Impacts to, and Recovery of, Tundra Vegetation from Winter Seismic Exploration and Ice Road Construction

Dave Yokel and Jay Ver Hoef

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Introduction

During the development of a land use plan (USDOI, BLM, 1998) for the northeastern portion of the National Petroleum Reserve in Alaska (NPRA), it became apparent to us that winter oil and gas exploration has the potential to affect more acres of land than any other component of oil/gas activities, including oil field development, on Alaska's North Slope. By measuring and recording the impacts of seismic trails and ice roads on vegetation, this long-term monitoring of affected areas documents impacts and recovery. Such documentation is necessary for both adaptive management of oil/gas activities, habitat management, NEPA compliance and for overall implementation of the Environmental Impact Statements/Integrated Activity Plans (EIS/IAPs) for the NPRA. The objectives are to measure the impacts of vehicles on vegetation in a quantifiable and repeatable manner with a sampling design that allows valid extrapolation of the results to other affected areas. Study plots vary by landcover type, impact type, and degree of impact. This allows a test of the hypothesis that impacts vary among vegetation types and vehicle types, and provides a measure for comparison over later years to document degree of recovery in each of these different situations.

Winter tundra travel has been shown to cause significantly less impact than similar activities carried out during summer, so most seismic exploration carried out since the late 1960s on the North Slope of Alaska and western Canada has been conducted during winter (Bliss and Wein 1972; Hernandez 1973, Reynolds 1982). This report addresses long-term (12 years) recovery of vegetation on seismic trails and ice roads used in the winters of 1999 and 2000. This has been a multi-year project because several years of data collection were required to determine vegetation recovery over time. The first interim results were reported during a symposium by Yokel (2004). A more comprehensive and longer-term study has taken place in the Arctic National Wildlife Refuge (ANWR) of northeastern Alaska. This latter study investigated impacts and recovery from seismic trails made in 1984 and 1985 (Felix and Raynolds 1989a; Emers et al. 1995; Jorgenson 2000; Jorgenson et al. 2010). Together, these 2 studies allow comparison of effects in slightly different terrain types and vegetation communities.

Study Area and Methods

Oil exploration began in the NPRA during the early 1900s, with field parties searching for oil seeps. It was continued by the U.S. Navy with an exploration drilling program from 1944 to 1952 (USDOI, BLM, 1998) and a seismic data acquisition program from 1944 to 1953 running 3,300 line miles (Gryc, 1988). In 1974 the Navy resumed its seismic program with contractors Tetra Tech, Inc., and Geophysical Services, Inc. This program continued through the spring of 1981, collecting 13,179 line miles of data, although Congress transferred the NPRA from the Navy to the Department of the Interior effective June 1, 1977. Industry interest in oil frontiers west of the existing Prudhoe Bay and Kuparuk oil fields in the 1990s resulted in a discovery

(Alpine) in the Colville River delta just outside the NPRA in the winter of 1994–1995 (Alaska Report, 1996) and renewed seismic exploration in the NPRA. The Alpine discovery revealed a new geologic play thought to extend westward into the NPRA, further increasing interest in the NPRA (Kornbrath et al., 1997).

Seismic exploration by the oil industry south and east of Teshekpuk Lake, the part of the NPRA nearest to Alpine, resumed in 1994 and continued annually between then and the initiation of this project in 1999. There was considerable geographic overlap among years and different industry groups. To ensure that study plots involved only impacts from the 1999 activity, all of the 1994–1999 seismic programs were depicted in a Geographic Information System, and the portion of the area covered by 1999 programs and no others was clipped out and saved as a separate layer. When data were first collected in summer of 1999, study plots were established only in that separate area roughly contained within a triangle defined by Teshekpuk Lake, Nuiqsut and Inigok, (Figure 1). In this way, all impacts observed in the first summer were reasonably known to have been caused by the previous winter's activities. No evidence of seismic exploration from the 1974–1981 programs was observed in the study area in 1999. It was assumed that if any of the plots established in 1999 overlapped a trail from the earlier period, a low-probability event due to the low density of earlier lines (grid average of 7 mi by 9 mi), effects of previous impacts on 1999 and later data collection would be negligible.

Seventy-seven plots were chosen from across the study area to represent the different vegetation types (6 major and 12 minor vegetation cover classes; USDOI, BLM, 2002) and trail types, with an attempt to represent the 4 disturbance levels at proportions similar to those throughout the seismic projects. An attempt was also made to obtain a reasonable sample size of each vegetation-trail type combination, but this was not entirely possible due to what actually existed on the ground and time limitations. From wetter to drier, the vegetation classes were aquatic - *Arctophila*, aquatic - *Carex*, flooded tundra - non-patterned, flooded tundra – low-centered polygon, wet tundra, moist tundra – sedge/grass meadow, moist tundra – tussock tundra, moist tundra – moss/lichen, shrub – dwarf, shrub – low, barren ground – sparsely vegetated, and barren ground – dunes/dry sand. Plots were further divided between trails made by seismic data acquisition vehicles (seismic trails) and those made by the movement of seismic camp trains between campsites (camp-move trails). In addition, 12 plots along the path of an ice road constructed and used in winter 2000 were established in the summer of that year. These 12 involved 7 of the above cover classes, excluding aquatic - *Arctophila*, moist tundra – moss/lichen, shrub – low, and both barren ground classes because the ice road route did not intersect those vegetation types.

Each of the 89 plots of disturbed vegetation was paired with a control plot. Disturbed plots were 10 m long and up to 8 m wide, and marked with rebar stakes in the center of each end and wooden stakes at each of 4 corners. The width of each disturbed plot was determined by the width of the trail; if trail width was >8 m, the plot was established in the center of the trail. Control plots were 10 m long and on an adjacent, undisturbed area of similar vegetation. They were marked by a rebar stake at each end with a wooden stake next to it. In addition, each disturbed plot had a 1 m^2 photo quadrat established, marked with rebar and wooden stakes, somewhere within its outer boundary. Wooden stakes could usually be seen easily from a helicopter when returning to a site in subsequent years, even if a stake had fallen over. Coordinates for all plots were recorded using a Global Positioning System.

Plot location and establishment, and initial data collection occurred in 1999 (July 16–24 and August 2–13) for seismic and camp-move trails, and in 2000 (August 16–19) for the ice road. The second through fifth major data collection efforts occurred in 2002 (July 24–August 1), 2005 (July 21–August 2), 2008 (July 22–August 1), and 2011 (July 17–24). Data have been analyzed after each year of collection. The original intent was to collect data until all plots had completely recovered, but this has proven infeasible because of the number of years it evidently will take for several plots to completely recover and the career tenure of the authors. This time issue was apparent when a sixth, reduced data collection effort was conducted in 2014 (July 17–18 and July 31–August 4).

All study plots were accessed by helicopter, based either in Umiat or Inigok. Depth of active layer was measured to the nearest centimeter using a 1 m steel probe at 20 points at 1–2 m intervals within each disturbed or control plot through 2011. No active layer data were collected in 2014. Ocular estimates in one of 4 impact classes (0–3; relative to the control plot; Table 1) were made through 2014 in each disturbed plot for decrease in total plant cover, decrease in shrub canopy, increase in exposed soil, structural damage to tussocks and hummocks, compression of standing litter or moss mat, and visibility of the trail from the ground and air (Felix and Raynolds, 1989a). An overall disturbance level (none, low, moderate or high; Table 2) was determined for each disturbed plot based on the combination of scores for each of the individual measures above (Felix et al., 1992). In addition, photos of the disturbed and control plots were taken from various angles from the ground and the air.

Analyses of the data through 2011 were conducted to examine initial disturbance levels, recovery levels, differences in depth of active layer between disturbed and control plots, and the influence of several factors (vegetation category and disturbance type, and in some cases year, plot type, or observation from air versus ground) on all these variables. Scores for recovery level of any particular time period were obtained by subtracting the overall disturbance level at the end of that period from the level at the beginning. All statistical analyses performed used a simultaneous likelihood ratio test with a multi-factor Analysis of Variance to determine the significance of the effects of various factors on disturbance level, recovery level, or thaw depth. These analyses examine the effect of each factor independent of the effects of the other factors. The ocular data from 2014 were not analyzed but are presented graphically as for previous years' data. No quantitative analysis of the photographs was attempted, and qualitative comparisons of photographs are not included in this report. All photographs have been archived at the Fairbanks District Office (FDO) of the Bureau of Land Management (prints from film cameras, 1999–2005) and digitally for all years on the FDO file server at \\ilmakfd3ds1\pub\Arctic\Yokel_vegetation_studies\recovery_seismic_trails_1999-2014\photos.

Results

Forty-seven study plots were established in seismic trails, 30 in camp-move trails, and 12 in ice road paths (Table 3) for a total of 89 plots. Suitable plots were found in all 12 minor vegetation categories for seismic trails, but in only 9 of the 12 categories for camp-move trails and only 7 of 12 for ice roads. The total number of plots established in any one vegetation-trail type combination ranged from 0 to 8.

Overall Disturbance Levels

Major Vegetation Categories

The overall disturbance level for all 89 plots in 1999/2000, sorted by major vegetation cover class, is represented in Figure 2. The same data, but for 2002, 2005, 2008, 2011, and 2014, are displayed in Figures 3–7, respectively. No statistical analyses are presented with these figures. Rather, Figures 2–7 are intended to convey a general impression about disturbance levels. Statistical significance of these impressions is presented later. Two circumstances are readily suggested by observation of these figures. First, some of the major vegetation categories are more heavily disturbed than others. Initial, overall disturbance estimates were greatest in the moist tundra and shrub classes, and least in the aquatic, wet tundra and barren classes. Second, vegetation recovery has occurred during the 15 years since the initial impacts.

Figures 2–7 display a progression toward lesser disturbance as time progresses. After 3 years, all aquatic classes were in the category of least disturbance, i.e. none to slight. Plots in the wet tundra class reached this condition in 6 years or less. The other major classes display an increased proportion of plots in the lowest disturbance category during each subsequent sampling period. However, some plots in the moist tundra and shrub classes remain substantially disturbed after 12 years and show a low level of disturbance even after 15 years.

Minor Vegetation Categories

Figures 8–13 show some of the same data as from Figures 2–7, but with each major class broken down into 2 or more minor classes. The major classes of aquatic and barren are not represented here because all minor classes within those 2 major classes reached the lowest level of disturbance within 3 years or less. Nor is the wet tundra major class displayed in Figures 8–13 because it has no further subdivisions, and all plots within that category reached the lowest disturbance level in 6 years.

The other 3 major classes, flooded tundra, moist tundra, and shrub, have 2 or 3 minor categories each, and there are some obvious differences among those minor types. Within the flooded tundra category, the low-centered polygon category sustained greater impacts than the non-patterned flooded tundra (Figure 8). All low-centered plots were initially scored as low or moderate disturbance levels, whereas the non-patterned plots were all at the "none" level of disturbance. With recovery over time, that difference between the 2 flooded tundra classes decreases yet is still evident after 12 years (Figure 12) and disappears after 15 years (Figure 13).

The 3 minor categories of moist tundra display differences in disturbance levels. The sedge/grass meadow class sustained mostly no or low levels of disturbance whereas the tussock tundra class received greater impacts including some plots at the high level. The moss/lichen category displayed a distinctly bimodal distribution of initial disturbance with 3 plots receiving none, 2 at moderate and one at high.

Both dwarf and low shrubs had plots with initial disturbance of low, moderate, and high, but only dwarf shrub had some plots with no disturbance. Figures 8–13 display a tendency for low shrub sites to recover more quickly than dwarf shrub sites. The factors responsible for this are discussed later.

Disturbance Type

Figures 14–19 present the same data as Figures 2–7, but are sorted by disturbance type rather than vegetation cover class. Table 4 shows the percent of plots for each trail type at various disturbance levels in each of the data collection years. Just as overall disturbance is not similar for all categories of vegetation, it is clear from Figures 14–19 and Table 4 that overall disturbance is also not similar for all categories of trail (disturbance) type. Trails made by vehicles used for seismic data acquisition received substantially less impact to tundra vegetation than did trails made by the movement of camp trains between camp sites or by the construction and use of ice roads. Although impact levels are similar between these 2 latter trail types in the initial summer following winter travel, our data suggest that the impacts of camp move trails may persist longer than those of ice roads.

Factors Affecting Overall Disturbance Levels in Each Year

Major Vegetation Category and Disturbance Type

Figure 20 shows how major vegetation class and trail (disturbance) type affected overall disturbance levels in 1999/2000. To interpret these graphical representations of simultaneous likelihood ratio tests with a multi-factor Analysis of Variance, one must understand that one of the variables within each factor (e.g., variable "barren ground" within factor "major vegetation category, Figure 20) was subjectively chosen to be represented with a value of zero and all other major vegetation variables were scored relative to it. Whether one variable scores negatively or positively is not by itself important; its height in the graph relative to other variables is the key. So for both major vegetation and trail type, variables with a positive score in Figure 20, i.e., their bars project above the horizontal axis, had a greater effect on disturbance level than did barren ground or ice road, respectively. Factors with a negative score, i.e., their bars project below the horizontal axis, had a lesser effect than barren ground or ice road, and less of course than the variables with positive scores. The effects of both major vegetation class and trail (disturbance) type on the initial level of overall disturbance were significant at the $p < 0.0001$ level. Plots in moist tundra or shrub vegetation displayed significantly greater impacts ($p = 0.03$ and $p = 0.002$, respectively) than those in any of the other 5 classes, among which there was no statistically significant difference. Plots on camp-move trails and ice roads displayed significantly greater ($p < 0.0001$) impacts than those on seismic trails, but no significant difference in impacts from each other.

Similar analyses of data from the 2002–2011 field seasons are shown in Figures 21–24. The pattern seen in 1999/2000 continued through 2008, although as impact levels decreased with time, the statistical significance of these patterns also decreased to the point where major vegetation class had only marginal significance ($p < 0.07$) on disturbance level in 2008 (Figure 23). Individually, none of the 6 major vegetation classes had effects on overall disturbance level significantly different from barren ground in 2008. However, plots on camp-move trails and ice roads still displayed significantly greater impacts than those on seismic trails in 2008, meaning that trail (disturbance) type still had a significant effect on disturbance level after 9 years. By 2011 (Figure 24), major vegetation category had no effect ($p = 0.40$) on remaining disturbance levels, although trail (disturbance) type still did ($p < 0.01$). Interestingly, after 12 years there appeared a trend for camp-move trails to display greater disturbance than ice roads, although this trend was not statistically significant ($p = 0.16$). Although these analyses were not conducted with the 2014 data, this general trend appears to have persisted (Figure 19). Twenty percent of camp-move plots still showed low levels of overall disturbance, whereas only 8.3 percent and 2.1 percent of ice road and seismic trails plots did, respectively

Minor Vegetation Category and Disturbance Type

Figures A1–A5 (Appendix A) represent the same data as in Figures 20–24, except that in A1–A5 the vegetation types are split into minor categories. Figures A1–A5 display the same general trends in vegetation effect on overall disturbance as in Figures 20–24, although the patterns seen in the figures are somewhat different because for major categories the barren ground class was assigned the zero score whereas for minor categories the wet tundra was assigned zero. Nonetheless, both moist tundra ($p = 0.03$) and shrub ($p = 0.002$) had scores signficantly different from zero in 1999 (Figure 20), and all 5 minor categories of those 2 major categories also had scores different from zero (Figure A1; sedge meadow, $p = 0.04$; tussock tundra, $p < 0.0001$; moss/lichen, $p = 0.02$; dwarf shrub, $p < 0.0001$; low shrub, $p < 0.0001$). In addition, once the flooded tundra category was split into its 2 minor categories, it can be seen in Figure A1 that the low-centered polygon class was different from zero ($p < 0.01$). This corresponds to the obvious difference in disturbance level between it and the non-patterned class as displayed in Figure 8.

In later years, as the individual significance of the moist tundra and shrub major categories on overall disturbance level diminishes with recovery, so too does the individual significance of the minor classes. Only the dwarf shrub minor category remains significantly different from zero in 2002 (Figure A2; $p < 0.01$), both dwarf shrub and tussock tundra are in 2005 (Figure A3; $p < 0.001$ and $p < 0.01$, repectively), dwarf shrub and moss/lichen are in 2008 (Figure A4; $p < 0.01$ for each), and only moss/lichen is in 2011 (Figure A5; $p = 0.01$). Caution is warranted when trying to interpret too much from these results among years. It may be safe to say only that they are due to different rates of recovery among the various minor vegetation categories (see below).

Recovery of Overall Disturbance Levels

Extent of Recovery

As a means to graphically represent recovery, Figure 25 shows how many sites were at each disturbance level in each year of data collection regardless of vegetation category or trail type. This histogram shows that among all plots, recovery continued over the 15 years of the study. Although a few plots did not acquire complete recovery over this time period, no plot remained in the highest disturbance category in 2011, and by 2014 there were none in the "moderate" disturbance category either. The most substantial gain in recovery occurred in the first 3-year period following disturbance, but notable gains were made in each period.

Factors Affecting Recovery

Figure 26 displays the effects of major vegetation cover class and trail (disturbance) type on recovery from 1999 to 2002. The effects of both major vegetation cover class ($p = 0.02$) and trail type ($p < 0.02$) were significant. Looking at Figure 26, it appears that there was subtantially more recovery among the flooded tundra, moist tundra, and shrub cover classes than among the other 3. Perhaps due to a lower sample size, however, flooded tundra recovery was not significantly different than that in the barren ground class ($p = 0.15$). Statistical significance of recovery in the moist tundra category compared to barren ground was only marginal ($p = 0.07$). Shrubs did recover significantly more than the barren ground category ($p = 0.02$). Within the trail type factor, there was significantly greater recovery in the camp-move trail category ($p = 0.02$) than in ice roads or seismic trails.

Figures 27–29 show similar results for the periods 2002–2005, 2005–2008 and 2008–2011, respectively. Major vegetation category did not have a signficant effect on recovery in any of these periods, during which there was increasingly less impact from which to recover (Figure 25). Trail type, however, did have significant effects on recovery in each 3-year period throughout these 12 years of the study. During 2002–2005, ice roads displayed greater recovery than the other 2 trail types. During 2005–2008, it was camp-move trails that showed greater recovery, although the difference was not significant during this period. Ice roads again showed the greatest recovery in the final period. Recovery over the first 12 years of the study is represented in Figure 30, where both major vegetation category and trail type had significant effects. As during the earliest 3-year period, among vegetation categories the moist tundra and shrub categories had the greatest effect on recovery, with both being significantly greater than the effect of the barren ground category ($p = 0.05$ and $p < 0.01$, respectively). Among trail types, the data suggest that ice roads had the greatest effect, although it was not significantly different than the effect of camp-move trails ($p = 0.46$).

Breaking major vegetation categories down into their minor parts can provide more insight into how recovery differs among vegetation types. Figure 31 shows the effects of minor vegetation category and trail type on recovery during the 1999–2002 period, and Figure 32 shows the same for the 12-year period 1999–2011. Minor vegetation category had a highly significant effect during both time periods ($p < 0.0001$), suggesting that there are some critical differences within major vegetation categories that are masked when lumped and analyzed. During the early 3-year period, low-centered polygons ($p = 0.001$), tussock tundra ($p < 0.001$), dwarf shrub ($p = 0.03$), and low shrub ($p < 0.001$) all showed greater effects on recovery scores than the wet tundra category. For the 12-year period 1999–2011, the same 4 as well as sedge meadow ($p = 0.03$) had greater effects.

Individual Categories of Impacts

Disturbance Levels by Trail Type

Ocular estimates for 7 different categories of disturbance were scored for each plot in each of the 6 years of data collection. These individual estimates were used to determine overall disturbance level, presented earlier, for each plot in each year. They were also used with multi-factor ANOVA to assess how different factors (year, major vegetation category, disturbance type and air versus ground for visibility) affected ocular estimates (next section), similar to the analyses for overall disturbance levels in Figures 20–24.

Figure 33 displays the results of the estimates for decrease in plant cover, sorted by trail (disturbance) type for each of the 6 years. As for overall disturbance level presented in Figures 2–19, no statistical analyses are presented with Figures 33–39. Rather, they are intended to convey a general impression about disturbance levels over time for each of the individual impact categories. The potential causes of these observed disturbance levels are examined statistically in the next section. Figure 33 suggests that plant cover is reduced more, and takes longer to recover, in camp-move trails and ice roads than in seismic trails. In fact, it had not recovered completely in these 2 trail types after 15 years.

Figures 34–37 tell a similar story for reduction in shrub canopy, increase in exposed soil, damage to tussocks or hummocks, and compression of litter or moss, respectively. The data for tussocks indicate somewhat greater initial damage than for plant cover, shrub cover, or exposed soil, with moderate-level impacts even occurring in some seismic trail plots. This is also the only impact category for which moderate impact occurred in some seismic trails after 12 years of recovery, although moderate levels were not assessed after 15 years. Compression of litter or moss, on the other hand, is the only category for which all 3 trail types showed complete recovery at all plots after 12 years. Figures 38 and 39 depict the level of visibility of trails from the ground and from about 100 feet in the air, respectively. See Table 1 for descriptions of the 4 impact levels in terms of visibility. Clearly, all 3 trail types can be highly visible from the air in the first summer. After 12 years, visibility is similar from the air and the ground for seismic trails and ice roads, but the visibility of camp-move trails remains slightly greater through 15 years.

Factors Affecting Disturbance Levels for Individual Categories of Impacts

Year, major vegetation category, and disturbance type all had significant effects on decrease in plant cover (Figure 40). The data indicate that recovery in plant cover occurred in each 3-year interval except the period between 2005 and 2008. Shrubs suffered significantly greater decrease in plant cover than did the barren ground category ($p = 0.03$). Moist tundra, which as a major category lumps tussock tundra with sedge/grass meadows and moss/lichen, showed the next greatest difference from barren ground but was not significant ($p = 0.10$). None of the other categories were different from barren ground. Among trail types, camp-move trails and ice roads displayed similar decreases in plant cover and both were significantly greater than seismic trails ($p < 0.0001$).

Decrease in shrub canopy showed similar patterns for the effects of the 3 factors, as did decrease in plant cover, with all 3 factors having significant effects, recovery occurring over the entire 12 years covered by this analysis, shrubs showing greater effects than other vegetation categories, and seismic trails being affected significantly less than camp-move trails or ice roads (Figure 41). In this case, however, camp-move trails received marginally less ($p = 0.06$) impact than ice roads. Increase in exposed soil (Figure 42) again resulted in the same patterns as the previous 2 factors, except this time the effect of major vegetation category was not statistically significant. Damage to tussocks and hummocks (Figure 43) showed one major difference from the previous 3 factors in that within the major vegetation categories, the moist tundra class received the greatest damage rather than shrubs. This is an obvious result since moist tundra is the major category that includes the minor category of tussock tundra.

Compression of litter or moss (Figure 44) was affected somewhat differently than the other individual disturbance categories. Major vegetation category did not have a statistically significant effect on compression, which was otherwise noted only for the exposed soil impacts. Disturbance type did have a significant effect, but the difference between the seismic trails and the other 2 trail types was much less. The greatest deviation from the previously seen patterns was that most of the recovery occurred in the first 2- to 3-year period, and after 6 years none of the remaining recovery from compression was statistically significant in scale. Observations in the field revealed that most of the compression occurred among sedges, with the standing dead leaves of previous years being flattened by the vehicles. In following summers, the new, green growth in these trails often contrasted sharply with the surrounding areas that contained a mix of standing dead, i.e., brown, and new green leaves.

Visibility could potentially be affected by 4 factors rather than the 3 in the preceding impact categories, with view from air or ground being the additional effect. All 4 factors had highly significant effects on visibility (Figure 45). The patterns seen for year, major vegetation category, and disturbance type were very similar to many of the previous impact categories: recovery occurred over most of the 12-year time period analyzed, but wasn't significant in the 2008–2011 period; shrubs had the greatest effect among major vegetation categories with moist tundra nearly as influential; and seismic trails were far less visible than camp-move trails or ice roads. Not surprisingly, trails were consistently more visible from the air than from standing on the ground. This difference does not look large in Figure 45, but is highly significant due to the consistency with which it occurred.

Active Layer Depth

Mean Depth of Active Layer

Of the 6 major vegetation cover classes, depth of active layer data were collected in only 4. Depth data were not collected in aquatic or barren ground plots. Figure 46 provides a general impression of active layer depths through each of 3 different comparisons (i.e., plot type, major vegetation category, and disturbance type). Each comparison contains all of the active layer depth data, so all data points are used 3 different times in Figure 46. It shows that active layer depth varies by year, and this annual variation follows the same pattern both within and among the 3 types of comparisons. Active layer was shallowest at the most plots in 2005 and deepest in 2008.

When comparing control plots to experimental (disturbed) plots (i.e., no trail vs. trail), the disturbed plots display a deeper active layer in each year data were collected, but by less than 2 cm (range = 0.1 – 1.9 cm). The least difference occurred in 1999 and the greatest in 2002. These differences between control and disturbed plots were statistically significant in 2002 (1.9 cm; p = 0.005) and 2005 (1.5 cm; p = 0.005), but not in 1999/2000 (0.1 cm; p = 0.81) or 2008 (0.9 cm; p = 0.19). In 2011 the difference was not significant at an alpha level of 0.05 (1.3 cm; p = 0.08). Because of this trend of decreased difference between plot types, active layer depth was not measured in 2014.

Among the 4 major vegetation categories, active layer was shallowest in the moist tundra class and deepest in the shrub class, with the exception that wet tundra was 0.3 cm deeper than shrubs in 2008. Flooded tundra was the second most shallow after moist tundra. When comparing active layer depth by disturbance type, camp-move trails were generally the deepest (0.1 – 3.6 cm deeper than seismic trails and 3.9 – 12.1 cm deeper than ice roads) and ice roads were consistently most shallow.

Factors Affecting Depth of Active Layer

Multi-factor Analysis of Variance (ANOVA) was used to determine the effects of year, plot type (disturbed vs. control), major vegetation class, and activity type on depth of thaw. This technique describes the effect of each of these 4 factors after accounting for any effects of the other 3. Figure 47 depicts the results of this analysis for depth of thaw, combining data for all 5 data collection years, 1999–2011. To interpret this graph, it is necessary to understand 2 points. First, depth of thaw was measured and analyzed as a positive number. The deeper the thaw is, the larger the positive number is. So, higher, positive bars in Figure 47 depict deeper thaw, which may seem counterintuitive if one incorrectly assumed the zero depth in the figure was ground level instead of the relative measure it actually is. Second, the statistical software lists each of the 4 factors in alphanumeric order, and then arbitrarily assigns a value of zero to the last category in each list, i.e., a score of zero for 2011, disturbed, shrub and ice road. The other categories' scores are relative to the zero. So looking at Figure 47, it can be seen that depths of active layer were greatest in 2008 and least in 2005, greater in disturbed plots than in controls, greater in shrubs than in the other 3 vegetation categories, and greater in camp-move and seismic trails than in ice roads. The differences in Figure 47 were statistically significant for year (p <0.0001), plot type (p = 0.04), and vegetation class (p = 0.006), but not for disturbance type (p = 0.19).

These same patterns of active layer depth were apparent for plot type, major vegetation category, and disturbance type when the data were analyzed separately for each year (Appendix B, Figures B1-B5), but statistical significance of the results varied among years. The per-year results for plot type were presented above under the "Mean Depth of Active Layer" section. There was no real difference between control and disturbed plots in the first summer following seismic testing or ice road construction and use. The greatest difference occurred 3 years after the activity and then gradually decreased over the following data collection years, except that there was a slight rise (not statistically significant) in 2011. Active layer depths were not recorded in 2014.

The effect of major vegetation category on active layer depth was most significant in 1999, slightly less so in 2002 and 2005, and marginally significant or not significant in 2008 and 2011. The effect of disturbance type on depth of active layer was not statistically significant in any of the 5 summers during which data were collected.

Interaction of Year and Plot Type on Depth of Active Layer

The ANOVA used to determine effects of the 4 factors on depth of active layer also revealed a significant interaction between year and plot type. Not only did active layer depths vary among years but also the amount of difference between active layers of disturbed and control plots varied among years. This interaction is represented graphically in Figure 48, which shows that the greatest overall change between any 2 data collection years was between 1999 and 2002.

Discussion

Overall Disturbance Level

Major Vegetation Categories

Examination of Figures 2–7 supports lumping the 6 major vegetation classes into 3 groups related to disturbance levels. First and by itself would be the barren (or sparsely vegetated) class, which displays little to no disturbance. (The definition of the "none" level includes the words "no," "slight," "widely scattered" and "occasional.") Since the disturbance being measured is to vegetation, plots with little to no vegetation are less likely to suffer significant disturbance. However, this does not mean that vehicles can travel in this vegetation category with impunity. As seen below for polygon levees and tussocks, microtopograhy can result in greater impacts by vehicles when not all portions of a track or tire are equally supported by the ground below. Areas of dry sand may have significant microtopographical relief (e.g., dunes) and there are some species of rare plants, such as *Mertensia drummondii*, that occur exclusively in dunes (Cortés-Burns et al. 2009).

The second group would include the aquatic, flooded tundra and wet tundra major vegetation categories. These are wetter habitats that typically have standing water, or at least saturated soils, and with the exception of polygonal tundra have minimal microtopography. The below-ground parts of plants, mostly sedges and grasses, are protected from vehicles by being encased in ice during winter, and the level character of the land minimizes disturbance of soils by heavy equipment. Most of the disturbance in these 3 classes is from the compaction of standing, dead vegetation, creating a phenomenon referred to as "green" trails visible for one to a few years. Green trails occur where only the new year's growth is left standing and the trail consequently has a much greener hue than the surrounding tundra, where much of the standing vegetation consists of dead sedge leaves from previous years.

As opposed to the wetter vegetation types, most impacts occur in the moist tundra and shrub categories. These 2 classes easily stand out from the other 4 as disturbed when examining Figures 2–7, and this is to be expected. The major class moist tundra includes the minor class tussock tundra, whose tussocks project above the surrounding land surface, presenting a microtopography that is very prone to disturbance by vehicles. Perhaps more damage prone than any other vegetation category are shrubs. Some low shrubs such as the diamond-leaf willow (*Salix pulchra*) have a substantial proportion of live tissue above snow level during winter. Frozen shrub branches are readily broken off by passing vehicles. Alternatively, arctic birch (*Betula nana*) were seldom broken but often killed outright by repeated passes of heavy camp-move trains.

Minor Vegetation Categories

Within the group containing the 3 wetter, major vegetation categories, the flooded tundra class stands out as receiving greater impacts. Within this category, the 2 minor vegetation categories of non-patterned flooded tundra and low-centered polyon tundra are in stark contrast to one another with regards to initial disturbance level, as discussed in "Results." All of the plots in the non-patterned tundra displayed disturbance of "none," whereas all of the plots in low-centered polygons showed either low or moderate disturbance (Figure 8). The reason is the higher microtopography due to polygon rims in the latter. These features, similar to tussocks or shrubs, project above the surrounding land surface and are susceptible to scuffing or partial removal by camp-move or ice road maintenance vehicles.

Among the moist tundra minor categories, the sedge/grass meadow class has very little microtopography whereas the tussock tundra class has substantial microtopography, resulting in greater impacts similar to the situation with low-centered polygons. The moss/lichen minor category is actually a mixed bag of 2 very different vegetation communities. Areas dominated by moss with little other plant cover, as opposed to moss growing as a bottom layer underneath a variety of taller, vascular species, tend to be very flat with sufficient soil moisture to freeze and protect the plants during winter. In addition, the moss itself is very low growing, which lends itself to adequate protection by snow cover. Lichens, however, tend to dominate on drier, sandier sites with a very thin soil layer, making it easier for vehicles to disturb or even remove this plant form. These differences account for the bimodal distribution of disturbance in this category. In addition, lichens are very slow growing, resulting in longer recovery times as evidenced by the time series represented by Figures 8–13.

Both low and some dwarf shrubs project far enough above the ground to facilitate greater damage from vehicles than for most other vegetation classes (Figures 2 and 8). In the case of low shrubs, this was consistently the case, as no plots were in the "none" disturbance level (Figure 8). Three of the dwarf shrub plots, however, did display no initial disturbance, which is possible when the site has little to no microtopography and the shrubs are so short as to be covered by adequate snow. When dwarf shrubs were damaged, it was not always because they stuck well above the snow surface but due to growing on tussocks or on very shallow soils that were scuffed away.

Despite low shrubs always suffering some initial disturbance, they recovered more quickly than dwarf shrubs (Figures 8–13). Part of recovery for both dwarf and low shrubs was due to replacement by grasses, a natural, intermediate stage in succession when the shrubs are killed. Emers et al. (1995), Emers and Jorgenson (1997), and Jorgenson et al. (2003) also reported colonization of shrub habitats or areas of exposed soil by grasses in the ANWR and on the Colville River delta, even if grasses were not present in the vicinity beforehand. Note this is not "restoration" of the site to its original condition and ecosystem, but "recovery" to a naturally occurring and functional ecosystem different from the original (complete recovery versus functional recovery *sensu* Walker et al., 1987). In other cases, low shrubs may recover (to the point of restoration) more quickly than dwarf shrubs because they tend to capture deep enough snow (Emers et al. 1995) that the underlying soils are protected, and stems either bend over or break off well above ground level. In the latter case, these stems can then sprout new branches, and the shrub canopy appears no different than surrounding shrubs after a few to several years.

Disturbance Type

The 3 disturbance types could be lumped into 2 categories after inspection of Figures 14–19. It is somewhat reassuring to confirm with these data that trails created during the acquisition of seismic data result in significantly less tundra disturbance than those from camp-moves or ice roads, since the former far surpass the latter 2 combined in total line miles of activity during winter exploration. Nonetheless, the impacts of camp-moves and ice roads are significant enough that any advances in technology for either activity could have positive effects for tundra vegetation. Besides showing that the 3 disturbance types vary from one another, Figures 14–19 display a trend of improvement within each disturbance category over 15 years, but also show that none of the categories has recovered completely in that time.

Anecdotally, a few of the camp-move plots may have gotten worse, rather than recovered, between 2002 and 2005 (Figures 15 and 16). This may be due to variation in how ocular estimates were made in the 2 years, i.e., observer error. Alternatively, the very thin layer of organic soil covering sand at these plots was disturbed or removed by the initial disturbance, and wind in the subsequent years may have scoured the area and prevented recovery. Regardless, the trend following 2005 is one of recovery (Figures 17–19).

A comparison of the percentage of seismic and camp-move plots in each of the 4 disturbance categories throughout the study (Table 4) with the results of a similar study in the ANWR (App. C of Jorgenson et al., 2010) shows some differences but also some similarities. The ANWR study includes data collected over 24 years, so this comparison looks only at its first 13–17 years. It also did not involve ice roads, so this comparison is of seismic trails and camp-move trails only. The greatest difference between the 2 was the initial disturbance level in seismic trails ($\chi^2 = 36.6$, $p < 0.001$). In the NPRA, 68 percent of plots showed little or no disturbance whereas only 14 percent of the ANWR plots were at that level. Thirty-two percent of the NPRA plots were at low disturbance but 72 percent of the ANWR plots were scored as low. None of the NPRA plots were scored as moderate whereas 14 percent of the ANWR plots were. Clearly, seismic trails were scored at greater initial disturbance levels in the ANWR. This difference may be due, at least in part, to a higher percentage of upland moist tundra and shrubs versus wetter graminoid communities in the ANWR, and Figure 2 confirms these are the 2 vegetation types that receive the greatest damage. The ANWR contains a lower proportion of flat, wet coastal plain and a higher proportion of foothills tundra than the portion of the NPRA in which our study occurred. But this difference may also be due to the type of seismic work done in each area. The ANWR seismic surveys involved long, straight lines used by both sending and receiving (of shockwaves) equipment, whereas most of the NPRA surveys placed the 2 equipment types on separate lines in a grid pattern. So in the ANWR each line probably received impacts from more individual vehicles, on average, than lines in the NPRA. Thirdly, the 2 seismic operations were conducted 15 years apart from one another, and the latter surveys may have involved some different equipment types causing less impact. In addition to these 3 possible explanations, the initial disturbance scores for the ANWR plots were done by photointerpretation, though work in subsequent years was conducted on the ground. After 3 to 4 years, the same trend of difference between seismic trails in the 2 studies existed, though it was less extreme ($\chi^2 = 8.2$, $p < 0.01$). Nonetheless, after 8–9 years, seismic lines in both areas had recovered to essentially the same levels ($\chi^2 = 0.0004$, $p = 0.98$).

A third study of seismic and camp-move trails was conducted for just one year in a relatively small area east of Nuiqsut by Jorgenson et al. (2003). This study occurred in the summer of 2002 on trails created in the winter of 2001, so it is not directly comparable to the intial disturbance data (i.e., first summer following disturbance) of the 2 studies discussed above. Thirty percent of the seismic trails in this study were scored at little to no disturbance, 66 percent as low, and 4 percent as moderate. None were scored as high. As a whole, these scores were intermediate in disturbance level compared to the NPRA (lowest) and the ANWR (highest) scores, and there were significant differences among the scores of the 3 studies ($\chi^2 = 40.5$; $p < 0.001$). The reason why the 3 studies had different results is fairly complex. Jorgenson et al. (2003) attribute the generally low level of disturbance found in their study to equipment type and terrain characteristics. The equipment used in that survey was similar to the NPRA study, and both were conducted on relatively flat terrain. The Nuiqsut study, however, involved a lower proportion of study plots in tussock tundra, which should result in lower disturbance scores than those for the NPRA. In addition to the reasons suggested above for the NPRA vs. the ANWR, there is now the additional issue of having an extra year of recovery before the Nuiqsut study. One more possible cause of differences may be that ocular estimates by different researchers were dissimilar, i.e., not calibrated among researchers. Regardless, all 3 studies concur in the finding that the majority of plots have initial (or nearly so) disturbance scores of none or low, few were scored as moderate and none as high.

Comparison of initial disturbance in camp-move trails between the NPRA and the ANWR shows the opposite, though less pronounced, difference from seismic trails for these 2 studies, i.e., 67 percent of the NPRA camp-move plots were initially scored as either moderate or high as opposed to only 32 percent of the ANWR plots ($\chi^2 = 17.4$, $p < 0.001$). No suitable explanation that wouldn't contradict the vegetation type explanation suggested for these 2 studies above is readily apparent for this opposite trend. The results from the plots in camp-move trails for the Nuiqsut study were comparable to those of the ANWR study; 29 percent were scored as moderate or high disturbance. After 15 years of recovery for the NPRA plots, 80 percent of camp-move plots had recovered to an overall disturbance score of none, while 20 percent remained in the low, moderate, or high categories. The ANWR scores were the same at both 13 and 17 years post disturbance, with 90 percent at none and 10 percent in the other 3 categories. At this point, sampled disturbance scores were still higher in the NPRA, but not significantly so ($\chi^2 = 1.31$, $p = 0.25$).

Factors Affecting Overall Disturbance Levels in Each Year

Major Vegetation Category and Disturbance Type

In 1999, 2002, and 2005 (Figures 20–22), both vegetation type and trail type had significant effects on overall disturbance scores. The same result was reported for one year post-disturbance for the Nuiqsut study (Jorgenson et al. 2003). Reynolds (1982) found that camp-move trails caused greater disturbance than seismic trails in southern NPRA, and Raynolds and Felix (1989) found the same in the ANWR. By 2008 in northeastern NPRA (Figure 23), enough recovery had occurred that vegetation type had only a marginally significant effect on disturbance score and by 2011 (Figure 24) it had no effect. Trail type had significant effects throughout the study. Although analyses similar to those depicted in Figures 20–24 were not done for the 2014 data, it was evident that trail type was still significantly affecting overall disturbance scores after 15 years (Figure 19; Chi-square = 4.83; $p = 0.028$). In 2014, no plots of any trail type were scored as moderate or high disturbance, but 20.0 percent of camp-move plots received a score of "low." Only 8.3 percent of ice road plots and 2.1 percent of seismic trail plots were score as "low." All other plots received a score of "none."

The left-hand portion of Figure 20 supports the earlier suggestion that one could lump the 6 vegetation classes into 3 groups related to disturbance levels. In fact, the statistics represented in Figure 20 suggest barren ground could be lumped with the 3 wetter categories, since none of the 4 categories of vegetation display significantly different effects from one another. This relationship was maintained throughout the study, which should be expected since as recovery progresses, there is continually less overall disturbance for vegetation category to affect. Furthermore, among the 3 disturbance (trail) types, Figure 20 shows no difference between camp-move trails and ice roads in their effect on overall disturbance score. Indeed, the data show no statistically significant difference in levels of disturbance between camp-move trails and ice roads in any year except for 2002 (Figure 21), when the difference was only marginally significant ($p = 0.07$). By 2011, with 12 years of recovery, neither seismic trails nor camp-move trails had significantly different affects on disturbance scores from those of ice roads, despite the appearances of the bars in Figure 24. Nevertheless, trail type as a whole still had a significant effect on disturbance because of the difference between seismic trails and camp-move trails.

Felix and Raynolds (1989a) classified vegetation in their study area somewhat differently than we did for our study, but the 2 classifications are similar enough to make comparisons. Their wet graminoid tundra class (similar to our aquatic, flooded tundra, and wet tundra classes) and moist sedge-shrub tundra class (similar to our moist tundra, sedge meadow class) generally had overall disturbance scores of "low" in the first summer following disturbance, whereas our analogues to these 2 classes were mostly scored as "none" or "low." Both studies observed a substantial portion of tussock tundra plots with "high" disturbance. In the southern NPRA, Reynolds (1982), using only 4 classes of vegetation, concluded that disturbance levels were greater in sedge tussocks and riparian willow than in either wet sedge meadows or dry upland meadows.

An important factor affecting disturbance levels for which we did not account in this study is snow depth. In fact, we did not have any data for snow depth for either the 1999 seismic surveys or the 2000 ice road. Reynolds (1982) observed impacts to tundra with 15 cm or more of snow, a standard threshold at the time for allowing vehicles on the tundra, and reported slower recovery of vegetation on trails created under lower snow conditions. Felix and Raynolds (1989b) collected data on snow depth and snow density (thickness of wind slab) during seismic surveys in the ANWR to compare to vegetation data collected the following summer. They found that both snow and slab depth were inversely related to disturbance level in tussock and moist sedge-shrub tundra. Our NPRA plots were all within a relatively flat area about 40 miles square, so snowfall was probably similar throughout. It would not be completely safe, however, to assume that snow conditions were the same for all plots because local terrain features a few to several feet high can affect how snow is redistributed by the wind. Since all seismic plots were from 1999 surveys and all ice road plots were from 2000, any difference in snowfall between years would only manifest itself in the effect of disturbance type on overall disturbance, i.e., seismic survey and camp-move trails versus ice roads. Thus having plots from 2 different (snow) years should not be a significant issue. Snow characteristics are important variables in determining disturbance to tundra vegetation, but not having them for this study should not confound, or detract from, our data analysis as conducted.

Factors Affecting Recovery

Recovery of disturbed plots continued throughout this study. In the first summer following seismic exploration or ice road construction and use, 44 percent of plots had an overall disturbance score of zero. That increased to 61, 67, 77, 87 and 91 percent in 2002, 2005, 2008, 2011 and 2014, respectively. Some of that "recovery" involved replacement of original species. Clearly, 15 years of recovery are not sufficient to eliminate all effects of disturbance. In the ANWR study, the worst impacts to tundra persisted through 2 decades of study, and the inference is that some will persist for several decades more (Jorgenson et al. 2010). An understanding of factors that promote or delay recovery may help prevent some of the worst impacts in the future.

At first glance, the results in Figure 26 showing effects of major vegetation category and trail type on recovery between 1999 and 2002 may seem counterintuitive. However, the height of each bar does not represent the condition of those plot types, with higher being better condition. Instead, height is a relative measure of how much recovery occurred in plots within each vegetation category or disturbance type. Those vegetation categories which display the least recovery compared to others (aquatic, wet tundra and barren ground), are simply those which had the lowest levels of disturbance to begin with, and therefore had little to no opportunity for recovery. This does not explain the relative recovery among the 3 disturbance types, for which seismic trails had the lowest initial disturbance scores and camp-move trails had essentially the same initial scores as ice roads. Clearly, camp-moves trails recovered significantly more during this first interval than did ice roads. This may be due completely to the fact that the first interval was 3 years for camp-move trails but only 2 years for ice roads, since the latter were constructed in the year following the seismic surveys. This relationship between the recovery of camp-move trails versus ice roads reversed itself 3 times over the next 3 intervals between data collection. Part of this can be explained by the apparent worsening of some camp-move trail plots between 2002 and 2005. The rest may just be due to the similarity in disturbance between the 2 trail types and random fluctuations from one data gathering period to another.

Major vegetation category had significant effects on recovery during the first interval (Figure 26) and over the initial 12 years of the study (Figure 30), but not during any other 3-year interval. Looking at minor vegetation category provides an intuitively obvious explanation for this. Those minor classes that showed the greatest initial disturbance, i.e., low-centered polygons, tussock tundra, and low shrubs, also experienced the greatest recovery. Again, much of the early "recovery" in low shrub plots was due to growth of grasses where shrubs had been. Similarly, for the ANWR study, Jorgenson (2000) reported that vegetation type affected both initial disturbance level and recovery rate. That study also showed that trails with initial disturbance scores of none or low usually improved well over time, whereas those with initial scores of moderate or high improved more slowly, or in some cases, not at all. There may be some confusion between cause and effect here. We excluded initial disturbance scores as an independent variable in our analyses of factors affecting recovery, because our earlier analysis of factors affecting initial disturbance scores showed that both vegetation type and disturbance type had highly significant effects. These latter 2 variables should be sufficient to explain recovery rates.

Individual Categories of Impacts

Disturbance Levels by Trail Type

Much of the disturbance results when veiwed from the perspective of individual impact categories are, understandably, similar to results from overall disturbance scores. However, one comparison that stands out with individual categories and cannot be seen from overall scores, is the difference in visibility of trails from the air versus from the ground (Figures 38 and 39). Actually, this difference is not as great as it first appears from the 2 graphs presented for 1999 because their *y* axes are at different scales. This difference is less apparent after 2002 and the 2 are then fairly similar through 2014. The reason for this is the change in features most noticeable from the ground versus the air. In the early years following disturbance, the "green trail" effect is the most easily perceived visual variable, and these long, straight lines of contrasting color on the tundra show up best from the air because one can see further (i.e., see longer segments of these lines). This effect fades over time, however, as the previous winter's standing dead mixes with the new green growth each spring, and then actual damage or death of plants or tussocks becomes the dominant variable for visual perception. This physical damage is most easily seen from up close, i.e., from standing on the ground and looking down. These factors affecting visibility may be relevant to any assessment of visual resources management for the area.

Factors Affecting Disturbance Levels for Individual Categories of Impacts

Disturbance levels decrease over time for all individual categories of impacts, but with one exception, impacts in each category remain at some level above "none" in some plots after 15 years. The exception is compression of litter and moss, which was visible in just a few plots after 2002 and in no plots by 2011. Fifteen years have not been sufficiently long to observe complete recovery from all individual impact categories at 11 of 89 (12 percent) plots, although they are near complete recovery. Some individual impact categories still ranged from "low" to "high" on 26 plots after 12 years of recovery, but after 15 years these last 11 plots had impact scores no greater than "low."

As was the case in the NPRA, Felix and Raynolds (1989a) reported that plant cover was lower on most disturbed plots than on controls. Their study of seismic survey and camp-move trails found that evergreen shrubs were most sensitive to disturbance. Bliss and Wein (1972), Chapin and Shaver (1981) and Jorgenson et al. (2003) found similar results. We also found evergreen shrubs to be very susceptible, but our ice road (and to a lesser extent seismic) plots suggested that arctic birch (*Betula nana*; a deciduous shrub) was the most sensitive species, with many individuals being killed and replaced by grass. Perhaps the compression under the ice has some different effects than traffic directly on snow.

Felix and Raynolds (1989a) observed that visibility of trails was usually the same from the air and the ground in the ANWR during the first summer post-disturbance, and both were correlated with disturbance scores. Ten years later, however, Emers and Jorgenson (1977) reported that visibility of trails was generally greater from the air. Our study found a marked difference in visibility in the early years following disturbance, with visibility being greater from the air for trails created both by seismic surveys and ice roads. By 2012, however, visibility was similar from air and ground in the NPRA, although camp-move trails still appeared a bit more visible from the air. The difference of these 2 results may be due to a phenomenon seen in the ANWR but not in the NPRA. Some of the trails in the ANWR subsided over time and became wetter, leading to a different vegetation community in the trails than immediately outside. These long, linear borders of vegetation communities were more easily seen from the air. In the vicinity of the Colville River delta, Jorgenson et al. (2003) noted that trails were distinctly visible overall for 2 years, with higher visibility on camp-move trails than seismic trails and on drier, shrubbier vegetation types than on wetter types. By the third year of their study, the continuity of the trail network was fading and most trails were difficult to perceive. By the seventh year, the grid system was not discernible but highly disturbed sites could be seen upon close inspection.

Active Layer Depth

Factors Affecting Depth of Active Layer

Of the 4 factors analyzed for potential to affect active layer depth between 1999 and 2011 (Figure 47), the one with the greatest effect is year. Weather fluctuates among years, and active layer depths vary accordingly. Day of year also affects active layer depths. In a study of recovery from wildfire in a nearby area to the east of the NPRA, Jandt et al. (2012) found that active layer depth increased by 0.79 cm/day for burned sites and 1.15 cm/day for unburned (control) sites between July 7 and August 2 in 2010 and 2011 combined. As with our study, burned sites (similar to our "disturbed" sites) had deeper active layers than control sites. When only unburned sites were analyzed, and done so by year, active layer depth increased by 1.45 cm/day for 2010 and 1.14 cm/day for 2011 (Miller, pers. comm.). We did not analyze our data for the "day of year" variable. Rather, we attempted to gather data during similar dates each year. All data were collected between July 16 and August 19, and in each of the 4 years following the first season of data collection our data were collected between July 17 and August 2. In 2005 and 2008, the years with the shallowest and deepest active layers, respectively, our data were collected during nearly identical periods (July 21 through August 2, 2005, and July 22 through August 1, 2008). Clearly, year had a significant effect.

Active layer depths of disturbed sites did not differ from those of control sites in the first year of our study. Similarly, Jorgenson et al. (2003) found no differences in thaw depths between disturbed and control plots one year after disturbance, regardless of disturbance type, vegetation type or overall disturbance level. In our NPRA study, the difference was greatest in 2002 (3 years post-disturbance) with disturbed sites being deeper by an average of 1.9 cm. Felix et al. (1992) and Emers et al. (1995) reported that in the ANWR, active layer depths were greater in disturbed plots 4 to 5 years and 7 to 8 years post-disturbance, respectively, and that after 7 to 8 years active layer depths were continuing to increase at some sites. At 10 years post-disturbance, 60 percent of the ANWR disturbed plots still had greater thaw depths than did controls (Emers and Jorgenson, 1997), and after 14 to 15 years active layer depth was still greater in disturbed plots for half of moist sedge-*Dryas* tundra sites, a fourth of moist sedge-willow sites, and only a few plots of wet graminoid, tussock tundra or riparian shrub (Jorgenson, 2000). In the NPRA, on the other hand, the difference between disturbed and control plots decreased with each additional interval between data collection efforts through 2008, but then increased slightly again in 2011. However, the differences between disturbed and control plots were not statistically significant in either 2008 or 2011.

Decreases in plant cover and shrub canopy (less shade), an increase in exposed soil (greater absorption of sunlight), and compression of litter or moss (less insulation over the cold soils) could all contribute to deeper thaw on disturbed plots, so as recovery occurred it made sense that the difference between disturbed and control plots became less. This does not explain, however, why there was no difference in the first summer following the disturbance. Felix et al. (1992) also found that active layer depth at disturbed sites increased between the initial summer and 4 to 5 years later. Perhaps the lighter color of the trail/ice road in the first summer following disturbance, before the dead vegetation weathers and darkens, increases the albedo and temporarily counteracts any effect of the disturbance (Yokel et al. 2007). In contradiction to these results, Lawson (1979) found that thaw depths in the path of an ice road built in the NPRA in 1978 were greater than on nearby control plots during the first summer following construction. Regardless of the outcome or the reason, Pullman et al. (2005), studying impacts of ice roads just east of the NPRA, argued that since inter-annual variation in thaw depths (8–13 cm) was greater than within-year/between-treatment differences (2–5 cm), the latter were probably not ecologically relevant.

It is not surprising that active layer depths were greater on shrub plots than other vegetation types in the NPRA, given that shrubs tend to grow on better drained soils with a deeper active layer. Although Figure 47 suggests that seismic exploration and associated camp moves cause greater depth of thaw than ice road construction, little can be made of this result since the differences were not statistically significant. If there is a real difference, it may be due to the later thaw of ice roads compared to surrounding snow in the first year of data collection.

Interaction of Year and Plot Type on Depth of Active Layer

The results of these measurements suggest that disturbance of the tundra by seismic exploration and ice road construction and use causes deeper thaw of the ground during summer. It appears that this effect is greatest from 3 to 6 years after the disturbance, and then the active layer in disturbed areas begins once again to equate with undisturbed areas. Although the difference between disturbed and control plots was statistically significant in 2 years, the greatest average difference was only 1.9 cm. Given this, and the relatively short time period during which the difference exists, it seems unlikely that this change in active layer depth is ecologically signicant.

The effect of year on active layer depth, although statistically significant, is not directly an issue. It merely reflects variation in weather among measurement years. However, a long-term trend of active layer depth increase would be a validation of effects of climate change. This kind of time series would require data collection over a longer period and this study was not meant to address this issue.

Conclusions and Management Implications

There are potential problems with comparing the results of different studies of tundra vegetation disturbance. Although the same disturbance scoring system was used in the NPRA as in other studies reviewed here, the system uses the observers' visual estimates of percent cover change. There can be differences among observers in both interpretation of vegetation conditions and estimation of percent of plots involved in any type of change. In addition, there may be small differences in terrain or vehicle types among studies. Nonetheless, our results generally support the studies of Jorgenson et al. (2003) and Jorgenson et al. (2010).

The stated objectives of this project were (1) to measure the impacts of seismic exploration and ice road use on tundra vegetation in a quantifiable and repeatable manner with a sampling design that allows valid extrapolation of the results to other impacted areas; (2) to allow a test of the hypothesis that impacts vary among vegetation types and disturbance types; and (3) to provide a measure for comparison over later years to document the degree of recovery under these different situations. Although 89 study plots comprise a substantial sample size from a logistical perspective, once those are broken down into 6 major vegetation categories or 12 minor vegetation categories, and the results are further split among 3 disturbance types, the sample sizes within each of these subcategories is small. The result is that some of the analyses likely do not have adequate statistical power to identify some real differences. The obvious trade-off, however, is cost. The results as presented in this report verify or suggest several differences, and enough of the important ones have been verified to meet all project objectives.

The main findings are that (1) the level of impact differs among both vegetation types and disturbance types; (2) recovery from disturbance continues over time and for a small proportion of sites was not complete after 15 years; (3) the rate of recovery differs among both vegetation types and disturbance types; and (4) depth of active layer differs by year, vegetation type, and whether or not a plot was disturbed, but does not differ significantly among disturbance types. The original intent was to follow the study sites until recovery was complete, but after 15 years post-disturbance the diminishing level of remaining potential recovery does not justify the costs of additional field effort. Although 12 percent of plots still displayed impacts after 15 years, the significance of these to management issues is debatable, especially considering their overall rarity on the landscape. Studies in the ANWR of seismic disturbance from over 25 years ago show that impacts still persist in a few settings.

The project represents 2 major values to the BLM: (1) better ability to assess the environmental impacts of the leasing program in planning documents, and (2) better information to use when assessing the performance of permittees. When the first leasing plan for the Northeast NPRA was developed in 1997, the BLM had no quantitative data from the NPRA to use in assessing the impacts of seismic exploration and ice road construction. This project has improved upon that in subsequent planning documents, increasing the BLM's ability to withstand legal challenges. With performance-based mitigation measures, the BLM needs better standards for assessing whether observed impacts from winter exploration are undue or unnecessary. These results could also be used to that purpose. In addition, the study results support the conclusion that no fertilizer application is necessary to promote recovery (Emers et al. 1995; Jorgenson et al. 2003). Finally, the project results suggest 2 possible ways to reduce levels of impacts if BLM managers decide that is necessary and justifies the additional cost to operators: (1) to the extent possible, constrain off-road vehicle use or ice road construction to those vegetation types with wetter substrates and less microtopography; and (2) continue to develop better technology for camp trains and ice road construction to reduce their impacts.

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Table 1. Disturbance rating scheme for individual ocular estimates (after Felix and Raynolds, 1989a.)

Disturbance Measure	Level	Description
Decrease in plant cover	0	No observable change
	1	0-25%
	2	25-50%
	3	Over 50%
Decrease in shrub canopy	0	No observable change
	1	0-25%
	2	25-50%
	3	Over 50%
Increase in exposed soil (organic or mineral)	0	None observed
	1	1-5%
	2	6-15%
	3	Over 15%
Structural damage to tussocks or hummocks	0	No observable damage, to slight scuffing
	1	Tussocks or hummocks scuffed
	2	Tussocks or hummocks crushed
	3	Crushed tussocks nearly continuous, or ruts starting to form
Compression of standing litter or moss mat	0	No observable compression
	1	Compression of standing litter; maybe slight scuffing
	2	Compression of mosses and standing litter; trail appears wetter than surrounding area
	3	Compression of mosses below water surface; standing water apparent on trail but not present in surrounding area
Visibility of trail (from ground or air)	0	Not visible; trail could not be discerned
	1	Barely perceptible; trail appeared discontinuous or could only be discerned from a particular viewpoint
	2	Visible; continuous trail could be discerned from most angles
	3	Easily visible; noticeable color change on trail; obvious contrast with undisturbed area

Table 2. Rating scheme for estimates of overall disturbance levels (after Felix et al., 19992.)

Disturbance Level	Description
None (0)	No impact to slight, or widely scattered, scuffing of higher microsites; occasional breakage of shrubs
Low (1)	Less than 26 percent decrease in vegetation or shrub cover and less than 6 percent soil exposed; compression of standing litter and slight scuffing in flooded, wet or moist tundra; tussock tops or hummocks scuffed
Moderate (2)	Vegetation or shrub cover decrease 26-50 percent and exposed soil 6-15 percent ; obvious compression of mosses and standing litter in flooded, wet or moist tundra and may have increase in aquatic sedges; over 30 percent of tussocks or hummocks crushed, but may show regrowth; scuffing of microsites common in non-tussock areas; portions of trail may appear wetter than surrounding area; in low shrub, some disruption of vegetative mat; may be some change in vegetative composition
High (3)	Over 50 percent decrease in vegetation cover or shrub cover and over 15 percent soil exposed; obvious track depression in flooded, wet or moist tundra; compression of mosses below water surface; standing water is apparent on trail, but is not present in adjacent areas in wet years; moist tundra changing to wet tundra; crushed tussocks or hummocks nearly continuous; general depression of the trail is evident; ruts may be starting to form; change in vegetative composition; in low shrub, vegetative mat and ground cover substantially disrupted

Table 3. Number of study plots in each minor vegetation category and trail (disturbance) type.

	Trail (Disturbance) Type			
Vegetation class	Seismic	Camp-Move	Ice Road	Total
Arctophila	3	0	0	3
Carex	4	2	1	7
Non-patterned	2	4	2	8
Low-centered	2	2	1	5
Wet tundra	6	2	1	9
Sedge meadow	8	2	1	11
Tussock tundra	5	6	4	15
Moss/Lichen	3	3	0	6
Dwarf shrub	5	6	2	13
Low Shrub	2	3	0	5
Sparse Vegetation	4	0	0	4
Dunes/Dry sand	3	0	0	3
Total	47	30	12	89

Table 4. Percent of study plots at each level of overall disturbance for each trail (disturbance) type in each year of data collection. (Disturbance levels: None = 0, Low = 1, Moderate = 2, High = 3.)

Trail Type	Seismic (47 plots)				Camp-Move (30 plots)				Ice Road (12 plots)			
Disturbance Level	0	1	2	3	0	1	2	3	0	1	2	3
1999/2000	68	32	0	0	17	17	43	23	17	33	25	25
2002	91	9	0	0	30	33	37	0	17	33	50	0
2005	96	4	0	0	37	43	13	7	33	67	0	0
2008	96	4	0	0	60	23	13	4	50	42	8	0
2011	98	2	0	0	70	20	10	0	83	17	0	0
2014	98	2	0	0	80	20	0	0	92	8	0	0

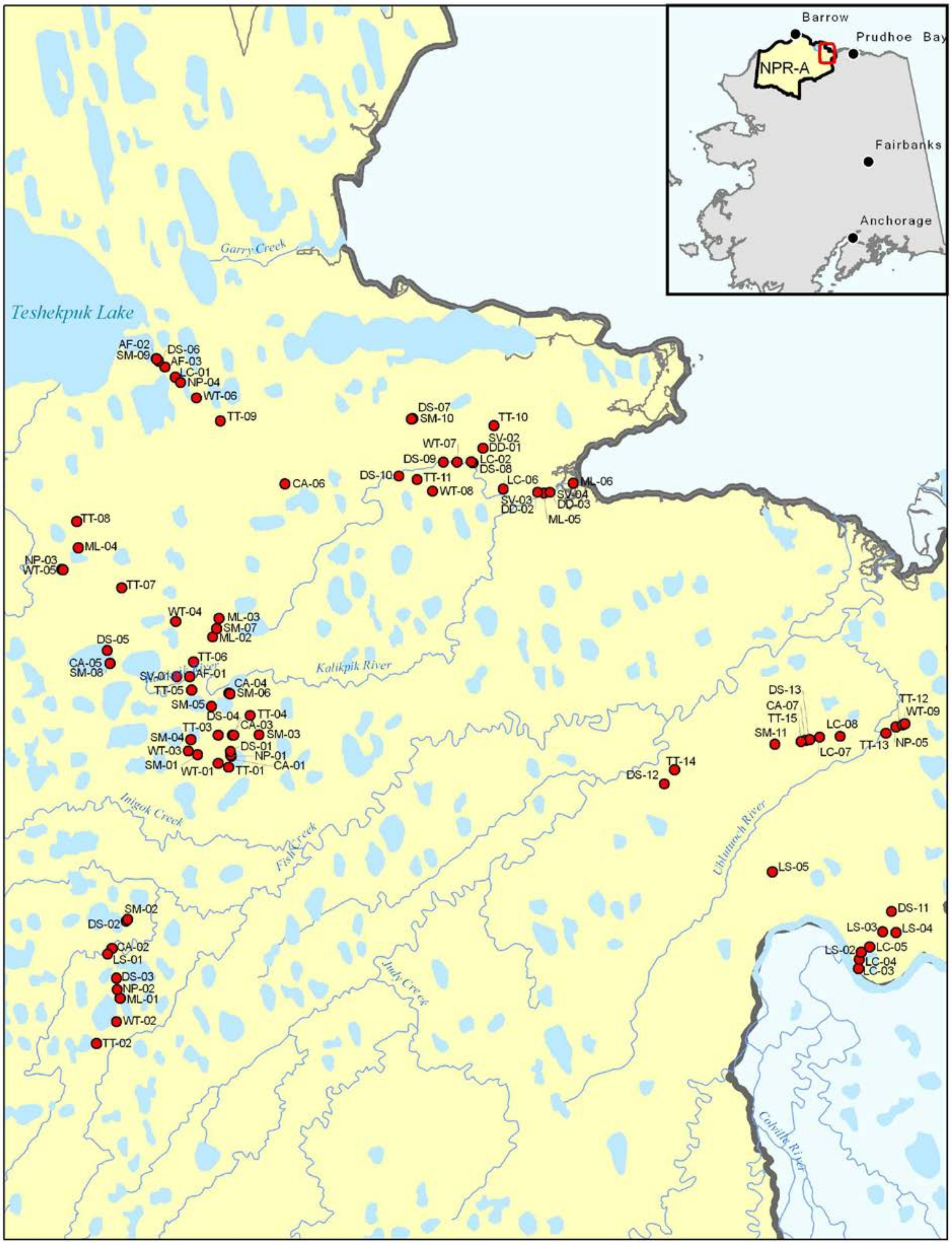

Figure 1. Locations of study plots in northeastern NPRA, North Slope, Alaska.

Overall Disturbance Levels: Major Vegetation Categories

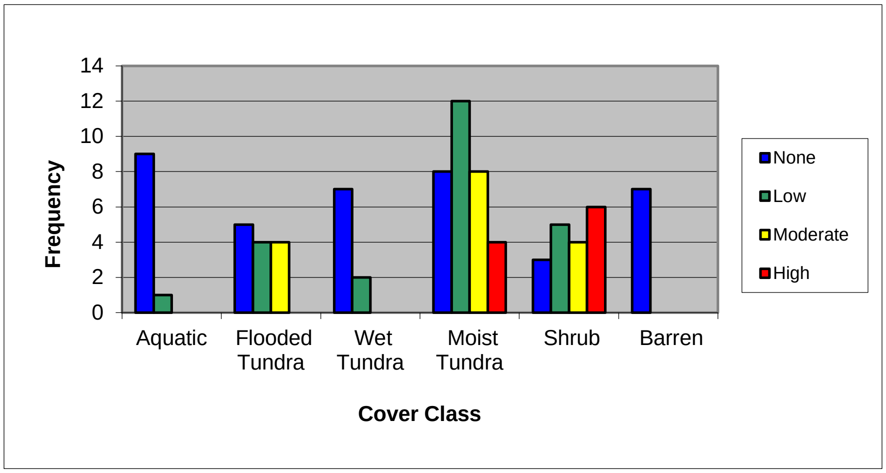

Figure 2. Overall disturbance levels by major vegetation category in 1999 (2000 for ice road).

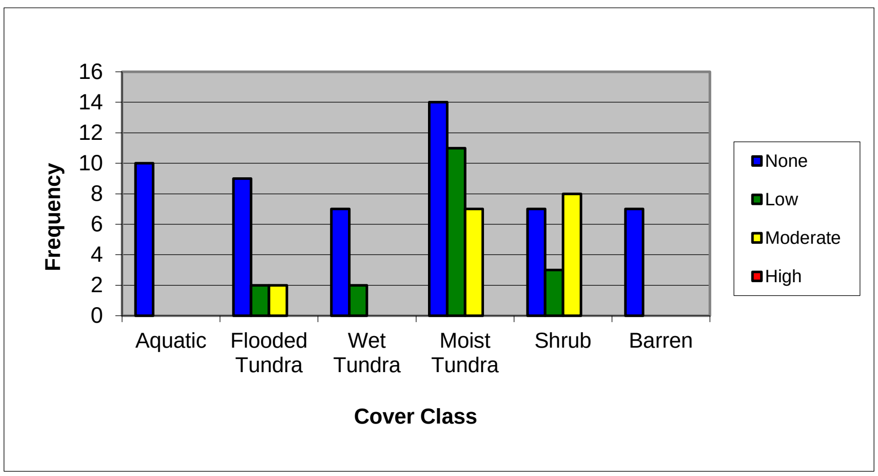

Figure 3. Overall disturbance levels by major vegetation category in 2002.

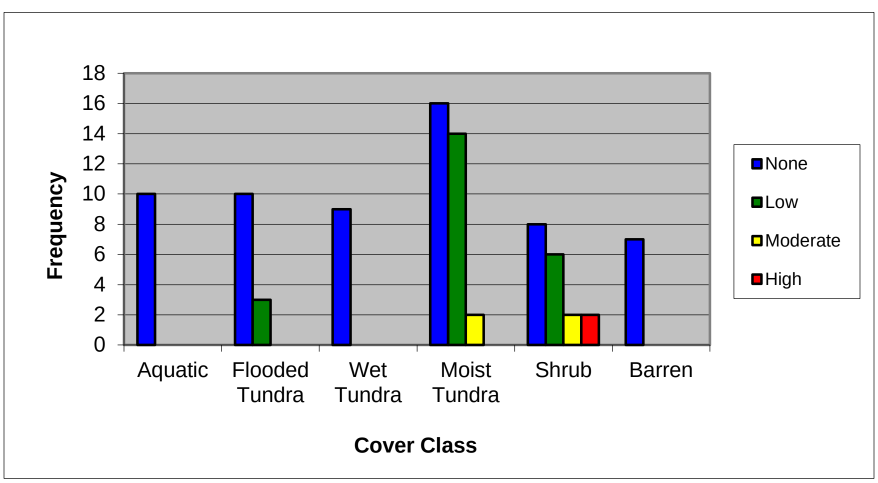

Figure 4. Overall disturbance levels by major vegetation category in 2005.

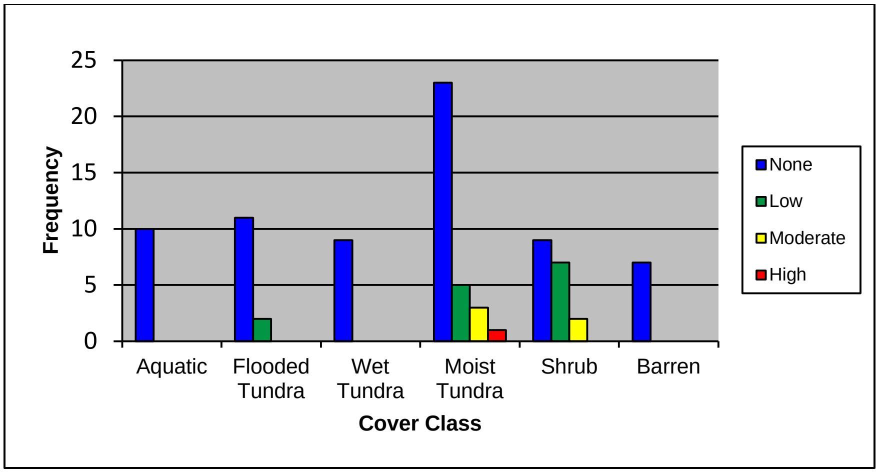

Figure 5. Overall disturbance levels by major vegetation category in 2008.

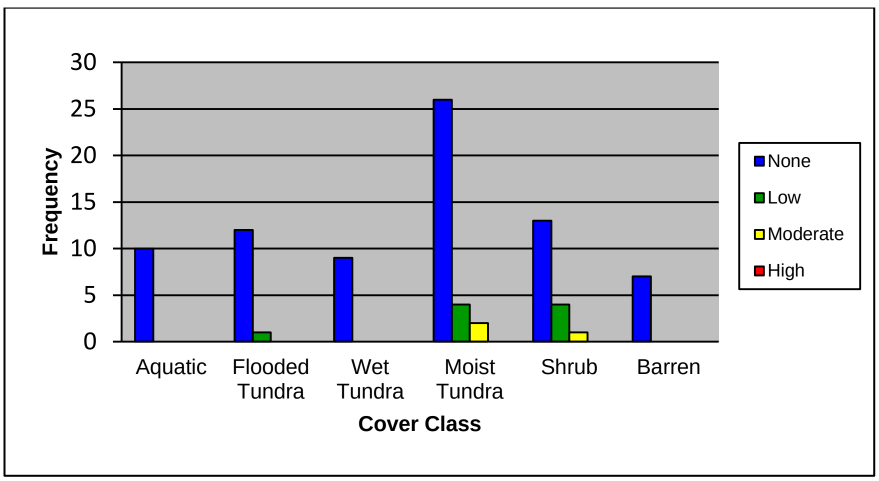

Figure 6. Overall disturbance levels by major vegetation category in 2011.

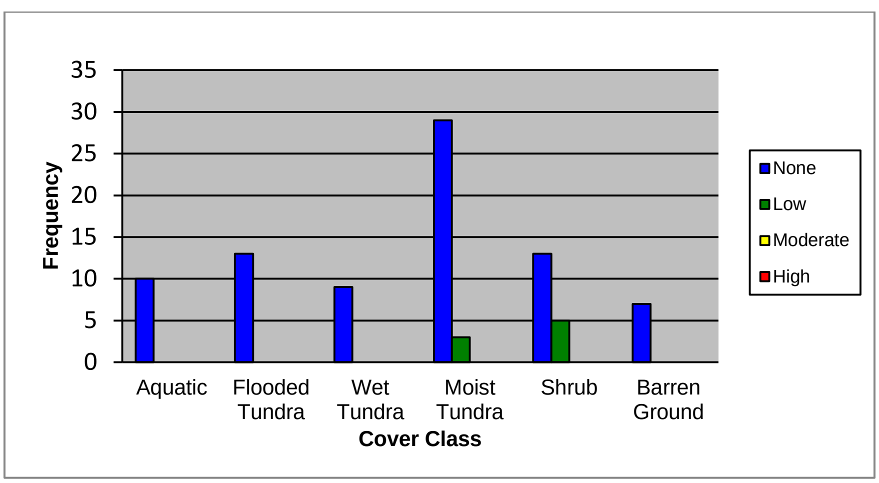

Figure 7. Overall disturbance levels by major vegetation category in 2014.

Minor Vegetation Categories

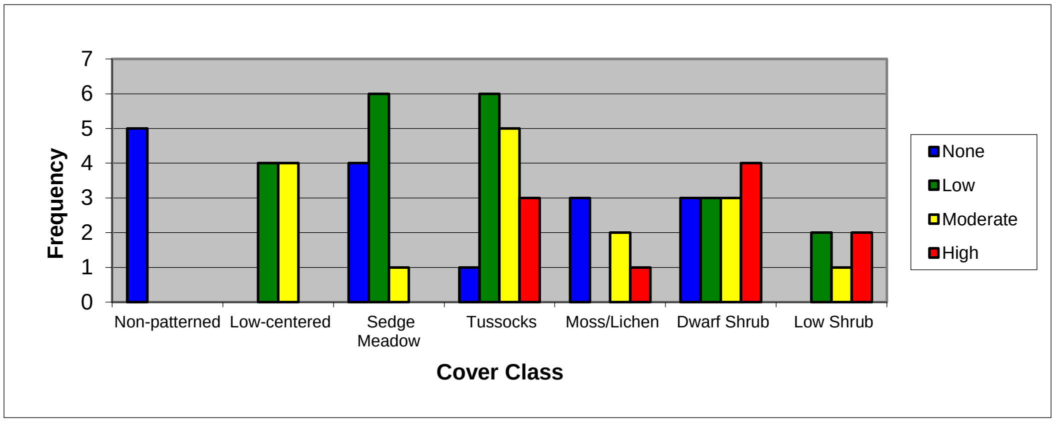

Figure 8. Overall disturbance levels in 1999 (2000 for ice road) for minor vegetation categories of the major categories flooded tundra, moist tundra, and shrub.

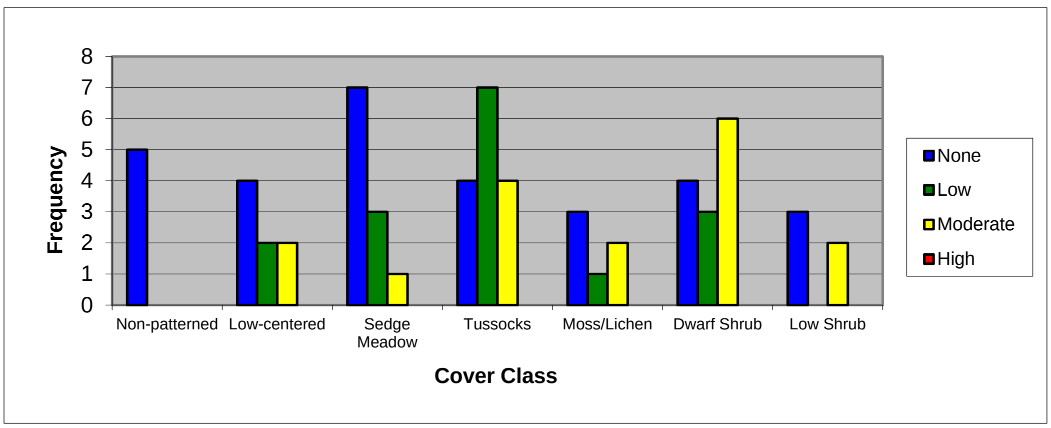

Figure 9. Overall disturbance levels in 2002 for minor vegetation categories of the major categories flooded tundra, moist tundra, and shrub.

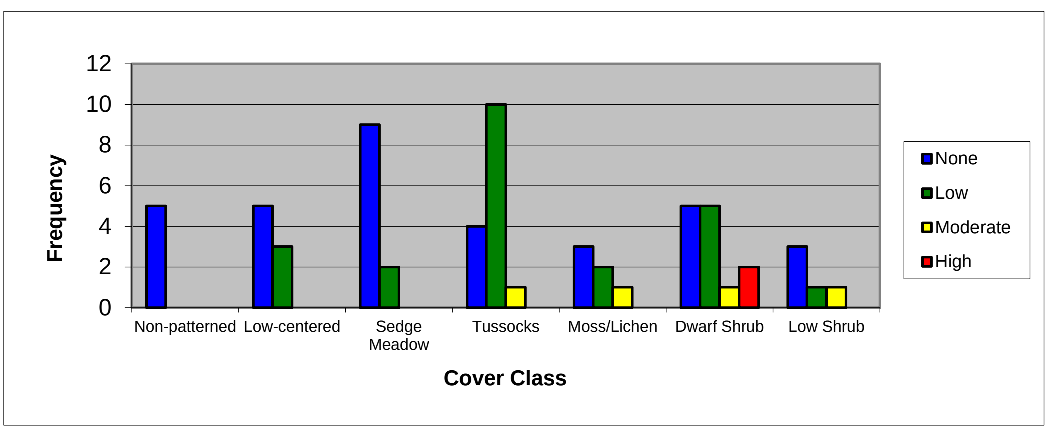

Figure 10. Overall disturbance levels in 2005 for minor vegetation categories of the major categories flooded tundra, moist tundra, and shrub.

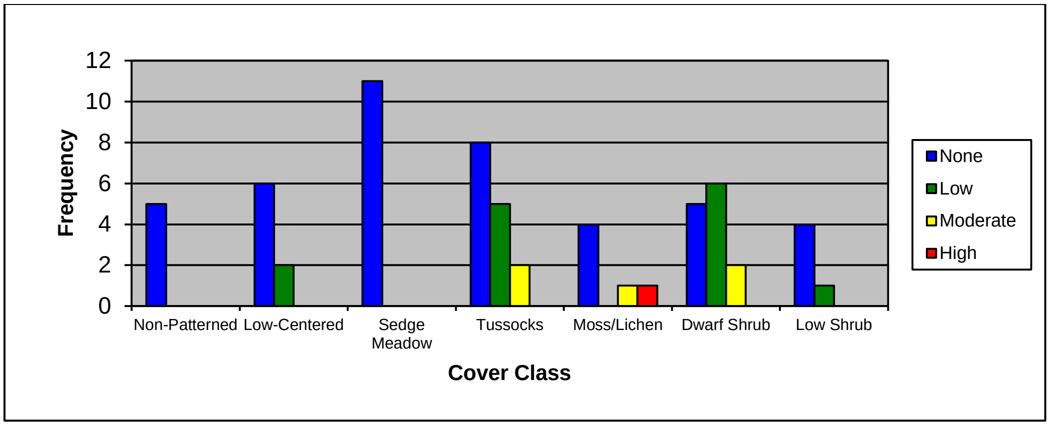

Figure 11. Overall disturbance levels in 2008 for minor vegetation categories of the major categories flooded tundra, moist tundra, and shrub.

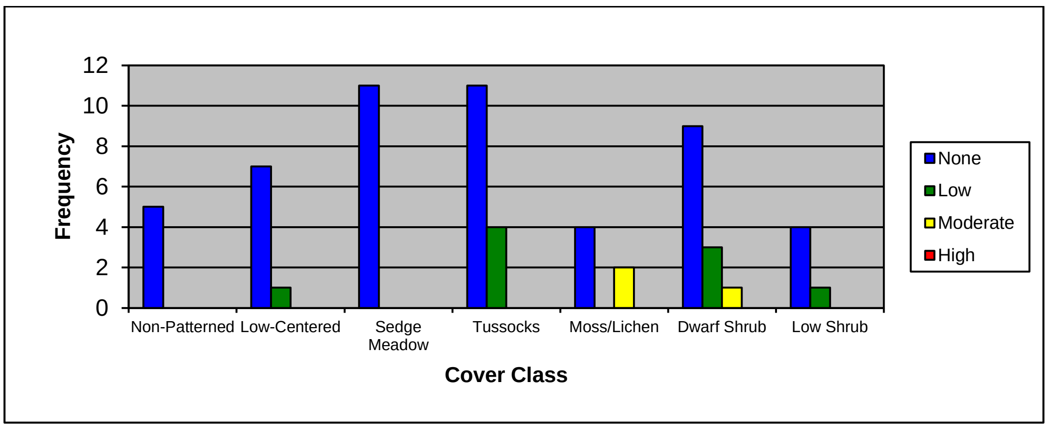

Figure 12. Overall disturbance levels in 2011 for minor vegetation categories of the major categories flooded tundra, moist tundra, and shrub.

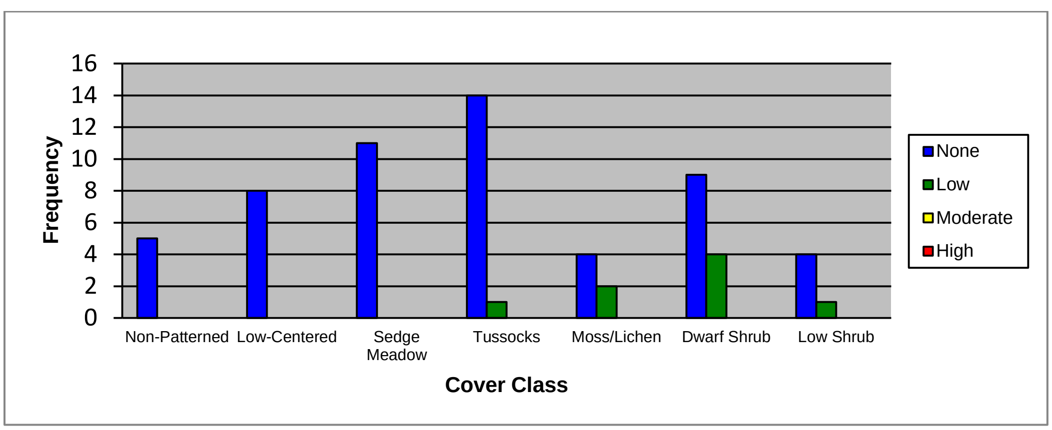

Figure 13. Overall disturbance levels in 2014 for minor vegetation categories of the major categories flooded tundra, moist tundra, and shrub.

Disturbance Type

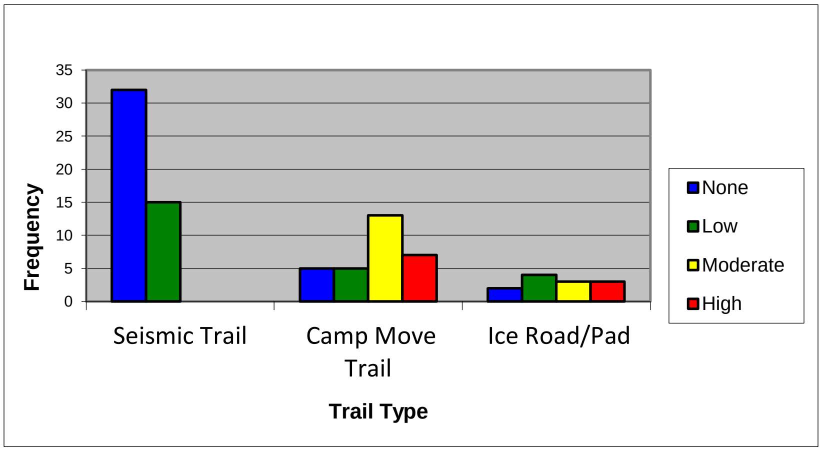

Figure 14. Overall disturbance levels by trail type in 1999 (2000 for ice road).

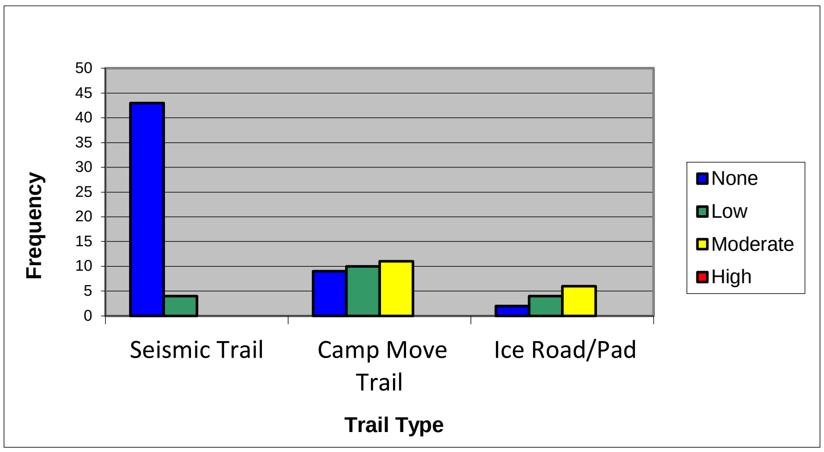

Figure 15. Overall disturbance levels by trail type in 2002.

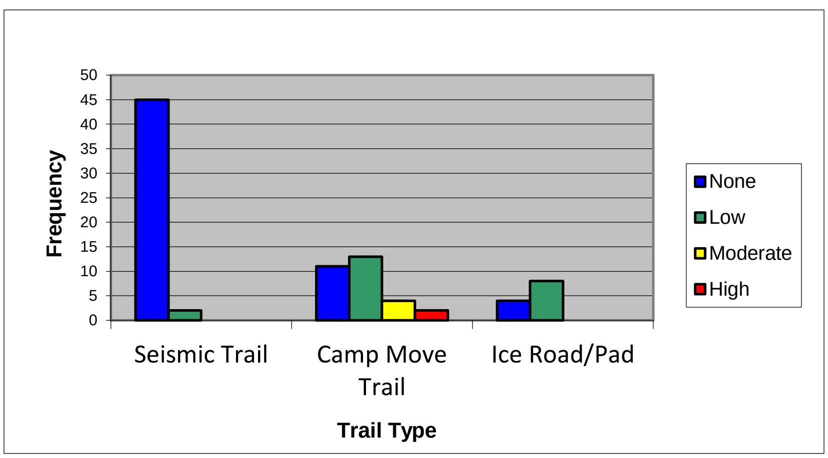

Figure 16. Overall disturbance levels by trail type in 2005.

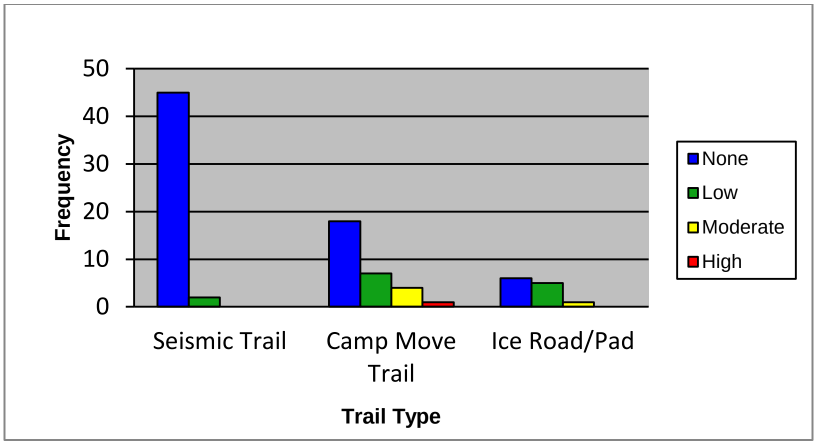

Figure 17. Overall disturbance levels by trail type in 2008.

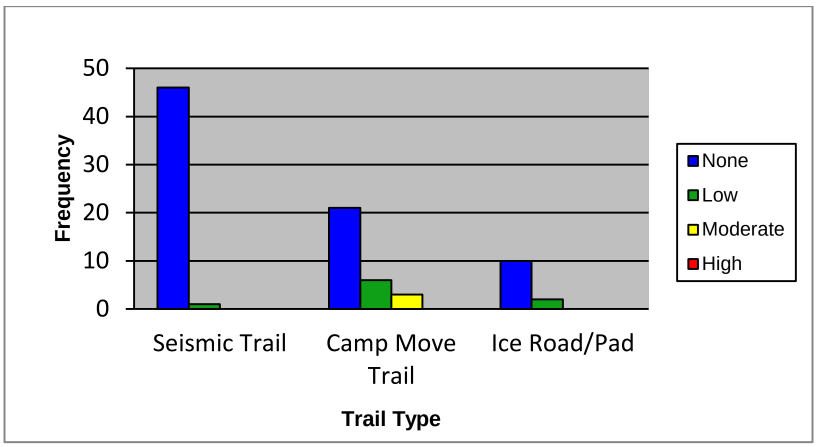

Figure 18. Overall disturbance levels by trail type in 2011.

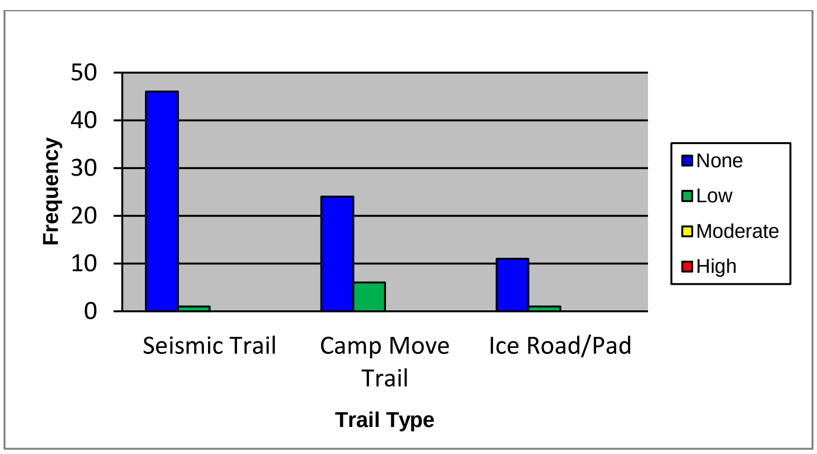

Figure 19. Overall disturbance levels by trail type in 2014.

Factors Affecting Overall Disturbance Levels in Each Year

Major Vegetation Categories and Disturbance Type

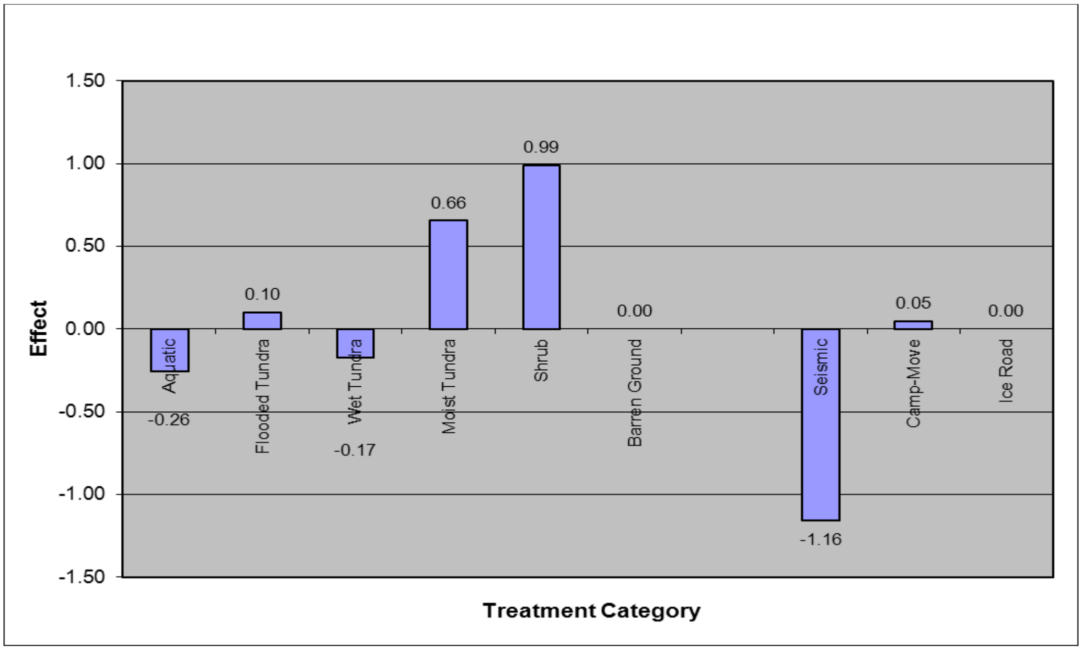

Figure 20. Effect of major vegetation category ($p < 0.0001$) and disturbance type ($p < 0.0001$) on overall disturbance levels in 1999 (2000 for ice road).

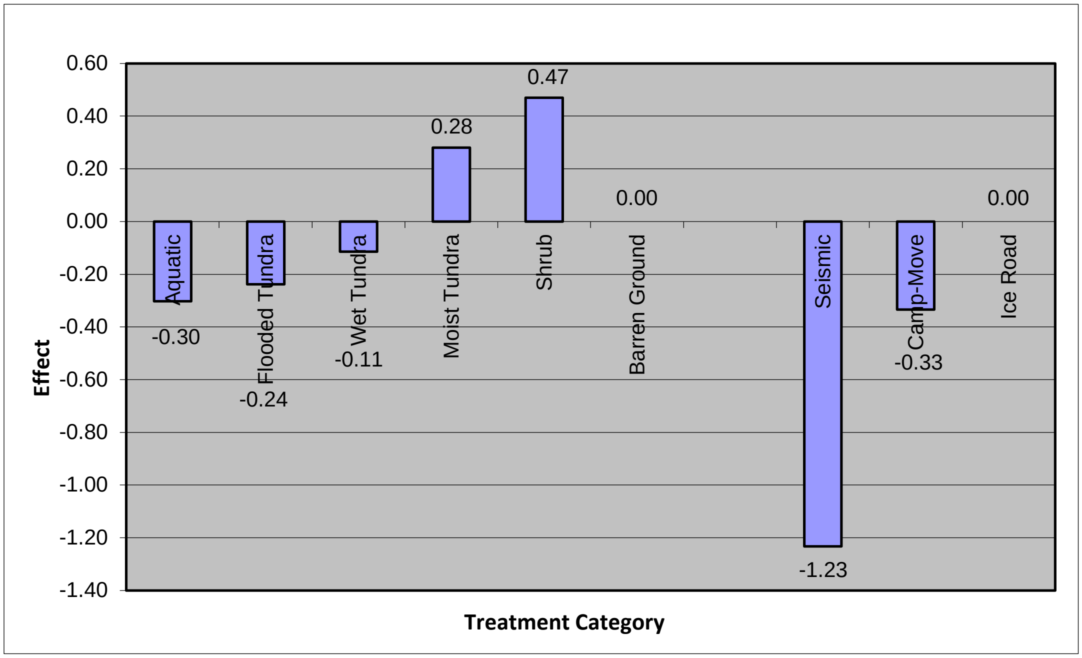

Figure 21. Effect of major vegetation category ($p < 0.001$) and disturbance type ($p < 0.0001$) on overall disturbance levels in 2002.

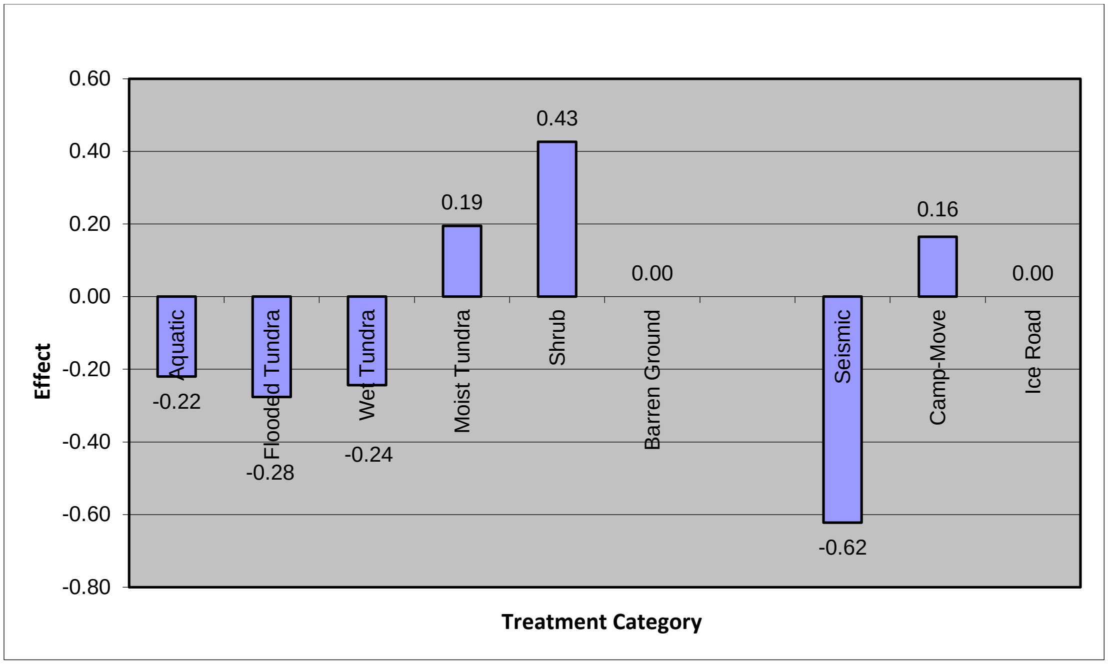

Figure 22. Effect of major vegetation category ($p = 0.001$) and disturbance type ($p < 0.0001$) on overall disturbance levels in 2005.

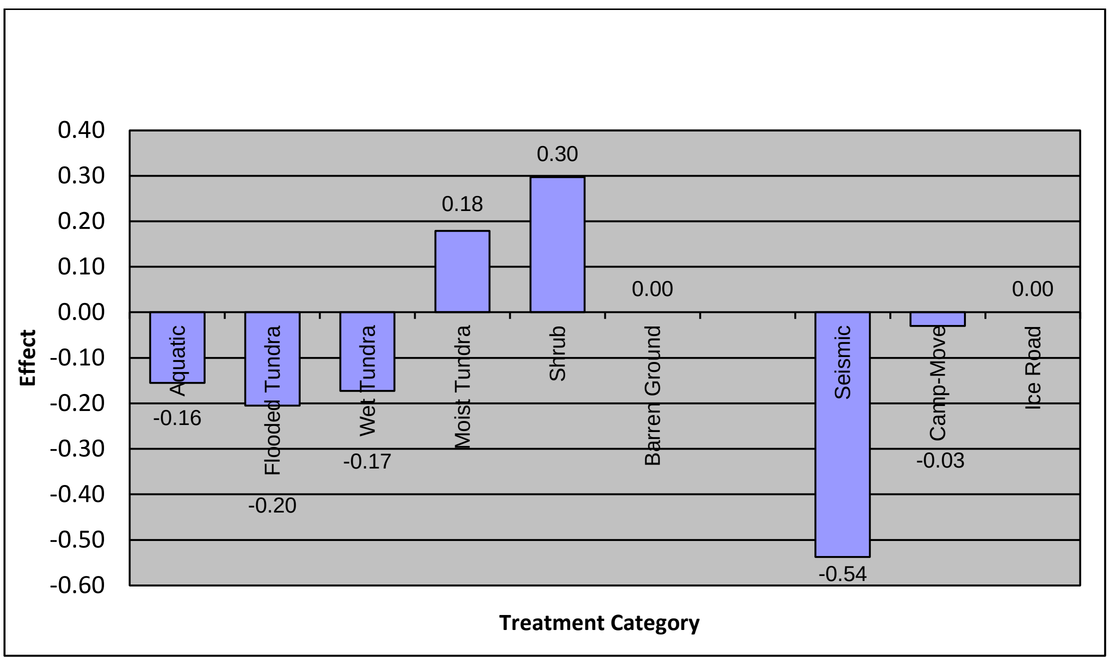

Figure 23. Effect of major vegetation category ($p < 0.07$) and disturbance type ($p < 0.001$) on overall disturbance levels in 2008.

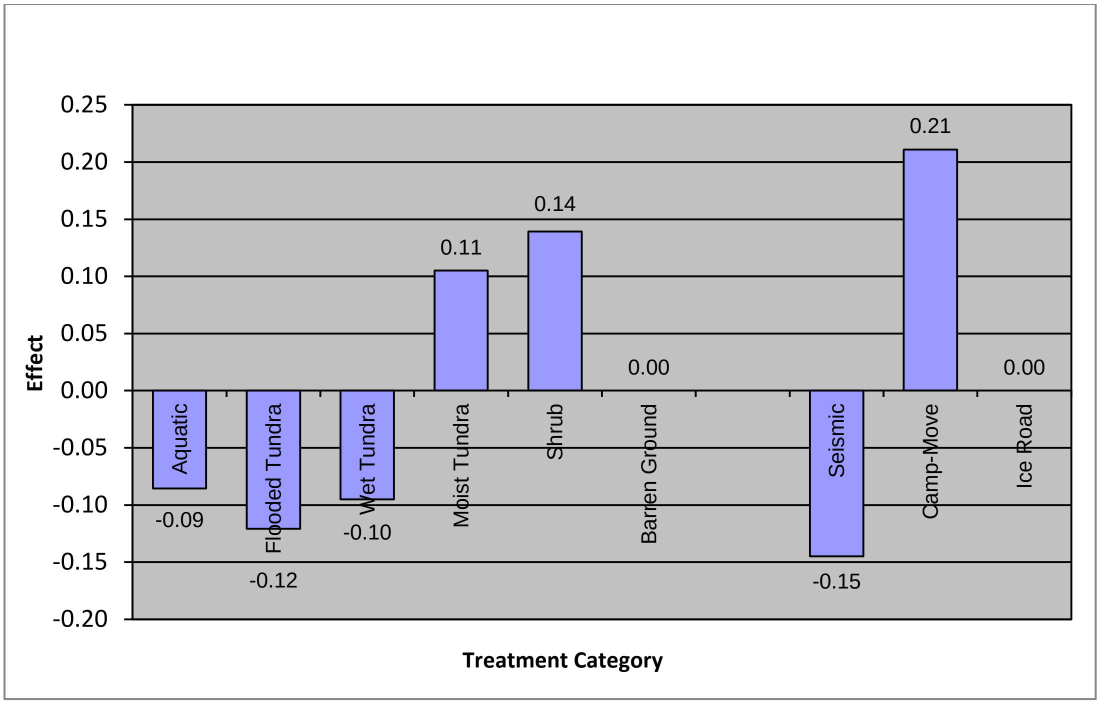

Figure 24. Effect of major vegetation category ($p = 0.40$) and disturbance type ($p < 0.01$) on overall disturbance levels in 2011.

Recovery of Overall Disturbance Levels

Extent of Recovery

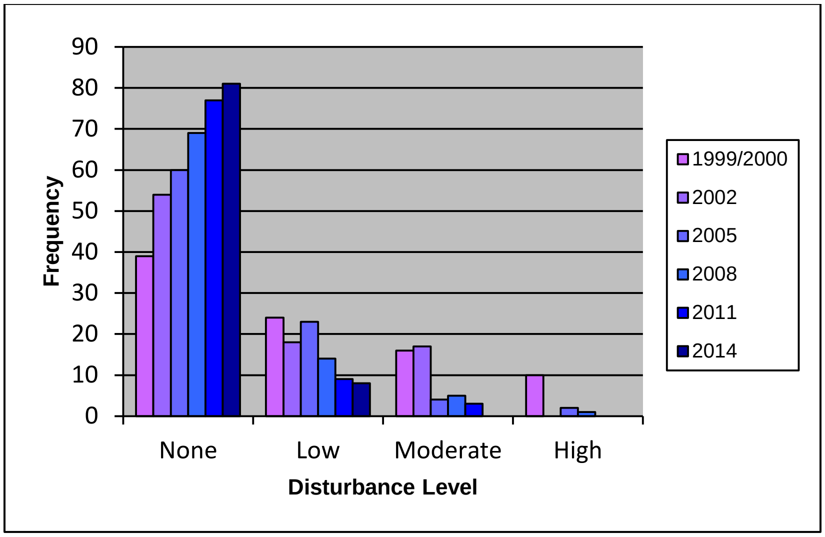

Figure 25. Number of study plots at each of 4 overall disturbance levels in each of 6 years, regardless of vegetation category or trail type.

Factors Affecting Recovery

Major Vegetation Categories and Disturbance Type

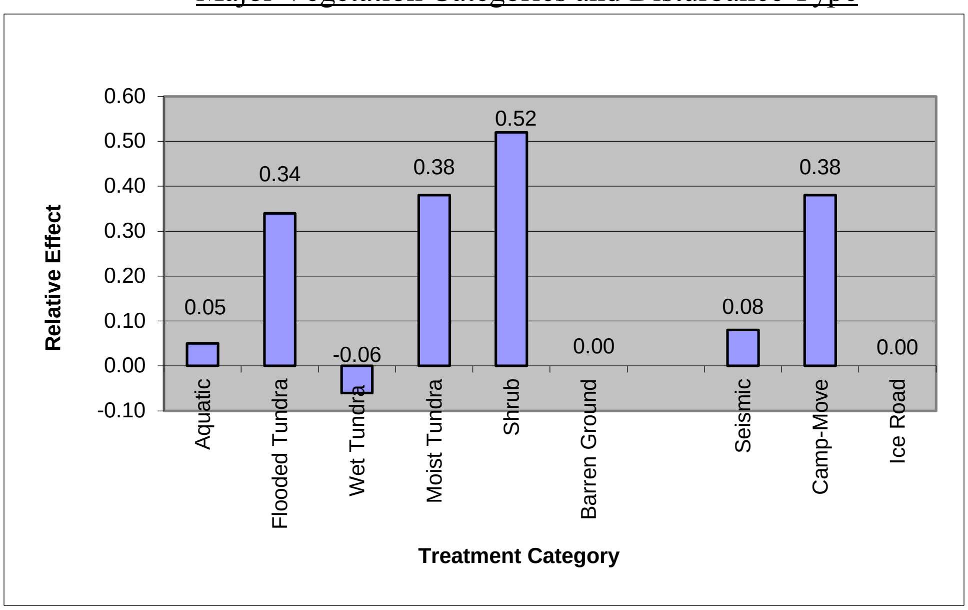

Figure 26. Effect of major vegetation category ($p = 0.02$) and disturbance type ($p < 0.02$) on recovery of overall disturbance levels between 1999 (2000 for ice road) and 2002.

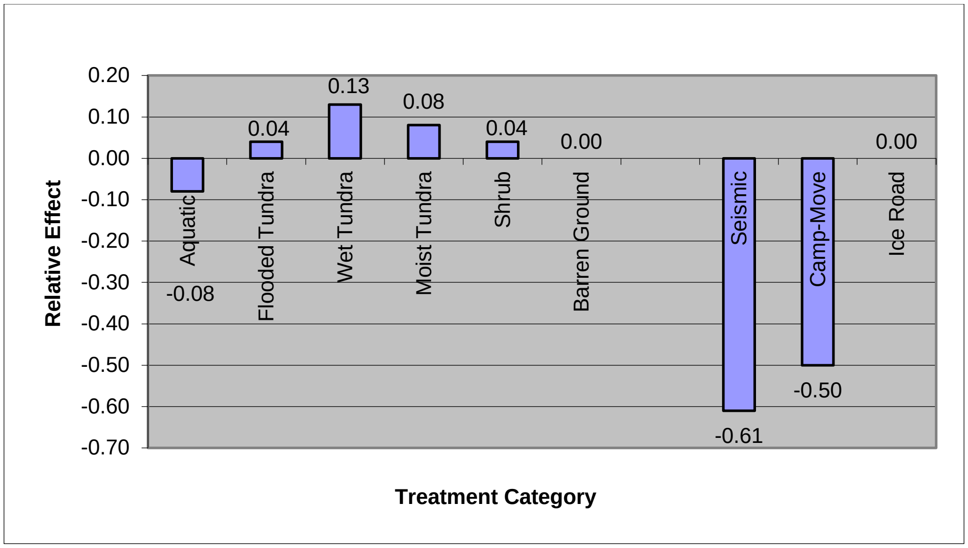

Figure 27. Effect of major vegetation category ($p = 0.86$) and disturbance type ($p < 0.0001$) on recovery of overall disturbance levels between 2002 and 2005.

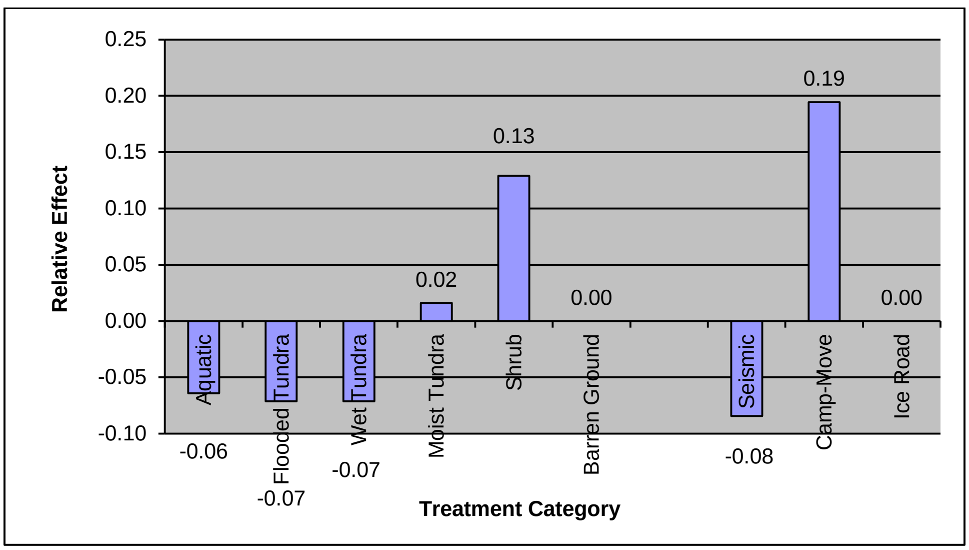

Figure 28. Effect of major vegetation category ($p = 0.72$) and disturbance type ($p = 0.02$) on recovery of overall disturbance levels between 2005 and 2008.

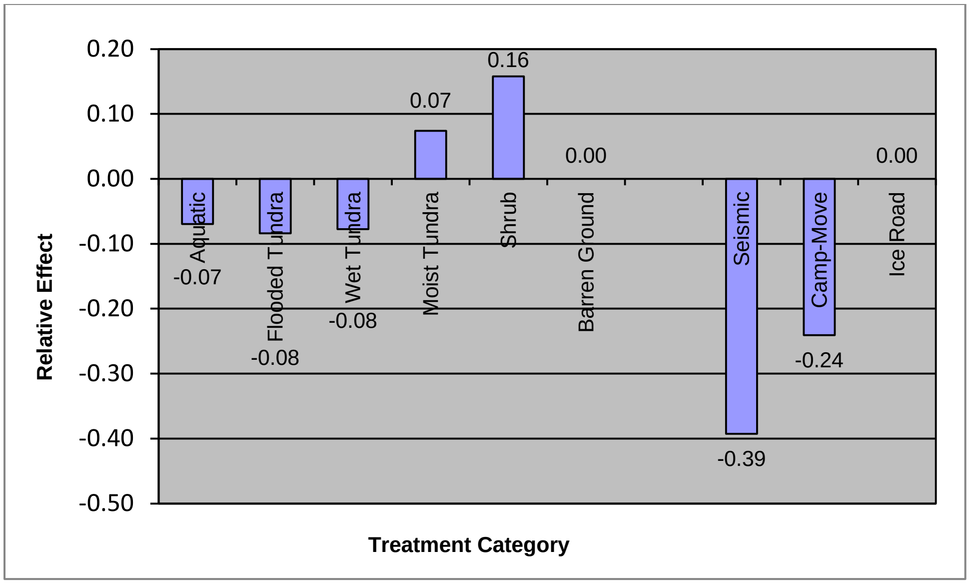

Figure 29. Effect of major vegetation category ($p = 0.21$) and disturbance type ($p = 0.001$) on recovery of overall disturbance levels between 2008 and 2011.

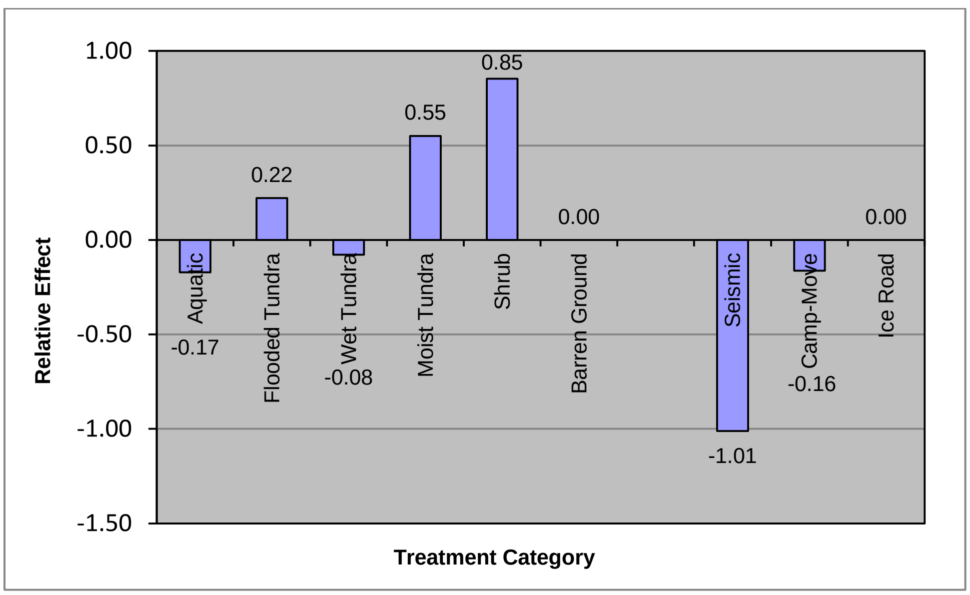

Figure 30. Effect of major vegetation category ($p = 0.0003$) and disturbance type ($p < 0.0001$) on recovery of overall disturbance levels between 1999 and 2011.

Minor Vegetation Categories and Disturbance Type

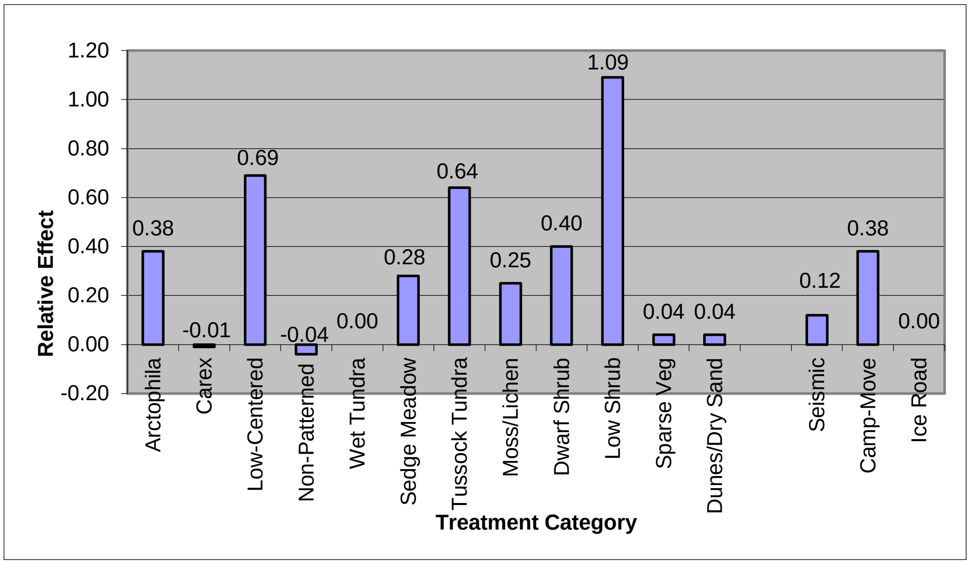

Figure 31. Effect of minor vegetation category ($p < 0.0001$) and disturbance type ($p < 0.02$) on recovery of overall disturbance levels between 1999 (2000 for ice road) and 2002.

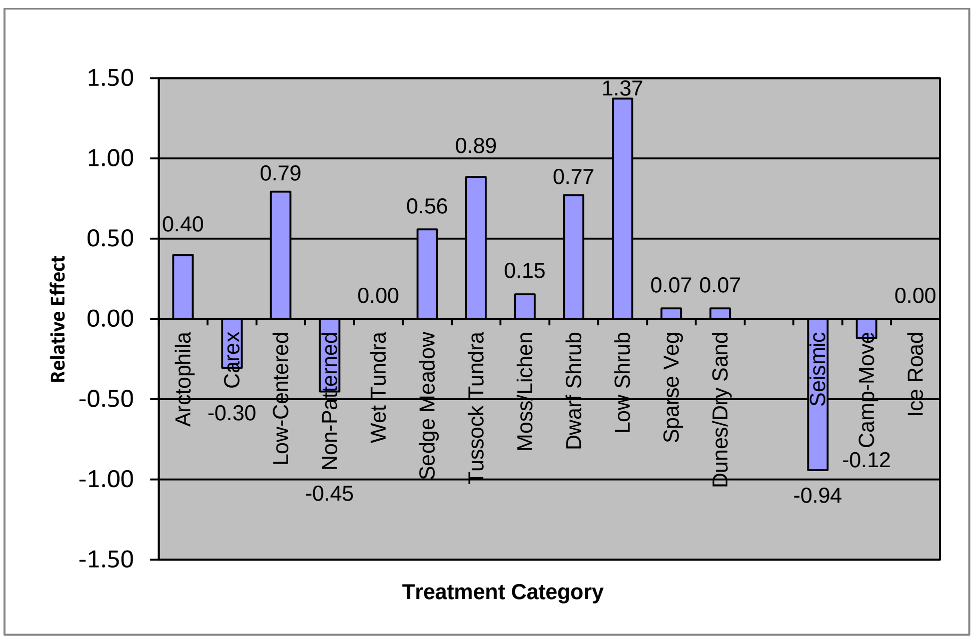

Figure 32. Effect of minor vegetation category ($p < 0.0001$) and disturbance type ($p < 0.0001$) on recovery of overall disturbance levels between 1999 and 2011.

Disturbance Levels for Individual Categories of Impacts

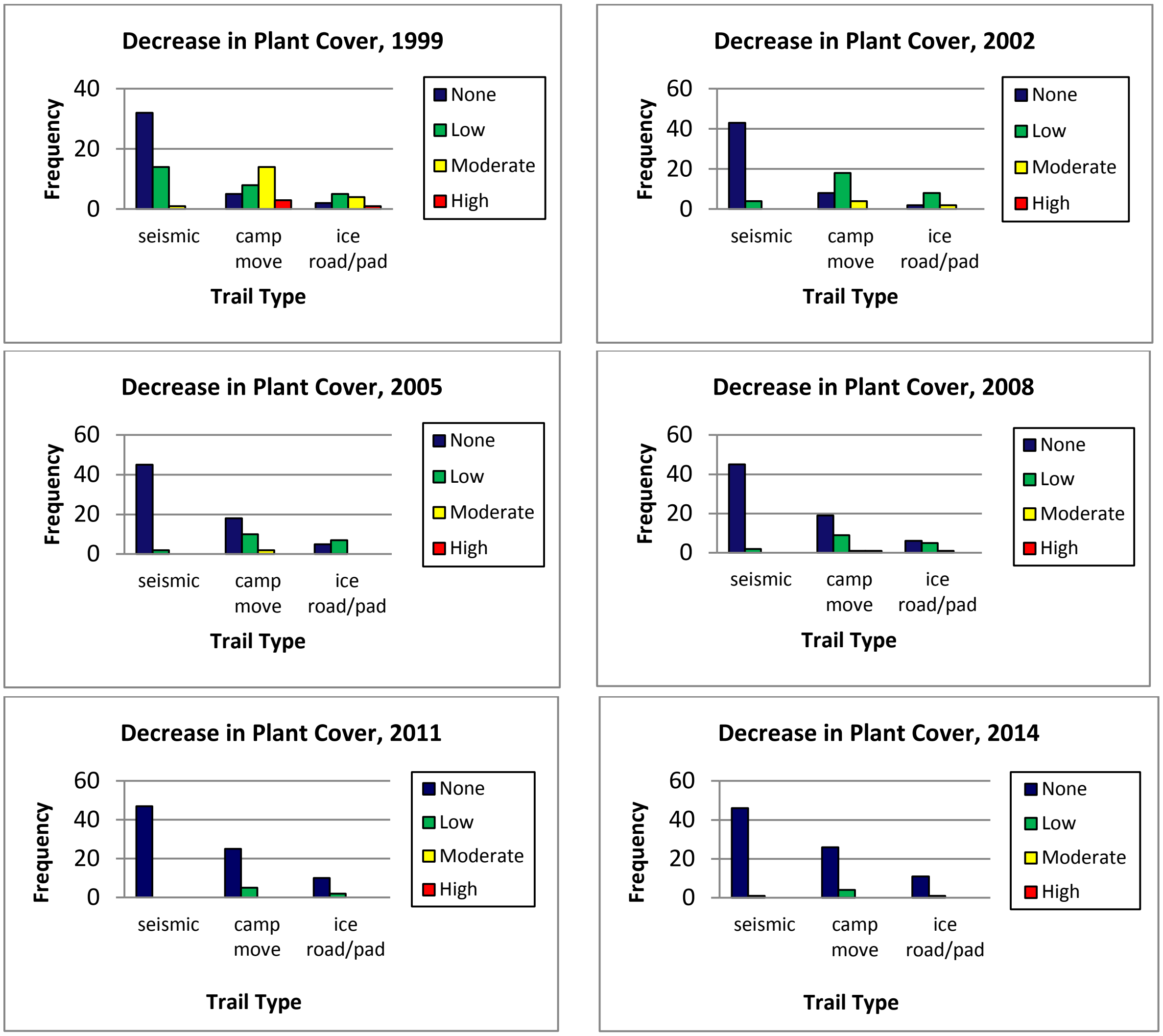

Figure 33. Decrease in plant cover, by trail type, during each of 6 years of data collection.

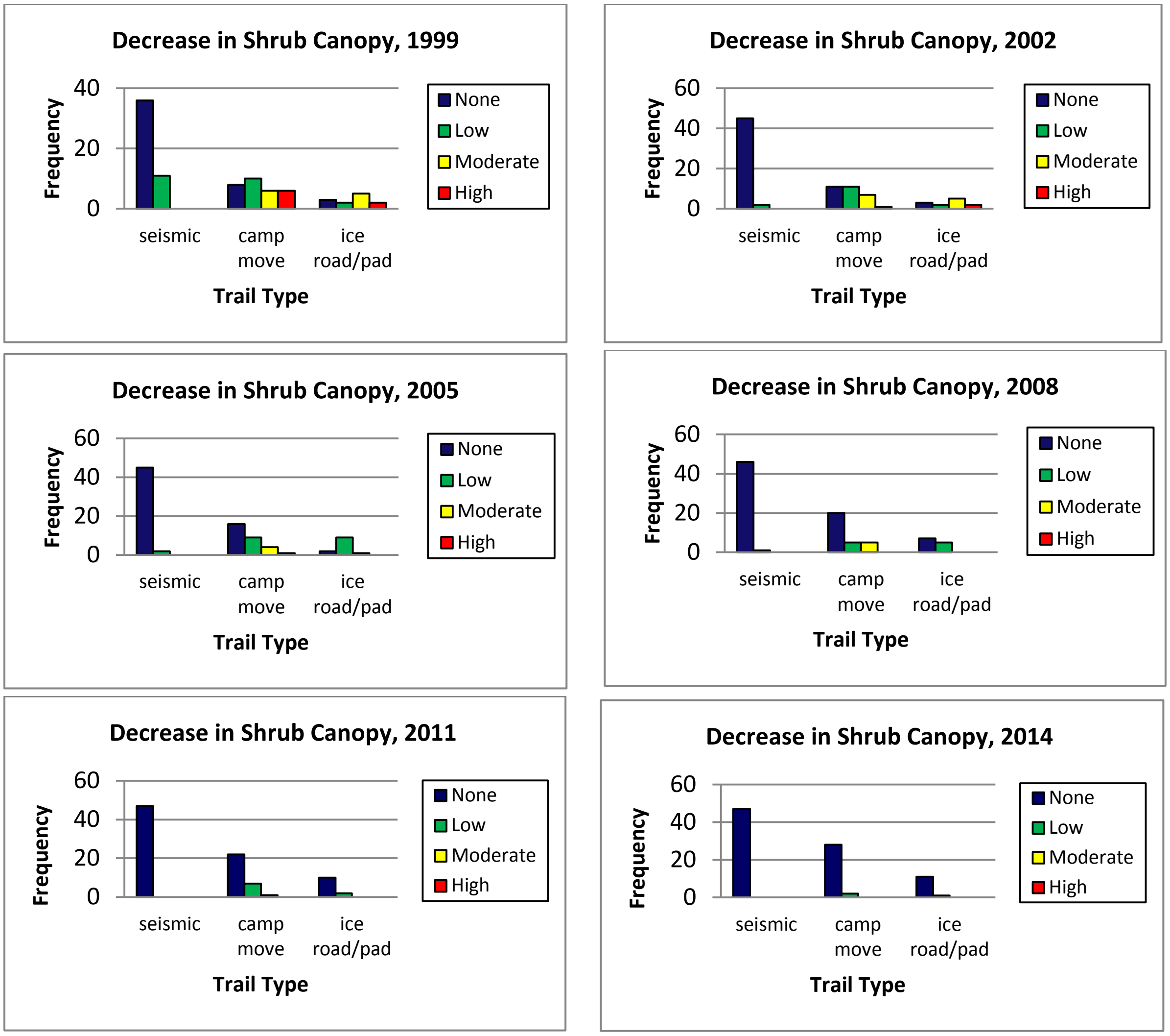

Figure 34. Decrease in shrub canopy, by trail type, during each of 6 years of data collection.

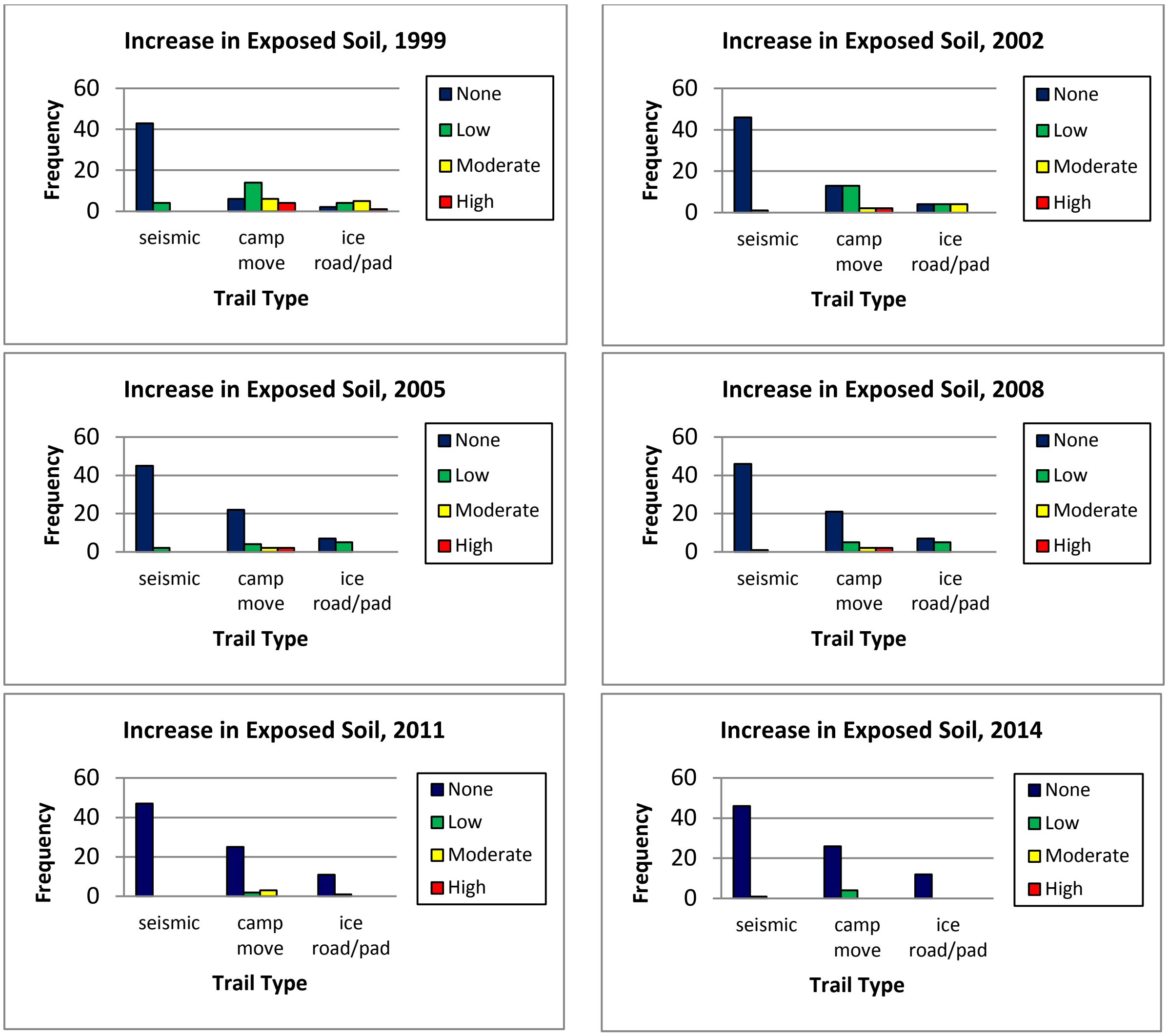

Figure 35. Increase in exposed soil, by trail type, during each of 6 years of data collection.

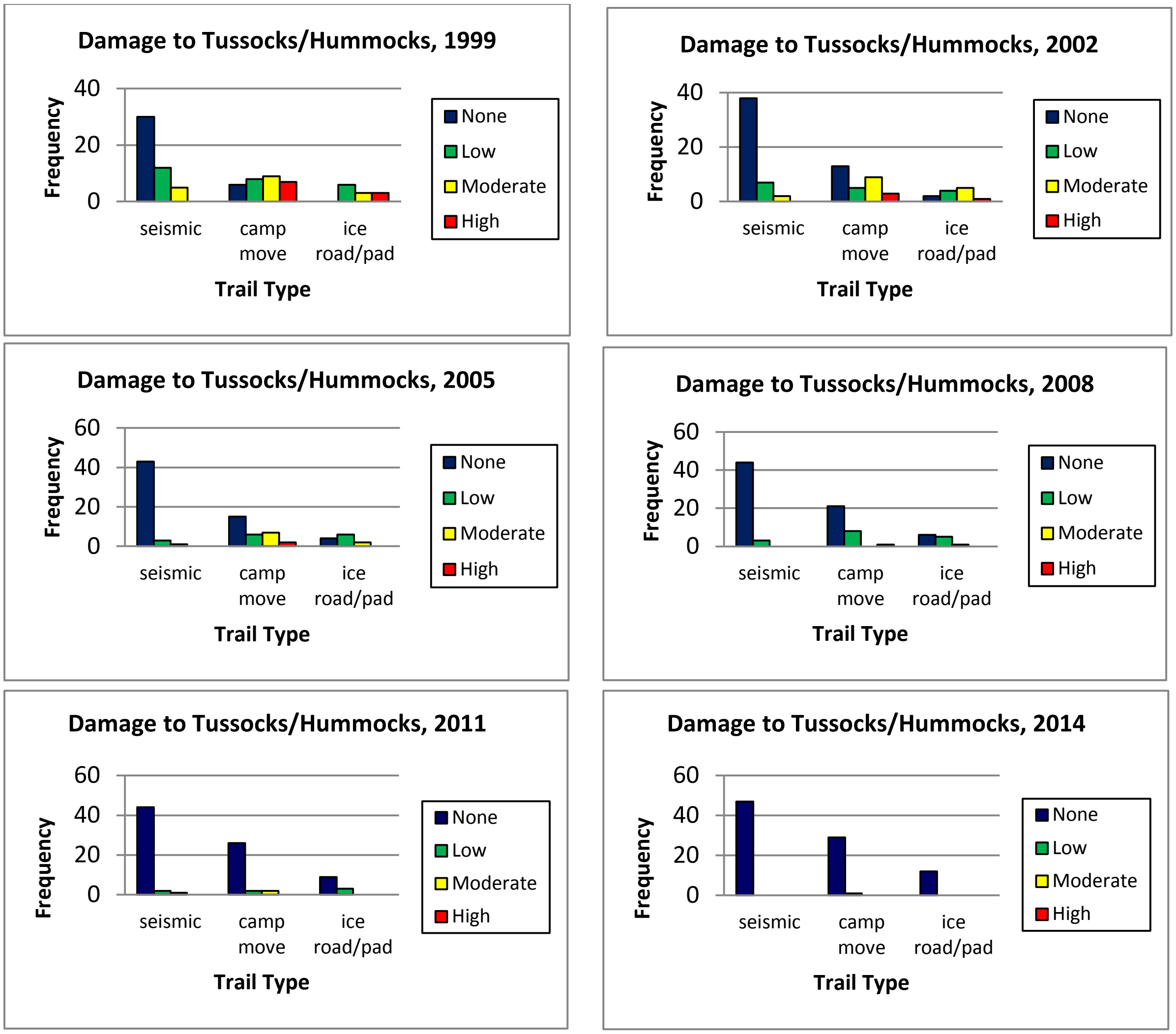

Figure 36. Damage to tussocks/hummocks, by trail type, during each of 6 years of data collection.

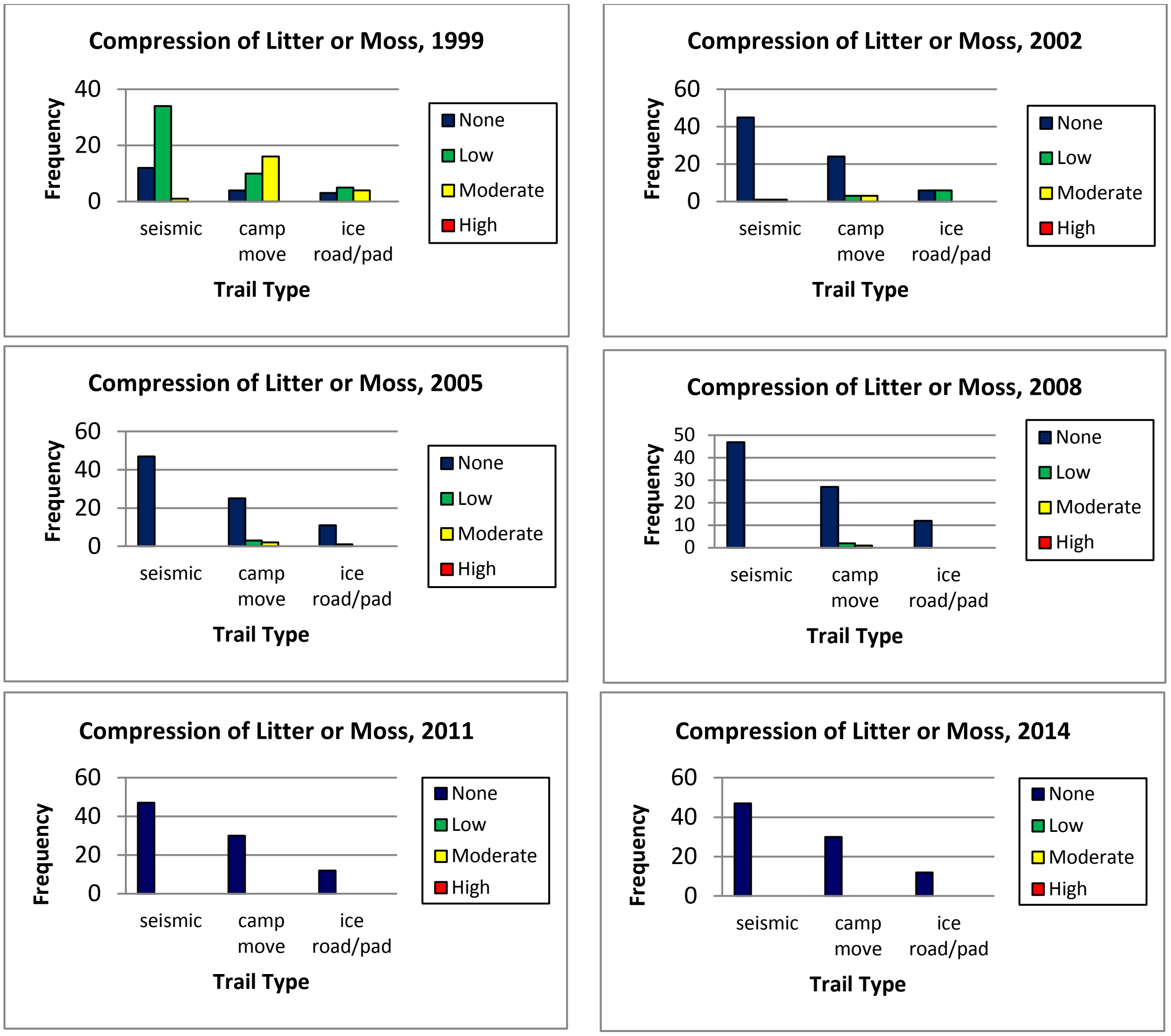

Figure 37. Compression of litter or moss, by trail type, during each of 6 years of data collection.

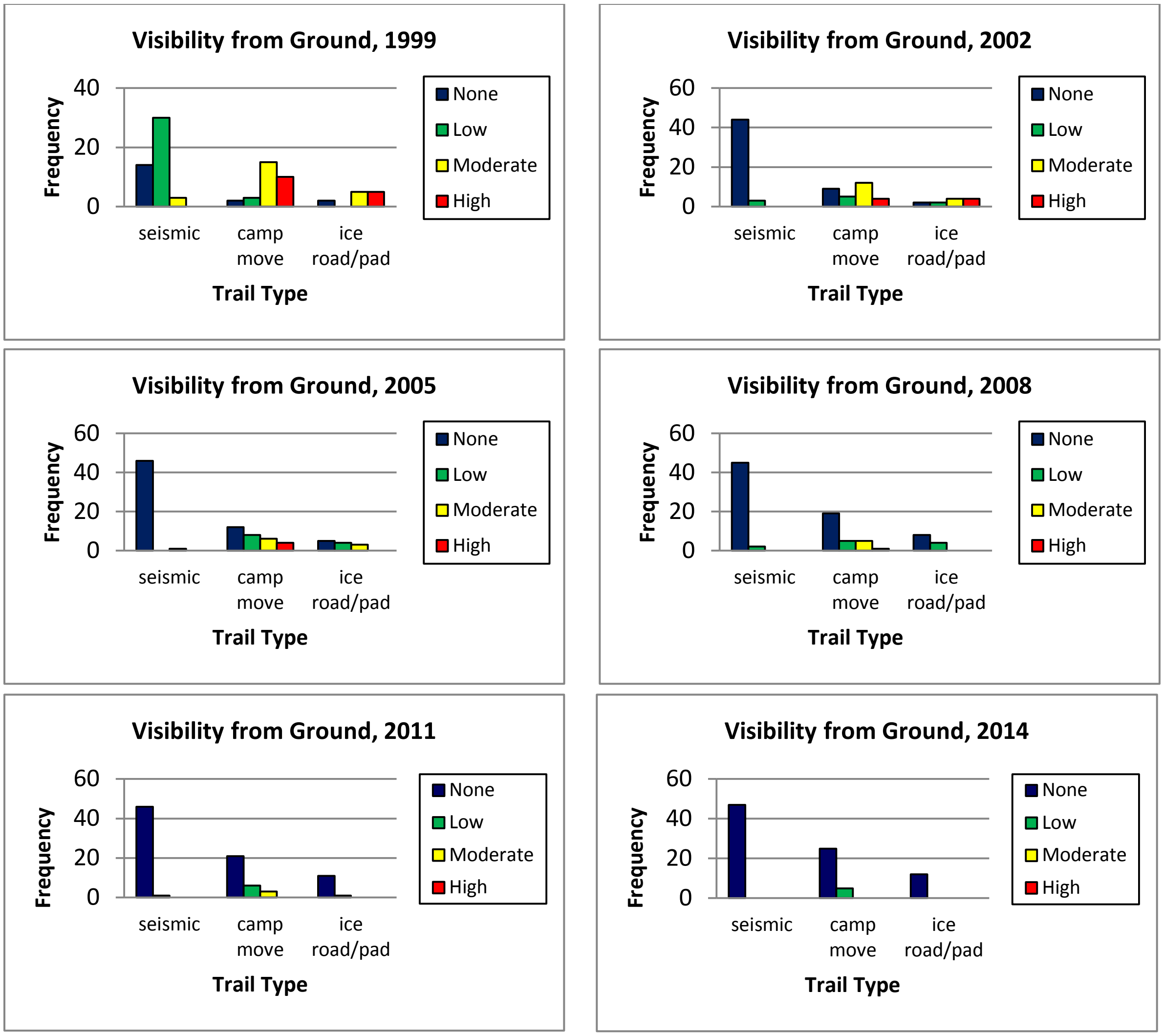

Figure 38. Visibility from ground, by trail type, during each of 6 years of data collection.

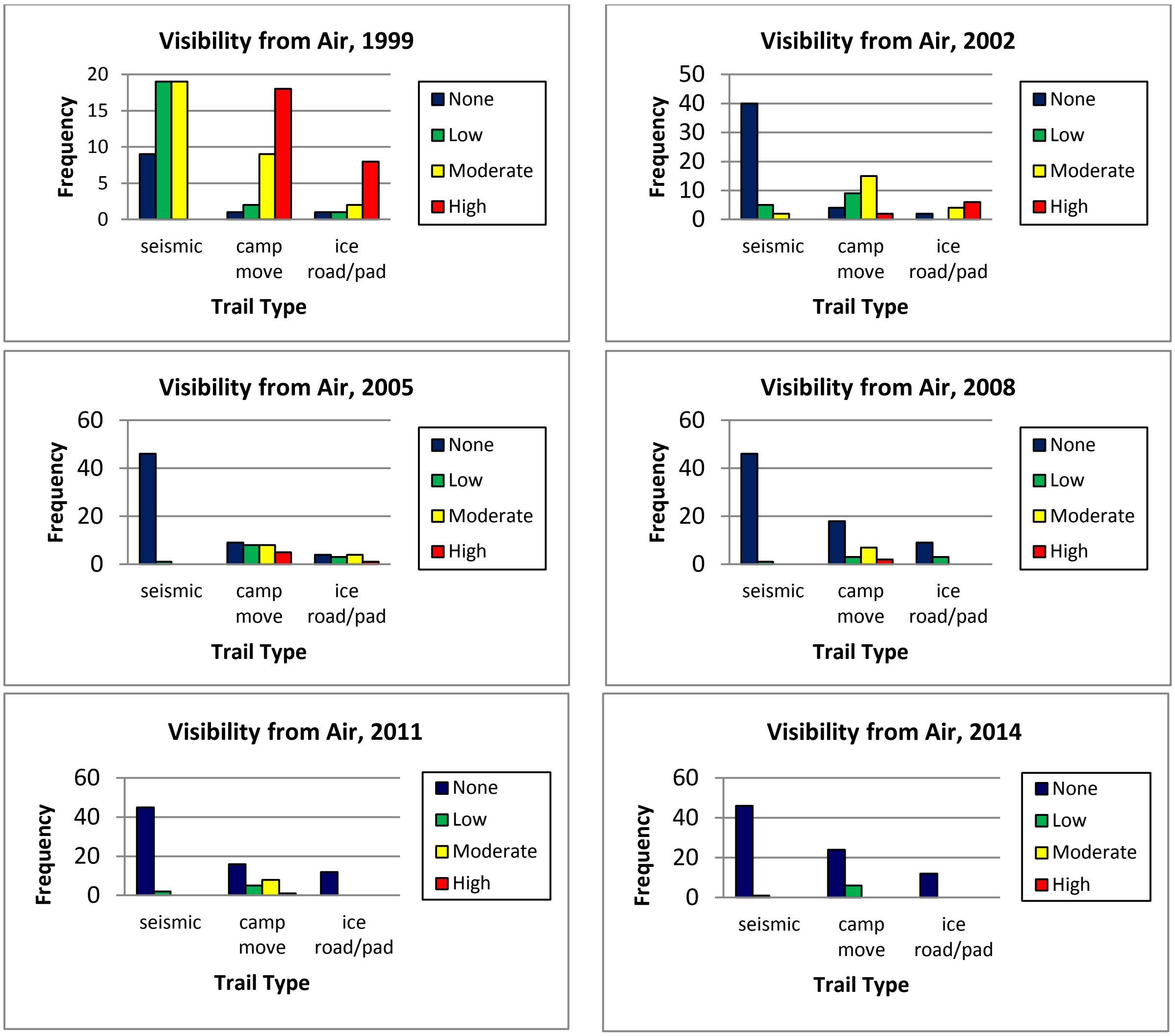

Figure 39. Visibility from air, by trail type, during each of 6 years of data collection.

Factors Affecting Disturbance Levels for Individual Categories of Impacts

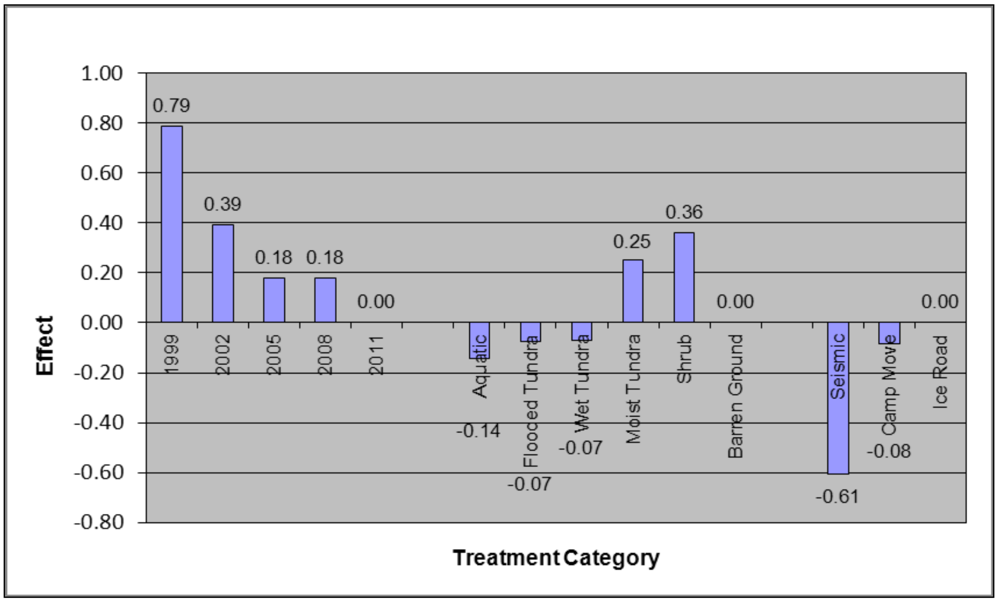

Figure 40. Effect of year ($p < 0.0001$), major vegetation category ($p = 0.0003$) and disturbance type ($p < 0.0001$) on decrease in plant cover, 1999–2011.

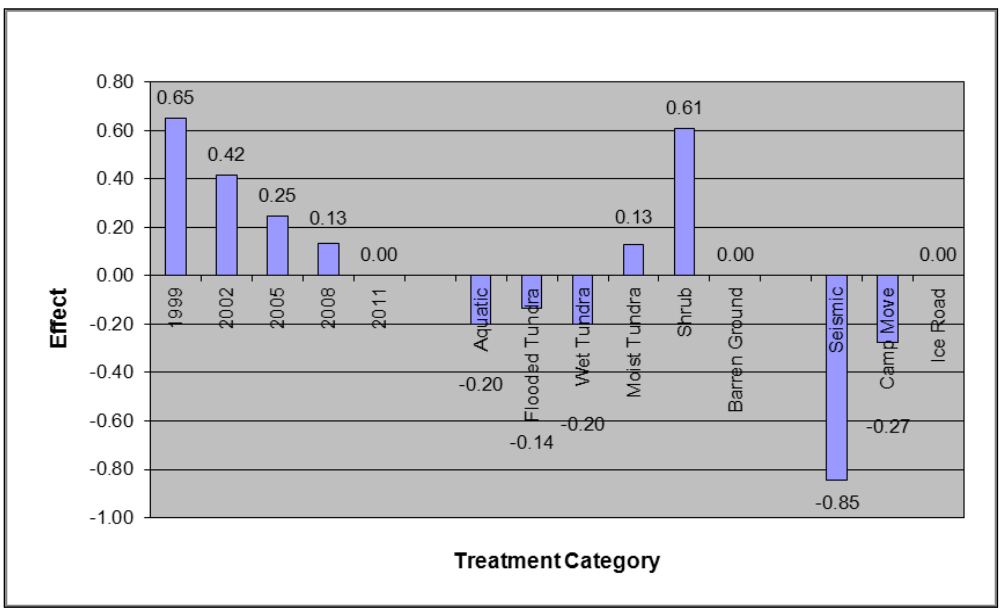

Figure 41. Effect of year ($p < 0.0001$), major vegetation category ($p < 0.0001$) and disturbance type ($p < 0.0001$) on decrease in shrub canopy, 1999–2011.

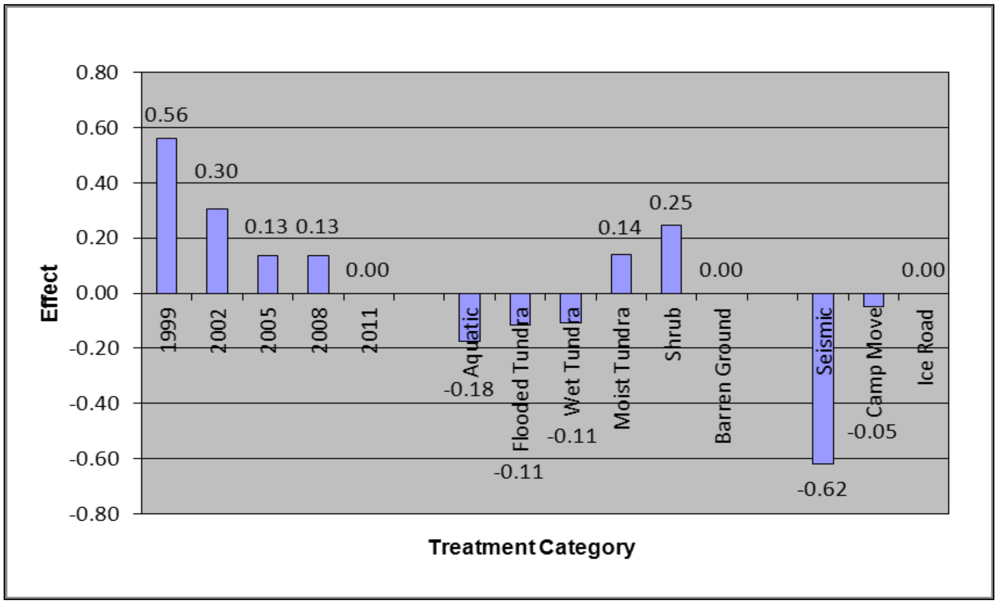

Figure 42. Effect of year ($p < 0.0001$), major vegetation category ($p = 0.14$) and disturbance type ($p < 0.0001$) on increase in exposed soil, 1999–2011.

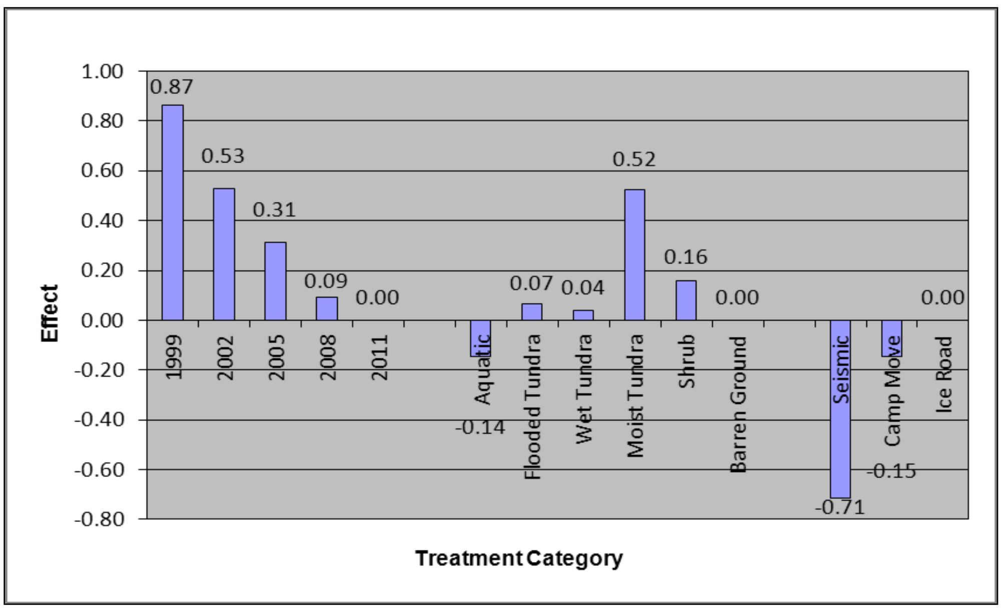

Figure 43. Effect of year ($p < 0.0001$), major vegetation category ($p < 0.002$) and disturbance type ($p < 0.0001$) on damage to tussocks and hummocks, 1999–2011.

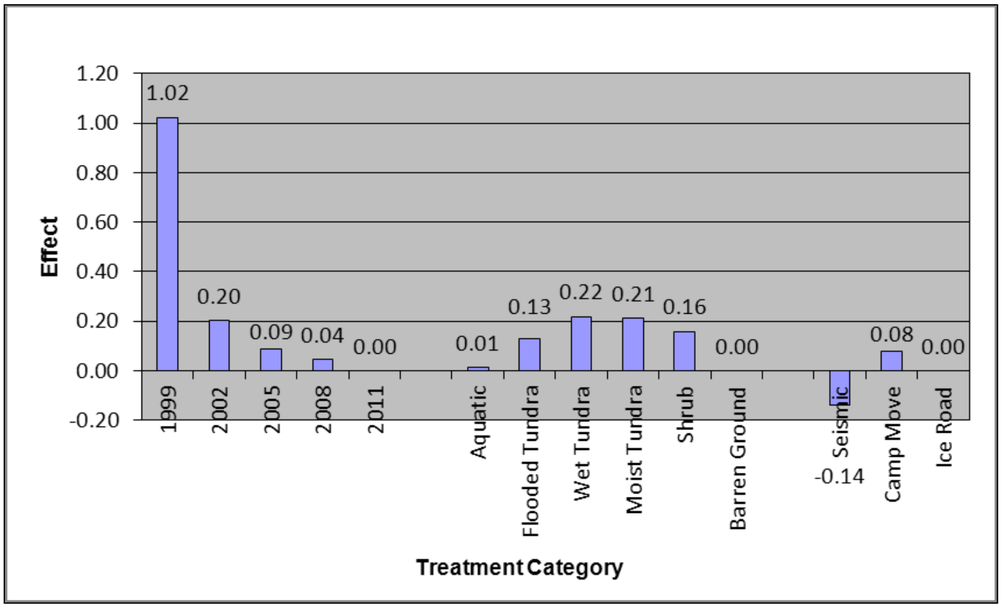

Figure 44. Effect of year ($p < 0.0001$), major vegetation category ($p = 0.15$) and disturbance type ($p = 0.002$) on compression of litter or moss, 1999–2011.

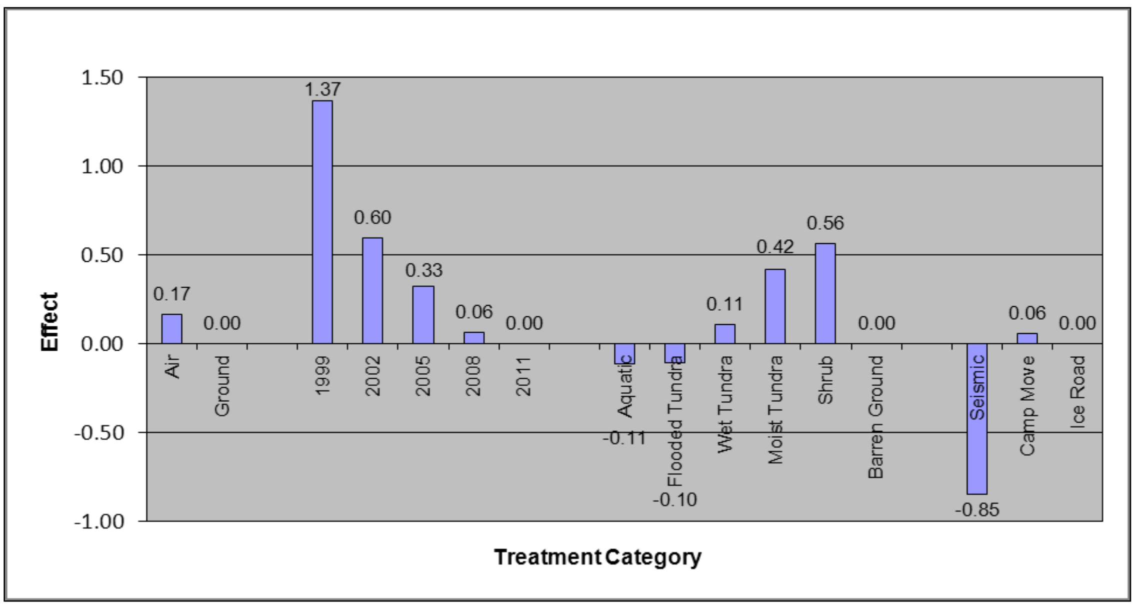

Figure 45. Effect of aerial versus ground view ($p < 0.0001$), year ($p < 0.0001$), major vegetation category ($p = 0.0001$) and disturbance type ($p < 0.0001$) on trail visibility, 1999–2011.

Active Layer Depth

Mean Depth of Active Layer

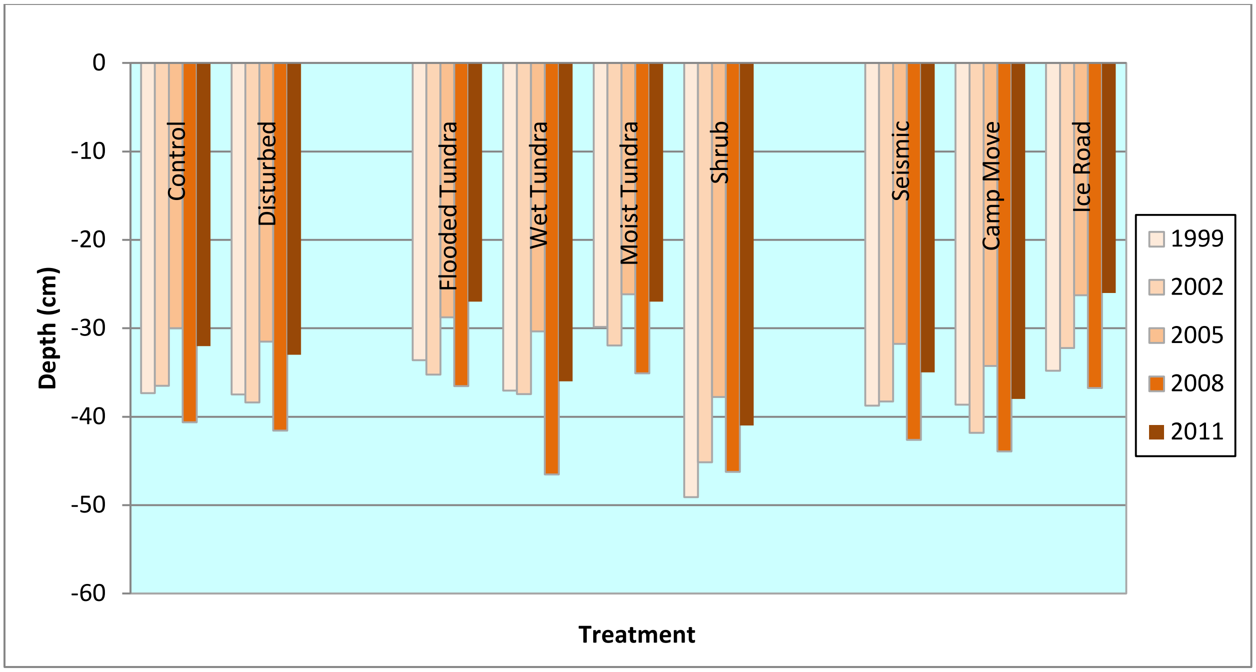

Figure 46. Mean active layer depths for each of 5 data-collection years, comparing controls to disturbed sites, 4 major vegetation categories and 3 disturbance types.

Factors Affecting Depth of Active Layer

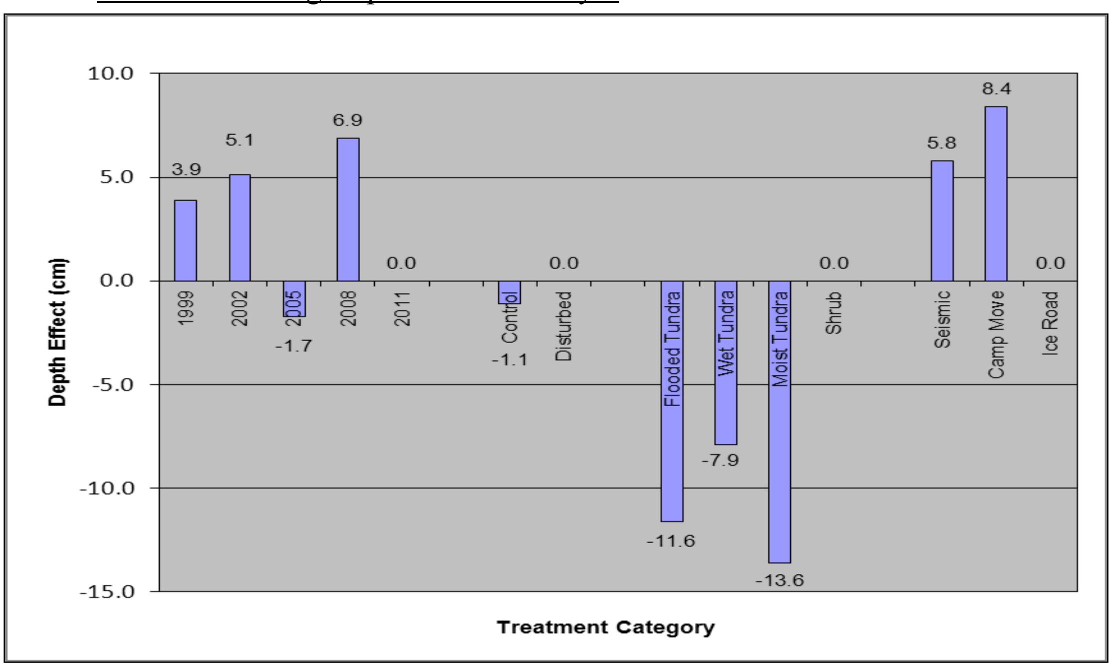

Figure 47. Effect of year ($p < 0.0001$), plot type ($p = 0.04$), major vegetation category ($p = 0.006$) and disturbance type ($p = 0.19$) on depth of active layer, 1999–2011.

Interaction of Year and Plot Type on Depth of Active Layer

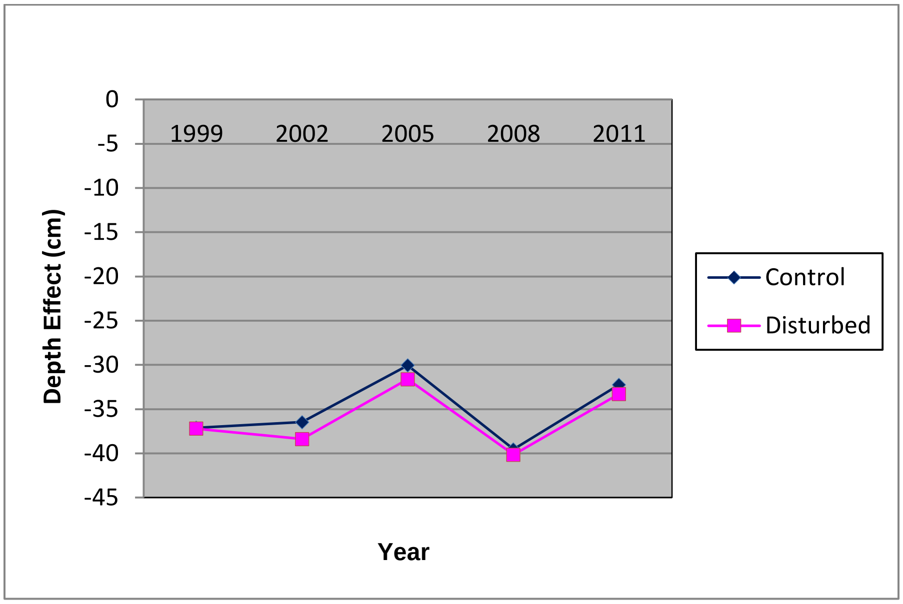

Figure 48. Effect of year-plot type interaction ($p < 0.0001$) on depth of active layer, 1999–2011.

Appendix A

Figures Displaying Factors Affecting Overall Disturbance Levels in Each Year
Minor Vegetation Categories and Disturbance Type

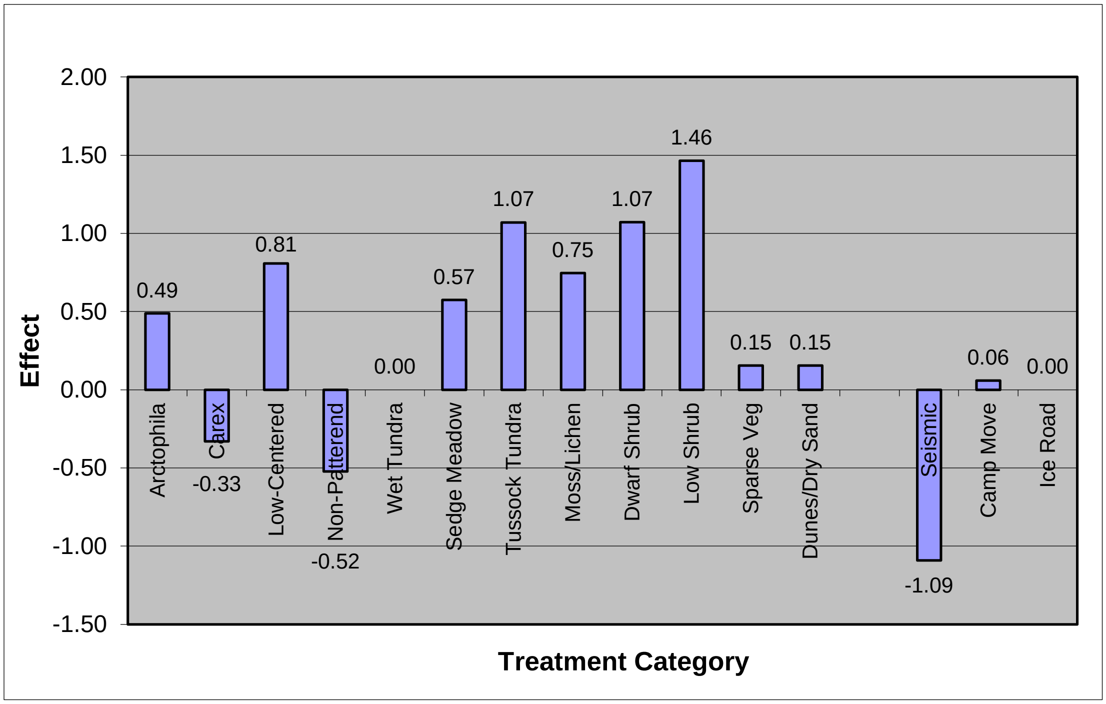

Figure A1. Effect of minor vegetation category ($p < 0.0001$) and disturbance type ($p < 0.0001$) on overall disturbance levels in 1999 (2000 for ice road).

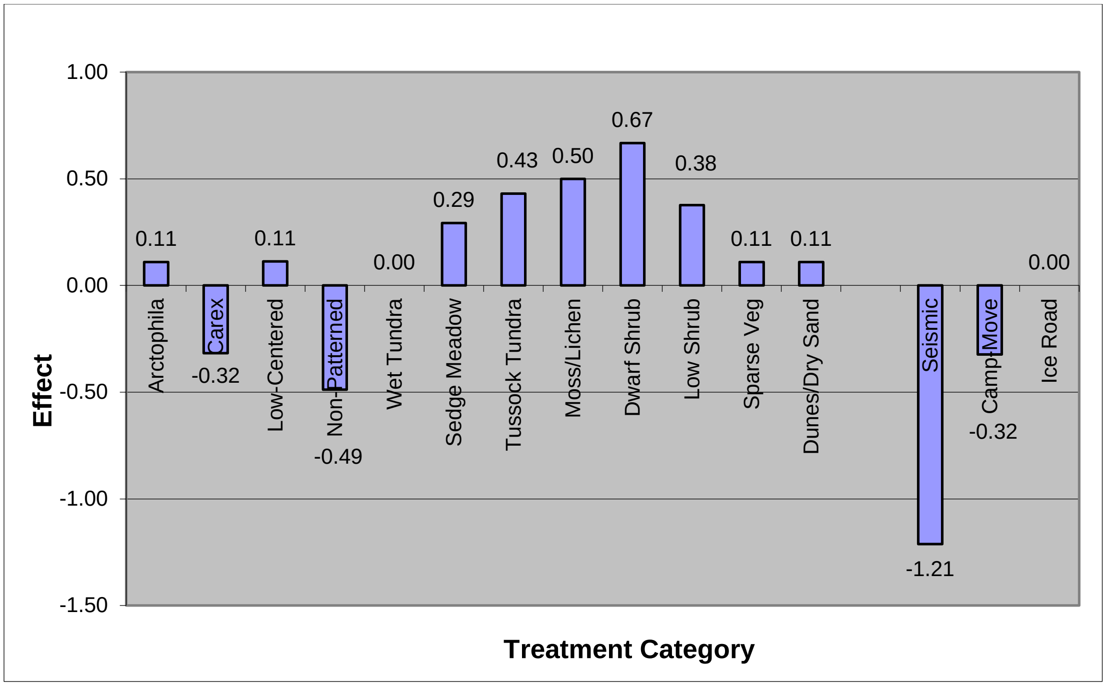

Figure A2. Effect of minor vegetation category ($p = 0.004$) and disturbance type ($p < 0.0001$) on overall disturbance levels in 2002.

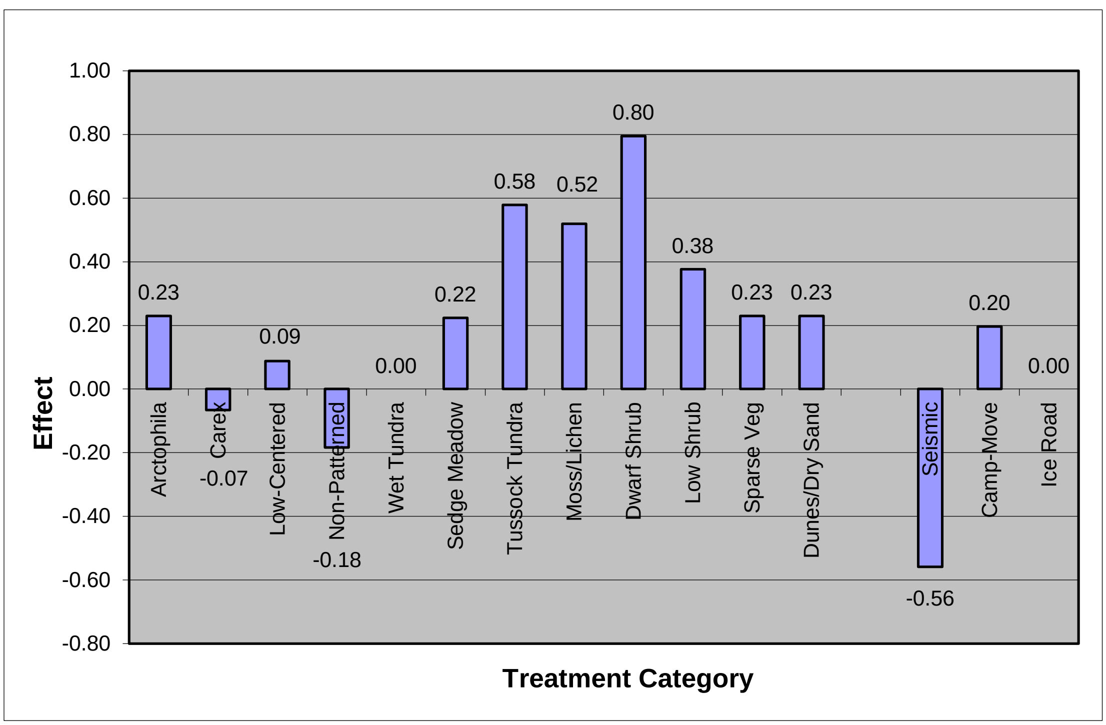

Figure A3. Effect of minor vegetation category ($p = 0.005$) and disturbance type ($p < 0.0001$) on overall disturbance levels in 2005.

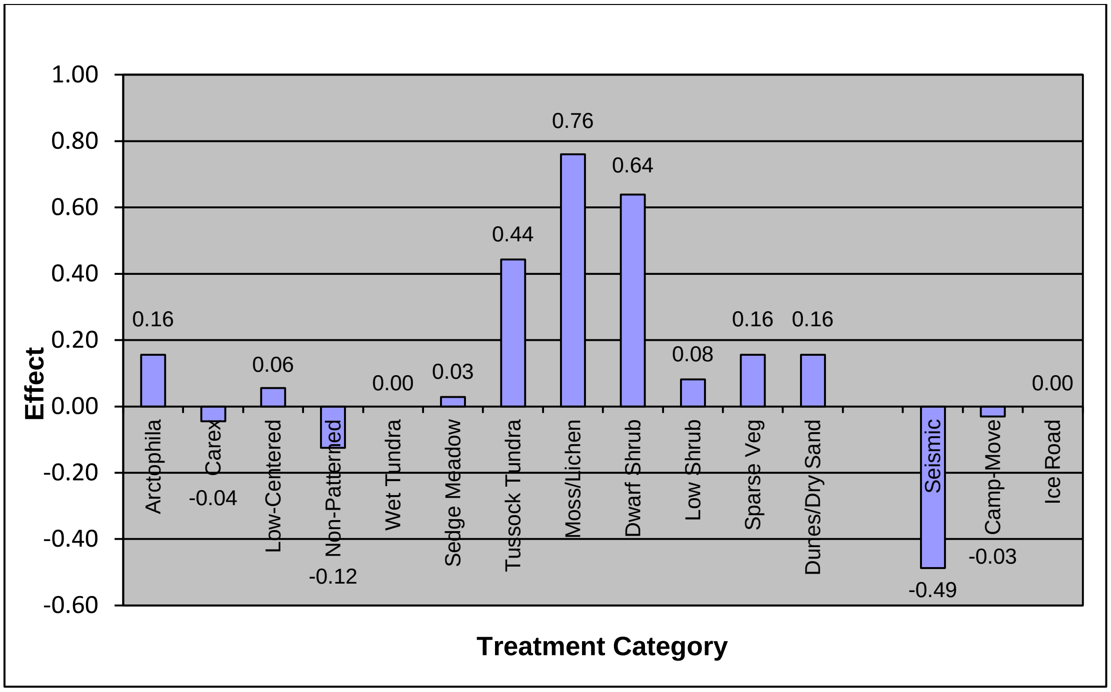

Figure A4. Effect of minor vegetation category ($p = 0.02$) and disturbance type ($p = 0.002$) on overall disturbance levels in 2008.

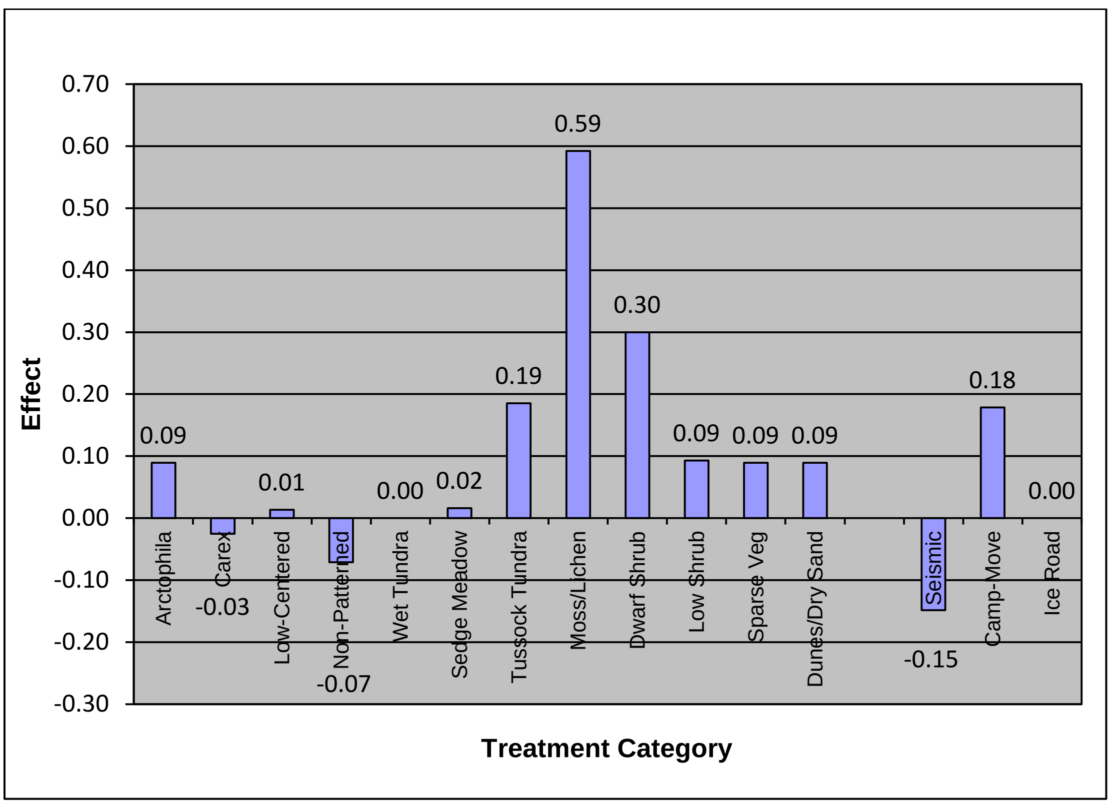

Figure A5. Effect of minor vegetation category ($p = 0.27$) and disturbance type ($p < 0.02$) on overall disturbance levels in 2011.

Appendix B

<u>Figures Displaying Factors Affecting Depth of Active Layer in Each Year</u>
<u>Plot Type, Major Vegetation Category and Disturbance Type</u>

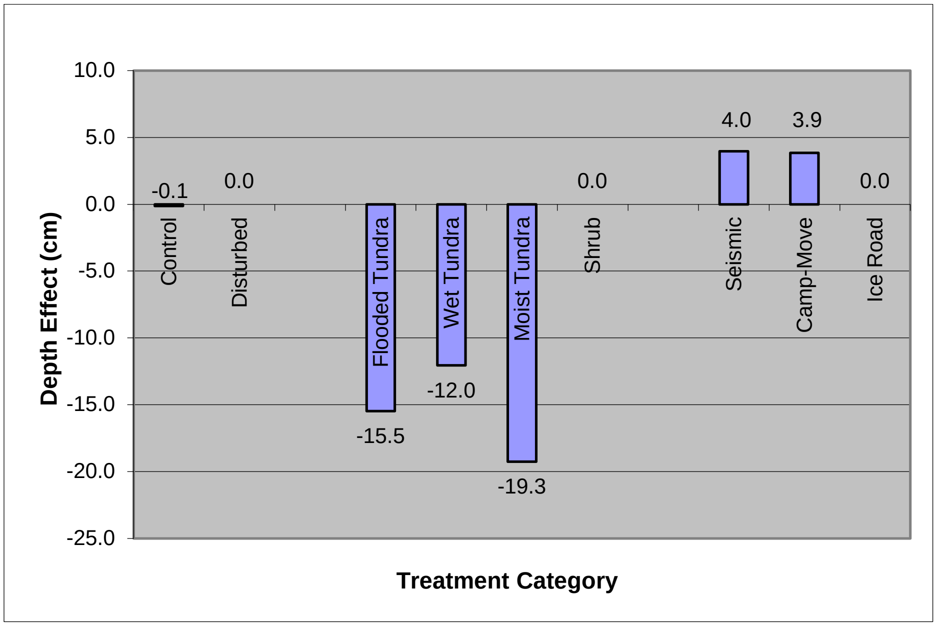

Figure B1. Effect of plot type ($p = 0.81$), major vegetation category ($p = 0.0001$) and disturbance type ($p = 0.67$) on depth of active layer in 1999 (2000 for ice road).

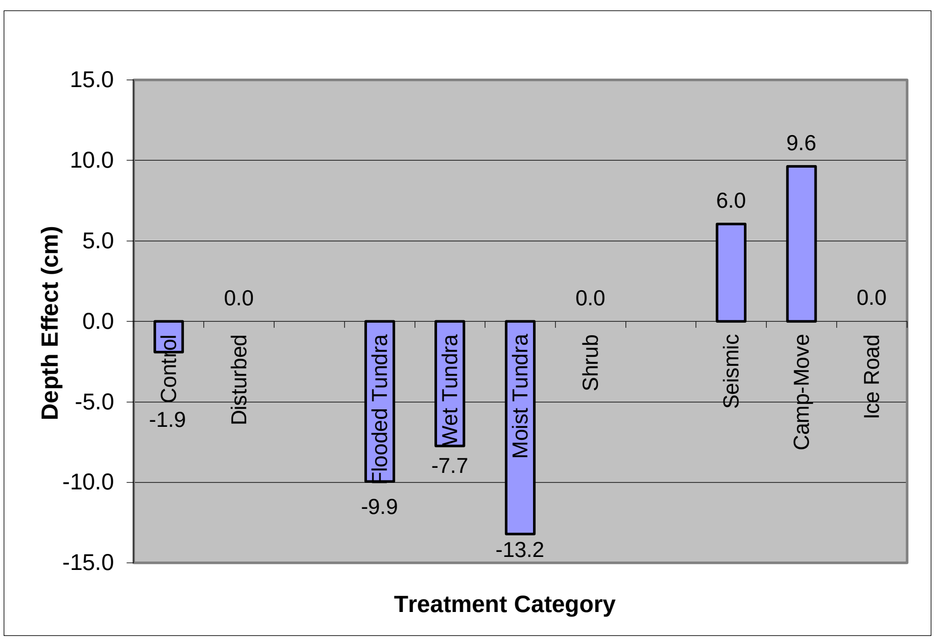

Figure B2. Effect of plot type ($p = 0.005$), major vegetation category ($p = 0.015$) and disturbance type ($p = 0.15$) on depth of active layer in 2002.

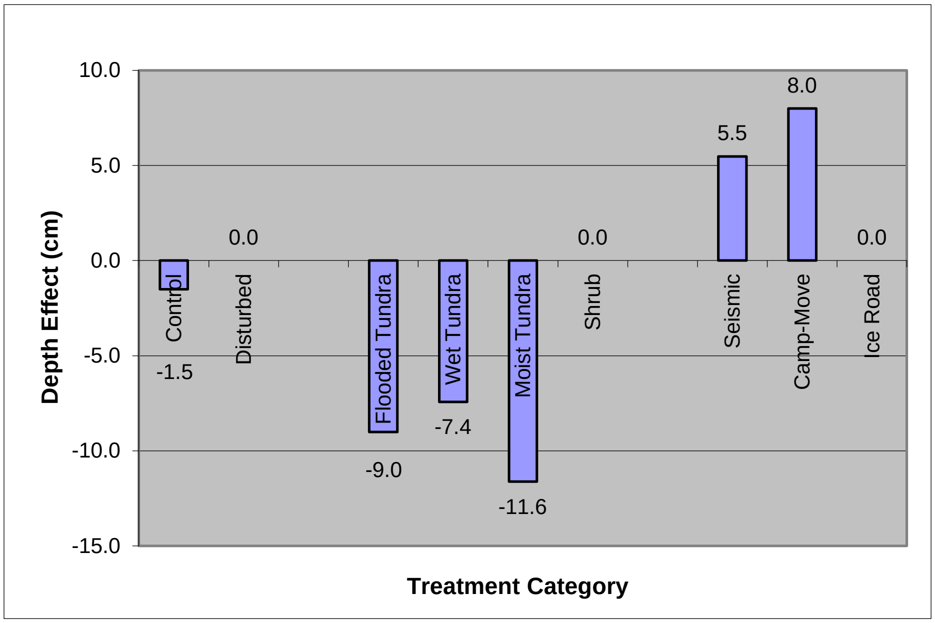

Figure B3. Effect of plot type ($p = 0.005$), major vegetation category ($p = 0.007$) and disturbance type ($p = 0.14$) on depth of active layer in 2005.

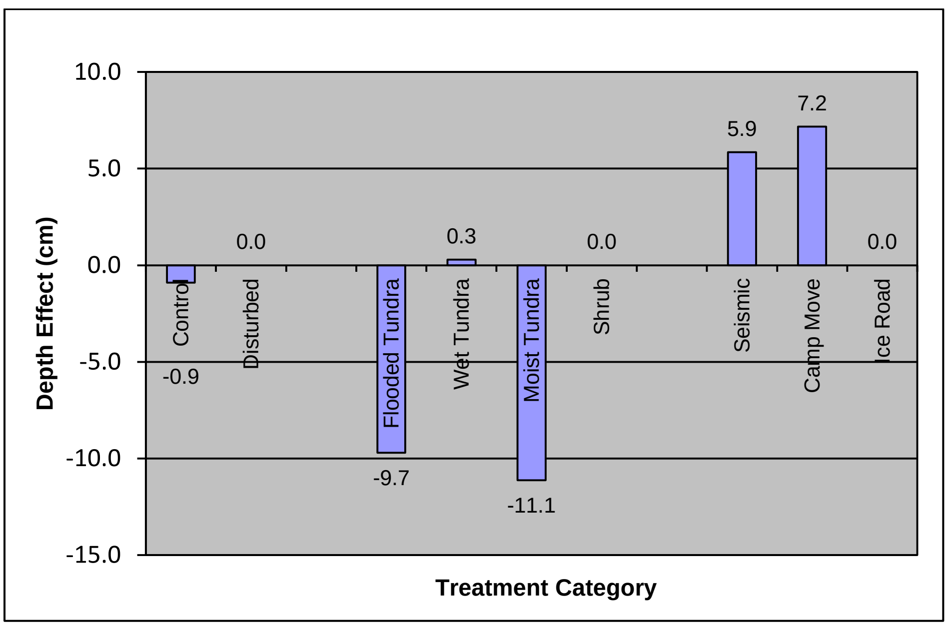

Figure B4. Effect of plot type ($p = 0.19$), major vegetation category ($p = 0.06$) and disturbance type ($p = 0.33$) on depth of active layer in 2008.

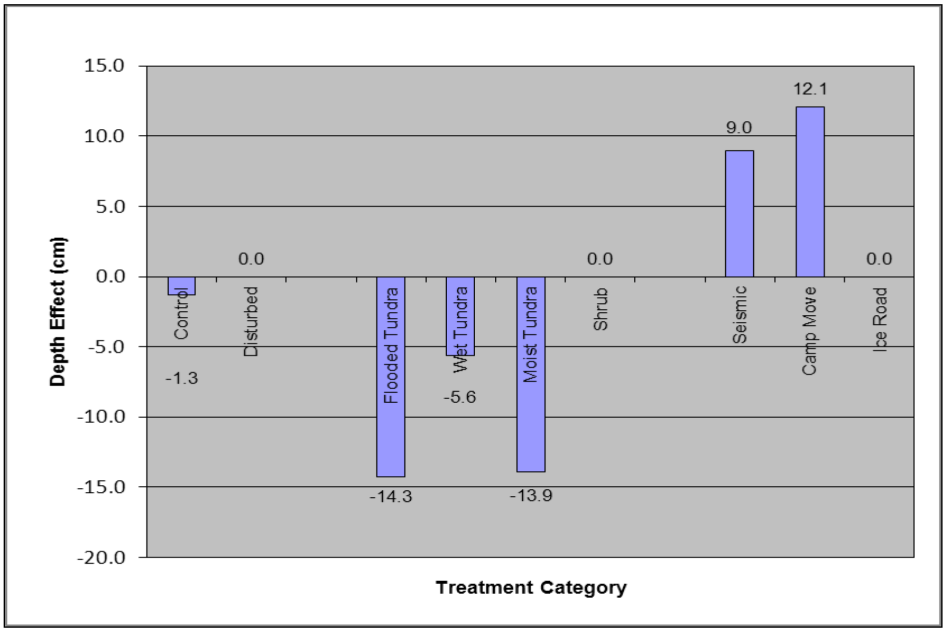

Figure B5. Effect of plot type (p = 0.08), major vegetation category (p = 0.08) and disturbance type (p = 0.12) on depth of active layer in 2011.