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Thaw Response of Tussock-Shrub Tundra to Experimental All-Terrain Vehicle Disturbances in South-Central Alaska

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ABSTRACT. The vehicle-induced subsurface thaw response in a tussock tundra area was experimentally measured in relation to increasing traffic (10, 50 and 150 passes) applied by different types of lightweight (100-450 kg) all-terrain vehicles (ATVs) compared with a heavier (1200 kg) tracked Weasel (M-29) at four different times during the thaw season: 1) early June, 2) early September, 3) at weekly intervals for 10 weeks from mid-June to early September, and 4) in late July of two successive years. Two years later, in August 1987, three frost-table profiles were constructed for each of 144 test lanes 30 m long by probing at 10 cm intervals along three horizontal reference lines. The test site in south-central Alaska is underlain by "warm" permafrost with a 35 cm thick organic horizon over an ice-rich mineral soil. Early in the thaw season when thaw depths are 10-20 cm, traffic by ATVs can produce as much or more subsurface thaw than a heavier Weasel. Later, in September, the Weasel produced more thaw than the ATVs. Traffic intensity (number of passes) also had a greater effect on thaw response in the spring than in the fall. The thaw response produced by traffic driven at weekly intervals throughout the summer was greater than that produced by traffic confined to early June or September. The downward progression of thaw from May to September results in changing soil moisture levels, bearing strengths and compressibility of the organic and mineral soil horizons.

Key words: all-terrain vehicles, tundra disturbance, permafrost thaw, experimental traffic, Alaska, Wrangell-St. Elias National Park, south-central Alaska

RÉSUMÉ. Dans une zone de toundra à touffes d'herbe, on a procédé à des mesures expérimentales de l'effet de dégel sous la surface, causé par le passage de véhicules, en fonction du volume croissant de circulation (10, 50 et 150 passages). Plusieurs types de véhicules ont été utilisés, allant du véhicule tout-terrain léger (100 à 450 kg) au Weasel à chenilles (M-29) beaucoup plus lourd (1 200 kg), à quatre moments différents durant la saison de dégel: 1) au début de juin, 2) au début de septembre, 3) à des intervalles d'une semaine pendant 10 semaines, de la mi-juin au début de septembre, et 4) à la fin de juillet durant deux années consécutives. Deux ans plus tard, en août 1987, trois profils du niveau de gel ont été établis pour chacune des 144 bandes d'essai de 30 m de long, en sondant à des intervalles de 10 cm le long de trois lignes de références horizontales. Le site des essais, dans le centre-sud de l'Alaska, contient sous sa surface un pergélisol tiède et possède un horizon organique de 35 cm d'épaisseur sur un sol minéral riche en glace. Tôt dans la saison de dégel, quand le dégel atteint de 10 à 20 cm de profondeur, la circulation par les véhicules tous-terrains peut causer autant ou plus de dégel sous la surface qu'un Weasel plus lourd. Plus tard, en septembre, le Weasel cause plus de dégel que les véhicules tous-terrains. L'intensité de la circulation (le nombre de passages) affecte aussi plus le dégel au printemps qu'à l'automne. L'effet de dégel causé par les véhicules conduits à des intervalles hebdomadaires durant tout l'été est plus grand que celui produit par la circulation limitée au début de juin ou de septembre. La pénétration du dégel de mai à septembre aboutit à des changements dans le niveau d'humidité du sol, les surfaces portantes et la compressibilité des horizons organiques et minéraux.

Mots clés: véhicules tous-terrains, perturbation de la toundra, dégel du pergélisol, circulation expérimentale, Alaska, parc national Wrangell-St. Elias, centre-sud de l'Alaska

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INTRODUCTION

During the past two decades, the use of lightweight off-road recreational vehicles or all-terrain vehicles (ATVs), weighing less than 500 kg, has accelerated dramatically in permafrost regions (Fig. 1A-D). They are used extensively for subsistence hunting and fishing in small villages (Racine and Johnson, 1988) and for recreation from highway access points. A wide range of both tracked and wheeled ATVs is available, and they are used on multiple-pass trails at different times of the thaw period.

Transit during the thaw period by heavier, industrial vehicles weighing over 1000 kg, such as the Weasel M-29 (Fig. 1E), is a well-known source of surface disturbance and thaw depth change in permafrost areas (Rickard and Brown, 1974; Abele *et al.*, 1984). Increased thawing results from changes in the insulative value of the surface vegetation and organic soil layer that is compressed and physically disturbed by the traffic (Brown and Grave, 1979). Over ice-rich soils, this increased thaw may lead to thermokarst and erosion (Lawson, 1986).

Less well known are the surface and subsurface effects of all-terrain vehicles weighing less than 500 kg. The hypothesis tested in this study is that in tussock tundra lightweight ATVs can produce as much subsurface thaw as a larger off-road vehicle weighing over 1000 kg. In addition, we hypothesize that this thaw response varies with the amount of traffic, the type of vehicle and the seasonal timing of use.

Experimental studies of larger off-road vehicles have related surface depression and thaw depth in the vehicle tracks to the number of passes. A 50-pass Weasel track in early August at Barrow produced 15 cm of surface depression and an 11 cm increase in depth of thaw two years after the test but returned to predisturbance levels within ten years (Abele *et al.*, 1984). Return of the active layer depth and surface rebound has been found to occur within twenty years in vehicle trails where no erosion or massive subsidence due to ground ice has occurred (Lawson, 1986; Everett *et al.*, 1985). However, little consideration has been given to the effects of the timing of traffic during the thaw period. Radforth and Burwash (1977) showed that seasonal thaw increased with the number of passes of 4000 kg Caterpillar-type vehicles and that June tests created less disturbance (rutting) than August tests.

TEST SITE

The test site is located on the northern edge of the Wrangell-St. Elias National Park in south-central Alaska, where recent concern over the impact of ATV traffic suggested the need for this study (Fig. 2). A fairly uniform 7 hectare area of moist tussock sedge tundra was chosen near

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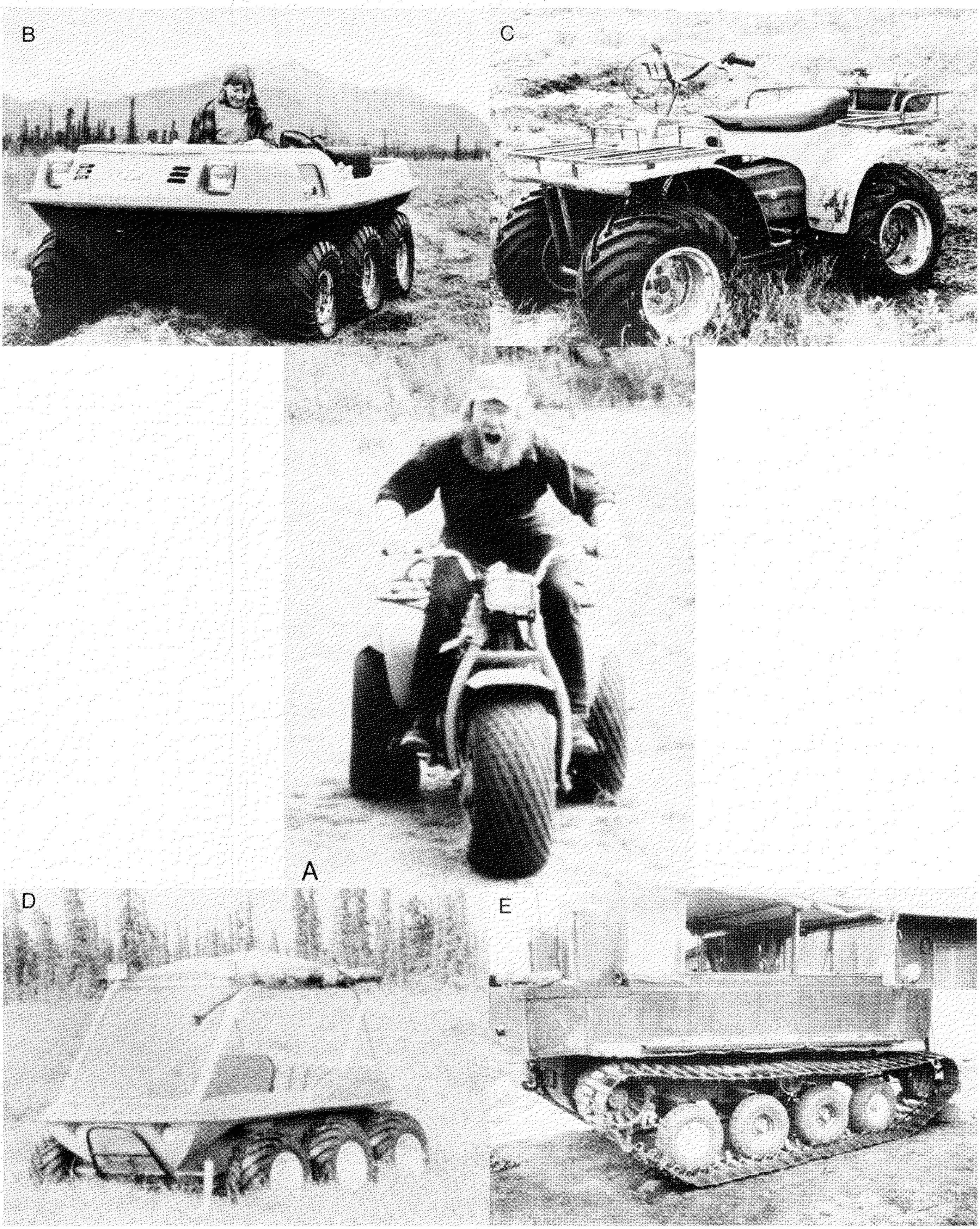

FIG. 1. Test vehicles used to create experimental surface disturbances in tussock tundra: A) Honda ATC; B) Argo; C) Honcho; D) Sidewinder; E) Weasel (M-29).

the regional tree line at an elevation of 990 m between Slana (667 m) and Nabesna (880 m). The area is on the drainage divide between the Copper River–Gulf of Alaska and the Nabesna River-Yukon River watersheds. The test site is bordered by well-drained glacial outwash with black spruce forest (Fig. 1B) and slopes gently 3-8% to the south.

The site is covered by a fairly uniform stand of low shrubs and cottongrass tussocks similar to the tussock sedge tundra dominant on gentle permafrost slopes throughout arctic Alaska (Miller *et al.*, 1984). (In the Viereck *et al.*, [1986] classification system, the vegetation is an "open, low mixed shrub-sedge tussock bog" type.) The major species include the cottongrass (*Eriophorum vaginatum*), ericaceous shrubs (*Vaccinium uliginosum, Ledum palustre*), dwarf birch (*Betua nana*) and mosses (*Aualacomium palustre, Sphagnum* sp.). Because of the characteristic tussock growth form of *Eriophorum vaginatum*, there is considerable microtopographic relief of 10-25 cm. Although thaw processes are well known in most tundra ecosystems (Brown and Grave, 1979), tussock tundra presents thaw measurement problems because of the surface microrelief.

The half-bog (histic pergelic cryaquepts) soils are poorly drained and acidic (pH=4.5), with 35 cm of peaty materials overlying little-differentiated mineral silty soils containing widely varying amounts of organics and occasional pebbles (Fig. 3). The organic horizon consists of a 15 cm thick Oi horizon of undecomposed moss, woody stems and sedge litter above an Oa or Oe horizon of more decomposed peats to 35 cm. In early June these soils were thawed to a depth of 10-12 cm and by early September, at the end of the thaw season, the active layer thickness was 50-60 cm. The underlying frozen mineral soil was ice rich with veins and plates and contained more than 200% (dry weight) of frozen water. There is no surface evidence of ice-wedge polygons or frost scars. The mean annual temperature for the nearest weather station (Slana, Alaska) is -2°C, with a July mean of 14°C and the January mean of -20°C. This and other studies (Greene *et al.*, 1960) show that the area is underlain by relatively "warm permafrost" compared with that of arctic areas of tussock tundra, where annual temperatures average -8 to -10°C.

METHODS

To test the effects of vehicle type, timing of use and traffic (number of passes) on summer thawing, a factorial experiment with randomized block design was employed. One hundred and forty-four test lanes 30 m long and 3.5 m wide were established on the 7 ha site (Fig. 1). Each lane was randomly assigned a single vehicle/traffic level/time treatment.

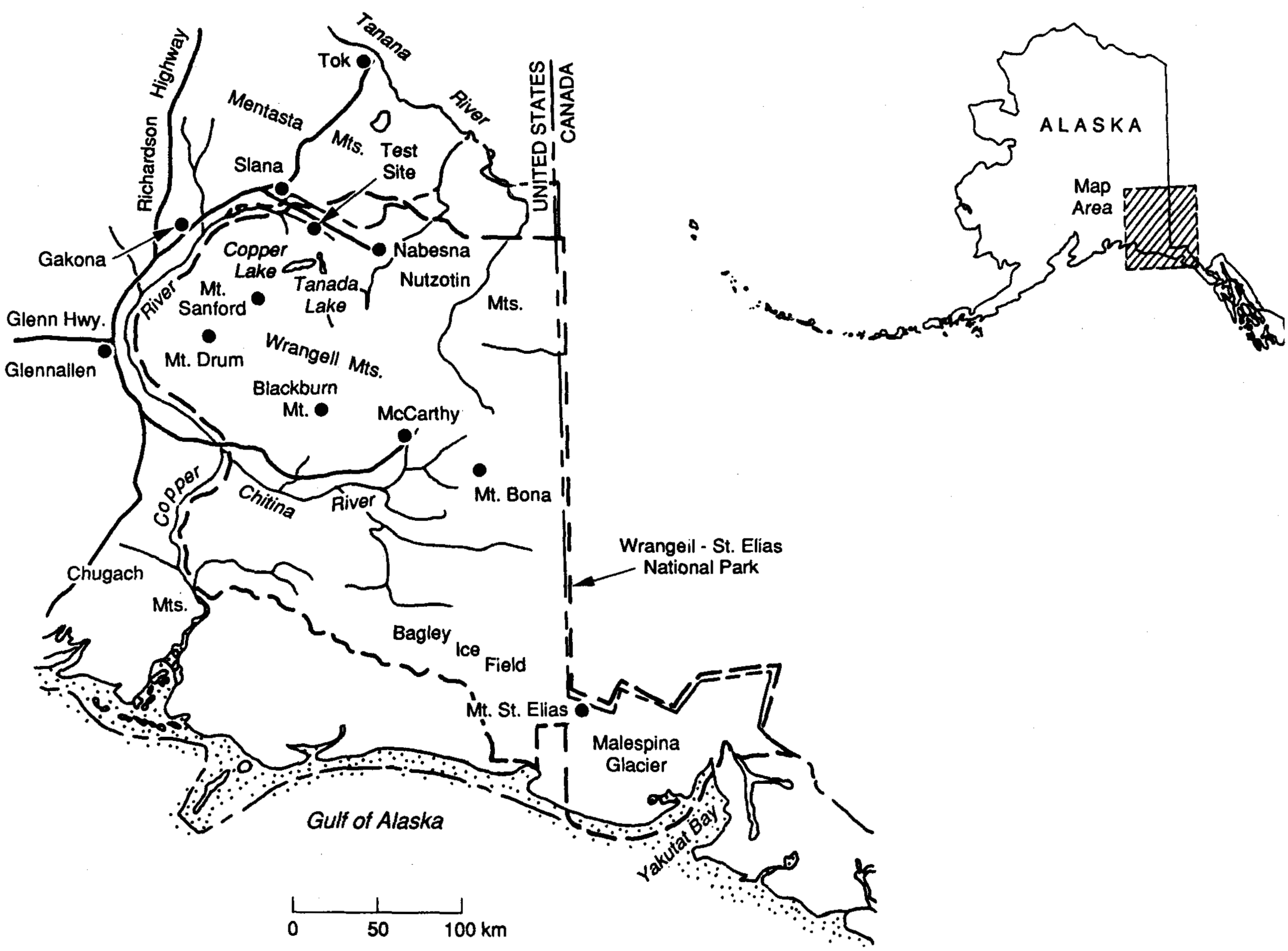

FIG. 2. Map of the Wrangell-St. Elias National Park in south-central Alaska showing the location of the study area in Alaska (inset) and the test site.

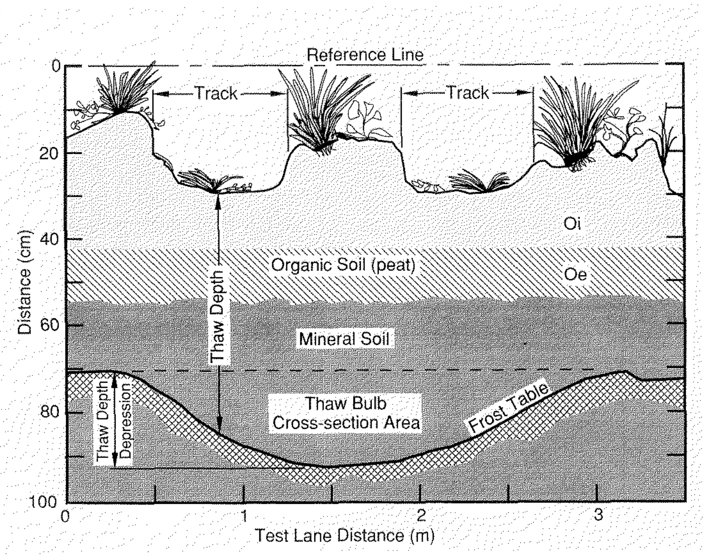

FIG. 3. Schematic showing surface and subsurface cross-sectional profile across a hypothetical test lane in late August. Method of measurement from a reference line and the terminology used in the text are shown. Distances from a reference line to the surface and to the frost table were measured at 10 cm intervals for 3.5 m.

Four types of ATVs and a 1200 kg Weasel were tested (Table 1; Fig. 1), including the three-wheel Honda All-Terrain Cycle (ATC), the four-wheel-drive Honcho and the six-wheel Argo. The fourth ATV (a six-wheel Sidewinder) was used in one test for comparison of the impacts of wheeled and tracked configurations.

Three traffic levels of 10, 50 and 150 passes were applied to the test lanes by driving down the center at approximately 8 $km \cdot h^{-1}$. The ATC had no reverse gear and was turned around at the end of the lane to make multiple passes. Other vehicles were driven in reverse on alternate passes.

Four sets of tests were conducted. 1) In early June 1985, when thaw depths were 10 cm, the ATC, Honcho, Argo and Weasel were driven for 10, 50 or 150 passes. 2) In early September 1985, when thaw depths were 60 cm, the same four vehicles made similar numbers of passes in a previously undisturbed portion of the site. 3) During a ten-week period extending from mid-June 1985 to early September 1985, while thaw depths increased from 10 to 60 cm, the same vehicles were used to make either 1, 5 or 15 passes per week. 4) In late July of both 1984 and 1985, when thaw depths were 35 cm, four vehicle types (ATC, Sidewinder with tracks, Sidewinder without tracks and Weasel) were driven at traffic levels of 10, 50 and 150 passes. This "summer rerun" treatment resulted in a total of 20, 100 and 300 passes being made over those test lanes during the two-year period.

TABLE 1. Types and characteristics of off-road vehicles used in experimental tussock tundra disturbance tests

Vehicle type	Weight (w/o driver) (kg)	Ground pressure ($kg \cdot cm^{-2}$)	Tires/ tracks	Footprint width (m)	Total width (m)
Weasel (M-29)	1200	0.07	tracks	1.2	2.1
Honcho	175	0.70	4 tires	0.8	1.2
All-Terrain Cycle	100	0.10	3 tires	1.0	1.1
Argo	350	0.18	6 tires	0.7	1.6
Sidewinder (wheels)	400	0.70	6 tires	0.7	2.0
Sidewinder (tracks)	450	0.14	tracks	0.8	2.0

To measure vehicle effects in each test lane, quantitative sampling of vegetation, terrain surface and depth of thaw was carried out at three permanently marked transects across each of the 144 test lanes in late August 1987, two years after the traffic loading. This paper reports only thaw-depth depression effects on the frost table.

Because of the microtopography, it was necessary to establish a level reference line above the surface from which to measure the distance to the ground surface and to the frozen layer at 10 cm intervals to construct a cross-sectional profile of the frost table (Fig. 3). The distance to the ground surface was measured with a metre stick and the distance to the ice-cemented frozen layer was measured with a sharpened steel probe. The location of each point relative to the vehicle disturbance, or track, was also recorded (in the track, outside the track or between the tracks). Each test lane was arbitrarily defined as 3.5 m in width, so 36 measurements were made for each of the three profiles per test lane (Fig. 3). During August 1987, a total of 432 frost table profiles were obtained involving 15 552 thaw depth measurements.

The difference between the thaw depth in the tracks versus that in the control test lanes without traffic is called the "thaw depth difference." Since it became apparent that thawing had extended laterally into the area outside the tracks, it was necessary to plot the 3.5 m long frost table cross-section beneath each test lane. By drawing a horizontal line connecting the ends of this profile, both the "thaw depth depression" of the frost table and the "cross-sectional thaw bulb area" were determined for each profile (Fig. 3).

Two types of statistical tests were used to analyze the results. Three-way analysis of variance (ANOVAs) tested the hypothesis that there was no effect of traffic level, vehicle type and timing of use on frost table depression and cross-sectional thaw bulb area. When a hypothesis was rejected, a Duncans multiple range test was used to show relationships between combinations of vehicle type and traffic level for each of the seasonal tests. In addition, the slope of thaw-response regression curves relating thaw depth depression and cross-sectional thaw bulb area to the number of passes was calculated for each vehicle type/time of use combination. A t-test was used to determine if these slope estimates were significantly different.

RESULTS

Thaw Depth Difference

The mean depth of thaw in the undisturbed control area in mid-August 1987 was 50 cm. In the tracks produced by all vehicles at all traffic levels, thaw depths beneath the depressed surfaces were generally the same or even less than 50 cm because the surface depression was equal to or greater than the thaw depression. However, thaw depths of 60-70 cm were measured in the area between the tracks of most 50- and 150-pass traffic lanes for the Honcho, Sidewinder, Argo and Weasel where lateral thaw had apparently occurred without surface depression. Where the wheels or tracks were relatively far apart, as in some Weasel and Argo test lanes, the frost table between the tracks was not depressed to as great a degree (Fig. 3) and a "hump" is visible in some profiles (Fig. 4). The three-wheel ATC and Honcho tracks were too close together to show this phenomenon.

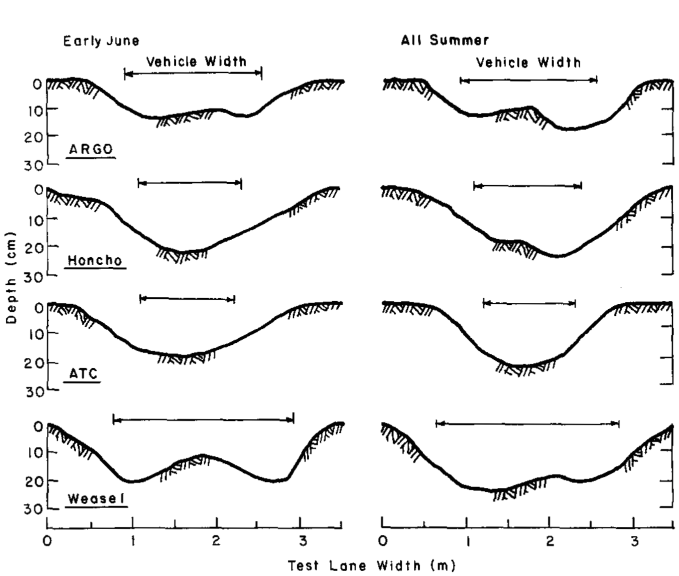

FIG. 4. August 1987 frost table depression profiles beneath off-road vehicle test lanes obtained by probing from a reference line. All eight profiles represent 150-pass test lanes produced during: A) early June 1985; and B) 15 passes each week for ten weeks from early June to early September 1985. Vertical exaggeration is 5 times the horizontal.

Thaw Depth Depression

The depression of the frost table increased with increasing traffic from less than 10 cm for 10 passes up to 24 cm under some 150-pass test lanes (Fig. 5). Differences in the thaw depression were generally significant between all traffic levels for each vehicle except between 50- and 150-pass lanes in the fall tests (Fig. 6).

Thaw Bulb Cross-Sectional Area

The frost table topographic profile shows the shape and cross-sectional area of the thaw bulb that develops beneath each test lane (Fig. 4). This provides additional information on the thaw response to the different treatments not available from single depth measurements. The cross-sectional thaw bulb under the test lanes increased from 0.08 m^2 in 10-pass lanes up to 0.32 m^2 in some 150-pass lanes (Fig. 5). Even though the thaw depth depression may be similar for two types of ATVs, the thaw bulb area produced by each may be significlantly different because of differences in lateral thaw related to vehicle width and footprint. For example, the 150-pass/all-summer/Weasel thaw bulb cross-sectional area is significantly greater than that for the 150-pass/all-summer/Honcho thaw bulb area, even though the thaw depth depressions for these two treatments were not significantly different (Fig. 5).

Thaw Response Curves

The general shape of the curves in Figure 6 relating thaw depth depression and thaw bulb area to the number of passes is logarithmic. Therefore, the natural log transformation of the number of passes permits calculations of linear regression slopes for each vehicle/seasonal treatment (Table 2). The steeper the regression slope, the greater thaw increases with increasing traffic.

The Weasel generally produced the greatest thaw response (highest coefficients) during the fall, all-summer and summer rerun tests. The Honcho produced as great or greater response than the Weasel from spring traffic. The Argo and ATC produced a significantly lower thaw response than the Weasel and/or the Honcho in all three seasonal tests.

All-summer tests clearly produced the greatest thaw response, followed by the spring and then fall tests. The summer rerun regression coefficients are high but were computed on the basis of 10, 50 and 150 passes rather than the actual 20, 100 and 300 pass totals produced over the two consecutive summers. If recomputed, the coefficients are not

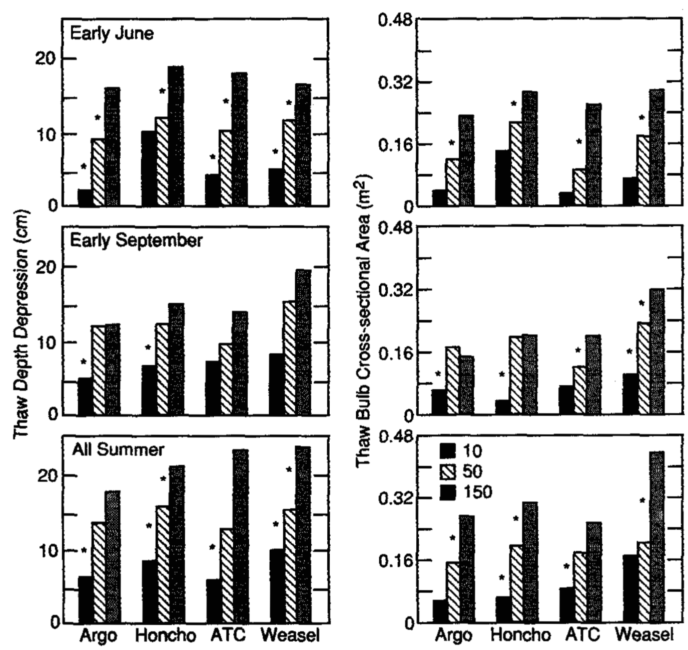

FIG. 5. Bar graph showing the thaw depth depression and the cross-sectional thaw bulb area created by four off-road vehicles driven over the same track for 10, 50 and 150 passes during early June and early September and weekly for ten weeks from early June to early September. An asterisk (*) indicates significant difference (P<.05) between two adjacent bars.

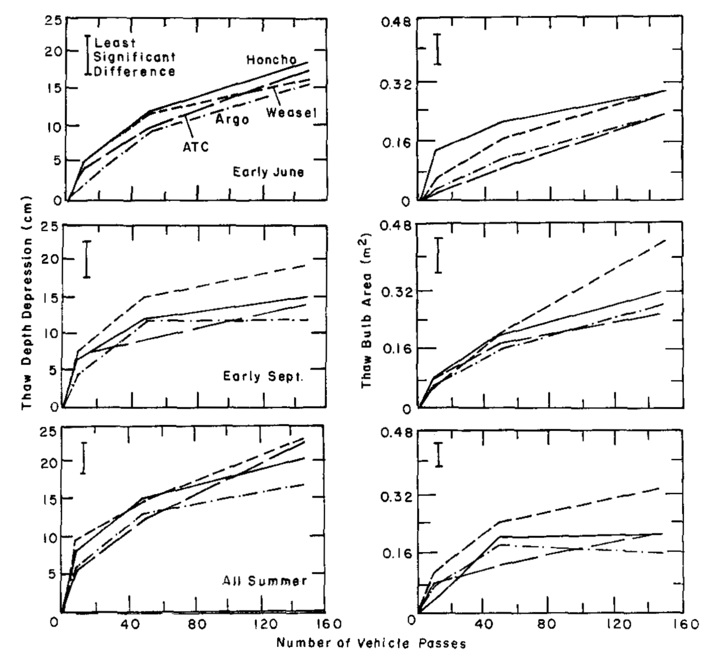

FIG. 6. Curves relating the traffic intensity (number of passes) to the maximum thaw depth depression and the cross-sectional thaw bulb area created by four off-road vehicles driven during early June, early September and weekly for ten weeks from early June to early September.

TABLE 2. Linear regression slope coefficients (b) for each vehicle and time of use treatment combination

Vehicle	Spring		All-summer		Fall		Summer-rerun[3]	
	Depth	Area	Depth	Area	Depth	Area	Depth	Area
Weasel	3.0b	31.6b	4.3b	44.5b	3.8b	37.7b	4.5b	41.3b
Honcho	3.6a	36.2b	4.0b	32.5a	3.0c	25.5a	ND	ND
ATC	2.9ab[2]	22.0a	3.8ab	28.0a	2.7ac	23.1a	4.1bc	35.4b
ARGO	2.5b	23.6a	3.3a	28.0a	2.6a	21.6a	ND	ND
Sidew-wheel	ND	ND	ND	ND	ND	ND	3.7c	40.5b
Sidew-track	ND	ND	ND	ND	ND	ND	2.7a	24.2a

[1]Calculated in the form of Y = b(LN(X)), where Y is thaw depth depression (D) or thaw bulb (A) and X is the number of passes.
[2]A t-test was used to compare regression slope coefficients between vehicles within a time of use. Significant differences at 0.05 level between these coefficients are indicated by non-matching letters within a column.
[3]If use 20, 100 and 300 passes, coefficients are 3.8, 3.5, 3.1 and 2.3 for thaw depth depression and 35.0, 30.0, 34.3 and 20.5 for thaw bulb area.
ND=Not determined.

significantly greater than those for the ATC and Weasel during the fall and spring tests. The importance of vehicle design on the thaw response is evident in the effects of installing tracks over high-ground-pressure tires on the six-wheel Sidewinder in the summer rerun test (Fig. 7). This lowered the ground pressure from 0.7 to 0.14 $kg \cdot cm^{-2}$ and reduced the thaw response coefficient to the lowest of any vehicle (Table 2).

DISCUSSION AND CONCLUSIONS

The original hypothesis that small ATVs can produce as much subsurface thaw in tussock sedge tundra as large off-road vehicles is not rejected. However, these effects on the frost table vary with the type of ATV, time of use during the thaw season and the amount of traffic. These differences may be related to the seasonal changes in the ability of the surface vegetation and thawing organic and mineral soil horizons to resist vehicle disturbance. The downward progression of thaw from May to September results in changing moisture levels, bearing strengths and compressibility of the organic and mineral soil horizons.

In early June, when thaw depths are shallow (10 cm), vehicle ground pressure may be a more important determinant of thaw disturbance than total vehicle weight. At this time, the high-ground-pressure (0.7 $kg \cdot cm^{-2}$) Honcho produced a greater thaw response than the low-ground-pressure (0.07-0.18 $kg \cdot cm^{-2}$) Weasel, Argo or ATC. In addition, the increase in thaw depression from 50 up to 150 passes for all vehicles was greater in the early June tests than in the early September tests. The shallow depth of thaw (10 cm) would result in a greater ability of the soil column to support heavy vehicles, but the high water content of the relatively undecomposed organics would make them more susceptible to compression or tearing by high ground pressures and cleated tires. Multiple passes at this time might therefore result in more rapid breakdown of the shallowly thawed internal organic soil structure.

In early September, when thawing is deep (60 cm), the heavier (1200 kg) Weasel produced significantly greater thaw response two years later than did the lightweight (100-350 kg) Argo, ATC or Honcho. In addition, higher traffic levels (150 passes) had less effect on thaw then than in the spring. These results suggest that at this time of the thaw season, total vehicle weight may be more important than ground pressure in determining surface disturbance and subsequent thaw. The deep thaw would provide less bearing strength for the heavier Weasel but may provide adequate support for the ATVs. In addition, this cushioning effect and lower moisture content than in June (due to internal drainage) could result in less destruction of the organic soils at higher traffic levels.

In the present experiment, when a given amount of traffic was dispersed over a ten-week summer period, a significantly greater thaw response was produced than from the same amount of traffic applied during a brief period in early June or September. Sequential off-road vehicle traffic over the same track represents a form of cumulative impact, since the impact of each new pass interacts with the impact of the prior passes. Greater interaction would be expected from temporally dispersed traffic than from closely spaced traffic. When the traffic is dispersed over a ten-week period, a new set of soil and vegetation conditions (due to the prior disturbance and changing weather conditions) would become established before each new traffic disturbance. However, when the traffic disturbance is applied all at once, there is no time for changed conditions to develop between passes. When traffic was concentrated during a one- to two-week period, but repeated in two consecutive summers to yield a

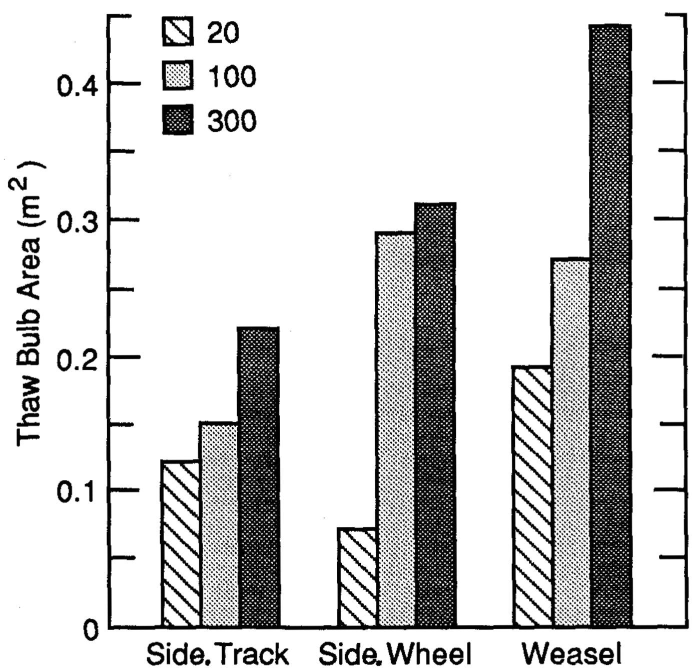

FIG. 7. Thaw bulb cross-sectional area created by 20, 100 and 300 passes (10, 50 and 150 applied in each of two consecutive years) by a six-wheel, 400 kg Sidewinder with and without rubber tracks and by a 1200 kg tracked Weasel (M-29).

total of 20, 100 and 300 passes, the thaw response was greater than the single-disturbance June or September tests and not significantly greater than that produced by the ATC and Weasel during the all-summer tests. This suggests that during the period between the two consecutive years of traffic, there may be some recovery of the vegetation and the soil active layer to water redistribution and ice crystal formation.

Vehicle width and lateral separation between wheels and tracks can influence the size and shape of the thaw bulb beneath vehicle trails (Table 1). The wide Weasel produced a significantly greater thaw response than the ATC, Honcho and Argo in terms of thaw bulb cross-sectional area in the fall and all-summer tests. The Weasel has the greatest footprint width of the vehicles tested, so it would be expected to produce greater lateral thaw than the other vehicles. In evaluating the overall impact of off-road vehicle disturbance on the active layer, lateral thaw and thaw bulb cross-sectional area should be considered in addition to vertical depth changes of the active layer. Prior studies have only considered depth changes (Abele *et al.*, 1984). In all test lanes, increased thawing extended some lateral distance beyond the area of the surface disturbance (Fig. 4).

Four years after the experimental tests, there appeared to be little or no surface instability beyond the track depressions and only limited hydraulic erosion. This is somewhat surprising in view of the relatively "warm" permafrost and high ice content of the mineral soils. It is not known whether additional thaw or surface subsidence will increase in future years or when the anomalous thaw depths will disappear. The test site relief is low and the vehicle track depressions run along the contours. In addition, the dramatic stimulation of tussock growth bordering most 50- and 150-pass tracks would help stabilize the site to reduce erosion and thaw. Here presumably warmer soils accounted for increased root growth and nutrient availability (Chapin and Shaver, 1981).

Land managers can regulate vehicle types, traffic levels and timing to reduce impacts on the frost table and active layer. If possible, traffic should be concentrated in time rather than dispersed throughout the thaw season. By confining the use of heavier vehicles with low ground pressures to early in the thaw season and lighter vehicles to late in the thaw season, changes in the frost table would be minimized in tussock tundra areas. Spatially dispersed traffic rather than continuous passage over the same track could reduce the effects of multiple passes (Raynolds and Felix, 1989). The installation of tracks on the six-wheel Sidewinder in the summer rerun significantly reduced the thaw response over that produced by wheels. Tracks redistribute the vehicle weight over the uneven ground surface to reduce surface disturbance to the intertussock area.

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