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The Role of Snow Cover in Limiting Surface Disturbance Caused by Winter Seismic Exploration

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ABSTRACT. The relationship between snow cover and the degree of surface disturbance caused by winter seismic vehicles was investigated on the Arctic Coastal Plain of the Arctic National Wildlife Refuge in northeastern Alaska. Ninety study plots were established on seismic lines and camp moves in tussock tundra and moist sedge-shrub tundra. Total snow depth and its components, slab layer and depth hoar, were measured during the winter. Plant cover changes, tussock disturbance, visibility and disturbance levels were determined at the study plots in the summer. Disturbance was found to be generally lower when snow depths were greater. In tussock tundra, plots with snow depths over 25 cm had significantly less disturbance than those with under 25 cm ($p < 0.05$). The relationship between snow cover and disturbance was less clear in moist sedge-shrub tundra, where disturbance appeared to be less at snow depths above 25 cm, but these differences were not statistically significant ($p < 0.05$). Slab depth, which does not include the loose layer of depth hoar, provided a better measure of protective snow cover in moist sedge-shrub tundra, as slab depths over 20 cm resulted in significantly less disturbance ($p < 0.05$). Moderate-level disturbance (25-50% decrease in plant cover) did not occur on trails where snow depths were at least 25 cm in tussock tundra and 35 cm in moist sedge-shrub tundra. Low-level disturbances (less than 25% decrease in plant cover) occurred on trails with snow depths as high as 45 cm in tussock tundra and 72 cm in moist sedge-shrub tundra.

Key words: surface disturbance, winter seismic exploration, seismic trails, tundra, snow depth, Alaska, Arctic National Wildlife Refuge, Arctic Coastal Plain

RÉSUMÉ. On a étudié le rapport entre la couverture de neige et le degré de perturbation de la surface due aux véhicules sismiques en hiver, dans la plaine côtière arctique du Arctic National Wildlife Refuge dans le nord-est de l'Alaska. On a établi quatre-vingt-dix terrains d'étude sur des lignes sismiques et sur le trajet entre les camps, dans la toundra parsemée de buttes de gazon et dans la toundra humide parsemée de cypéracées et d'arbrisseaux. On a mesuré l'épaisseur totale de la neige et de ses composantes, la plaque et le givre de profondeur, au cours de l'hiver. On a déterminé les changements dans la couverture végétale, la perturbation de la toundra à buttes de gazon, les niveaux de visibilité et de perturbation sur les terrains d'étude en été. On a en général trouvé que la perturbation était moindre quand la couche de neige était plus épaisse. Dans la toundra parsemée de buttes de gazon, les terrains avec des épaisseurs de neige de plus de 25 cm avaient été perturbés nettement moins que ceux dont la couverture de neige était inférieure à 25 cm ($p < 0,05$). Le rapport existant entre la couverture de neige et la perturbation était moins évident dans la toundra humide parsemée de cypéracées et d'arbrisseaux, où la perturbation semblait moindre lorsque l'épaisseur de la neige était supérieure à 25 cm, mais ces différences n'étaient pas statistiquement significatives ($p < 0,05$). L'épaisseur de la plaque de neige, qui ne comprend pas le givre de profondeur, fournissait une meilleure évaluation de la protection de la couverture de neige dans la toundra humide parsemée de cypéracées et d'arbrisseaux, vu qu'une plaque supérieure à 20 cm donnait lieu à une perturbation nettement moindre ($p < 0,05$). Une perturbation moyenne (25 à 50% de diminution dans la couverture végétale) ne s'est pas produite sur les pistes où la profondeur de la neige était d'au moins 25 cm dans la toundra à buttes de gazon et de 35 cm dans la toundra humide à cypéracées et à arbrisseaux. Les perturbations faibles (moins de 25% de diminution dans la couverture végétale) avaient lieu sur les pistes dont la couche de neige était aussi épaisse que 45 cm dans la toundra à buttes de gazon et 72 cm dans la toundra humide à cypéracées et à arbrisseaux.

Mots clés: perturbation de surface, exploration sismique d'hiver, pistes sismiques, toundra, épaisseur de la neige, Alaska, Arctic National Wildlife Refuge, plaine côtière arctique

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INTRODUCTION

The future of the Arctic Coastal Plain of the Arctic National Wildlife Refuge (ANWR) is presently being debated by the U.S. Congress, with proposals ranging from designating the area as wilderness to opening it for development of oil and gas resources. The Alaska National Interest Lands Conservation Act of 1980 (ANILCA, U.S. Public Law 96-487) authorized limited geological studies, including seismic exploration, to determine the oil and gas potential of ANWR's coastal plain. Baseline studies of the area's fish and wildlife resources (Garner and Reynolds, 1985) were required to provide Congress with information on the possible biological effects of further oil and gas exploration or development.

The Arctic National Wildlife Refuge was established for the primary purpose of conserving wildlife habitat, including that of the Porcupine caribou herd, migratory birds, polar bears, grizzly bears, muskox, wolves and wolverines. The calving grounds of the Porcupine caribou herd extend across the Coastal Plain from the Canning River, the westernmost boundary of the Arctic Refuge, to the Babbage River in Canada. Many migratory bird species use the Coastal Plain for nesting and staging grounds.

There is a high degree of public interest in the aesthetic and wilderness qualities of the Coastal Plain. Wilderness, as defined by the Wilderness Act of 1964 (U.S. Public Law 88-577) is an area that "generally appears to have been affected primarily by the forces of nature, with the imprint of man's work substantially unnoticeable." The Coastal Plain within the ANWR is the only portion of this unique habitat in the United States that remains substantially unaltered by human activities.

Winter seismic exploration was conducted on the Coastal Plain of ANWR in 1984 and 1985, as authorized by ANILCA. Approximately 2000 km of seismic line, arranged in a 5 x 10 km grid pattern, were completed between January and May of both years. This study was conducted during the 1985 seismic program. The vibrator technique, utilizing large trucks (vibrators) to provide an energy source, was used for collection of the seismic data in 1985. Collection of data along

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each seismic line required multiple passes by tracked vehicles, including vibrators, small personnel carriers (Bombardiers), geophone trucks, and a recording vehicle. Ski-mounted camps pulled by D-7 Caterpillar tractors created a second series of trails adjacent to the seismic lines. Trails created by the seismic program were visible the following summer due to changes in plant cover, soil exposed and track depression (Fig. 1).

FIG. 1. Trail through moist sedge-shrub tundra. Note compression of vegetation in track.

Most studies of winter vehicle traffic on tundra have focused on the construction of snow- or ice-capped roads to protect vegetation (Abele, 1963; Adam and Hernandez, 1977; Keyes, 1977; Johnson and Collins, 1980). Studies of seismic traffic have found that winter exploration caused less surface disturbance than summer operations (Bliss and Wein, 1972; Hernandez, 1973). Although the protective nature of snow cover has long been recognized, the amount of snow cover needed to protect the tundra from disturbance due to off-road vehicle traffic has not been well defined.

Two studies, Reynolds (1982) and Densmore (1985), considered changes in plant cover due to winter vehicle traffic under differing snow conditions, although neither study had detailed snow data available. Reynolds (1982) noted over 50% reduction in plant cover on vehicle trails even when at least 15 cm of snow was present, and that vehicle trails created under low snow cover conditions recovered more slowly than trails created during a year with higher snow cover. Densmore (1985) found no clear relationship between tussock damage on trails from four different years and the relative amounts of snow cover during these years. Site-specific snow data were unavailable, and the lack of a relationship was attributed to snow distribution patterns, since snow on tussock-covered slopes is subject to wind scouring, even in heavy snowfall years.

Federal regulation (U.S. Department of the Interior, 1983) required that seismic exploration be conducted in the winter, when there was adequate protective snow cover to prevent significant disturbance to wildlife habitat. An average snow depth of 15 cm was required before vehicles were permitted on the tundra. The relationship between snow cover and the degree of surface disturbance by seismic vehicles was investigated to provide information for regulating and monitoring future seismic exploration.

STUDY AREA

The study area included over 600 000 ha of the Arctic Coastal Plain and Foothill Provinces of northeastern Alaska between 142°W and 147°W and north of 69°34′N (Fig. 2). It is bordered by the Beaufort Sea on the north, the Brooks Range on the south, the Aichilik River on the east and the Canning River on the west. The study area is located in Low Arctic Tundra, as defined by Murray (1978), and is vegetated by low-growing plants, including dwarf shrubs, sedges, grasses, forbs, mosses and lichens. Shallow soils (less than 0.5 m) are underlain by permafrost, and the ground surface remains frozen from about mid-September to mid-May. Snow is usually present by mid-September and remains until early June (Garner and Reynolds, 1985).

METHODS

Ninety study plots (10 m sections of trail) were randomly located on seismic lines or camp-move trails in the two most common vegetation types: tussock tundra (43 plots) and moist sedge-shrub tundra (47 plots) (Walker *et al.*, 1982). Plots were located on seismic lines where one pass of a vibrator plus multiple passes of other seismic vehicles had occurred or on camp-move trails where a single pass of a cat-train had occurred.

Tussock tundra plots were dominated by tussock cotton grass, dwarf shrubs and mosses and included the following two community types. On acidic soils, *Eriophorum vaginatum* L. was found with the dwarf shrubs *Salix planifolia* Pursh ssp. *pulchra* (Cham.) Argus, *Betula nana* L. ssp. *exilis* (Sukatsch.) Hult., *Ledum palustre* L. ssp. *decumbens* (Ait.) Hult., and *Vaccinium vitis-idaea* L. ssp. *minus* (Lodd.) Hult. Non-vascular plants included the mosses *Hylocomium splendens* (Hedw.) B.S.G., *Sphagnum* spp. L., *Aulacomnium turgidum* (Wahlenb.) Schwaegr., and the lichens *Cladonia* spp. and *Cladina* spp. On more neutral or basic soils, the dwarf shrubs *Dryas integrifolia* M. Vahl. and *Salix reticulata* L. ssp. *reticulata* were more common, as were the moss *Tomenthypnum nitens* (Hedw.) Loeske and *Cetraria* spp. lichens. Soils were moderately drained and typically included thin deposits of fine loess on top of coarser materials. Excess ice contents of soil in tussock tundra were variable, ranging from 2 to 25% in the top 30 cm of soil (Felix *et al.*, in press).

Moist sedge-shrub plots were dominated by sedges, dwarf willows and mosses, including the following species: *Eriophorum angustifolium* Honck., *Carex aquatilis* Wahlenb., *Salix planifolia* ssp. *pulchra*, *Aulacomnium turgidum*, *Tomenthypnum nitens* and *Hylocomium splendens*. This vegetation type typically occurred on saturated soils consisting of fine-grained deposits, with a moderately thick organic layer intergrading into well-decomposed organic-mineral material. Excess ice contents of soils in moist sedge-shrub tundra were highly variable, ranging from 5 to 45% in the top 30 cm of soil (Felix *et al.*, in press).

The plots, which were established between January and April, were sampled immediately after vehicle passage and marked with survey lathe for relocation. Total snow depth, slab depth and depth hoar thickness were measured

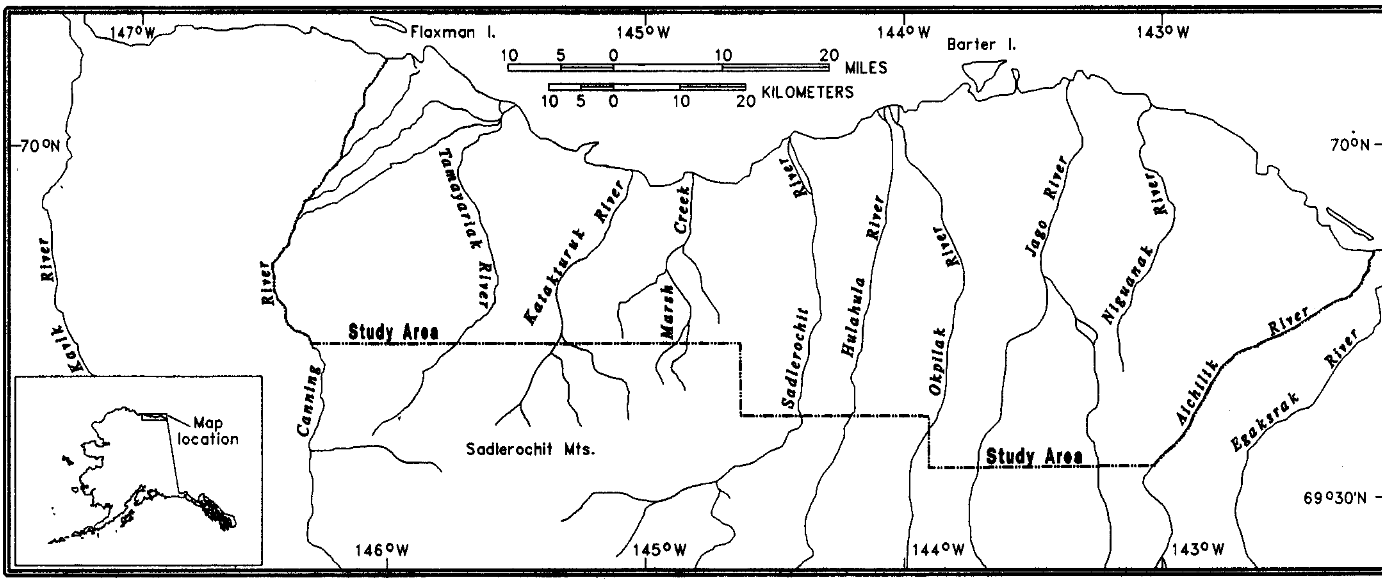

FIG. 2. Map of study area on the coastal plain of the Arctic National Wildlife Refuge.

systematically at 20 points along a 10 m line transect adjacent and parallel to the vehicle trails. Depth hoar is the loose, large-crystalled snow next to the ground surface, and slab depth includes all snow layers above the depth hoar.

Plant cover, tussock disturbance, visibility and disturbance levels were determined at the study plots during the following summer, at the time of maximum plant growth (July to mid-August). Disturbance was estimated by comparing each study plot to a control plot located in an adjacent undisturbed area of similar vegetation. Plant cover estimates were obtained along two 10 m transects in each disturbed and control plot, using the line-intercept method (Mueller-Dombois and Ellenberg, 1974). Looking vertically down at the tape, the distances covered by the following categories were noted: ground cover, canopy cover, deciduous shrub cover, dead plants or litter, exposed soil and water. Ground cover was a measure of the amount of area covered by live plants. Total plant cover was calculated as the sum of ground cover and canopy cover (all plants that were layered above other live plants). Deciduous shrub cover was estimated separately in the moist sedge-shrub plots.

Damage to tussocks was measured in two belt transects (2 x 4 m on wide trails, or 10 m x the width of each vehicle track) on each disturbed plot. The numbers of tussocks in the following categories were counted: undisturbed, scuffed (broken tillers evident) and crushed (peat core exposed and/or tussock cracked). Percentages of disturbed tussocks (scuffed and crushed) and crushed tussocks were calculated.

The visibility of disturbance was rated on the ground and from the air (at 60 m altitude) as a measure of the visual impact as seen by visitors hiking and flying over the Coastal Plain. Four levels of visibility were defined based on Abele (1976) (Table 1). The range of surface disturbance caused by seismic activity was divided into four classes for each vegetation type, based on plant cover changes, increases in exposed soil and changes in micro-relief or surface height of trails (Table 1).

Data were analyzed separately for tussock tundra and moist sedge-shrub tundra. Simple linear regressions were performed to test whether correlations occurred between snow depths and disturbance measures, using the BMDP statistical soft-

TABLE 1. Visibility and disturbance level ratings for seismic trails on the Coastal Plain of the Arctic National Wildlife Refuge, Alaska, 1985

Rating	Description
Visibility	
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
Tussock tundra disturbance	
0	None – no impact to slight scuffing of tussocks or occasional breakage of shrubs
1	Low – scuffing of tussock tops; vegetation damage 5-25%; exposed soil less than 3%
2	Moderate – over 30% of tussocks crushed, with scuffing common; vegetation damage 25-50%; exposed soil 3-15%
3	High – crushing of tussocks nearly continuous; ruts starting to form; vegetation damage over 50%; exposed soil over 15%
Moist sedge-shrub disturbance	
0	None – no impact or a few widely scattered scuffed microsites
1	Low – compression of standing dead; some scuffing of higher microsites or frostboils if present; less than 25% vegetation damage
2	Moderate – obvious compression of mosses and standing dead; trail may appear wetter than surrounding area; scuffing of microsites common, small patches of soil may be exposed; vegetation damage 25-50%
3	High – obvious track depression; over 50% vegetation damage; compression of mosses below water surface; in wet years, standing water on trail that is not present in adjacent area

ware package (Dixon *et al.*, 1981). The mean disturbance levels of snow depth classes were tested using one-way analysis of variance and Bonferroni's test for multiple comparisons (Dixon *et al.*, 1981). Distributions of visibility and disturbance levels within snow depth categories were tested with chi-square analyses using SPSSX (SPSS Inc., 1986).

RESULTS

Variable snow cover occurring over the Arctic Coastal Plain provided tundra vegetation with little protection from disturbance in some places and complete protection in other places (Figs. 3, 4). Higher microsites (tussocks and hummocks) often had thin snow cover and were easily damaged by winter seismic vehicles. Deeper snow found in drainages greatly reduced impacts to underlying vegetation.

FIG. 3. Single cat-train trail through area with low snow cover. Crushed vegetation and micro-relief are visible in the trail.

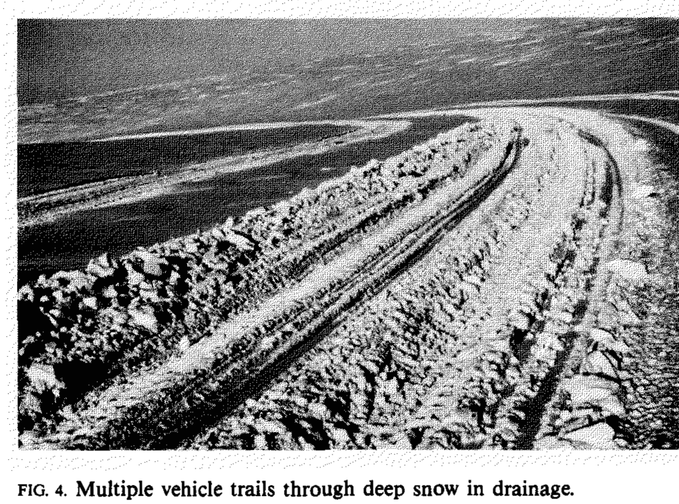

FIG. 4. Multiple vehicle trails through deep snow in drainage.

Snow depth and disturbance were inversely related (Fig. 5). The relationship between total snow depth and disturbance was significant ($p < 0.01$) for all disturbance measures in tussock tundra (Table 2). The strongest relationships occurred between snow depth and percentage of tussocks disturbed and crushed, with 74% and 60% of the variations respectively explained by snow depth. For all other disturbance measures, the coefficients of determination were low, indicating that snow depth explained only a small portion of the total variation in disturbance. The relationship between slab depth and disturbance was similar to that between total snow depth and disturbance.

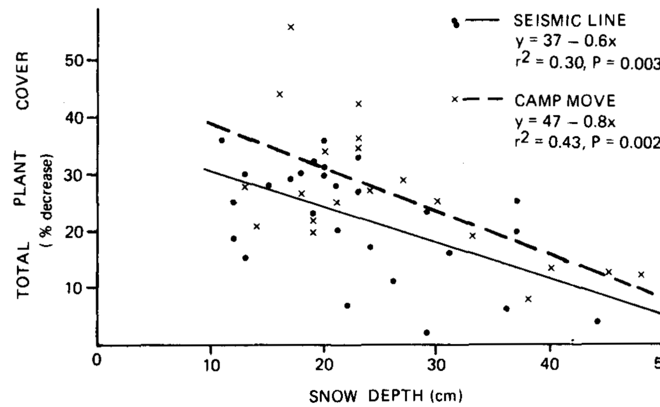

FIG. 5. Relationship of snow depth to percentage decrease in total plant cover ((D-C)/C x 100) on disturbed trails (D) compared to adjacent controls (C) in tussock tundra, Arctic National Wildlife Refuge, Alaska.

TABLE 2. Linear coefficients of determination (r^2) for the relationships between total snow or slab depths and disturbance on winter seismic trails, Arctic Coastal Plain, Alaska, 1985

	Tussock tundra		Moist sedge-shrub	
Disturbance measures	Snow	Slab	Snow	Slab
Ground cover (% decrease)[1]	0.26**[3]	0.29**	0.05	0.10*
Total plant cover (% decrease)[1]	0.30**	0.32**	0.07	0.14*
Deciduous shrub cover (% decrease)[1]			0.18**	0.22**
Soil exposed (%)[2]	0.16**	0.14**	0.04	0.05
Bare ground (%)[2]	0.27**	0.30**	0.06	0.06
Tussocks disturbed (%)	0.74**	0.68**		
Tussocks crushed (%)	0.60**	0.53**		

[1]The % decrease of ground cover, total plant cover, and shrub canopy is calculated as ((D-C)/C x 100), where D = % cover on the disturbed plot and C = % cover on the control plot.
[2]The % of soil exposed and bare ground is calculated as D-C.
[3]*,**indicates that the regression line is signficant at $p < 0.05$ and 0.01 respectively.

Camp moves generally caused more disturbance than seismic lines. This difference was statistically significant (analysis of variance for comparison of two regression lines, $p < 0.05$) for total plant cover decrease in tussock tundra (Fig. 5), but not for other measures of disturbance.

In moist sedge-shrub tundra, slab depth appeared to be a better measure of protective snow cover than snow depth (Table 2). Damage to plants decreased significantly ($p < 0.05$) as slab depth increased, but as in tussock tundra, the coefficients of determination were low. The relationships of exposed soil and bare ground to slab depth were not significant.

When snow depths were divided into classes, disturbance in tussock tundra was significantly lower on vehicle trails with total snow depths over 25 cm (Table 3). Levels of disturbance on plots with snow depths of 11-15 cm and plots with 15-25 cm did not differ significantly in most cases.

In moist sedge-shrub tundra, disturbances to plant cover in each snow depth class were similar to those in tussock

TABLE 3. Mean levels of disturbance that occurred under various snow depths on winter seismic trails in tussock tundra, Arctic Coastal Plain, Alaska, 1985

	Total snow depth[1]					
	11-15 cm		15-25 cm		> 25 cm	
Disturbance measures	x̄	SE	x̄	SE	x̄	SE
Ground cover (% decrease)[2]	19.2ab[4]	2.9	25.1a	2.1	10.8b	1.9
Total plant cover (% decrease)[2]	25.3a	2.3	29.8a	2.0	15.1b	2.1
Soil exposed (%)[3]	4.5a	1.3	3.4a	0.5	1.2b	0.4
Bare ground (%)[3]	17.0ab	2.3	21.0a	1.9	9.3b	1.6
Tussocks disturbed (%)	82.6a	2.0	70.8a	2.4	39.5b	4.2
Tussocks crushed (%)	48.0a	3.2	27.2b	2.8	4.6c	1.5

[1]N=8 for 11-15 cm snow depth; 24 for 15-25; and 15 for > 25.
[2]The % decrease of ground cover and total plant cover is calculated as ((D-C)/C x 100), where D = % cover on the disturbed plot and C = % cover on the control plot.
[3]The % of soil exposed and bare ground is calculated as D-C.
[4]a,b,c, — means with the same letter do not differ significantly, one-way analysis of variance and Bonferroni's multiple comparisons, $p < 0.05$.

TABLE 4. Mean levels of disturbance that occurred under various slab depths on winter seismic trails in moist sedge-shrub tundra, Arctic Coastal Plain, Alaska, 1985

	Slab depth[1]					
	<10 cm		10-20 cm		>20 cm	
Disturbance measures	x̄	SE	x̄	SE	x̄	SE
Ground cover (% decrease)[2]	22.4a[4]	3.3	19.1ab	6.5	9.6b	1.6
Total plant cover (% decrease)[2]	27.2a	3.5	22.7ab	6.3	12.5b	1.6
Shrub cover (% decrease)[2]	42.7a	5.2	55.5a	6.1	18.3b	4.9
Soil exposed (%)[3]	1.0a	0.5	0.4a	0.2	0.3a	0.2
Bare ground (%)[3]	13.7a	2.3	12.6a	3.6	7.5a	1.2

[1]N = 20 for < 10 cm slab depth, 8 for 10-20 cm, and 15 for > 20 cm; except for shrub cover where N = 17 for < 10 cm, 8 for 10-20 cm, and 14 for > 20 cm.
[2]The % decrease of these disturbance measures is calculated as ((D-C)/C x 100), where D = % cover on the disturbed plot and C = % cover on the control plot.
[3]The % soil exposed and bare ground is calculated as D-C.
[4]a,b,c — means with the same letter do not differ significantly, one-way analysis of variance and Bonferroni's multiple comparisons, $p < 0.05$.

tundra; however, differences among snow depth classes were not significant ($p < 0.05$). Significant differences did occur among slab depth classes, and disturbances to plant cover were less at slab depths over 20 cm than at slab depths under 10 cm (Table 4). Only small amounts of exposed soil and bare ground occurred on trails in moist sedge-shrub tundra, and no differences occurred among snow or slab depth classes.

Visibility and disturbance levels of trails in tussock tundra decreased significantly ($p < 0.01$) as snow cover increased (Table 5). Higher visibility ratings and disturbance levels occurred less frequently in the two snow depth classes over 25 cm. No moderate disturbances occurred on seismic lines or camp moves when snow depths were over 25 cm. Low-level disturbances occurred at snow depths as high as 45 cm.

Disturbance level ratings in moist sedge-shrub tundra decreased significantly as slab depths increased (Table 6). Disturbance levels were lower for slab depths over 20 cm and higher for slab depths less than 20 cm. No moderate-level disturbances occurred at slab depths over 20 cm or snow depths over 35 cm. Low-level disturbance occurred on one plot that had a mean snow depth of 72 cm. No significant relationships occurred between visibility of trails and snow or slab depths in moist sedge-shrub tundra, where even low levels of disturbance left visible trails.

DISCUSSION

In summary, snow depths over 25 cm were more effective than lower snow depths in controlling the amount of disturbance resulting from seismic vehicles. These findings confirm and quantify Reynolds's (1982) conclusion that increased snow depth reduced disturbance to tundra and emphasize the need for site-specific data (the lack of which resulted in Densmore [1985] finding no correlation).

Many other factors were also important in determining the amount of disturbance that occurred, especially at lower snow depths. Traffic pattern was held constant by limiting this study to seismic lines and camp moves. However, variation occurred in numbers and types of vehicles on seismic lines and weights of individual cat-trains on camp-move trails. Disturbance to tundra vegetation and surface stability increases with the number of vehicle passes and higher ground pressures (Bellamy *et al.*, 1971; Abele *et al.*, 1984).

Vegetation types in this study were limited to tussock tundra and moist sedge-shrub tundra, but within these types there was a variety of plant communities with differing species compositions. Individual plant communities were impacted differently depending on the presence of sensitive species, the

TABLE 5. Observed and (expected) frequencies of visibility ratings and disturbance levels within total snow depth classes on winter seismic trails in tussock tundra, Arctic Coastal Plain, Alaska, 1985

	Disturbance ratings							
	Visibility — air[1]		Visibility — ground[1]			Disturbance level[2]		
Snow depth (cm)	1	2	0	1	2	0	1	2
< 15	0(2)	8(6)	0(1)	0(2)	8(5)	0(1)	2(4)	5(2)
15 - 25	3(6)	21(18)	0(2)	4(6)	20(16)	0(3)	13(13)	10(8)
25 - 30	2(2)	5(5)	0(0)	4(2)	3(5)	1(1)	6(4)	0(2)
> 30	6(2)	2(6)	3(1)	4(2)	1(5)	4(1)	4(4)	0(3)
	$X^2 = 16.0$, 3 df $p = 0.001$		$X^2 = 28.3$, 6 df $p < 0.001$			$X^2 = 25.2$, 6 df $p < 0.001$		

[1]Visibility ratings: 0-not visible; 1-barely visible; 2-visible.
[2]Disturbance levels: 0-none; 1-low; 2-moderate.

TABLE 6. Observed and (expected) frequencies of disturbance levels on winter seismic trails within snow slab depth classes in moist sedge-shrub tundra, Arctic Coastal Plain, Alaska, 1985

	Slab thickness (cm)				
Disturbance level[1]	<10	10-20	20-30	>30	Total
1	10(13)	5(6)	8(6)	7(5)	30
2	8(5)	3(2)	0(2)	0(2)	11

[1]Disturbance levels: 1-low; 2-moderate.
X^2 = 8.8, 3 df, p = 0.032

amount of canopy cover and the amount of moss cover. Studies have shown that arctic species do not all respond similarly to disturbance. Shrubs, especially evergreen shrubs, are more sensitive than sedges to disturbance (Bliss and Wein, 1972; Chapin and Shaver, 1981). Lichens and mosses are also sensitive to disturbance (Hernandez, 1973; Lawson *et al.*, 1978).

The micro-relief of an area was important in determining its susceptibility to disturbance, because high mounds or tussocks had less snow cover and were easily crushed or scuffed by vehicle tracks. Temperature was also important in determining the impact of vehicles on shrub canopies. Shrubs were more brittle and broke easily at sub-zero temperatures, but bent rather than breaking at higher temperatures.

The difficulty of measuring disturbance in moist sedge-shrub tundra may have contributed to the lack of strong relationships. Estimates of changes in plant cover and canopy cover on trails were based on comparisons with equivalent undisturbed areas. An equivalent nearby area was often difficult to find, as plant cover of individual species, especially shrubs and mosses, was highly variable in this vegetation type. Compression of the vegetative mat was one of the main impacts of higher disturbance levels in moist sedge-shrub tundra, but consisted of small changes in elevation in the initial year that were difficult to measure. These small differences could become important in subsequent years due to continued sinking of the trails, resulting in wetter habitats on trails and species composition changes (Challinor and Gersper, 1975; Felix *et al.*, in press; Raynolds and Felix, 1988). The amount of track depression that occurs depends on the ice content of the soil (Everett *et al.*, 1985; Lawson, 1986), which was highly variable in our study area.

Preliminary results from unpublished follow-up studies indicate that the impacts measured in this study were not just temporary, but have caused long-term changes in the vegetation on many of the trails. Four growing seasons after the disturbance occurred, 55% of sites had not changed from their initial disturbance classification, based on plant cover, species composition and trail visibility. Forty percent of the plots had lower disturbance levels, but only 13% of these returned to a "no disturbance" classification. Another 5% of the plots had higher disturbance levels than reported in the initial season after disturbance.

CONCLUSION

In tussock tundra, over 25 cm of snow was needed before a measurable decrease in disturbance occurred. The snow had to be deep enough to cover the tussocks (10-20 cm in height) and provide a protective layer over the top. In moist sedge-shrub tundra, slab depth appeared to be a better measure of protective cover than total snow depth. Plots with over 20 cm slab depth had significantly less disturbance that those with lower slab depths. Average depth hoar in moist sedge-shrub tundra plots ranged from 5 to 15 cm. Therefore, plots with over 20 cm slab depths had total snow depths of at least 25 cm. Snow cover would have to be very deep to completely prevent visible disturbance, since low-level disturbances occurred at snow depths as high as 45 cm in tussock tundra and 72 cm in moist sedge-shrub tundra.

Therefore, average snow depths above 25 cm were more effective in controlling disturbance than the 15 cm average snow depth required by the U.S. Fish and Wildlife Service. Snow depths of 15 cm prevented vehicle tracks from digging directly into the vegetative mat, but did not provide sufficient cover to prevent disturbance to underlying vegetation. The minimum snow depths needed to decrease disturbance would have been greater had other stipulations not been enforced by the U.S. Fish and Wildlife Service. Both cat-trains and vibrators were required to avoid traveling in the same trail, since the most severe impacts in 1984 occurred on narrow trails with multiple vehicle passes (Felix and Jorgenson, 1985). Cat-trains and sometimes seismic line vehicles were required to detour around sensitive areas and were routed through areas of deep snow to minimize disturbance.

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