

Environmental Conservation Vol 1 (101-110)

Snowmobile Impact on Three Alpine Tundra Plant Communities

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INTRODUCTION

Recent advances in the design of over-snow vehicles have made formerly remote alpine tundra areas accessible in winter to increasing numbers of people each year. One of the most popular of the motorized snow vehicles is the snowmobile. Its manoeuverability, comparatively light weight, and low cost, make it a favourite vehicle for work and recreation on the tundra. Because of their reputation for minimal damage to the tundra vegetation, snowmobiles were chosen as vehicles for winter access to weather stations administered by the Institute of Arctic and Alpine Research (INSTAAR) of the University of Colorado. The weather stations are located on Niwot Ridge, 8 miles (13 km) north of Nederland, Boulder County, Colorado, in the Front Range of the Rocky Mountains. The careful records on snowmobile travel compiled by Mr Ralph Greene, then manager of the Mountain Research Station of INSTAAR, made this area ideal for the study of the effects of snowmobile travel on alpine tundra vegetation*.

Marr & Willard (1970) summarized climatic data for the alpine tundra at Niwot Ridge. They described summers as cool and occasionally punctuated by sleet, hail, and snow-storms. Autumns were described as dry and cold, with a few warm days. Winters are long, windy, very cold, and cloudy. Blizzards are frequent and severe. Much of the snow is blown off the tundra. Spring storms deposit snow on the tundra, because of their reduced wind-velocity. Melting of the snow provides some moisture for tundra plants. Spring is cool and wet initially, but an interval of drought occurs in June. 'Strong winds and a major part of the tundra's precipitation come from the west' (*Ibid.*).

Scott & Billings (1964) give the alpine growing-season as 40–70 days.

Plant communities in the alpine areas of the Front Range have been described by Osburn (1958), Marr (1967), and Marr & Willard (1970). Tundra vegetation has been recognized as being among the lowest of terrestrial ecosystems in biomass (dry grams/square metre) and in productivity (dry grams/square metre/year), according to Whittaker (1970). Xeric alpine tundra vegetation is approximately 10% as productive as mesic alpine tundra vegetation, and has approximately 50% of its biomass (Scott & Billings, 1964). Somewhat comparable expectations have long been entertained for arctic ecosystems (Polunin, 1934, 1945, 1948). These data suggest a potentially low rate of recovery for damaged tundra vegetation, when compared with other ecosystems, and an especially low rate for xeric fellfield vegetation.

Willard & Marr (1970) stated that various alpine tundra communities showed the following order of susceptibility to trampling by humans: (1) those with a high content of soil-moisture were most easily damaged, (2) tall herb ecosystems came next, then (3) fellfields, and finally (4) turfs were most durable. They listed the following species as having the greatest tolerance to trampling: *Kobresia myosuroides*, *Oreoxis alpina*, *Geum rossii*, and *Bistorta* (*Polygonum*) *bistortoides*. In their study of the recovery rates of various ecosystems from the effects of trampling, Willard & Marr (1971) concluded that the *Kobresia* turf was most resistant to disturbance, but would require 'several hundred and possibly even a thousand years for ecological processes to produce a persistent ('climax') ecosystem in some of the areas modified by visitor activities,' in Rocky Mountain National Park. Recovery of fellfield vegetation after many years of trampling was also observed to be slow.

This paper will attempt to correlate a known amount and duration of snowmobile traffic with

*For an authoritative account of 'Effects of Vehicles on Arctic Tundra', *see* Warren E. Rickard & Dr Jerry Brown's illustrated article in our first number, pp. 55–62.—Ed.

ıanges in plant and soil cover in three alpine tundra ant communities. The work was done during the ımmer growing-season.

METHODS

escription of Impact

In October 1968, a snowmobile route was marked on iwot Ridge from the T-Van shelter to the City of Boul-ɜr watershed fence, at an altitude of approximately ,400 feet (3,475 m). Where the route traversed rock-rewn, snow-free areas, the rocks were raked off and iled at the side of the road. The *Ski-doo Travel Log* f the University of Colorado's Mountain Research tation lists 225 individual snowmobile trips on the ɔute during the period of November 1968 to May 969. During the following season's period of Novem-er 1969 to May 1970, a total of 285 individual trips ɾere recorded. The snowmobile route received, ıerefore, an impact of 1,020 passages (forth or back) ver a period of two winters prior to this study. The ki-doo, made by the Bombardier Company, was the ehicle most often used on the route. It has two flat, ıovable skis (Fig. 1). The rubber track which serves o propel the vehicle is located behind the skis. The pressure exerted against the ground by the Ski-doo track is 0.27 lb/in^2 (18.8 gm/cm^2).

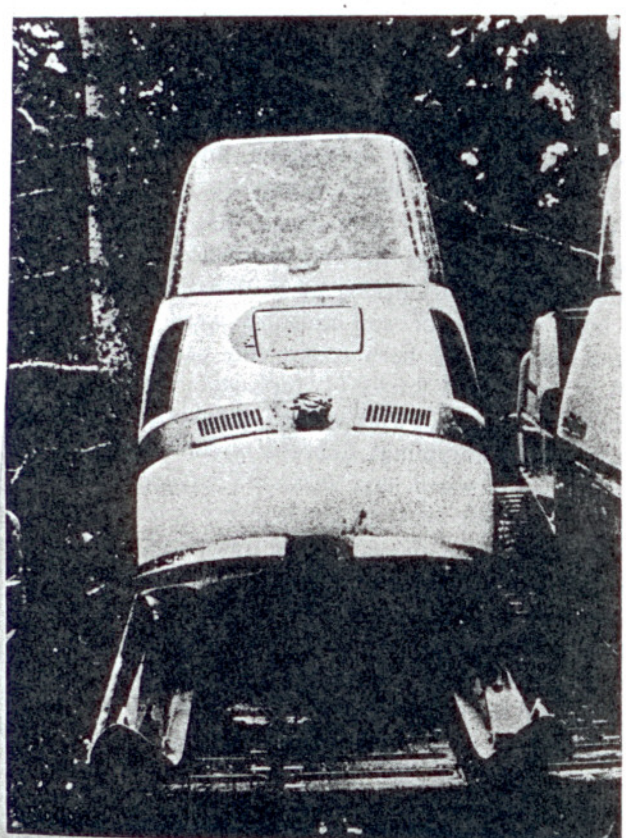

FIG. 1. *Front view of 'Ski-doo' snowmobile. Note the two skis with protuding central ridges. The skis are ca 90 cm apart.*

This general area has also received an undetermined amount of foot impact by visitors during the long time that it has included a tundra research centre. An undetermined amount of plant collecting has also been done in this area. These activities were apparently of a random nature and affected damaged and control sites equally.

The Study Areas

Three study sites were selected along the snowmobile route. All sites were of the type generally described as winter snow-free, due to the high winds accompanying winter snows depositing most of the snow in the sub-alpine forests (Marr & Willard, 1970). An observation by one of us (A.M.G.) at the end of December 1970 revealed that snow was retained only on the leeward side by clumps of plants, to a depth of a few centimetres, in all ecosystems studied. In the spring a cover of snow remained over the entire tundra because of a reduction of wind velocity (Marr & Willard, 1970). At the first site, which we shall refer to as FS, rocks, bare soil, and cushion-plants, were prominent features of the landscape. *Kobresia myosuroides* was entirely absent from this site. The route here traversed a 7° east-facing slope (Fig. 2).

FIG. 2. *Sloping fellfield (FS) area showing snowmobile route through centre and jeep road in background. The snowmobile route is ca 1 m wide. This portion of the route shows damage that is heavier than typical, and was not sampled. Photo taken during growing-season.*

The second study site, FF, resembled the first in having rocks, bare soil, and cushion-plants, as prominent features of the landscape, but differed in having many isolated tussocks of *Kobresia myosuroides*. The second site was flat and had a southern aspect. In the vegetation, both sites corresponded to the Cushion-Plant Stand-type of Marr (1967).

The third stu meadow area *myosuroides* a sponded to the The third site raking had be depression an north, south, merged with t retain the mo prominent *Ko*

Methods of St

At each of 1 metre 'quad rods. One of along the snow adjacent to it the snowmob three 10 m × designated as reasons). Th FF-C, and K strip quadrat actual quadra constructed w from one edg frame was pla coverage in th various categ square metre 10 m × 1 m so that the ea the route, wa ing portion c hitherto enco present, and a of 1, to whicl for the specie a species wi assigned a va species, prese not sampled Importance values for c designation. in the 10 m

In the area heavy dama mobile route of the area co area which damage, one light damag SSE is ther the FS area.

The third study site, KF, was a flat but well-drained meadow area with prominent coverage by *Kobresia myosuroides* and *Geum rossii*. The vegetation corresponded to the *Kobresia* Meadow Stand-type of Marr. The third site had few rocks, and consequently no raking had been done on it. This site was in a slight depression and was bordered by a small rise to the north, south, and west. To the east it gradually merged with the FF area. The KF site appeared to retain the most 'leeward snow' because of its many prominent *Kobresia* tussocks.

Methods of Study

At each of the three study-sites, two 10 metres by 1 metre 'quadrats' were permanently marked by steel rods. One of these 10 m × 1 m strips was situated along the snowmobile route and the other was situated adjacent to it on a site that remained undisturbed by the snowmobiles and thus served as a control. The three 10 m × 1 m strips on the snowmobile trail were designated as FS-E, FF-E, and KF-E (*see* below for reasons). The controls were designated as FS-C, FF-C, and KF-C, respectively. Each 10 m × 1 m strip quadrat was subdivided into ten 1 m × 1 m actual quadrats. A 1 m × 1 m wooden frame was constructed with a wire strung one decimetre (10 cm) from one edge of the frame and parallel to it. The frame was placed on each 1 m × 1 m quadrat and the coverage in the 1 dm × 1 m area was estimated for various categories of ground-cover. A total of one square metre was thus sampled for coverage in each 10 m × 1 m strip. The frame was consistently placed so that the eastern portion of the quadrat, lying across the route, was sampled for coverage. In the remaining portion of each 1 m × 1 m area, the plants not hitherto encountered in the quadrat were recorded as present, and all species in the quadrat were given a value of 1, to which the actual value for coverage was added for the species in the 1 dm × 1 m section. For example, a species with 4.5 dm² coverage in a quadrat was assigned a value of 5.5 for that quadrat, while another species present only in the part of the quadrat that was not sampled for coverage, received a value of 1. The Importance Value (I.V.) of a species is the sum of the values for coverage and presence, and lacks a unit designation. It was calculated for each plant species in the 10 m × 1 m strip.

In the area of FS, damage to vegetation varied from heavy damage over about two-thirds of the snowmobile route to very light damage on about one-fifth of the area concerned. The FS-E strip was placed in an area which had approximately one-quarter heavy damage, one-half moderate damage, and one-quarter light damage (Fig. 3). The destruction recorded in FS-E is therefore lighter than the average damage on the FS area. Difficulty in choosing a control site in the

Fig. 3. *View of FS-E strip looking east towards T-Van shelter and vehicle. The width of the snowmobile route (centre foreground) is 1 m. Photo taken during growing-season.*

KF area necessitated the construction of a 2 m × 5 m 'quadrat' for KF-C rather than the typical 10 m × 1 m strip. When observed in December 1970, KF-C had approximately 5 m² of coverage by a snow-drift. The drift was approximately 15 cm deep on the average, and ranged from a few centimetres to a maximum of 30 cm in depth; it may well be a lasting feature of the site.

Permanent records of the vegetation in each quadrat of each strip were made by photography. A frame 200 mm × 180 mm in dimensions was constructed. The frame was placed at the inner edges of each of the corners, and at the centre, of each 1 m × 1 m quadrat, and the vegetation inside of the frame was photographed (Fig. 4) with a 35 mm single-lens reflex camera mounted on a tripod.

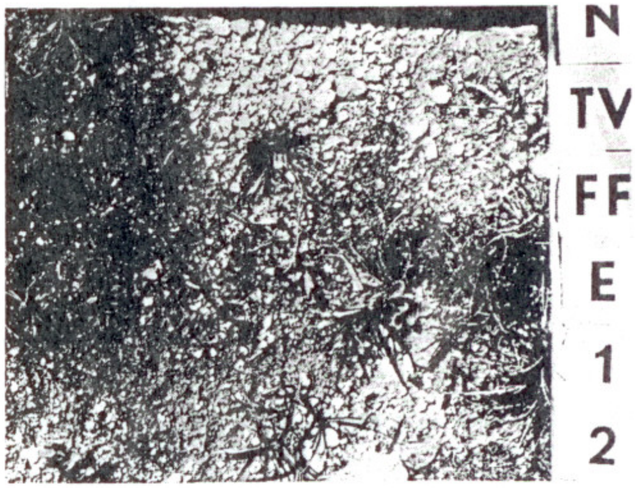

Fig. 4. *Vegetation persisting in an area 200 mm by 180 mm on the snowmobile route through the flat fellfield (FF). Masses of exposed* Kobresia *roots are visible at left-center and right-centre of the photo. Prominent living plants are* Kobresia, Carex rupestris, *and* Hymenoxys acaulis. *One side of frame is seen on right and the shadow of another above. Photo taken during growing-season.*

Soil samples were taken from two places adjacent each 10 m × 1 m strip. Soil was sampled at the rface, at 10 cm below the surface, and at 30 cm low the surface. The results of the analysis of the il samples are given in Table I.

The soils are alpine turf soils of the Ptarmigan series etzer, 1956). They are well-drained, acid, alpine, mineral soils with an organic surface horizon which is often matted with roots. The soils are frequently stony, with coarse fragments forming a large part of the volume—especially at depth. They often occupy windswept snow-free ridges, although Ptarmigan soils can develop in nivation hollows provided they are well drained.

There is no significant difference in soil between the control (C) and experimental (E) plots of any of the three communities under study, although there may have been a loss of organic matter from the soil of the experimental plot of the *Kobresia* meadow (KF). The *Kobresia* meadow has a strikingly different soil from that of the flat (FF) and sloping (FS) fellfields. These last are essentially identical in physical properties except that the sloping fellfield has more pebbles at 30 cm. The *Kobresia* meadow has a well-formed turf layer with a higher organic-matter content, fewer pebbles and granules, and more silts and clays, than the fellfields. Soil reaction (pH) is fairly uniform within each soil profile, and uniform among the th

TABLE I

Summary of the Analysis of the Soils from the Three Plant Communities under Study. Values are means of two samples from each treatment and depth. Percentage moisture is the loss of water based on the oven-dry weight after an air-dry <2000μ sample is dried at 105°C. Percentage organic material is based on the loss on ignition at 500°C for two hours of a 5 gm, <2000μ, oven-dry, sample. Soil reaction was determined on a soil–water suspension (1 : 2.5 by weight) of <2000μ sample with a glass electrode. Pebble (64–4 mm) and granule (4–2 mm) percentages were derived by seiving the air-dry bulk samples. The sand (2000–63μ) and silt (63–3.9μ) percentages were obtained by seiving, and the clay percentage (<3.9μ) by the pipette method. (Table prepared by Patrick J. Webber.)

Parameter	Depth of Sample	*Kobresia* Meadow (KF)		Sloping Fellfield (FS)		Flat Fellfield (FF)	
		Control	Experiment	Control	Experiment	Control	Experiment
% Moisture	0 cm	4.4	3.9	1.3	1.3	1.6	0.9
	10 cm	3.2	2.9	1.5	1.5	1.2	1.3
	30 cm	2.9	2.1	1.3	1.4	1.1	1.1
% Organic	0 cm	33.6	28.8	6.6	8.4	9.1	4.5
	10 cm	15.5	14.2	6.3	6.2	4.4	3.9
	30 cm	11.6	8.0	4.6	5.4	3.0	2.9
pH	0 cm	5.6	5.8	5.7	5.6	5.9	6.0
	10 cm	5.4	5.4	5.2	5.4	5.5	5.7
	30 cm	5.3	6.0	5.5	5.4	5.7	5.8
% Pebbles	0 cm	2.0	0	13.9	13.0	19.1	24.7
	10 cm	19.4	2.3	31.9	40.8	19.3	12.3
	30 cm	49.7	73.2	58.2	61.2	19.2	14.7
% Granules	0 cm	4.7	2.5	11.3	18.5	7.7	13.2
	10 cm	8.8	3.7	11.7	9.3	16.7	11.1
	30 cm	6.0	6.2	9.0	9.8	12.0	12.9
% Sand	0 cm	53.2	62.0	72.6	75.3	73.8	81.1
	10 cm	55.0	55.6	63.9	68.9	72.4	59.9
	30 cm	52.3	56.5	62.6	68.5	64.8	57.0
% Silt	0 cm	23.3	21.0	16.5	14.1	15.1	11.4
	10 cm	19.0	25.4	22.0	19.1	17.2	28.1
	30 cm	20.1	23.9	24.8	18.9	24.6	29.3
% Clay	0 cm	23.6	17.0	11.0	10.7	11.1	7.6
	10 cm	26.1	19.1	14.2	12.1	10.5	12.1
	30 cm	27.6	19.7	12.7	12.7	10.7	13.8

plant communities, ranging from 5.2–6.0 and averaging 5.6.

The difference of snowmobile impact on these communities may be related to the following substrate or soil differences: there will be soil binding and a cushioning effect by the turf layer, and a reduction of shearing between stones and vehicle track, on the *Kobresia* meadow as contrasted to the stony fellfields.

RESULTS

Table II summarizes the results of the analysis of coverage at each of the three sites. Absolute coverage of living plants (in square decimetres) decreased in each of the strips on the snowmobile route, when

TABLE II

Absolute Coverage (in dm²).

	FS-C	FS-E	FF-C	FF-E	KF-C	KF-E
Bare soil	33.30	69.45*	34.70	60.85*	13.60	25.60
Rocks	26.84	07.03*	27.89	18.50*	03.09	03.15
Soil lichens	06.55	00.44	14.75	00.55	06.02	04.39
Rock lichens	08.35	01.06	13.25	01.55	01.88	00.72
Dead plants	06.37	02.84	05.62	08.00	03.22	13.24
Living plants	35.86	24.75	33.67	15.55	93.06	75.64
TOTAL	117.27	105.75	129.88	105.00	120.87	122.74

* Rocks were manually removed in FS-E and FF-E to facilitate snowmobile travel. Increase in bare soil is partly due to soil being newly exposed after this rock removal.

compared with their respective controls. In the FS area, FS-C had 11.11 dm² more coverage by living plants than did FS-E. FF-C had 18.12 dm² more coverage in this category than did FF-E. KF-C had 17.42 dm² more living plant coverage than did KF-E. Coverage by dead plants showed an increase in the damaged plots FF-E and KF-E over their corresponding controls. The category 'dead plants' includes: those branches with apparently dead apical meristems, physically attached to living plants; identifiable, completely dead plants; unidentifiable, completely dead plants. Not included in this category are dead basal leaves attached to living stems and dead plants covered by lichens. In the FS-C site the situation was complicated by large amounts of dead *Selaginella densa*, normally found with the living parts. In FS-E *Selaginella*, both living and dead, is in large part mechanically removed from the soil by snowmobile action.

The category 'soil' includes bare organic soil and mineral soil as well as all soil covered only by lichens. When one allows for the increase in the 'soil' category due to the raking of rocks (in FS-E and FF-E), one still finds a marked increase in the soil coverage on those strips, compared with their controls. The figures for soil coverage in the damaged plots can be corrected for manual removal of rocks in the following way: the figure for absolute coverage by rocks left in the damaged quadrat is subtracted from the figure for coverage of rocks in the control quadrat; the coverage thus obtained is subtracted from the soil coverage of the damaged quadrat. In FS-E, 16.34 dm² of increased soil-coverage can be ascribed to snowmobile damage and possibly to erosion of vegetation adjacent to the missing rocks. In FF-E, 16.66 dm² of increased soil coverage can be attributed to the causes mentioned above. In KF-E no rocks were removed and the 12.00 dm² increased coverage in this category can be ascribed directly to snowmobile damage. In all cases the increased soil coverage was of the bare mineral or humus type.

Soil lichens showed a marked decrease in coverage in the FF-E quadrat when compared with the control, FF-C. A decrease in soil lichen coverage was also noticeable in FS-E when compared with FS-C. Less marked but nonetheless present was a decrease in soil lichens in KF-E.

Rock lichens showed a marked decrease in per cent coverage due to snowmobile travel. In FF-C, 47% of the rock surface was covered with lichens, whereas in FF-E only 8% of the rock was lichen-covered. In FS-C, 31% of the rock was lichen-covered, whereas in FS-E only 15% of the rock was lichen-covered.

Table III summarizes the percentage composition of the total plant cover in each strip (apart from lichens, etc.). In the FS quadrats, living cushion-plants consistently showed decreased per cent coverage in the damaged plot; among these were: *Arenaria obtusiloba*, *Arenaria fendleri*, *Paronychia sessiliflora* var. *pulvinata*, *Silene acaulis*, *Eritrichium aretioides*, and *Phlox pulvinata*. Living graminoids usually showed increased per cent coverage in the damaged plot; among these were: *Carex rupestris*, *Calamagrostis purpurascens*, *Festuca brachyphylla*, *Helictotrichon mortoniana*, *Poa glauca*, and *Allium geyeri*. *Lloydia serotina* exactly retained its per cent coverage in the damaged plot. *Geum rossii* and *Oreoxis alpina*, morphologically similar rosette plants, showed marked increases in per cent coverage in the damaged quadrats. Both dead and living *Selaginella densa* decreased in per cent coverage in the damaged quadrats, its absolute coverage thus decreasing in the FS area as a result of snowmobile damage.

TABLE III

Percentage of Total Plant Coverage in the One Metre Square Sample in Each Strip.*

Species		FS-C	FS-E	FF-C	FF-E	KF-C	KF-E
obresia myosuroides	Dead	—	00.00	00.56	18.00	00.28	10.45
	Alive	—	00.00	31.43	20.68	47.05	43.60
eum rossii	Dead	00.05	—	—	—	—	—
	Alive	10.94	34.29	08.40	12.48	19.05	08.15
elaginella densa	Dead	11.44	03.08	10.00	07.26	02.15	02.17
	Alive	13.36	09.17	12.55	07.01	04.69	05.59
arex upestris	Dead	—	—	—	00.08	00.01	00.01
	Alive	06.99	09.39	08.83	07.30	05.18	07.31
renaria btusiloba	Dead	01.14	00.18	00.41	00.17	—	00.20
	Alive	06.73	01.38	04.66	01.15	02.10	04.78
lox lvinata	Dead	00.05	00.72	—	—	—	—
	Alive	05.87	05.00	01.83	02.72	00.01	00.00
lygonum iviparum		00.17	—	00.25	00.30	04.13	01.70
reoxis lpina		04.59	08.95	—	00.89	01.45	02.79
ymenoxys icaulis		02.56	01.09	05.29	01.49	00.01	00.02
renaria endleri	Dead	—	—	00.03	00.04	—	00.02
	Alive	03.20	01.34	01.30	01.57	00.34	00.15
aronychia sessiliflora	Dead	00.38	00.14	—	—	—	—
	Alive	05.47	00.83	00.00	00.08	—	—
Iaplopappus pygmaeus		00.81	01.49	00.31	00.72	00.00	—
arex rossii		05.19	00.00	02.57	03.35	00.00	00.00
rtemisia scopulorum		—	—	—	—	05.25	00.21
ilene acaulis	Dead	00.36	—	—	00.93	—	—
	Alive	08.48	03.77	00.76	01.70	00.05	00.81
Bistorta bistortoides		00.12	00.91	—	—	01.66	00.68
Eritrichium aretioides	Dead	00.24	—	00.20	—	—	00.05
	Alive	03.58	00.07	01.71	00.34	00.00	00.66
Calamagrostis purpurascens		02.01	05.11	02.16	00.00	—	00.00
Trifolium dasyphyllum		00.62	01.27	00.00	01.70	00.00	03.48
Festuca brachyphylla	Dead	00.47	—	—	—	—	—
	Alive	00.71	00.98	00.00	00.00	00.32	01.24
Primula angustifolia		00.21	00.00	01.02	00.34	00.04	00.12
Helictotrichon mortoniana	Dead	—	00.54	—	—	—	00.00
	Alive	—	00.91	—	—	—	00.02
Poa glauca		00.26	01.52	00.18	00.00	00.38	01.18
Mosses		00.64	—	00.18	—	01.99	00.33

* A short line (—) indicates absence of the species from the test area. A full zero (00.00) indicates presence but no significant coverage. This table includes only plants with per cent coverage > 01.00 in at least one square metre equivalent in one of the strips studied.

It is poorly rooted and easily removed by abrasion. Dead *Selaginella*, at least on this sloped site, is probably more easily removed than living *Selaginella*—which could account for the marked decrease in per cent coverage by dead *Selaginella*.

In the FF area, the behaviour of *Kobresia myosuroides* in response to snowmobile traffic was of great interest. The per cent coverage of dead *Kobresia* rose from 0.56 in the control to 18.00 in the damaged strip. Living *Kobresia* decreased in per cent coverage from 31.43 in the control to 20.68 in the damaged strip. The proportion of dead to living *Kobresia* changed markedly with damage. Only 1.75% of the *Kobresia* present in FF-C was dead, whereas 46.54% of the *Kobresia* present in FF-E was dead. There was an apparent decrease in absolute coverage of *Kobresia*, dead and living, in the damaged strip, which may, however, have been due to caution in identifying, as *Kobresia*, remnants of dead plants. Other species showing a marked decrease in per cent coverage in the FF area were: *Selaginella* (dead and alive), *Arenaria obtusiloba*, *Hymenoxys acaulis*, *Eritrichium aretioides*, and *Calamagrostis purpurascens*. Per cent coverage of living plants increased markedly for *Geum rossii*, while other plants showing increased coverage were: *Carex rossii*, *Phlox pulvinata*, *Trifolium dasyphyllum*, and ten other plants of lesser importance and smaller changes in cover.

In the KF area, visible effects of snowmobile damage were slight by the end of the second summer, though present during that spring. Only 0.59% of the *Kobresia* was dead in KF-C, whereas 19.34% of all *Kobresia* was dead in KF-E. Total coverage of dead *Kobresia* increased from 0.28% of the total plant cover in KF-C, to 10.45% of the total plant cover in KF-E. Living *Kobresia* showed a decreased per cent coverage in KF-E from that in KF-C. *Geum rossii* and *Artemisia scopulorum* also showed marked decrease in per cent coverage in KF-E. This decrease may well be due to an initial under-representation in the damaged strip rather than to snowmobile damage. *Polygonum viviparum* was the only other plant of high Importance Value to show a decrease in per cent coverage in KF-E. *Selaginella densa* showed decrease in living per cent coverage in the other damaged strips, but in KF-E it showed an increase in living per cent coverage. *Trifolium dasyphyllum*, *Oreoxis alpina*, *Silene acaulis*, and *Carex rupestris*, all showed marked increases in per cent coverage in the damaged KF plot. The major portion of damage in the *Kobresia* meadow community was apparently absorbed by the *Kobresia* itself.

Importance Values for the seven most important plants in each strip are given in Table IV.

In each 10 m × 1 m study area the ten quadrats were analyzed for percentage similarity (P.S.). The fifth quadrat, counting from west to east, was arbitrar

TABLE IV

First Seven Importance Values for Living Plants in the Six Study Strips.*

	FS-C	FS-E	FF-C	FF-E	KF-C	KF-E
1.	*Selaginella densa* (15.64)	*Geum rossii* (19.46)	*Kobresia myosuroides* (22.35)	*Kobresia myosuroides* (14.87)	*Kobresia myosuroides* (55.30)	*Kobresia myosuroides* (48.75)
2.	*Geum rossii* (14.62)	*Carex rupestris* (12.59)	*Selaginella densa* (14.93)	*Geum rossii* (12.94)	*Geum rossii* (28.34)	*Geum rossii* (17.24)
3.	*Silene acaulis* (13.58)	*Selaginella densa* (11.53)	*Carex rupestris* (13.47)	*Carex rupestris* (11.72)	*Artemisia scopulorum* (15.05)	*Carex rupestris* (16.50)
4.	*Arenaria obtusiloba* (12.84)	*Phlox pulvinata* (11.38)	*Geum rossii* (13.30)	*Selaginella densa* (11.65)	*Carex rupestris* (14.99)	*Selaginella densa* (14.97)
5.	*Phlox pulvinata* (12.48)	*Oreoxis alpina* (10.47)	*Hymenoxys acaulis* (12.08)	*Phlox pulvinata* (10.64)	*Selaginella densa* (14.52)	*Arenaria obtusiloba* (14.25)
6.	*Paronychia sessiliflora* (12.31)	*Haplopappus pygmaeus* (10.41)	*Arenaria obtusiloba* (11.83)	*Arenaria fendleri* (10.37)	*Polygonum viviparum* (13.98)	*Polygonum viviparum* (11.51)
7.	*Carex rossii* (12.19)	*Paronychia sessiliflora* (10.23)	*Carex rossii* (11.01)	*Arenaria obtusiloba* (10.27)	*Arenaria obtusiloba* (12.02)	*Festuca brachyphylla* (11.10)

* I.V. obtained as indicated on page 103.

chosen as the reference community, and was compared with the others by the following formula:

$$P.S. = \frac{2\omega}{A+B}$$

where: A = sum of the absolute coverages of community components of quadrat 5

B = sum of the absolute coverages of community components of any other of the ten quadrats.

ω = sum of the lesser coverage values of the community components that A and B have in common.

The results of the test are summarized in Table V. The percentage similarity among 1 m × 1 m quadrats in any study area differed greatly, depending upon whether one used coverage of vascular plants, dead or alive, alone (the community), or whether one used coverage of vascular plants together with bare soil, rocks, rock lichens, and soil lichens (more properly, the ecosystem), in calculating the numbers. It was found that the P.S. was greater for any set of quadrats when the last-mentioned components were added to the 'community,' to comprise an 'ecosystem' as the basis for calculations. Bray & Curtis (1957) considered a P.S. of 80 as being indicative of identical communities. This figure is approached (as a mean) in our FF and FS quadrats only when the 'ecosystem' concept of calculation is applied. The broadened concept of coverage categories, therefore, seems more useful than the narrow view in an understanding of damage.

Reference to Table V shows that mean P.S. is greater in FS-E (80) than in FS-C (68). This difference may be the result of the high coverage in the bare soil category in all quadrats of FS-E, as a result of removal of rocks and direct snowmobile damage. The greater

TABLE V

Percentage Similarity (P.S.) of Sample Plots. Based on Dead and Living Plant, Bare Soil, Rock, Soil Lichen, and Rock Lichen, Coverages.*

Control (C) or Experimental (E) Plot	Community Type		
	Sloping Fellfield (FS)	Flat Fellfield (FF)	Flat *Kobresia* Meadow (KF)
E	80 (72–87)	81 (74–86)	65 (57–73)
C	68 (54–79)	72 (56–91)	57 (44–69)

* Numbers in parentheses are P.S. ranges; mean P.S. for plot is the figure above those in parentheses.

uniformity in FS-E can be interpreted as the result of extensive damage to the original community. A similar relationship exists between FF-C and FF-E. Again, the greater mean P.S. in the E quadrat can be explained by reference to extensive bare-soil coverage attendant upon rock removal and vegetation loss. The Flat *Kobresia* meadow quadrats (KF-E and KF-C) show lower P.S. figures than their respective fellfield counterparts. These data may be interpreted as reflecting, in the case of the E quadrats, a less severe snowmobile impact and the lack of human interference (i.e. no ock removal). In the case of the C quadrats, the large mounts of 'rock,' 'bare soil,' 'soil lichens,' and 'rock ichens,' in the fellfield communities (FS-C, FF-C), may ave contributed heavily toward a general uniformity, which resulted in high P.S. values. KF-C was mostly overed by living plants, which comprised many different species. It is likely that the distribution of coverage among the many species (each recorded as a separate entity, as opposed, for example, to the lumping of all soil lichens in the category 'soil lichens'), contributed to the lower P.S.

In an attempt to understand the effects of snowmobile travel and rock removal on the absolute coverage of the vegetation of the three ecosystems studied, a statistical analysis was undertaken. In each ecosystem the absolute coverage of each vegetational component of the control area strip was compared with that of the damaged area strip. The coverage, for each quadrat, was converted to logarithms to equalize variance of strips in the two areas and a t-test was performed on the transformed data (Sokal & Rohlf, 1969). Table VI lists values of t for statistically significant components of the three ecosystems. The results are considered statistically significant if the hypothesis of equal coverage is rejected at the 0.05 significance level. 'Strongly significant' is used for the 0.001 significance level.

TABLE VI

t-Values for Comparison of Damaged and Control Areas for Plant Components of the Three Ecosystems†.

Plant Components	Ecosystems FS	FF	KF
Soil lichens	10.87***	12.71***	.38ns
Rock lichens	4.31***	7.07***	—
Dead plants (unidentified)	2.83*	.18ns	—
Kobresia myosuroides (alive)	—	2.51*	1.27ns
Selaginella densa (dead)	5.61***	1.91ns	.66ns
Selaginella densa (alive)	2.59*	2.46*	1.01ns
Arenaria fendleri	2.85*	.78ns	—
Arenaria obtusiloba	4.17***	3.47**	2.16*
Phlox pulvinata	2.90**	1.04ns	—
Carex rupestris	.69ns	2.59*	.65ns
Hymenoxys acaulis	—	5.53***	—
Polygonum viviparum	—	—	3.65**

† ns = not significant; line (—) indicates absence of species from ecosystem or insufficient coverage for the test. If any vegetational component had insufficient coverage for all the ecosystems, then the test was not performed. No vegetational component was listed unless it had a change of coverage that would be significant at the 0.05 level in at least one ecosystem. Other notations as follows:
* = t significant at 0.05 level, 18 degrees of freedom.
** = t significant at 0.01 level, 18 degrees of freedom.
*** = t significant at 0.001 level, 18 degrees of freedom.

In general, the statistical analysis of data on vegetation coverage supports the interpretations of snowmobile effects (*sensu lato*) suggested by the other methods of analysis used. In the FS area, differences in the soil lichen and rock lichen coverages were strongly significant. Low matted and cushion-plants (*Selaginella*, *Arenaria* spp., etc.) also showed strongly significant differences in coverage. In the FF area, again, soil lichens and rock lichens showed st ongly significant differences in coverage due to snowmobile travel. Here cushion and matted plants did show some significant differences in coverage, but none (with the exception of *Hymenoxys acaulis*) was highly significant. *Kobresia* (living) showed significant differences in coverage only in the FF area. These data may be interpreted as supporting the contention that damage to cushion- and mat-plants is reduced when *Kobresia* is present. In the KF area the ecosystem s owed minimal change as a result of snowmobile travel. The significant difference in *Polygonum viviparum* coverage may be unrelated to snowmobile impact but due instead to differences in winter snow-cover associated with the snow-drift observed on FF-C.

DISCUSSION

Nature of Snowmobile Impact

The snowmobile effects damage to plants in many ways. One source of destruction is the scraping of the soil, where snow is lacking, by the skis and rubber treads. This removes soil lichens, rock lichens, and such plants as *Selaginella densa*, and causes damage to the leaves of taller plants. Damage also results from the gouging of the soil by wear-rods under t skis as the front of the vehicle drops after having achieved a high point. Gouged areas were noticed at various sites along the snowmobile route. No plants survived in the heavily-gouged areas.

The weight of the snowmobile and driver causes breakage of stems and the crushing of leaves even when there is some snow-covering. These effects from foot travel were studied by Marr & Willard (1970) and by Scott-Williams (1967) for similar plant communities. Increased torque against the ground, in areas where the snowmobile stalls and then starts up or accelerates rapidly, causes damage to or removal of plants. Vegetation is often completely missing from these areas. Moguling, or the tendency of the vehicle to accentuate undulations in topography, may also cause damage to plants (Ralph Greene, pers. comm.).

Effects of Snowmobile Impact

In general, snowmobile travel has the effects of increasing the amount of bare-soil coverage in a community, decreasing the coverage of living vascular plants, and decreasing the coverage of soil lichens and rock lichens. For the most part, plant reaction to sno

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mobile traffic can be evaluated in terms of differential destruction of mature individuals of plant species. Seedlings, while encountered occasionally, play a minor role in plant coverage in both damaged and control quadrats. Marked shifts in per cent coverage of plant species (Table III) between damaged and control plots in the same community can often be attributed to differential survival of mature plants of certain species and destruction of others.

Assessing reactions of plant species to snowmobile damage is greatly complicated by the presence of small and large rocks, which often shelter plants. It was noted that plants growing near remaining rocks in the snowmobile route were able to survive when all the plants around them had been destroyed. There was little species-correlation with survival under those circumstances. Casual observations of the rock-free, most heavily damaged sites in the cushion-plant communities usually revealed the survival of *Geum rossii*, *Lloydia serotina*, and, less often, *Bistorta bistortoides*. The first species has an apical meristem at the soil surface, surrounded by fleshy leaf-bases. The latter two have apical meristems located below the soil surface, where they are little subject to the effects of the snowmobile. This is especially true of *Lloydia*, which may have bulbs a few inches below the soil surface.

In the cushion-plant community where *Kobresia* was entirely lacking, heaviest reduction in coverage occurred to depressed, semi-woody plants with stems and winter buds exposed above the soil level, e.g. *Arenaria obtusiloba*, *Silene acaulis*, and *Paronychia sessiliflora* var. *pulvinata*. *Phlox pulvinata*, which is less woody, showed less reduction in coverage. Those plants which bear their winter buds at the soil surface, protected by dead parts, and those which bear their buds below the soil surface, are least susceptible to snowmobile damage in this community. This would explain the increased coverage of graminoids and rosette plants in damaged sites in the FS area. Scott-Williams (1967) found similar destruction of cushion-plants due to extensive foot impact.

In the cushion-plant community where *Kobresia* was present, that plant suffered the greatest destruction due to snowmobile traffic. This destruction was reflected in the large percentage of dead *Kobresia* in the damaged plot. Some cushion-plants showed reduction in per cent coverage owing to damage in this community; but the effect was not as marked as in the *Kobresia*-free cushion-plant community. *Kobresia* forms dense, resistant clumps of basal sheaths (tussocks) which often surpass the surrounding vegetation in height. Isolated *Kobresia* tussocks apparently do not bend with the impact of the snowmobile and are subject to the full force of the vehicle in this community.

The effects of the snowmobile traffic were least noticeable in the densely-vegetated *Kobresia* meadow community. Again, *Kobresia* suffered heaviest destruction; but destruction was much less severe than in the cushion-plant community. This may be due to the almost continuous mat which the *Kobresia* tussocks form here. Apparently, even in the absence of snow, the skis and track of the snowmobile travel on the tops of the mass of tussocks where little resistance is evidenced. Most of the damage to *Kobresia* in KF-E occurred in sites where *Kobresia* patches grew on small, sharp rises in topography (as, for example, where a prominent rock was covered with vegetation) or where isolated patches of *Kobresia* were surrounded by vegetation that was much lower in stature. Willard & Marr (1970) similarly recognized the excellent resistance of *Kobresia* meadow vegetation to foot impact. They presented a detailed analysis of the patterns of disturbance.

It should be noted that the snowmobile damage to the vegetation on Niwot Ridge was probably of greater severity than would be expected from undirected recreational travel. Recreational drivers would be expected to avoid snow-free areas wherever possible, thus reducing, considerably, the impact on vegetation. Also, it is unlikely that large numbers of stones would be removed by random travel on those snow-free areas. Willard & Marr (1970) noted erosion of top-soil and destruction of plants adjacent to sites from which stones had been removed. Destruction of the community is therefore thought to be accelerated by the removal of stones. Nevertheless, this study does indicate the patterns of damage that are to be expected when snowmobiles travel on snow-free alpine tundra areas.

CONCLUSIONS

(1) In communities that are snow-free in winter, damage by snowmobiles was severe to lichens, *Selaginella*, and to relatively prominent, rigid cushion-plants. Part of the damage to these communities in the present study may have been due to the manual removal of rocks, necessary for the operation of snowmobiles in snow-free areas.

(2) *Kobresia*, present in isolated tussocks in a cushion-plant community, absorbed the major portion of snowmobile impact. As *Kobresia* is thought to form the climatic climax community in this ecosystem, differential damage to it should seriously retard succession.

(3) Snowmobile travel on uniform, closed *Kobresia* meadows inflicted much less damage to most plants, including *Kobresia* itself, than did similar travel on a sparsely vegetated community.

(4) Plants best able to survive the heaviest snowmobile impact were those with small stature and little

woodiness, or with buds well-protected at or below the soil surface.

(5) Snowmobile traffic should be carefully restricted to snow-covered areas. Whenever this is not feasible, the least destructive and easiest alternative is travel on mature, well-vegetated *Kobresia* meadows or similar well-drained plant communities.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Dr Jack D. Ives, Director of the Institute of Arctic and Alpine Research, for financial and logistic support, and to Mr Ralph Greene, former manager of the INSTAAR Mountain Rearch Station, for providing records of snowmobile travel, for valuable information on snowmobile performance and surface impact, and for reading the manuscript. The authors also wish to thank Mr Patrick J. Webber for many valuable suggestions during the course of the field work and for reading the manuscript, Mr Charleton Loder for help in many aspects of the research, Miss Regina Bogdanski for her untiring secretarial and technical assistance, Mr Rolf Kihl for an exhaustive soil analysis, and Dr James Campbell for critically reading the manuscript.

This project was supported by an NSF grant to the Institute of Arctic and Alpine Research, University of Colorado and, partially, by NSF Grant GY-8559, to A. M. Greller.

SUMMARY

This paper describes the effects of 1,020 passages of snowmobiles, made over two winters, on three regularly winter-snow-free alpine tundra plant communities. A cushion-plant community on a 7-degrees slope showed a 31% reduction in total living plant coverage due to snowmobile impact. Destruction was greatest to soil lichens, rock lichens, and the cushion-plants *Arenaria obtusiloba*, *Arenaria fendleri*, *Paronychia sessiliflora* var. *pulvinata*, *Silene acaulis*, *Eritrichium aretioides*, and *Phlox pulvinata*. Graminoids generally survived to increase in importance. On a flat site, a cushion-plant community with *Kobresia myosuroides* as its most important species, showed the greatest loss of living-plant coverage, namely 46%. This was due primarily to the destruction of *Kobresia*, although *Selaginella densa*, *Arenaria obtusiloba*, *Hymenoxys acaulis*, and *Eritrichium aretioides*, also showed heavy losses. In a *Kobresia* turf community, destruction was decidedly less severe than in the cushion-plant communities, reduction in total living plant coverage being only 19%. It is suggested that the closed nature of the *Kobresia* turf, with its stiff tussocks, enables it to absorb impact well. It is recommended that snowmobile travel be confined to *Kobresia* or similar turfs when such travel is necessary under snow-free conditions.

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