liquid water movement in the frozen ground moving toward the ice front; and (3) intrusive ice, which forms vertical wedges as a result of percolation down open cracks in the ground. Together, these three forms of ice greatly alter the permafrost environment, altering strength, thermal properties, and susceptibility to disturbance.

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c. Active Layer

Above the permafrost is found the active layer. The active layer is that portion of the ground that thaws and refreezes in an annual cycle in response to seasonal temperature change (Hinkel et. al 1996). On state lands of the North Slope, active layer thickness varies between 20 cm and 100 cm. Factors affecting the depth of the active layer include: (1) winter and summer air temperature, (2) depth, duration, and temporal deposition patterns of snow; (3) the type of minerals and grain size of the parent material; (4) the vegetative canopy; (5) peat layer thickness; and (6) moisture content (Paetzold et al 2000; Luthin and Gwymon 1974).

Because of this complex interaction of so many variables, the thickness of the active layer can change markedly over very short distances (Nelson et. al 1997). Indeed, active layer thickness can differ by as much as 300% along a single short transect (Hinkel et. al. 1996). There is also great inter-annual variation in active layer thickness, changing as much as 100% from year to year (Romanovsky, Sergueev, and Osterkamp 2003; Osterkamp and Romanovsky 1997). In the coastal plain near Prudhoe Bay, active layers of 40-50 cm are typically encountered, while on the foothills, active layer depths can vary even more from 28-60 cm (Brown 1997; Brown and Grave 1979).

Each winter, the active layer freezes both from the top down and the bottom up (Romanovsky, Sergueev and Osterkamp 2003). Freezing in the active layer first starts in the autumn from the bottom along the permafrost interface and moves up, followed approximately two weeks later by freezing from the ground surface down (Osterkamp and Romanovsky 1996; Romanovsky and Osterkamp 1997). This process of bottom up freezing starts when the ground surface temperature drops below +2 degrees Celsius (Osterkamp and Romanovsky 1996; Romanovsky and Osterkamp 1997). Along the coastal plain near Prudhoe Bay, active layer freeze up tends to start in mid September and is completed sometime during the second half of November. In all, freeze up typically requires about 65-70 days from inception to completion, with about 64% of the frozen active layer resulting from bottom up freezing (Osterkamp and Romanovsky 1997). Once complete freeze up has occurred in the active layer, the drop in temperature stalls at about –1 degree centigrade due the latent heat effect of liquid water in the frozen soil (Hinkel et. al. 1996). This point is called the zero curtain effect

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and may last for about 20 days, after which the drop in temperature throughout the active layer is quite rapid (Hinkel et. al. 1996). During the time of the zero curtain effect, moisture migrates vertically to the frost front, desiccating parts of the active layer. Once completely frozen, the active layer temperature becomes considerably colder than the temperature of the permafrost below it due to its nearer proximity to the extremely cold ambient air temperatures.

Just as the depth of the active layer possesses a high degree of natural variation within a short spatial distance, the date of freeze up is also highly variable (Romanovsky, Sergueev and Osterkamp 2003). Depending upon prevailing weather conditions, complete freeze up may occur any time within a 40-day range. However, a distinct trend towards a later active layer freeze up has been documented; from 1987 to 2001, the complete freeze up date has shifted later in the season by approximately 30 days (Romanovsky, Sergueev and Osterkamp 2003).

Because the active layer is a critical component of the arctic ecosystem -it is the zone within which almost all biological, hydrological, and chemical activity takes place- (Hinzman et. al. 1991), this project attaches great attention to changes in the active layer. Organic material is also transported through the active layer and sequestered in permafrost through percolation into ice wedges and through ground mixing by cryoturbation (Bockheim et. al. 1999). Disturbance that affects the thermal regime influencing the active layer and its thickness, may have the potential to trigger important ecological consequences such as thermokarst, alteration of biological productivity, and carbon release.

3. Snow

The temporal and spatial pattern of snow depth and density exerts an important influence on permafrost and active layer dynamics (ARC 2003). Large inter-annual variation in total snow depth, variation in intra-seasonality of snowfall events, and the moisture content of the snow all make understanding the influence of snow a complex undertaking. Snow depth and density at any one geographic location change greatly over time due to weather events that can erode existing snow or redeposit new snow in drifts, or forming hard crusts. In general, snow tends to persist on the ground for approximately 9 months per year, usually dry in moisture content, and wind packed with

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a firm crust (Benson and Sturm 1993). The International Commission on Snow and Ice of the Association of Scientific Hydrology, in collaboration with the International Glaciology Society, issued a uniform international classification system for seasonal snow on the ground which standardized descriptions of snow based upon density, grain shape and size, liquid content, impurities, hardness, temperature and strength (Colbeck et. al. 1990). The project relies upon this classification system to define a slab layer.

Two primary types of snow are found on the North Slope coastal plain and foothills: veneer facies that interact with the tundra surface and drift facies that form deep deposits. These two types of snow possess profoundly different properties (Benson and Sturm 1993). About half of all deposited snow is eventually redistributed by wind creating a very dynamic snow environment (Benson and Sturm 1993). Snow is an efficient insulator and can protect the ground from heat loss contributing to a late freeze up if heavy snow deposition occurs early in the season and generate a warmer thermal regime in the frozen active layer that may persist throughout the winter season (Stieglitz et. al. 2003; Romanovsky and Osterkamp 2000). Maximum average end of year snow depths range from 35 cm on the coastal plain to over 70 cm in the foothills (Romanovksy, Serbueev and Osterkamp 2003).

4. Vegetation

Micro-topography, climate, moisture regime and soil chemistry interact to strongly influence local vegetation composition and distribution on a very small scale, creating a complex mosaic of tundra vegetation community types on the North slope (Walker et. al. 2002). Ecologists have classified these complex patterns employing a number of approaches, identifying as many as 30 distinct communities or generalizing to as few as 5 primary community types. The project relies on a system which recognizes 6 broad vegetative community types: (1) wet sedge meadows; (2) sedge/dwarf shrub; (3) sedge tussock; (4) shrub tussock; (5) shrub; and (6) Dryas terraces (Modified from Muller et. al. 1999). The coastal plain is dominated by sedge communities; while tussock and shrub communities prevail in the foothills. (A list of plant species found at the two modeling sites is included as Appendix C attached to this report).

Wet sedge meadows are frequent on the coastal plain and represent poorly drained areas of low relief and ice rich permafrost (Jorgenson, T. et al. 2003). Associated with

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either non-patterned ground or low centered polygons, wet sedge meadows are dominated by *Carex aquatilis* and *Eriophorum angustifolium*. Attending the dominant sedges are abundant bryophytes and *Salix* species.

Table 1. North Slope Vegetation Community Types by Percent Terrestrial Cover (Modified from Muller et. al. 1999)

Vegetation Community	**Coastal Plain** (Approximate % cover)	**Foothills** (Approximate % cover)
Wet Sedge	31	4
Sedge/Dwarf Shrub	30	22
Sedge Tussock	15	3
Shrub Tussock	12	41
Shrub	7	28
Dryas Terraces	5	2
Total	100	100

Sedge/dwarf shrub tundra is found on patterned ground with high center polygons, or a mix of high centered and low centered polygons, in moderately drained areas with moderate to high ground ice content. Dominant plant species include *Carex bigelowii* as well as *C. aquatilis, Eriophorum angustifolium* and dwarf shrubs such as *Betula nana, Salix reticulata, Cassiope tetragona* and *Vaccinium vitis-idaea* (Jorgenson, T. et. al. 2003). Bryophytes such as *Hylocomium* and *Dicranum* are also prevalent.

Tussock tundra exhibits a low mounded physiognomy comprised principally of *Eriophorum vaginatum* and accompanied by such woody species as *Ledum decumbens, Vaccinium vitis-idaea, Salix planifolia,* and *Salix phlebophylla*. Because tussock tundra tends to be moderately to well drained, lichen serve as a major constituent of the community. Hummocks are a frequent topographical feature and provide drier microsites for a host of vascular forb species. Ice content tends to be low to moderate on these sites.

Shrub communities are those dominated by low willows such as *Salix lanata* and *Salix planifolia* as well as *Betula nana* and *Vaccinium.* These well drained communities are often found along riparian margins or upland side slopes and contain lower volumes of segregated and intrusive ground ice than the other vegetation communities.

Dryas terraces are relatively infrequent, dry sites located along well drained riparian benches, upland crests, and sandy side slopes in areas that typically lack patterned ground. These areas are dominated by *Dryas integrifolia* and co-dominants of lichen and *Salix reticulata*.

Plant communities are not only affected by abiotic factors, but they also influence the abiotic environment. Evapotranspiration from living plants, especially mosses can lower soil surface temperatures considerably (Williams and Smith 1989). Various plant communities also exert an influence with different insulation properties; bryophytes, for example impede the development of deep active layers by promoting low temperatures through efficiently conducting heat under wet summer conditions and then becoming an effective insulator later in winter when the moss becomes dry (NRC 2003).

According to some investigators, it can be argued that tundra vegetation communities are not fragile at all, but rather, quite resistant and resilient as a necessary adaptation to an inherently unstable physical environment dominated by continual natural disturbance processes (Crawford 1997). This study only addresses the potential resistance of abiotic tundra characteristics to different types and intensities of anthropogenic disturbance, so that managers may learn to avoid disturbance or anticipate the level of disturbance from exploration activities. At this time, DNR leaves the important issue of ecological resiliency for further investigation by others.

5. Frequent Terrain Landforms

Cryoturbation, solifluction, segregated ice formation, intrusive ice and the near surface presence of permafrost combine to generate a suite of topographic features that distinguish arctic tundra ecosystems. These various physical forces mark the arctic as the epitome of a stressed, disturbance driven ecosystem of great instability (Crawford 1997). Cryoturbation involves the churning of soil associated with freezing and thawing ground and is the primary force in creating characteristic arctic topographic features (Williams and Smith 1989). Solifluction is the down slope creep of soil located in the

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permafrost as a result of frost heave expansion and the force of gravity in association with subsequent thaw (Davis 2001).

a) Patterned Ground Polygons

Patterned ground is the product of ice wedge formation and is the dominant landform feature on the coastal plain. Polygons form as a result of cooling contraction cracks in the ground as a sharp temperature gradient develops in early winter when ground surfaces are rapidly cooled prior to snowfall (Davis 2001). Water percolates down these cracks, which penetrate into the permafrost, and freezes, creating intrusive ice. As the process repeats itself over time, wedges of pure ice, oriented vertically with the wide end at the top, develop. These wedges can be a meter wide at the top and taper to a point 3 m below the surface. Wedge formation along interconnecting contraction cracks form the polygons, much as drying mud forms cracks.

b) Hummocks

Hummocks form bumpy ridges and small mounds where permafrost is overlain by a relatively deep active layer (Mackay 1980). Hummocks appear to be composed of fine grained parent material overlying a bowl shaped thaw bulb depression on the surface of the permafrost/active layer margin (Mackay 1980). The freeze-thaw cycle produces a circulation pattern within the thaw bulb; in which the upper portion is extremely active early in the summer and the lower portion most active with the onset of autumn (Mackay 1980). Soil movement is downward at the margins of the bulb and upward in its center, creating the irregular bumpy surface so indicative of the arctic. Hummocks tend to form slowly in mesic environments and are thus usually vegetated, offering a small well drained micro-climate and terrain feature that absorbs solar radiation along its elevated, though small slopes. Hummocks form in both the coastal plain and foothills.

c) Frost Boils

Frost boils, sometimes called frost scars, are circular mounds 1-5 m in diameter that rise about 0.35 m in height above the surrounding terrain and often void of vegetation. Found in silt rich substrate in poorly drained areas, they form above a thaw bulb as a result of a combination of forces including differential frost heave, excess pore pressure, and cryostatic pressure (Davis 2001; Shilts 1978).

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d) Thermokarst

Thawing of permafrost containing excess ice results in ground subsidence and is called thermokarst (Williams and Smith 1989). Usually, thermakarst subsidence is the result of some modification in the heat flux to increase melting at the subsurface. Because excess ice can constitute more than 50% of permafrost volume, the ground collapses into the vacant whole left by the melted ice, making a sink hole like feature (ARC 2003). Thermokarst is very unstable. Even a small subsidence can expand substantially along the margins. If water begins to pool in the depression, thermokarst will usually accelerate due to the greatly efficient thermo-conductivity of water and its ability to infiltrate deep into any permafrost cracks.

E. Description of Tundra Travel Ecological Effects

There is surprisingly little data published in the scientific literature that address the environmental conditions that either exacerbate or mediate disturbance impacts associated with winter tundra travel. The research that has been reported has been primarily retrospective in nature. As a consequence most studies on the subject lack base line data for controls, lack standardized experimental design for identifying type and intensity of disturbance, and lack measurements of the existing suite of environmental conditions present at the time the activity occurred. These previous studies also rely predominantly upon qualitative and subjective measures of disturbance.

The earliest studies addressed the disturbance effects associated with summer tundra travel (Bliss and Wein 1972; Hernandez 1973; Gersper and Challinor 1975; Abele, Brown and Brewer 1984; Chapin and Shaver 1981). These studies found significant severe disturbances with long term changes in soil temperature, depth of the active layer, soil bulk density, soil pH, microbial activity, ground subsidence, and soil moisture regimes. As a result of these findings, state and federal agencies moved to limit most tundra travel to winter months only (See Tundra Travel Management History in Appendix D).

A few vehicles are permitted by DNR to travel on the tundra in summer. Such permission, however, is limited to those vehicles that use very low surface pressures,

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such as rolligons and flat track tucker snowcats. All summer travel is subject to total closure for wildlife protection purposes during key periods in migration and reproduction cycles.

Nearly all knowledge of seismic winter activity disturbance on tundra resources is the result of a long-term study conducted by the U.S. Fish and Wildlife Service in the Arctic National Wildlife Refuge started in the mid 1980's (NRC 2003). Limitations in study design limit the applicability of the results of the FWS work (NRC 2003). However, the USFWS study represents pioneering work and makes a substantial contribution to the effort to understand the effects of winter tundra travel and is therefore relied upon by DNR for guidance (Emers, Jorgenson, and Raynolds 1995; Felix et. al. 1992; Felix and Raynolds 1989a; Felix and Raynolds 1989b).

The USFWS researchers adopted a system defining different levels of disturbance ranking from low to high on a subjective numerical scale of 0-3 (Emers, Jorgenson, and Raynolds 1995; Felix et. al. 1992). Under this system, disturbance was classified as low if less than 25% of total vegetation was "damaged" and less than 5% of the trail surface had exposed mineral soil. The studies defined moderate disturbance as 25%-50% vegetation "damage" and 5%-15% of the track surface with exposed mineral soil; high disturbance levels were defined as those plots with greater than 50% vegetation "damage" and greater than 15% of soil surface exposed. Tussock disturbance was likewise ranked subjectively, with a numerical value of 0 if no disturbance was observed, a 1 if the tussock was slightly scuffed, a 2 if the tussock was crushed but still living, and a 3 if the tussock was shattered and dead.

According to the USFWS study, all vegetation community types exhibited little resistance to disturbance from winter tundra travel activities (Emers, Jorgenson, and Raynolds 1995; Felix et. al. 1992). However, at low levels of disturbance, most community types were capable of demonstrating resiliency (Emers, Jorgenson, and Raynolds 1995; Felix et al.1992). Dryas terraces and tussock communities seemed to have the least resistance to change (Emers, Jorgenson and Raynolds 1995; Felix and Raynolds 1989a,b; Raynolds and Felix 1989). Wet graminid communities demonstrated the greatest resistance to disturbance (Emers, Jorgenson and Raynolds 1995; Felix et. al. 1992; Felix and Raynolds 1989 a,b; Raynolds and Felix 1989). These studies found that

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changes, especially in highly disturbed sites, could continue long after the initial event (Emers and Jorgenson 1997; Emers, Jorgenson and Raynolds 1995). In one case study, the investigators found at high levels of disturbance, the resilience amplitude may have been exceeded resulting in the replacement of one community by another (Felix et. al. 1992).

In most cases, these studies indicate that shrubs are disproportionately affected with significant decreases in overall relative vegetative cover the first growing season after the passage of vehicles (Felix and Raynolds 1989a,b). Of the shrubs, evergreens seem to decrease the most as a result of disturbance (Emers and Jorgenson 1997; Emers, Jorgenson and Raynolds 1995; Felix et. al. 1992). On most disturbed plots, a species composition change occurred with an increased dominance of those species associated with more mesic and hydric sites, favoring increased cover by graminids, and disfavoring lichens (Emers, Jorgenson and Raynolds 1995; Felix and Raynolds 1989). While bryophyte and forb relative cover often did not decrease significantly, substantial changes did occur in species composition, favoring hydric and mesic genera within the life form classes.

Several studies describing the changes in physical environment, as a result of summer tundra travel, may be useful in explaining the mechanisms for some of the changes detected in vegetation communities following winter travel (Kevan et. al. 1995; Abele, Brown, and Brewer 1984; Chapin and Shaver 1981; and Gersper and Challinor 1975). Soil temperature was higher in disturbed areas; thaw depth of the active layer was deeper; soil density in tracks was higher, soil pH became higher; and microbial activity increased. These changes appear to have resulted in the degradation of underlying permafrost, causing significant alteration to the biological and physical environment (Brown 1997; Walker and Walker 1991).

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II. STUDY DESIGN

The study is designed to link those environmental characteristics which influence tundra resistance to disturbance, (and which can be easily field measured), to the environmental effects associated with off road tundra travel. DNR tested vehicles that are commonly used in oil and gas exploration activity and represent a range of drive mechanisms and weight. The study evaluated a Tucker, Challenger, Front End Loader, and D7 Tractor. Measurements were taken to identify disturbance and include change in depth of active (thaw) layer, soil temperature, change in soil moisture, soil micro-topography related to rutting and track depressions, vegetation productivity, and change in vegetation life form composition and cover.

A. Study Sites

The study approach used standardized field trial tests conforming to a randomized design. Two test locations were selected to generate a model for each of the two primary ecosystems found on the North Slope. These two areas are the Coastal Plain and the Foothills. The coastal case study area is located near the Prudhoe Bay oil field infrastructure about four miles south of Deadhorse; the foothills case study area is located near Happy Valley adjacent to the Dalton Highway road corridor; 62 miles south of Deadhorse.

Each case study location had to satisfy five selection criteria. First, the area had to be free from previously recorded seismic exploration or other disturbance generating anthropogenic activity. Second, the study area needed to be within one mile of the long term soil and water temperatures and snow monitoring data arrays set up by the National Science Foundation through the University of Alaska, so that study measurement results could be evaluated in context with long term climate trends. Third, the areas had to be located next to the existing road system. Fourth, an area suitable for staging had to be located within ¼ mile for ease of unloading and loading heavy equipment from trailers pulled by large semi-truck tractors. Fifth, the road surface between the staging area and the study location had to be a gravel surface, as the equipment would shatter hardened roads such as asphalt at anticipated temperatures in winter. Both study areas were sited on the basis of these criteria subjectively.

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B. Treatment Cell Configuration

Each study area was divided into rows of treatment cells, each cell measuring 100 by 50 m. To the extent practicable, the treatment cells were configured to form blocks of ten cells formed by two adjacent rows of five cells. These blocks were then spaced and oriented to allow vehicle access to each cell in order to perform the treatments without affecting the other cells in the vicinity (Figures 3 and 4). Each study area therefore contained 30 treatment cells.

Within each cell, three 5 m transects were created. One transect was located at each end of a cell, oriented with the length of the cell. A third transect was located in the center of the cell, oriented perpendicular to the length of the cell (Figure 5). The ends of each transect were marked by a metal survey arrow driven into the ground at each end. Further marking was accomplished with wood stakes driven into the ground one meter beyond each survey arrow, in line with the transect. These stakes extended approximately 1 m above ground and had both reflector tape and steel shiners attached. These wooden markers served as “gates” measuring 7 m wide, within which treatment vehicles would pass, ensuring consistent driving over the transects.

In the Foothills study area, the rows of treatment cells were oriented parallel to the hillside contour. An elevation reading was taken at the middle transect of the center cell in each row and recorded.

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Figure 3: Foothills Study Site Treatment Cell Configuration

(Shaded cells show those plots used in the first treatment date; one for each treatment, for purpose of example).

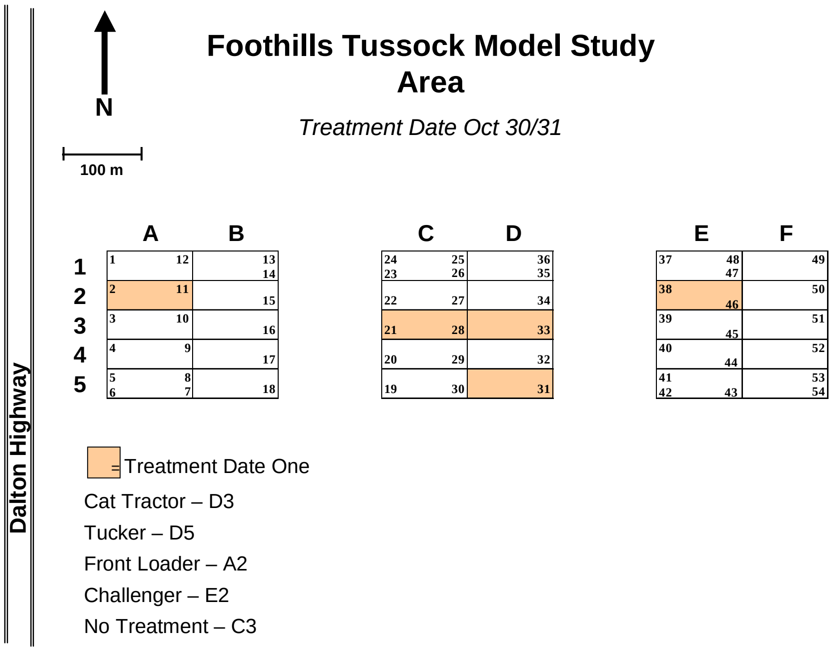

Figure 4: Coastal Plain Study Site Treatment Cell Configuration (Shaded cells identify those treatments tested on the first treatment date, for purpose of example.)

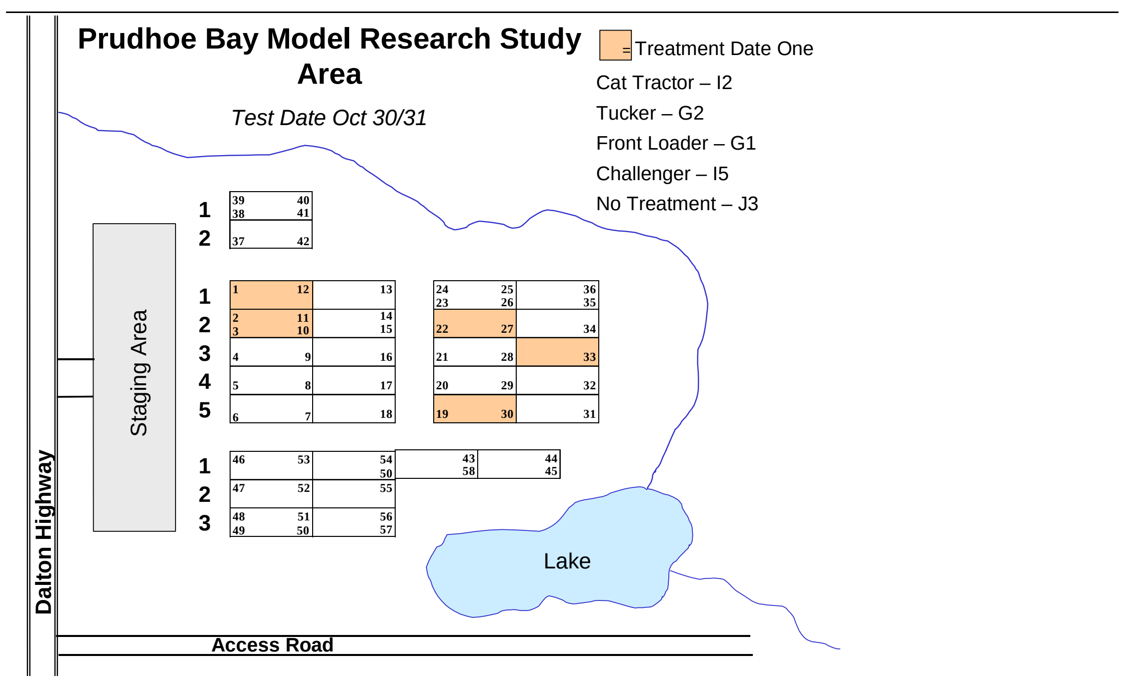

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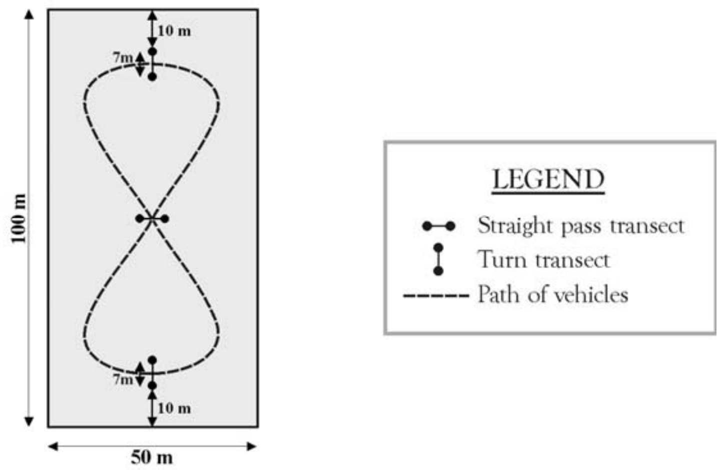
Figure 5: Treatment Cell Design with Transect Placement



After staff located all transects and gates for the treatment cells, a helicopter was chartered to fly above each study area searching for indications of past anthropogenic disturbance, not originally detected at ground level. Of particular note, the search focused to find “green trails” which denote past tundra travel activity (Chapin et. al. 1988). If found, these green trails were to be marked by tossing rocks with blue flagging taped from the helicopter, following the trail in a “bread crumb” style. Any transects affected would be moved slightly to avoid the disturbance. As a result of these overflights, trails were noticed in two cells requiring the location adjustment of three transects in the Foothills study area and one cell with one transect affected by prior disturbance in the Coastal Plain study area.

C. Treatment Cell Measurements

Prior to the winter field tests, each of the 60 cells (30 for each study area) was sampled creating base line data along each of the three transects, in each cell, during July-August, 2003. Base line measurements included: (1) depth of active (thaw) layer, (2) vegetation community type; (3) vegetation composition by genera (established with a hybrid “point frame”/ “intersect” sampling system); (4) vegetation life form cover (using the same hybrid sampling system); (5) soil temperature at a depth of 15 cm; (6) soil

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moisture at a depth of 15 cm; (7) soil micro-topography; (8) tussock frequency and condition; (9) shrub frequency and condition; and (10) vegetation productivity as measured by chloroplast density estimated with the percent of photosynthetically active radiation (PAR) absorbed.[1]

Each cell within a particular study area was then randomly assigned one of six treatment dates and one of five treatment types (See Appendix B for the complete assignment of treatment type and treatment date by cell for each study area).

The day before each treatment date, winter measurements were taken along each transect within the treated cells for that date. Winter measurements included: (1) snow depth; (2) ground hardness; (3) snow slab presence; and (4) snow slab thickness.

D. Treatment Design

Treatments consist of an assigned vehicle type making five consecutive figure-8 passes within an assigned cell on an assigned date, passing over each of the three transects within the cell. Each treatment cell, therefore, had only a single vehicle type pass through the transects on a single date.

Five treatment vehicle types were used on each test date. The five vehicle types are as follows: (1) cleat tracked Snowcat; (2) wheeled front-end loader; (3) rubber tracked challenger; (4) caterpillar D-7 dozer and a (5) “no treatment” treatment. Vehicle types were selected upon the basis of equipment availability and transportability, and type of equipment frequently used in cross tundra travel for seismic exploration and ice road construction (Figures 6a-d). They were also chosen to represent a range of weight, drive types (wheel and track) and steering mechanisms. (Vehicle specifications are discussed in Appendix I).

Treatment dates were designed to span a suite of environmental conditions potentially present during tundra travel. Treatment dates were established for: (1) October 30 2003; (2) November 14, 2003; (3) December 4, 2003; (4) December 16, 2003; (5) January 5, 2004; and (6) January 20, 2004.

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[1] PAR measurements were taken only during the second summer field season after the winter treatments.

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A specific vehicle made five passes in a figure-8 pattern in each cell designated for a particular test date. One transect is located to bisect each turning point at the ends of the figure-8 to provide data on left and right turns. A third transect bisects the middle "thoroughfare" of the figure-8 to provide data on straight travel. (Figure 5).

After the winter field season, DNR returned to the two study areas during the following summer in July-August, 2004 to re-measure each transect in each treatment cell for change detection. Natural ecological disturbance and change was accounted for, and calibrated, by referencing to change detected within the "no treatment" cells using the summer 2003 measurements with the subsequent summer 2004 measurements. In this fashion, **disturbance is defined as a change from base line exceeding that observed for natural inter-annual variation for each of the measurements**.

Figure 6: Treatment Vehicle Types

a. Tucker

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b. Front End Loader

c. Challenger

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d. D7 Dozer

Data from the 2003 and 2004 field seasons are integrated into a multiple regression model enabling DNR staff to predict disturbance responses under differing combinations of environmental conditions with known types and intensity of tundra travel. This model will provide enhanced information and serve as an additional tool for DNR in deciding appropriate opening dates for winter tundra travel.

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III. STUDY METHODS AND TECHNIQUES

A. Measurement Error Analysis

Measurement error is that difference among multiple readings of the same sample measurements which is attributed to the observer. It arises from inappropriate use of instrumentation, mistakes in taking readings, transcription error, and anticipatory bias. This project incorporated rigorous methods to reduce measurement error.

Prior to embarking upon field measurements, staff technicians underwent intensive training and testing to reduce measurement error. Each technician was required to complete and repeat three times the full suite of summer measurements for set a of six faux transects. Measurement error was calculated after completing each transect and adjustments made until each staff person's error was less than +/- 2%. If measurement error was not reduced to less than 2%, then that technician was not allowed to perform the particular measurement in the field on the actual plots. Two percent was the selected threshold because it represented the precision for most of the instrumentation.

In the field, measurement error continued to be monitored. Protocols required that 5 treatment cells within each study area be selected at random for measurement error analysis. Immediately following recording measurements for a cell, technicians would make a random draw to determine if the cell should be sampled again. This process was repeated after each cell so that staff had no knowledge if a particular cell was a measurement error replicate. At the end of each summer field season, the measurement error was calculated for each study area (Table 2). Due to the inclement and dangerous conditions for winter measurements, no measurement error analyses were conducted. It is probable that the winter error rates would be considerably higher than the summer data, given the darkness, cold temperatures, and high winds encountered during the winter field season. However, safety protocols precluded the additional time replication would have required staff to be exposed to hypothermic/frost bite conditions.

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Table 2: Measurement Error Analysis Results for Summer Data

	Coastal Plain 2003	Coastal Plain 2004	Foothills 2003	Foothills 2004
Active Layer Depth	+/- 1.0%	+/- 1.7%	+/- 1.9%	+/- 2.0%
Soil Temperature	N/A	+/- 1.3%	N/A	+/- 1.7%
Soil Moisture	+/- 0.9%	+/- 1.1%	+/-1.3%	+/- 1.1%
Micro-topography	+/- 0.07%	+/- 0.03%	+/- 0.13%	+/- 0.09%
PAR	N/A	+/-2.0%	N/A	+/-2.3%

Transcription error was prevented using a detailed data entry check protocol. Data was entered from field data sheets into separate SAS files twice. Then the two files were compared cell by cell pursuant to a software program and inconsistencies identified for investigation. Inconsistent cells were corrected by reference to the original data sheets and errors eliminated. In addition, all data entry was made on a separate computer that was not connected to the internet to prevent virus corruption. Finally, any individual having contact with the data sheets or SAS files had to sign chain of custody forms to ensure protection of information.

B. Measurement Protocols-Summer

Before measurements could be taken, the study areas had to be divided into treatment cells with the desired configuration. This was accomplished through ground survey using the traditional system with a transom level, rod, and chain. Once the cells were established, each of the four cell corners were marked with metal survey arrows and wooden stakes sporting reflective tape, coded numbered aluminum tags, and cell name inscribe on the wood with permanent black ink. GPS coordinates were taken at each of the four cell corner stakes, as well as at each of the transect end stakes, to assist in finding the cell and transect survey arrows in the event animals, weather, or humans destroyed the identifying stake. Each transect had a single stake marked by a metal tag demarcating it as the starting reference point for all measurements along the transect and to identify the left and right sides along the transect. Great care was employed in alignment and placement of the transect rod between the metal survey arrows to ensure

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that the 2003 baseline measurements and the 2004 post treatment measurements were in nearly identical locations along the transect for maximum accuracy in change detection.

After the transects were established, measurement duties were divided among the field staff on the basis of which staff person had achieved the lowest measurement error rate for each measurement type. In order to avoid disturbing the transect, the observer always positioned him/her self on the right side of the transect and took measurements to the left side, reaching over the transect. This approach minimized trampling of sampled area.[2]

Because of both the rapid rate of phenological development within the vegetation community and the physical, abiotic changes due to the brief, but intense arctic summer, all measurements should be taken during as short a temporal window as possible to prevent encountering ecologically important changes near the end of the measurement window from that at the beginning. As a result, most researchers try to confine their measurement season to no more than a two week period sometime from mid-July to early August (Vavrek et. al. 1999; Kevan et. al. 1995; Felix et. al. 1992; Chapin and Shaver 1981). Protocols for this project call for all summer measurements to be taken within a three-day window at each of the study areas (Table 3). All PAR absorption measurements were taken within a single day at each of the study areas because it was assumed that this particular measurement might be the most sensitive to phenological change during this critical time shift of inflorescence to senescence encountered in late July and early August.

So long as the measurement window duration remains the same, departure from the same window period between the 2003 and the 2004 field seasons should not constitute a confounding variable because the change in base line is calibrated to take such variation into account through reference to the “non- treatment” cells and the manner by which disturbance is defined.

Table 3: Sampling Window-Summer Measurements

[2] The orientation of which side to sample on and which side to observe from was reversed on the Coastal Plain due to a miscommunication.

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Location	Dates	Duration (Days)
Foothills 2003	July 17-July 19	3
Coastal Plain 2003	July 30-August 1	3
Foothills 2004	July 12-July 20	9
Coastal Plain 2004	July 25-July 27	3

To take measurements, a 5 m transect rod was placed snugly between the survey arrows identifying the transect location. This rod was divided into ten 50 cm units and numbered 0 through 10. Measurements were taken and entered onto data sheets according to the following sequence:

1. Identify Study Site
2. Identify Treatment Cell Number
3. Identify Gate Number and Type (Left Turn, Straight, Right Turn)
4. Start with Right Gate, then sample Straight Gate, then end with Left Gate
5. Place 5 m Plant Transect Rod between transect survey arrows.
6. Note Slope with Clinometer and Aspect of each Gate Transect
7. Note Degree Orientation of each Gate Transect with hand held Compass
8. Note Right and Left Side of Transect based upon orientation
9. Observer must remain on the **RIGHT** side of transect and make all measurements on the **LEFT** side of transect as determined from the transect reference point.
10. Begin taking measurements.
11. Soil Temperature
12. Soil Moisture
13. Depth of Active Layer
14. Micro-topography
15. Tussock Frequency and disturbance level
16. Shrub Frequency and disturbance level
17. PAR (performed only in summer of 2004)
18. After all transects had been measured in a study area, transect photos were taken from a height of 2.2 m with a field of vision oriented lengthwise down the transect from the reference point.
19. Aerial photos of each treatment cell were taken from a helicopter at a height of approximately 40 m.

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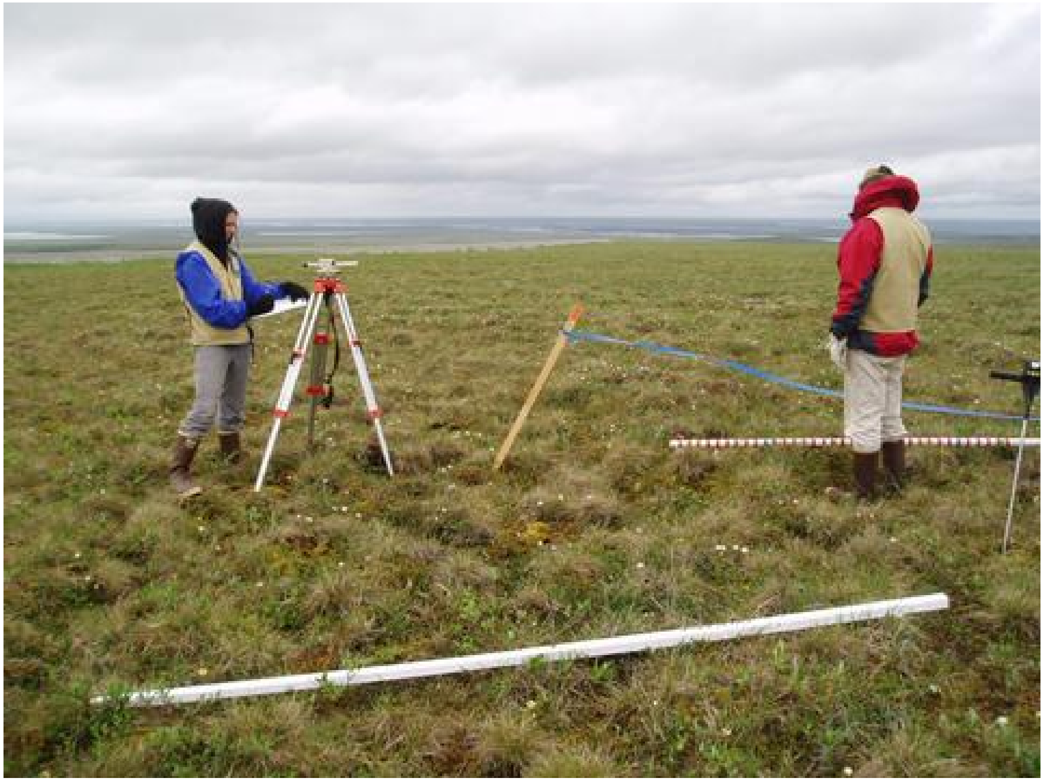
Figure 7: Summer Measurements in the Field (Foothills Study Site)



C. Measurement Protocols-Winter

At the time of each test date, staff measured the appropriate five treatment cells and each of the three transects within the cells. These measurements were taken the day prior to the vehicle treatments. In order to leave the actual transects unmolested by the measurement process, a proxy transect was established parallel to the transect at a distance of 2 m. All snow depth, ground hardness, and slab presence measurements were taken along this second transect. Data collected along the second transect was assumed to be the same for the actual transect. This procedure prevented the trampling of snow, the creation of snow pits to measure depth and ground hardness, and the use of the ratchet plunger for snow slab detection from altering snow and ground properties prior to the treatments.

Staff took all winter measurements at three locations for each transect. These locations were the two ends and the middle point.

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Figure 8: Winter Measurements in the Field (Coastal Plain)

D. Measurement Methods

1. Output Variables

a) Depth of Active Layer

Technicians measured the depth of active layer by steadily pushing a calibrated, pointed metal rod into the ground to the point of refusal (Affleck and Shoop 2001; Brown et. al. 2000; Vavreck et. al. 1999; Nelson et. al. 1997). While this is the most frequently used technique, it is understood that this system may involve some level of measurement error in finer grained soils by over-estimating depth if the rod penetrates into the softer top most layer of permafrost (Nelson et. al. 1997; Brown and Grave 1979). Depth is measured by reading the increment measurement on the rod from the ground surface to the point. To reduce measurement error associated with the subjective determination of the ground surface in thick vegetation, DNR affixed a loose washer on the rod. After the rod had been inserted into the ground to the point of refusal, the washer was pressed downward to the point of resistance, marking the ground surface next to the appropriate increment on the rod. Active layer was read to the nearest 0.5 inch. All data was subsequently converted to cm.

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b) Soil Temperature

Soil temperature was recorded with an insulated probe attached with a thermister at its tip. The probe was pushed 15 cm into the ground and left 30 seconds to equalibriate. Temperature was read to the nearest 0.1 F degree. After the temperature probe malfunctioned for unknown causes, temperature was measured with a digital soil probe, which took an average temperature along the 15 cm long probe length in the ground. The new instrument therefore introduced error by indicating a warmer reading than that at the appropriate depth. All temperature data was then converted to centigrade.

c) Soil Moisture

Soil moisture was recorded with a Spectrum soil moisture probe using magnetic resonance, which estimated percent of total volumetric water content between two probes. Moisture was recorded to the nearest one percent.

d) PAR (Photosynthetically Active Radiation)

In an effort to use a quantitative and objective measure of plant stress to replace the qualitative approaches used in earlier studies, DNR used instrumentation that measured the percent of ambient photosynthetically active radiation (PAR) absorbed by vegetation. The instrument was affixed to standard height staff 1.3 meters above the ground to ensure consistency of the measurement area. Ten evenly spaced measurements were taken along the transect, between each measurement mark on the transect. The instrument measured the average absorption of PAR within a 6 in diameter circle. Unlike all other measurements, PAR was performed without baseline data in 2003. Instead, treatment cells were compared to the no treatment cells, which served as a control.

Due to a brief growing season and relatively low productivity rates, most initial growth by tundra plants is supported by stored nutrients, therefore reducing the effect of annual weather variation, or disturbance, on total community productivity in any one year (Chapin and Shaver 1981; Chapin et. al. 1988). Thus, the productivity of a site, for which PAR is used as a proxy, reflects more an average of prevailing conditions over several preceding years rather than the most recent environmental conditions.

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Therefore, the PAR measurement may systematically underestimate the extent of stress induced by the treatments.

e) Microtopography

Microtopography was measured along the transect with use of a transom and rod. Eleven measurements were taken at 50 cm intervals from 0 to 5 m. All measurements were taken as a vertical departure from the reference reading at point 0 on the transect. Measurements were read to the nearest mm.

f) Life Form Description

Each transect was described subjectively in 10 increments by the dominant life form class relying upon ocular estimates. Each increment was 50 cm in length. Life form classes were (a) graminoid; (b) herbaceous forb; (c) woody shrub; (d) bryophyte; and (e) lichen. Other descriptors used, of dominant for the segment were bare earth, water, rock, or trash.

g) Tussock Assessment

Tussock disturbance was based upon the subjective, qualitative scaled used in prior tundra travel disturbance studies performed by the U.S. Fish and Wildlife Service and the University of Alaska. This scale is fully described by Emers (Emers and Jorgenson 1997). The scale is 0 for no disturbance; 1 for low disturbance; 2 for moderate disturbance; and 3 for high disturbance. The presence of a tussock was noted as present or absent at each of the 50 cm marks along the transect. Those tussocks along the transect that did not lie at a 50 cm mark, were not counted.

h) Shrub Assessment

Shrub disturbance was another qualitative and subjective measurement employed from previous studies reported in the literature. At each 50 cm mark along the transect, the presence or absence of a shrub was noted. Disturbance was described as 0 for none, Low if secondary or tertiary branches were broken, and High if the primary branch or stem was broken.

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i) Inventory by Genera

A horizontal rod, with 100 increments spaced at a 5 cm interval, was used to inventory the transect. At each increment, the plant at first intersect was recorded by genera. Thus, each of the 3 transects within a treatment cell was described along 100 points, giving a relative cover by genera.

2) Input Variables

a) Ground Hardness

Ground hardness in winter is measured by use of a drop hammer that drives a 12-inch probe into the ground. A 15 lb. weight is lifted by the operator and allowed to drop freely a prescribed 24 inches along a shaft, striking a plate to which the probe is attached. This approach removes all influence of the operator from the measurement. Hardness is described by how many drops it requires to drive the probe into the ground to a depth of 12 inches. The 3/8-inch diameter probe is scribed at one inch increments to allow measuring the number of drops at various depths if such a measurement is desired. It must be pointed out that all ground hardness measurements, as expressed in terms of drops to penetrate 12 inches, is assumed to be an ordinal scale. No controlled laboratory tests have been conducted to ascertain how the number of drops relate to actual hardness. Thus, while 12 drops is assumed to be harder than 11 drops, and 13 drops harder than twelve, no inference is made as to how much harder 12 may be than 11 or how much harder 13 is than 12.

Ground hardness measurements were taken at three locations along a snow trench dug parallel to each transect within a treatment cell at a distance of 2 m from the transect so as to leave it unmolested prior to application of the treatment vehicle. Three ground hardness measurements were taken at along each transect; one in the middle and one at each end of the trench. Measurements were taken the day before treatment was applied.

b) Snow Depth

A snow depth measurement was taken at each point along the snow trench where the ground hardness measurements were taken. Snow depth is measured to the nearest 0.5 inch and later converted to cm.

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c) Snow Slab Presence and Thickness

DNR evaluated a snow slab by means of an objective and quantitative system. Staff determined the presence of a snow slab if the snow resisted penetration by a handheld, spring ratchet penetrometer, calibrated in the lab to equal the International Snow Classification System defining a hardness index of “R4-High” (See Colbeck et. al. 1990). This laboratory designed standard and test corresponded well to field measurements indicating a snow slab density of 0.45-0.55 grams per cubic cm, which is consistent with published literature. If the observer was able to depress the ratchet penetrometer fully without breaking through the snow, a slab was recorded as present. The slab was then measured for thickness to the nearest 0.5 inch and later converted to cm.

3. Potentially Confounding Variables

The Foothills study area poses the possibility of confounding variables due to a marked variation in topography influencing elevation, slope, and aspect. Regression analyses were run to identify if baseline conditions were correlated with changes in topography at the scale of the study area.

a) Elevation

A regression was performed with elevation as an independent variable and the dependent variables depth of active layer, soil moisture, and soil temperature. Only the depth of active layer was significantly related to change in elevation.

b) Aspect

No significant relationships were found as a result of aspect, due to the consistency of aspect in each study site across treatment cells.

c) Degree Slope

No significant relationships were found with slope, probably as a result of slope uniformity.

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E. Determination of Whether to Have Separate Models for Each Study Area

An early question that had to be answered by DNR was whether the two study areas are sufficiently different in ecological characteristics to warrant different management under separate models. Given the large sample sizes (n=990 for DAL, n=900 for PAR, n=540 for soil moisture and temperature), a z-test was used to compare means on untransformed data. Results found a highly statistically significant difference (at $p<0.01$) between the Foothills and Coastal Plain study areas for each of the four characteristics (Table 4). DNR acknowledges that it would be possible to build a unified model that could be used for both ecosystem types (tussock and wet graminid). However, for purposes of management approach, DNR determined that separate models for each system would encourage manager recognition of the distinctive differences created by the heterogeneity in elevation and slope, and differential temperature and precipitation regimes. Therefore, DNR believes it prudent to create models for each study area, to assist agency decision making.

Table 4. Comparison of Characteristics Between Study Sites. Significant to $P<0.01$

Characteristics 2003	**Coast Plain Mean (SDev)**	**Foothills Mean (SDev)**
Depth of Active Layer (cm)	44.65 (7.5)	19.8 (7.9)
Soil Moisture (%)	83.2 (8.7)	44.2 (21.0)
Soil Temp (C) *	6.3 (1.2)	2.0 (1.6)
PAR Index *	145 (31)	288 (27)

* denotes measurements were taken in 2004 on the No Treatment cells

F. Regression Analysis Methods

Generalized Linear Models, using the SAS ® program, were used to identify relationships among winter variables, summer variables, and treatment vehicle effects. Because winter measurements were taken along a parallel transect and a different number of measurements taken, all winter data is expressed as gate means. These means are then applied to the individual summer transect measurement points for purposes of regression.

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Disturbance effects were not observed equally along the transect line. Those measurements at the extreme ends of each transect were more similar to no treatment cell means than to the vehicle treatment cell means. This can logically be explained, as only the central portions of the transect were traversed by vehicles. Taking all points along the transect could bias the results, systematically under identifying change and disturbance effects. Therefore, the model was designed to take into account this pattern along transects and categorized data as either "inside" or "outside" depending upon the location of the measurement point along the transect. The investigation also found a difference in result between the straight gate and the turn gates of the figure 8. The straight gate received 10 passes of each vehicle while the two turn gates received 5 passes each. Results indicated greater disturbance effects associated with the straight gate than the turn gates; this may be a function of the greater intensity of treatment related to the number of passes.

G. Baseline Description

DNR conducted baseline surveys for each study area during the 2003 summer field season. The Foothills study area, located 20 miles north of Happy Valley, contains a mosaic of tussock and moist sedge/shrub tundra and therefore represents community types that comprise approximately 65% of total natural vegetative cover found generally in the Foothills. The Coastal Plain study area, situated about 3 miles south of Deadhorse, is a mosaic of wet graminid and moist sedge/shrub tundra and therefore represents about 64% of total vegetative cover typically found in the Coastal Plain. Wildlife, such as musk ox, caribou, wolf and grizzly bear were infrequently seen on both study areas. Grazing and trampling by ungulates may serve as an unaccounted for confounding variable within the study sites, but are assumed to be negligible in impact for the purposes of this study.

1. Ecological Change and Calibration to Natural Disturbance Regime

The available scientific literature discussing the processes of cryoturbation, active layer freeze thaw cycles, and soil moisture and temperature regimes strongly suggests significant inter-annual variation associated with the tundra, in addition to significant differences in these same characteristics across short spatial dimensions. As a result, it is necessary to ensure that study results are calibrated to take into account the natural

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change when defining disturbance as a departure from baseline. The no treatment cells are used for this purpose.

The summer of 2004 was both warmer and drier than the previous summer in 2003 on the coastal plain and foothills study sites. It appears that this may have manifested itself in deeper active layer depth and altered soil moisture levels. It is important to note that though mean values for treatment gates within each no treatment cell changed from 2003 to 2004, the relative ordering of these mean values remained the same in both years. This indicates success in transect placement ensuring re-measurement of the same points, as well as success in identifying a consistent trend of natural change on the coastal plain and foothills study sites.

2. Coastal Plain Site

a) Pre-treatment Description

In 2003, prior to treatment, vegetation in the Coastal Plain study area consisted of a mosaic formed by wet sedge meadows of *Carex* species and a moist sedge/shrub community type. This low canopy exhibits a nearly uniform physiognomy. A list of total species observed within the study area pursuant to a Releve survey is included as Appendix C attached to this report. The study area features a terrain dominated by high centered polygons, with frequent hummocks and frost boils. Though present, tussocks were rare within this study area.

Active layer depth found in the Coastal Plain study area averaged 44.6 +/- 0.45 cm within a 95% confidence interval (standard deviation of 7.5; n=990). Mean soil temperature on No Treatment cells in 2004, at a depth of 15 cm, was 6.3 +/-0.37 degrees C within a 95% confidence interval (standard deviation of 1.2; n=540). Percent volumetric soil moisture content at depth of 15 cm averaged 83.2 +/-0.72 percent (standard deviation of 8.7; n=540).

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Microtopographical relief is characterized by the presence of high center polygons and hummocks. Geometrically arranged trenches, bordering the polygons, mark the presence of ice wedges. These trenches were typically 10-30 cm deep and frequently partially filled with melt water. Hummocks were irregularly distributed across the study area and ranged in height from 15-40 cm. Frost boil carapaces created dome like relief often 30 cm high and approximately 1 m across.

Figure 9: Coastal Study Site Aerial View (Post Treatment, 2004)

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Figure 10: Sedge Meadow Community Type (No Treatment Cell)

The dominant characteristic of the Coastal Plain study area is it flatness. Only six of the thirty plots showed a discernable slope. In each of these six plots, the slope measured less than 1%, with a gentle southeast aspect. Elevation change is 1 m on the study area, from a low point of 14 m to a high point of just 15 m.

b) 2003/2004, No Treatment Cells

On the coastal plain, the average active layer depth, on the no treatment cells, changed by 2.4 cm, from a depth of 44.65 cm to 47. 05 cm (SD 2.5; n=198). This change was not uniform along all measurement points. Instead, the change in the depth of active layer at any one point in the no treatment cells, between years 2003 and 2004, is significantly related to the 2003 active layer depth ($p<0.0001$; r sq= 0.30). In other words, the deeper the active layer in 2003, the less change in active layer depth in 2004. This situation makes intuitive sense. The deeper the active layer, the more energy is needed to penetrate through the soil and melt frozen ground. A comparison of each transect gate in all no treatment cells demonstrated this consistent pattern. Because cells were

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assigned randomly within the study site, it is assumed that there are no spatial anomalies across the study site that departs from this pattern.

Soil moisture levels likewise changed between the baseline and post treatment years. On the no treatment cells, the volumetric soil moisture content declined from a base line value of 83 % to a subsequent value of 76%. The change in soil moisture also was not uniform, and instead was significantly related to the moisture content of the previous year ($p<0.0001$; r sq=0.51). Thus, the greater the 2003 soil moisture content, the less change was observed in 2004.

Because of equipment malfunction in 2003, no reliable baseline data exists for soil temperature at a standardized depth of 15 cm. Therefore, the no treatment cell temperatures were used as comparison controls and no calibration techniques were employed. PAR index measurements were treated in a similar manner as soil temperature because the scanning equipment was not available in 2003.

2. Foothills Site
   a) Pre-Treatment

Vegetation community types within the Foothills study area are dominated by non-acidic sedge and shrub tussock tundra. A list of plant species found within the study area pursuant to a Releve survey is included and Appendix C attached to this report.

Terrain within the Foothills study area is defined primarily by a north-facing slope without visual evidence of solifluction or other form of frost creep. Hummocks and frost boils are infrequent. The geological bedrock of the hillside is composed of course grained sand stone and poorly consolidated conglomerate containing clasts consisting of chert, white quartz, and fine grained quartzite (Mull and Adams 1989).

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Active layer depth averaged 19.8 +/-0.49 cm within a 95% confidence interval with a standard deviation of 7.9 (n=990). Mean soil temperature on No Treatment cells in 2004 was 2.0 +/- 0.07 degrees C within a 95% confidence interval with a standard deviation of 0.89 (n=540). The observation that the Foothills study area has cooler soils and a shallower active layer than in the Coastal Plain study area, is contrary to what one would expect to find based upon a review of the available literature. However, this situation can probably be best explained by the fact the Foothills study area is situated upon a slope with a predominant northerly aspect, resulting in colder site conditions. Soil moisture, as measured by percent volumetric water was 44.2 +/-1.49 percent within a 95% confidence interval with a standard deviation of 21.0 (n=540).

Microtopography is characterized by the near ubiquitous presence of tussocks. In addition, the hillside upon which the study area is located possesses a gentle rolling nature. The gradient of the slope averages 4% with a northerly aspect ranging between 320 to 050 degrees. Elevation change on the site is 42 m, ranging from an elevation of 320 m at the base of the slope to 362 m at its top (Table 5).

Table 5. Foothills Study Area: Treatment Cell Row by Elevation (m)

Cell Row	A	B	C	D	E	F
Elevation	320	326	334	339	349	362

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Figure 11: Foothills Study Site Aerial View (2004)

Figure 12: Tussock Vegetation Community (No Treatment Cell)

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b) 2003/2004, No Treatment Cells

Like the Coastal Plain sedge meadows, the tussock tundra of the Foothills study site experienced a natural increase in depth of active layer from 2003 to 2004, indicative of the prevailing warmer and drier conditions during the summer 2004. The degree of change eclipsed that found on the Coastal Plain, however. Tussock communities experienced an increased active layer depth of approximately 5.6 cm (SDev 4.84; n=198) from a depth of 19.8 cm in 2003 to 25.4 cm in 2004. The relationship of change in active layer to the previous year depth levels was significant. Like the Coastal Plain, the deeper the active layer, the less change in 2004 ($p<0.001$; r sq.= 0.19; n=990).

The effect of a warmer summer season on the Foothills site seems to have increased soil moisture. Soil moisture changed by 3.7% from 44.2% in 2003 to 47.9% in the year 2004 (SDev 13.9; n=540). This trend, opposite that observed on the Coastal Plain, may make intuitive sense. The Foothills, with a shallower active layer, would increase the water volume measured at the standardized depth of 15 cm in part because of the closer proximity of the nearly impermeable permafrost. In this case, the higher the soil moisture in 2003, the greater the increase in soil moisture in 2004 ($p<0.0001$; r sq.=0.14; n=540).

IV. RESULTS AND DISCUSSION

A. General Introduction to Results

It is important to acknowledge that there are many approaches toward constructing a regression model and that numerous value judgments are made in selecting predictor variables (covariates) as well as the generation of interactive variables for use as predictor variables. This model should therefore be viewed in the context of an iterative process as part of an adaptive management strategy. As new information becomes available and as DNR improves its understanding of the tundra, the model will surely be refined and modified in upcoming years.

A number of assumptions are necessary in generating and using a general linear model. These assumptions include (1) normality of errors and homogeneity of error; (2) independence of observations; (3) linearity of the relationship between independent and dependent variables. In this model, the assumptions of homogeneity and normality were

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tested and found to be reasonably satisfactory. However, independence is assumed, though truly unlikely. Values along a transect are probably correlated with each other in some way.

The models presented here were created by using a process of backward stepwise regression. Models were constructed by initially including a large number of possible predictors and interactions, and then progressively removing non-significant predictors. The resulting models are a product of the predictors considered and the process of predictor elimination. There are other models that could be legitimately suggested from the collected data.

DNR investigated the relationship of the following variables with the response variable of change in the active layer depth: (1) ground hardness, (2) snow slab thickness, (3) overall snow depth, (4) treatment type, (5) whether measurement points were in the center of the transect or at its margins, (6) whether the vehicle type was turning or going straight, (7) 2003 depth of active layer, (8) operator, and the interaction of treatment type with all of the above. This produced a set of 36 possible model co-efficients. Predictor variables were then reduced upon the basis of significance of contribution to the response variable. Selection was also based upon those variables that were marginally significant but produced larger disturbance predictions in homage to the precautionary principle.

As a result, a wet/moist sedge tundra model (r sq=0.272; F value 21.38; n=990) was generated to predict change in active layer depth using ground hardness, snow slab thickness (subjected to a log transformation), measurement points located near the center of the transect (to maximize potential disturbance predictions), treatment type, vehicle direction (to maximize potential disturbance predictions), the interaction effect of vehicle type with ground hardness, the interaction effect of vehicle type with snow slab, and the depth of active layer in the preceding year (2003). A similar model was used to predict change in soil moisture (r sq=0.326; F value 21.34; n=540).

A tussock tundra model to predict changes in active layer (r.sq=0.375; F value 21.41; n=990) was generated using snow depth, treatment type, elevation, operator, active layer depth the previous year, and the interaction effects of snow depth with vehicle type, and treatment type with elevation. Similarly, a model for change in soil moisture was also created for tussock tundra (r sq= 0.279; F value 8.33; n=540).

Following construction of the model, a check for normality was performed by constructing a plot of the residuals with normal percent probability. It is assumed that the plot should track a straight line. This was done and determined by eye to be satisfactory. Residuals were also plotted against predicted response values to determine the general scatter. The plots exhibited a random display suggesting that the variance of the original observations is constant for all values of the response values. Finally, studentized residuals were plotted to determine if any point with high values is influencing the least squares fit.

Aerial flights over the study sites revealed visible figure eight patterns expressed on treatment cells as green trails. This phenomenon is discussed at length by Chapin et. al. (1988) and Felix and Raynolds (1989a,b) and is assumed to be ephemeral if the physical disturbance is at a low intensity. This study did not evaluate tundra resistance to, nor the persistence of, these green trails. However, continued over-flights will monitor them in coming seasons.

B. Winter Description

The Coastal Plain study area ground froze harder than the Foothills study area, as measured by the slide hammer. Snow depth on the Coastal Plain study area was also considerably less throughout the winter study period. A summary of Coastal Plain and Foothills study areas average ground hardness and snow characteristics by treatment date is included in Table 6 (n=45) for each treatment date. The University of Alaska Geophysical Institute maintains soil temperature and moisture arrays near each DNR study site. The soil temperature profile for each treatment date is also included in Table 6 c.

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Table 6: Ground and Snow Characteristics

a. Coastal Plain Ground Hardness and Snow Depth by Treatment Date

(dpf=drops per foot of slide hammer; snow depth and slab in cm)

Date	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
Ground Hardness (SDev)	11 dpf (3.5)	27 dpf (6.7)	74 dpf (20.2)	89 dpf (23.6)	83 dpf (19.2)	105 dpf (30.2)
Snow Depth (SDev)	15.24 (6.41)	12.58 (3.01)	16.00 (5.28)	15.52 (3.87)	16.03 (4.58)	18.65 (6.22)
Snow Slab (SDev)	0 (0)	0.28 (0.9)	1.6 (2.0)	0 (0)	2.1 (3.1)	1.6 (5.7)

b. Foothills Ground Hardness and Snow Depth by Treatment Date

(dpf=drops per foot of slide hammer; snow depth and slab in cm)

Date	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
Ground Hardness (SDev)	3 dpf (2.2)	4 dpf (2.5)	25 dpf (12.5)	23 dpf (13.4)	18 dpf (11.6)	25 dpf (14.8)
Snow Depth (SDev)	23.28 (5.58)	27.96 (6.66)	22.21 (5.80)	29.77 (7.10)	28.7 (6.64)	27.88 (8.18)
Slab (SDev)	0 (0)	0.16 (0.83)	1.10 (2.64)	1.63 (3.05)	2.11 (3.93)	0.22 (1.51)

c. Soil Temperature by Test Date for 1 Foot Profile (expressed in degrees C at cm depths).

Coastal Plain/Wet Sedge Study Site

	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
15 cm	-0.42	-1.49	-6.21	-8.01	-8.15	-14.72
23 cm	-0.28	-0.88	-5.25	-7.65	-8.01	-14.19
30 cm	-0.13	-0.38	-4.34	-7.28	-7.87	-13.66

Foothills/Tussock Tundra Study Site

	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
10 cm	-0.52	-2.46	-7.42	-7.62	-12.34	-10.22
18 cm	-0.08	-1.31	-6.51	-6.78	-11.50	-9.95
30 cm	-0.04	-0.71	-5.49	-5.95	-10.57	-9.86

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Air temperatures at the time of treatments became progressively colder during the winter. Table 7 portrays the ambient air temperature on the day of the treatment for each study site at the time treatments began.

Table 7. Ambient Air Temperature in degrees C at Time of Treatment

Date	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
Foothills	-1	-18	-27	-30	-48	-38
Coastal Plain	-2	-26	-33	-17	-27	-30

C. Input Variables

1. Ground and Snow Influences

a) Ground Hardness

Freeze up of the ground and its hardening exhibited a sinosoidal curve trend (Table 6) at both study sites. Little change in ground hardness was recorded during the first two test dates in October to mid-November, then a period of intense change where the ground hardened quickly, occurred between test date two in November and test date three in early December. After which, the ground hardened only slightly more, as measured with the slide hammer, during the final three test dates from late December to late January, despite extreme, persistent cold air temperatures. This pattern is consistent with previously published literature and the observation of a zero curtain effect as discussed in Section II.

Mud streaks and ice crystals were visible on the drop hammer probe tip during ground hardness measurements taken during each of the six test dates, though the frequency of such occurrences diminished markedly after test date three. These observations seem congruent with reported literature that suggests significant quantities of liquid water remain in frozen ground, diminishing gradually to about 5% of volumetric water with decreasing temperatures.

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Published literature suggests that an increased level of soil moisture content contributes to increased ground hardness. The data and regression analyses appear to substantiate this observation. A significant relationship between soil moisture and ground hardness was observed during treatment date two that coincides with the period of intense freeze-up ($p=0.02$). No significant relationship between moisture and hardness was found before or after this point. This conforms to what one would expect to find. Soil moisture contribution to ground hardness derives from the structural strength of ice and bonding with soil matrix. When ground is thawed, such as during test date one, little or no ice is present. Once the ground is thoroughly frozen, as assumed during test dates three through six, ice is already formed and no appreciable contribution by soil moisture is made to hardness. Therefore, one would expect to find the relationship strongest during test date two.

A slight positive relationship was also found between ground hardness and snow slab thickness ($p<0.0001$). As snow slab increases, the insulation capacity of the snow decreases (higher density and higher water content increase energy conducting properties of snow). Thus, a small increase in ground hardness is associated with those areas where deep slabs form.

Ground hardness and its interactive effect with treatment type contributed to changes in active layer depth and soil moisture in wet/moist sedge tundra. Consequently, ground hardness was included in those models. However, ground hardness was not found to contribute significantly to changes in active layer and soil moisture in tussock tundra and therefore, not included in the tussock models.

b) Snow Depth

Typically, a bimodal snow deposition pattern dominates the North Slope. Heavy snows occur early in the season and again much later toward the end of winter as air masses adopt a more spring like pattern. In the interim, dry air dominates and little snow falls. By the time of the first treatment date on October 30, 15 cm of snow was already on the ground in the coastal plain and 23 cm in the foothills. These levels of snow cover did not change appreciably during the series of tests (Table 6). The presence of a large amount of snow cover by the first treatment date, with vary little variation in cover over the course of the next five treatments, made it difficult to identify the effects of snow cover

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on disturbance by regression or other analysis techniques. Therefore, the regression models are not directly applicable without a minimum threshold of 15 cm snow depth in the wet/moist sedge tundra and a minimum threshold of 23 cm in tussock dominated tundra terrain.

According to the available literature, it is assumed that snow provides a physical buffer to ground compression and mechanical abrasion. At a certain point, snow depth probably reaches a level where the protective effect is completely manifested, and little or no additional influence results from an increase in snow cover.

Snow depth did influence disturbance effects in models for tussock-dominated terrain, contributing to significant changes in active layer depth. For example, the more snow present, the less the increase in the active layer depth over natural change, depending upon the vehicle type. As was anticipated, the model found that snow had its most profound effect under the tractor and loader treatments, and its least effect under the tucker and challenger treatments. Snow depth had no significant contribution to changes in soil moisture in tussock terrain, and therefore, was not included in the model.

In the models presented here, it appears that threshold level for snow depth contribution to change in active layer depth and soil moisture in the wet/moist graminid communities was achieved, or nearly so, prior to the initiation of treatments. Therefore, the effects of snow depth could not be fully modeled.

c) Snow Slab Thickness

Snow slabs appeared to have a significant effect in reducing disturbance effects, particularly with heavy vehicle treatment types such as the tractor and the loader in wet/moist sedge tundra. Thicker snow slabs in wet sedge vegetation communities reduced the increase in the depth of the active layer for each treatment type. The influence of snow slab was most pronounced with the tractor and loader, and the least with the tucker and challenger. Slab thickness also affected the change in soil moisture. The thicker the slab under a particular treatment type, the less change in soil moisture. Snow slab influence was greatest with the tractor and loader treatments, and lowest under the tucker and challenger. These model findings regarding the role of snow slab are consistent with the U.S. Fish and Wildlife Service study, which suggested a similar

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relationship. It is assumed that the presence of hard snow slab offers some form of physical barrier that ameliorates the types of mechanical effects to soil properties that precipitate changes in active layer and soil moisture in the wet/moist graminid community types.

The role of snow slab was not significant, however, in influencing changes in tussock tundra soil moisture and active layer depths. As a result, the model for these tundra types did not include slab as an input.

2. Vehicle Types

Treatment vehicles may impact the depth of active layer in two ways. First, if the vehicle is light, an early treatment may have the effect of increasing ground hardness and reducing the depth of active layer the following summer. This phenomenon is called “pre-packing” and is frequently employed as a technique in preparation for ice road construction. Driving over unfrozen ground with snow cover compacts the snow reducing its insulation capacity, allowing the ground to freeze harder and deeper more quickly. As a result, summer active layer depths tend to be shallower following “pre-packing” because of the additional energy to thaw the harder, more deeply frozen ground.

Another effect of vehicle travel is that heavy vehicles may compact the vegetation/peat/soil complex, resulting in a reduction of summer insulation capacity, allowing for more efficient transfer of incoming solar energy to penetrate to the thaw front. Under such circumstances, the thaw depth will increase, creating a thicker active layer the following summer. Both possible effects were suggested in the study results.

D. Magnitude of Observed Changes

Disturbance levels, as expressed in terms of depth of active layer and moisture change, are less than the investigators expected (See Appendices F & G). Consequently, the changes in these measures predicted by the model are also quite modest. At first, these observations seemed contrary to the established literature. A closer examination of the DNR findings and a detailed scrutiny of the literature, however, gives rise to an interpretation that the study’s results and the existing literature are not inconsistent with one another.

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The primary literature on seismic exploration impacts to tundra stems from a series of articles originating out of a set of long term studies conducted by the U.S. Fish and Wildlife Service from 1984-present on the Coastal Plain of the Arctic National Wildlife Refuge. The federal study identified four levels of disturbance on a scale of 0-None; 1-low; 2 moderate; and 3-high (Emers et. al. 1995; Felix et. al. 1992; Felix and Raynalds 1989a, b). These investigators defined a level 1 low intensity disturbance as: (1) 0-25% reduction in vegetative ground cover; (2) 0- 5% of ground surface with exposed bare mineral soil; (3) tussocks and hummocks scuffed. The intensities increased accordingly from this level to a level 3 high intensity disturbance defined as (1) >50% reduction in vegetative cover; (2) >15% of ground with exposed bare mineral soil; and (3) nearly continuous crushing of tussocks and the formation of ruts. Under level 1 low intensity disturbance, the USFWS investigators found no significant difference between control and treatment plot active layer depths in wet graminid, moist sedge, and tussock tundra types the first year after the seismic activity (Felix et. al. 1992).

It is important to note that in the DNR study, observed disturbance levels in all treatment plots across all treatment types and dates, (coastal or foothills), did not exceed that which the USFWS study described as a level 1 low intensity damage. Unlike the USFWS study, the DNR investigation found statistically significant changes in the depth of the active layer and soil moisture associated with treatment type and snow/ground hardness condition, even though disturbance was limited to the low intensity category. These changes drive the models generated by the DNR study.

As mentioned before, change occurred naturally between 2003 and 2004 in both the active layer depth and soil moisture in wet sedge and tussock tundra types (Table 8). The observed departure from this natural baseline change attributable to the treatments was greater in tussock tundra than in wet sedge tundra, in both absolute and relative terms. These findings mirror results reported in the USFWS study. For example, during the first treatment trial, the various vehicle types produced departures from the baseline that were markedly greater in tussock environments than in wet/moist sedge tundra. (Table 9 a & b).

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Table 8. Natural Base Line Change 2003 to 2004

Change in Characteristic	Wet/Moist Sedge Tundra	Tussock Tundra
Active Layer Depth (cm)	2.5 cm deeper	5.6 cm deeper
Soil Moisture (%)	7% decrease	3.7% increase

(Note: Sedge tundra DAL was 44.6 cm and soil moisture was 83% in 2003; tussock tundra DAL was 19.8 cm and soil moisture was 44% in 2003).

Table 9a. Change by Treatment, Trial Date One, Tussock/Foothills Tundra.

Characteristic	Tractor	Loader	Challenger	Tucker
Active Layer	7.1 cm deeper	5.9 cm deeper	10.0 cm deeper	4.8 cm deeper
Soil Moisture	13.7% greater	12.7% greater	14.0% greater	10.7% greater

(Note 2003 active layer depth was 19.8 cm, 2003 soil moisture was 44%.)

Table 9b. Change by Treatment, Trial Date One, Wet Sedge/Coastal Plain Tundra.

Characteristic	Tractor	Loader	Challenger	Tucker
Active Layer	0.9 cm deeper	3.5 cm deeper	0.9 cm deeper	3.1 cm deeper
Soil Moisture	6.3% less	11.5% less	8.5% less	8.0% less

(Note 2003 active layer depth was 44.6 cm, 2003 soil moisture was 83%)

E. Evaluation of Potential Utility of Other Disturbance Measures

DNR could not create models for change in soil temperature and PAR absorption index because these measurements were not taken in 2003. Equipment was not available to conduct PAR Index measurements and equipment malfunction invalidated the 2003 soil temperature data. As a result, this study simply discusses the potential utility of these measures in identifying disturbance effects. DNR concludes that further evaluation, study, and monitoring must be conducted before integrating PAR and micro-topography into a routine and reliable system for disturbance detection. Soil temperature holds little promise as a useful measure.

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DNR did not model changes between microtopography in 2003 and 2004 because there were no measurable changes. Lack of change in microtopography may be the result of a true lack of change, or it may be that the measure is subject to a lag time, which exceeds the length of this particular inquiry. Further monitoring should address this question.

1. PAR Absorption Index

This measurement is a ratio based upon the amount of ambient photosynthetically active radiation striking the ground surface and the amount reflected off the ground (and vegetation). The difference is assumed to be absorbed. PAR Absorption Index is used as a proxy for plant disturbance and replaces the more subjective approaches currently employed by DNR. The Index has no base line for calibration because the equipment did not become available until 2004. Therefore, all treatment cell measurements are compared to the pooled no treatment measurements that serve as a control.

Several environmental variables significantly influence PAR in the no treatment cells. Mean gate PAR values are significantly related to both soil moisture ($p<0.0003$) and depth of active layer ($p<0.001$). Thus, the more soil moisture and the deeper the active layer, the higher the PAR Index value. Therefore one finds that those treatments whose effects on active layer and soil moisture are most influenced by ground hardness and snow depth probably change PAR values. The relationship of PAR Index to active layer depth and soil moisture may reduce its value as a separate indicator of disturbance in the field.

PAR Index measurement are intended to replace the qualitative and subjective measures previously used to identify disturbance to vegetation on the 0-3 point scale used in earlier studies. This is important because of the high measurement error associated with the qualitative vegetation disturbance approach. Evaluation of the consistency of value assignment to vegetation on the 0-3 scale found error that typically exceeded 15%. Therefore, use of this subjective measure may produce misleading results, and, because of its numerical scale, may infer a level of precision that is not present. Therefore, DNR will continue to attempt to refine the potential use of PAR Index for field applications to replace the subjective, qualitative measurements.

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2. Soil Temperature

Soil temperature at a 15 cm depth was highly related to the depth of the active layer ($p<0.001$; r sq=0.72). Therefore, it is of limited utility and is recommended to be abandoned as an indicator of disturbance.

3. MicroTopography

Change in microtopography carries the potential for utility in controlled experiments, but due to the time, effort, and skill involved may be of limited value as a field measure. However, it is recommended that the study plots continue to be surveyed for change in order to determine if trends develop later that are not now discernable. DNR did not find any evidence of rutting in any transect in any treatment plot **(**Appendix G**).**

4. Variability

DNR investigated the potential effect treatments may have on the variation of active layer depths, soil temperature, soil moisture and PAR, to determine if treatments suppressed or increased variation. No trends in the coefficient of variation were observed among the treatment types, nor treatment types and treatment date. Therefore it is assumed that use of evaluation of variability for a specific measure is not an effective indicator of disturbance.

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V. CONCLUSIONS

A. Management Implications

These models do not attempt to infer when a resources manager ought to open the tundra for off road travel by particular vehicles. Instead, the model identifies the change in important abiotic drivers of change, in the tundra ecosystem, that one may expect as a result of vehicle passage under varying snow and ground conditions. It is imperative to emphasize that these models only describe what is expected to occur within the study sites. No statistically valid inference can be drawn from the model to describe that which is occurring elsewhere on the tundra. These models merely represent an understanding of processes and relationships that are helpful to understanding interrelationships in the very dynamic tundra environment. Their utility is as an illustrative input, not a precise predictor.

An example of the use of the model for management purposes is included here. Assume that the freeze up conditions in a future year approximates the conditions that developed over the course of the winter in 2003-2004. If one wishes to predict the change and its departure from natural baseline inter-annual variation that would occur by approving the use of a challenger, the utility of the models readily presents itself.

Assuming conditions were similar to that on October 30, 2003 we input the following variables: Ground Hardness 11; Snow Depth 15 cm; and Snow Slab 0.9 cm where the previous summer Depth of Active Layer was 40 cm. Now consider if the manager wishes to use a Challenger on a wet sedge plain community type. Running the model, the land manager could expect a departure in the change in the depth of the active layer of 3.1 cm beyond that which would normally occur, absent the vehicle passage.

Now, if the Manager wished to see what type of change may occur if s/he waited until the conditions changed to those similar to the treatment date of December 4, 2003 the manager would change the inputs. On that date the ground hardness was 74, snow depth 16 cm and a snow slab was present with a thickness of 1.6 cm. Taking these values we see that the departure from the natural change in depth of active layer would be 0.57 cm. If the manager wished to determine the potential protection that might be

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realized by waiting, the manager could input the conditions that were found in late December. Under these conditions of a ground hardness of 89, snow depth of 15.5 cm and a slab thickness of 0 cm, we see that the expected departure is 0.56 cm, an insignificant difference. Thus, no advantage in environmental protection could be gotten by delay, waiting for harder ground.

Of course, natural resources management is a splendid blend of art and science, and decisions must never be reduced to a mere quantitative model that removes the discretion from field personnel. Therefore, the model should be viewed as simply an additional tool, to be taken into consideration, when a manager weighs the many values that compete in typical decisions.

B. Recommendations

These models represent a first, important step in bringing quantitative and objective techniques to decision makers concerning the effects of off road tundra travel activities. With this information, DNR can better anticipate the degree of disturbance associated with tundra opening decisions.

It is recommended that DNR continue monitoring of the modeling study plots on the Coastal Plain and the Foothills. This information should be utilized to determine if trends, not apparent at this time, manifest themselves on the landscape. Use of the models should also adopt an adaptive management strategy, under going continual refinement as new information becomes available following rigorous field monitoring. Finally, extensive in-field monitoring, as tundra travel activities commence, should accompany any decision utilizing model results to verify prediction accuracy. These monitoring activities should then be used to further adjust and improve the model for subsequent application.

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VII. APPENDICES

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