Likely impacts of snow grooming and related activities in the West Otago ski fields

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CONTENTS

Abstract

Concern has been expressed over the possible effects of snow grooming and related activities on vegetation and soil properties in those ski fields on Department of Conservation Recreational Reserve land in West Otago. A comprehensive review (including an annotated bibliography) was made of the overseas and New Zealand literature in order to assess the likely impacts associated with winter recreational activities (especially snow grooming) on vegetation and soil in alpine and sub-alpine environments. The review highlights both the indirect and direct effects arising from snow grooming and snow-pack compaction. In the latter case, heat flow rates, and length of snow retention are observed to increase, while porosity, permeability, and water holding capacity decrease. These effects flow through to the soil in the form of increased frost penetration, and prolong the time the soil remains frozen. These can in turn alter soil microbial activity, and the composition of plant communities through changes in the length of the growing season and soil moisture availability. Based on the literature review and site visits to Coronet Peak, the Remarkables, and Treble Cone ski fields, greatest damage is likely to be sustained by cushion plant communities on convex slopes and hummock crests, but tussock plants can be compressed and decapitated by grooming and skiing wherever the snow pack is thin. Recommendations are made for establishing a vegetation and soil monitoring programme using relocatable marked transects at selected groomed and ungroomed sites in the West Otago ski fields.

1. Introduction

In 1995, Landcare Research was approached by the Department of Conservation to submit a proposal to assess the environmental impacts of recreational snow activities at the West Otago ski fields of Coronet Peak, the Remarkables, and Treble Cone, all of which are on DoC Recreational Reserve land. This arose because of concern expressed over the possible effects of snow grooming and other snow cat activities on sub-alpine and alpine vegetation and soil properties. The major issue was whether managers need to place limits on commercial ski activities, especially in below-average snow years. It was recognised that any constraints in operations would need to be backed up with properly researched data. Some of the specific concerns raised were:

- The extent and nature of vegetation damage in highly sensitive areas such as cushionfields and wetlands, and whether this was likely to be permanent or temporary.
- Whether some species or communities are more sensitive to disturbance than others.

- Whether there is a snow thickness threshold below which grooming and other activities should not be permitted.

A proposal outlining a 4 year research plan was duly submitted. In the first year it was proposed to undertake a comprehensive literature review to establish the nature and scope of the problem, and to set up of preliminary field trials for a comprehensive vegetation and soil monitoring programme. In subsequent years the monitoring programme was to continue, with the possibility of conducting trials using snow groomers and cat ski vehicles under controlled field conditions.

Approval was given to proceed with a 1 year pilot study commencing in July 1995.

2. Objectives

The objectives of the pilot study were:

- To conduct a comprehensive review of overseas and New Zealand literature to assess the likely impacts associated with winter recreational activities (especially snow grooming) in alpine and sub-alpine environments on vegetation and soil.
- To assemble this information in an annotated bibliography.
- To summarise the findings.
- To visit ski fields on DoC Recreation Reserve land in West Otago in the summer to identify at-risk areas such as cushionfields and wetlands, and other areas subjected to frequent snow grooming, and to provide a preliminary assessment of vegetation and soil disturbance.
- To make recommendations on the basis of the literature review and the site visits for a monitoring programme to establish quantitatively the nature and extent of disturbance attributable to these activities.

3. Literature review with summaries

3.1 ENVIRONMENTAL IMPACTS OF OVER-SNOW VEHICLES

Snow groomers are designed to move on top of the snow surface and therefore have a large track surface area-to-distributed weight. For the two common Kassbohrer groomers used in the West Otago ski fields (types 260D and the heavier 330), the weight-to-track surface area relationship is about 0.05 kg cm^{-2}. Despite this favourable weight-to-distribution ratio, overseas research clearly demonstrates that over-snow vehicles such as snow groomers **do** have a substantial and lasting impact on vegetation and soil (e.g., Bayfield 1971, Keane *et al.* 1980). The effects may be direct, i.e., where actual contact is made between the vehicle and the surface, or indirect through snow compaction.

Much of the early research on this topic and especially that conducted in the 1970s, refers to impacts arising from snowmobile activity. These machines are rare in New Zealand and are normally confined to tracks and trails. However, the resultant impacts on the snowpack, and thus on the underlying vegetation and soil, are likely to be similar to those arising from snow grooming. Thus extensive reference is made in this review to the role of snowmobiles in causing changes to vegetation and soils.

The literature on the environmental impacts of vehicles in cold climates also discusses impacts associated with all-terrain vehicles (ATVs) across alpine and arctic tundra surfaces where there is no protective snow cover (Appendix 1). This gives an indication of the degree of impact likely to be associated with snow groomers and snowmobiles where snow cover is locally absent.

3.2 SNOW COVER PRESENT

Of all the snow management practices on ski fields, snow compaction has the greatest influence on snowmelt and runoff. As Kattelmann (1985a) explains, snow grooming mechanically alters snow grains and redistributes them. This mechanical disturbance breaks off the small points of new snow crystals, destroying the weak existing bonds between them, and bringing the new grains into much closer contact than occurs naturally. Snow metamorphism is artificially accelerated, and snow density and hardness are increased. In addition, the layered structure of the snowpack is changed. All this has both thermal and hydrological implications, which in turn impact on the soil and vegetation.

The greatest increase in compaction occurs in the initial pass of a vehicle or skier. For example, Keddy *et al.* (1979) found 75% of the compaction occurred in the first pass of a snowmobile.

3.2.1 Thermal changes

The thermal conductivity (i.e., the rate at which heat energy passes through a unit area with a given temperature gradient) of the snow pack increases in proportion to the square of the density (Kattelmann 1985a). Pesant (1987) found the thermal conductivity of compacted snow to be 2.5 times higher than that of uncompacted snow with the density of the former being 58% higher. Snow density under a snowmobile track was 1.7 times that of the control areas, resulting in a heat flux 5 times that of undisturbed snow (Pesant, 1987).

3.2.2 Hydrological changes

By compressing snow grains closer together, snow permeability and porosity are reduced. This change in snow pore space and crystal structure results in reduced water holding capacity of snow. This reduces the snow's ability to slow down the rate of runoff and to moderate the effects of thawing in spring (Neumann & Merriam, 1972). Some workers have found that snow compaction increases the duration of snow lie in the spring (Kattelmann, 1985b; Ives, 1974). However, when it occurs snowmelt runoff may be rapid because water does not take time draining through the profile.

Neumann and Merriam (1972) found the water holding capacity of snow under snowmobile tracks to be reduced by 70% near the surface and 40% at depth.

In summary, snow compaction:

- Is greatest in the first pass.
- Increases snow density.
- Decreases snow permeability and the ability of liquid water to drain through the profile.
- Reduces porosity of snow resulting in snowmelt runoff occurring more rapidly.
- Increases heat flow through snow, leading to colder snow and soil temperatures.
- Increases snow retention in spring.
- Changes snow pore space and crystal structure resulting in reduced water holding capacity of snow which reduces ability of snow to slow runoff and to moderate effects of thawing in spring.

3.3 IMPACTS OF SNOW COMPACTION ON SOIL

During compaction, the snow is pressed against the soil surface thereby removing the insulating layer of air which would otherwise reduce heat loss from the soil to the atmosphere. These reduced temperature gradients through the snow result in increased frost penetration into the soil (Wanek 1971) and prolong the time that the soil is frozen. For example, the A-horizon under compacted snow froze approximately one month earlier and thawed 2–3 months later in the spring. The soil also tends to thaw at the surface, rather than uniformly through the profile, leading to overwetting and thinning of the thawed surface layer.

Soil temperatures under snow on ski slopes can be 5–7 times colder and frost penetration 7–11 times greater than on control slopes (Baiderin 1983). The freezing depth of undisturbed soil was 15 cm compared with a maximum of 104 cm under compacted snow. In areas that experience the combined effect of winter and summer recreational loads, freezing depth increased to 165 cm (Baiderin 1980). Soil surface temperatures can be 2–11°C cooler than beneath snow (Wanek 1971, Foreman *et al.* 1976).

A significant hydrologic effect of deep soil freezing under compacted snow arises from the additional time required for complete thawing compared with undisturbed soil. The zone of water at or near the soil surface where it becomes immobilised by freezing is one of the important characteristics of frozen soils. The moisture content of frozen soil approaches the saturation point with a range 2–3 times higher than the unfrozen portion of the profile (Pesant 1987). However, this is probably not a major problem in New Zealand where the depth of soil freezing is unlikely to exceed 50 cm even in high alpine areas.

Changes in the soil temperature regime and decreases in organic matter and soil pore space can affect soil organisms. Colder temperatures under snowmobile tracks were the presumed cause of a 100-fold reduction in soil bacteria and a 2- to 10-fold reduction in soil fungi (Wanek 1971). Similar reductions could be expected where snow is compacted by groomers.

Schrind (1971) describes the effects of mechanical compaction by snowmobiles upon the subnival microclimate and concludes that the reduced insulative qualities are the major causative factors in the destruction of the microclimate. By reducing temperature gradients within the snow, compaction can have a significant impact on soil organisms inhabiting subnival environments. Snowmobile-induced snow compaction can result in bacterial activity being delayed by two weeks in spring. The increased snow density and changes in thermal conduction result in slower snowmelt, which may impact on bacterial decomposers. Litter decomposition may therefore by significantly affected (Neumann and Merriam 1972). Meyer (1993) found that the use of grooming machinery on ski runs in Austria reduced the abundance of the whole soil fauna by 70%.

In summary, snow compaction by snowmobiles and groomers affects soil by:

- Decreasing soil temperature.
- Increasing frost penetration in soil.
- Increasing the time that soil takes to thaw.
- Causing soil to thaw at the surface rather than uniformly through the profile, leading to overwetting and thinning of the thawed surface layer.
- Increasing snow density and thermal conductivity, resulting in slower snowmelt, which in-turn impacts on bacterial decomposers and litter decomposition.
- Retarding sudden snowmelt which is likely to cause changes in vegetation composition through changes in length of growing season and soil moisture distribution, and increases in soil erosion by wind, water and needle ice.
- Reducing temperature gradients within the snow which can impact on organisms inhabiting the subnival environments through increased metabolic requirements.
- Causing a 70% reduction in abundance of whole soil fauna.

3.4 IMPACTS OF SNOW COMPACTION ON VEGETATION

Snowmelt occurs later and tends to be more rapid on compacted ski areas compared with undisturbed areas. Thus irrespective of whether actual surface damage occurs, over a period of years it is probable that retarded snowmelt will cause a change in the composition of affected plant communities through changes in (a) the length of the growing season, (b) soil moisture distribution, and (c) soil erosion by wind, water and needle ice (Hamilton 1981, Price 1985).

The colder temperatures under compacted areas retard the growth and flowering of early spring flowers and reduce their seed productivity and viability. In addition, perennial herbs with large underground storage organs often perish due to intracellular ice crystals producing cytolysis (Wanek 1974).

Surface compression at moist tundra sites resulted in the replacement of shrubs and mosses by hydrophytic sedges (Emers *et al.* 1995). Felix and Raynolds

(1989a) found that the compression of the vegetative mat was one of the main vehicle impacts in moist sedge shrub tundra. In Europe, workers have found that snow grooming can damage plants by causing oxygen deficiencies in the soil (Newsely *et al.* 1994). Snow compaction induces low temperatures in the subnival environment through the pressing of free water into snow pores at low layers. This forms an ice layer at the soil surface (Price 1985), which stops the oxygen supply to the soil. Plant growth can also be retarded through starvation when prolonged snow cover prevents vascular plants from photosynthesizing. Prolonged snow cover as a result of snowmobile use or snow grooming can also retard seed germination so that some species cannot complete their life cycle. (Wanek 1971, 1974).

Plants can lose their frost resistance through prolonged snow lie, and become easily damaged at low temperatures after the snow melts (Larcher 1985). Other workers (e.g., Wanek 1971, 1974) found that snow compaction by snowmobiles can kill plants or render them more prone to disease as a result of the induced lower temperatures. Woody plants also become more susceptible to breakage at low temperatures.

Snow compaction also reduces plant cover (Reynolds 1982, Felix and Raynolds 1989a, b), and can change species composition (Baiderin 1980, 1983, Bayfield 1980, Emers *et al.* 1995, Tischendorf 1975 (in Grabherr 1985), Pignatti 1993). Plants have different levels of vulnerability and ability to recover from the effects of snow compaction. The characteristics which determine their vulnerability are the timing of flowering, and growth form and size. Prolonged snow lie adversely affects early spring flowering perennials and ephemeral plants as they have a shorter growing season. Baiderin (1980, 1983) observed in Russia that early spring flowering plants dropped out of the plant community and were replaced by later flowering species.

Erect woody plants are most vulnerable to damage by over-snow vehicles, especially when the woody stem protrudes out of the snowpack (Forbes 1992, Rickard and Brown 1974). Irrespective of snowpack type, climate and over-snow vehicle used, sedge communities are least vulnerable to adverse impacts whilst evergreen shrubs and mosses are more vulnerable (Emers *et al.* 1995, Felix and Raynolds 1989a). In Europe, high alpine grasslands are considered to be the most resistant plant community whilst mire communities are very sensitive (Bayfield 1980). Small plants with buds well protected at or below the surface, with little woodiness are considered to be the least affected. Where the snowpack is minimal, leaves of taller plants and prominent rigid cushion plants are damaged whilst individual tussocks are decapitated, lichens removed, and soil scraped by vehicle treads (Greller *et al.* 1974).

It is generally recognised that disturbance to soil and vegetation by over-snow vehicles is reduced as snowpack depths increase. Studies in the Alaskan tundra where winter seismic vehicles are used showed a 25–30% decrease in plant cover where tussock tundra plots had a snow depth of only 25 cm, whilst a 45 cm snowpack was required to reduce disturbance further (i.e., <25% decrease in plant cover). However, moist sedge-shrub tundra was more sensitive to disturbance, requiring a 72 cm snowpack depth before such low levels of disturbance were observed (Felix and Raynolds 1989b).

In summary, the main impacts from snow compaction on vegetation include:

- Short-term increase in litter and bare ground.
- Changed plant composition.
- Upland dwarf shrub-sedge-heath damaged more by compaction than wetland sedge.
- Non-vascular plants (e.g., mosses) and evergreen shrubs suffer more than graminoids and tend to be replaced by sedges.
- Prolonged snow cover starves vascular plants.
- Snow compaction may induce plants to lose their frost resistance due to increasing snow lie.
- Sub-zero temperatures make shrubs more prone to snapping rather than bending.
- Compaction slows early spring growth and vigour.
- Changes in plant composition with early spring flowerers being adversely affected.
- Alpine meadows and wetlands, and rocky soil vegetation (cushionfields) are most vulnerable to permanent destruction.
- Rhizomatous plants recover faster than others.
- Small plants with buds well protected at or below surface and with little woodiness are least affected.
- Plants show different levels of susceptibility to damage: evergreen shrubs > willows > tussock sedges > lichens.
- Tussocks often scraped off by vehicles and bare patches did not recover.
- If the root system is damaged recovery is very slow.
- From studies in the Alaskan tundra:
- Over-snow vehicles used on a >25 cm snow cover kept impact on tussock down to a 25–50% decrease in plant cover.
- For moist sedge-shrub a minimum snow depth of 35 cm was required to keep disturbance to a 25–50% decrease in plant cover.
- There was little disturbance (i.e., <25% decrease in plant cover) where snow depths exceeded 45 cm over tussock tundra and 72 cm for moist sedge shrub tundra.
- Most winter damage is in the vicinity of hummocks where soil and vegetation are more exposed.

3.5 DIRECT DISTURBANCE TO SOIL AND VEGETATION WHERE SNOW COVER IS SPARSE OR ABSENT

The use of snow grooming machinery on ski fields is likely to have the greatest adverse impact on soils and vegetation when it is used in areas of very little or no snow cover, such as at the start and towards the end of the ski season. Where a protective snowpack layer is not present there is no buffering of the vegetation from the weight and shearing effect of the moving vehicle's treads and blades. The resultant removal, breakage, or shearing off of vegetation leads to an increase in the proportion of bare ground (Price 1985). The weight of the machine compresses both vegetation and soil, resulting in decreased infiltration rates. Risk of soil erosion is increased (Grabherr 1985, Felix *et al.* 1992), especially by surface runoff and wind, aided by frost heave during frequent freeze-thaw cycles. This type of damage is most likely on convex slopes and crests of hummocks where snow cover is thin (Price 1985). The harsh alpine environment and short growing season makes regeneration of such damaged areas slow. Indeed, it may take over 1000 years for the soil and vegetation to become fully re-established after such damage (Bell and Bliss 1973).

Experience in Scotland has shown that the passage of vehicles or skiers over thawed soil surfaces results in vegetation and soil removal (Watson *et al.* 1970) with most damage occurring on exposed hummocks. Such bare patches then become desiccated, overheated and further eroded during the summer months. A study in Austria found that this resulted in a decline in the earthworm population of 85%, and in soil fauna biomass of 94% (Meyer 1993).

In North America, snowmobile use in a snow-free area of alpine Kobresia tussocks resulted in the leaves of taller plants and prominent rigid cushion plants being damaged. Differential damage to tussocks occurred in open tussocklands, resulting in serious retardation to plant succession. Areas with denser tussock cover experienced less damage (Bayfield 1980).

The degree of damage is influenced by vegetation structure. In Alaska, the passage of summer seismic exploration vehicles over Arctic tundra has lead to a decrease in vascular and cryptogamic species richness, a reduction in woody species and impaired dicotyledon seedling re-establishment (Forbes 1992). Woody species were worst affected, being replaced by monocotyledons. Lichens and mosses are especially slow in regenerating.

In recreational trampling experiments in subalpine North American ranges, Cole (1995) found that plant morphology played a major part in the way different plants respond to disturbances. Erect forbs were more susceptible to damage than caespitose or matted plants. Plants with perennating buds located above the ground surface were less resilient than other plants as these are the parts that are damaged. Bell and Bliss (1973) noted that most of the damage was done during the first pass.

Based on the foregoing and on additional information obtained during the literature survey (Appendix 1), the following general comments can be made with reference to situations where snow is absent:
The degree of impact increases with the number of vehicle passes, with most damage done during the first pass.
Saturated areas are damaged more than dry ones by ATVs.
Impacts were considered significant where the number of passes exceeded 25.

In summary, the effects of direct disturbance on soil can be:

- Decreased infiltration rates resulting in more surface runoff.
- Increased bare ground and soil erosion.
- Depleted amounts of C, K, and P.
- Increased levels of NO_3 and NH_4.
- Increased available soil PO_4.
- Reduced soil redox potential.
- Reduced exchangeable acidity.
- Higher levels of exchangeable bases (Ca, Mg, K, Na).
- Higher soil pH.
- Changed floristic composition.

- Reduced soil arthropod abundance although diversity may remain unchanged.
- Increased bulk densities.
- Increased soil temperatures.
- Accelerated and deeper soil thaw.
- Lower moisture percentages.
- Thawed surfaces are most altered.

The effects on vegetation can be:
- Reduced cover and altered floristic composition.
- Vascular biomass reduced by 88%.
- Very slow recovery if the root system is damaged.

The extent of damage depends on vegetation type, morphology, and anatomical features; for example:
- Tall shrubs were more susceptible than low growing plants and graminoids.
- Lichens and mosses took longer to regrow than other plants after damage by ATVs.
- Woody species were more vulnerable than forb meadow; sedge meadow was most resistant to disturbance.
- Caespitose, matted, rosetted hemicryptophytes and geophytes were more tolerant than chamaephytes (i.e., they have perennating buds above the ground surface).
- Matted and rosetted plants were more resistant than erect forbs and plants with perennating buds above ground.
- Prominent rigid cushion plants and leaves of taller plants were damaged.
- Wetter vegetation types were more severely affected than drier ones.

3.6 RESEARCH IN NEW ZEALAND

Only a few studies have been conducted to investigate the impacts of snow grooming on vegetation on New Zealand ski fields. At the Broken River ski field, in the Craigieburn Range, Canterbury, no significant difference in the groundcover or species composition of the *Chionochloa pallens/rigida* tussock grassland was noted after one season's use of a snow groomer on a deep snowpack (Wardle and Wardle 1992). At Turoa ski field in the North Island, 12 years of monitoring showed that tracked vehicles and skiers had produced a significant decline in total vegetation cover on alpine gravelfields and stonefields (Rogers and Kimberley 1990), probably reflecting a loss of the more fragile vegetation species. Arkwright (1984) concludes that the normal operation of the ski field at Turoa has caused no significant changes in species composition. Construction activity was observed to be degrading sensitive herb and prostrate shrub communities in the central lift area.

A vegetation monitoring programme was established on the Remarkables ski field basin in 1984, before the development of the ski field (Knight Frank 1994). Twelve transects were established to help gain an understanding of the impact of skifield development and ski related activities on the vegetation in the basin. These transects were re-monitored in 1988 and 1993. The results showed 50% of transects to have been modified through major earthworks during track formation. In one case suspected snow groomer damage increased bare ground and exposed rock. A decrease in mat plant abundance was observed on some transects. However, as these transects were established prior to knowing exactly where ski runs and grooming were to take place, it is not possible to attribute changes in vegetation cover with the specific impacts of snow groomers.

3.7 IMPLICATIONS FOR VEGETATION ON SKI FIELDS IN WEST OTAGO

Drawing on the literature review (Appendix 1) and observations made in the field (Appendix 2) the likely long-term impacts of snow grooming on vegetation at West Otago ski fields are summarised below:

- Physical damage (i.e., breakage or compression) to vegetation is most likely in areas of low snow cover especially crests of hummocks and convex slopes, leading eventually to an increase in bare ground and more dead vegetation.
- Change in species composition is likely, due to a reduction in vulnerable species and replacement by more resilient ones.
  Vulnerability can be a result of:
  - Phenology.
  - Early spring flowerers (e.g., *Abrotanella* sp., *Pimelea prostrata, Gaultheria depressa, Chionohebe* sp.) may have difficulty completing their reproductive functions when there is a prolonged snow cover and may die off.
  - Life form.
  - Woody and also herbaceous plants which have renewal buds less than 25 cm above the ground surface (i.e., chamaephytes) are vulnerable to physical damage by groomers where there is little or no snow. Such species include: *Dracophyllum pronum, D. uniflorum, Pimelea prostrata, P. oreophila, Chionohebe pulvinaris, C. ciliata, Gaultheria depressa.*
- Change in species composition can also be due to the slow rate of recovery of damaged species such as lichens.
- Tussock-forming vegetation, especially where it is not dense, is likely to be compressed (resulting in the centre of the plant dying off) or to be decapitated by groomers where there is no or very little snow.
- Species composition is likely to change even when there is a good snow depth, as grooming commences at the start of the ski season when there is less snow, and ski runs experience snow compaction every winter.

Whilst it is difficult to separate the impacts of snow grooming machinery from those induced by high skier numbers, the following observations were made during field visits to the West Otago ski fields of Coronet Peak, the Remarkables, and Treble Cone. Additional comments can be found in Appendix 2.

- The crowns of tussock vegetation (especially *Chionochloa macra, C. rigida, Celmisia lyallii*) appear to become flattened, resulting in the centre of the plant dying back. This was especially noticeable at Treble Cone and Coronet Peak.

- The cushionfield communities found on knolls and hummocks at Treble Cone appear to change in their species composition with lichens disappearing accompanied by an increase in bare ground and dead vegetation.
- *Dracophyllum* prostrate shrubs are flattened and branches snapped off (Coronet Peak, Treble Cone).
- Snow groomer track marks were observed on wetland vegetation in The Remarkables ski field and cushionfield vegetation at Treble Cone with exposed soils and compressed vegetation .

4. Monitoring programme

Based on the literature review and the the information collected during the field visits we believe that the potential for damage to vegetation and soil from snow grooming both directly and indirectly through snow compaction is sufficiently serious to warrant further more detailed analysis. Accordingly, we propose the following monitoring programme.

4.1 VEGETATION AND SOIL MONITORING PROPOSALS

4.1.1 Aim

To set up relocatable marked transects and photopoints to record any vegetation and soil changes associated with ski field activity, in particular snow groomer use. It may not be possible to separate the impacts of snow groomer use from high skier use, but the former will undoubtedly have a greater effect. In addition, impacts relating to stock grazing (at Treble Cone and Coronet Peak ski areas) may be indirectly recorded.

4.1.2 Characteristics to record

It is considered that any impacts of snow grooming on vegetation and soil will best be highlighted by the following characteristics:

- Ground cover (% vegetation, dead vegetation, bare ground, rock, litter).
- Species composition (noting whether a species is flowering or not).
- Species percentage cover.
- Biomass of tall vegetation.
- Depth of A-horizon.
- Soil bulk density.
- Soil penetration resistance.
- Soil shear resistance.
- Evidence of disturbance directly attributable to snow grooming.

4.1.3 Methods

The previously listed vegetation and soil parameters would be recorded along the established transects as early as possible in the summer and also before the onset of winter. These data will enable comparisons to be made of disturbance to vegetation and soils in both a temporal and spatial context. Differences between groomed and ungroomed areas should become readily apparent and any seasonal changes over the summer should also emerge as a result of the monitoring programme. With the onset of winter, snowpack depth and snow densities will be measured at selected groomed and ungroomed sites on the transects at monthly intervals.

Tussock grasslands

- Fixed line transects (total length 50 m) using Scott height frequency measurements to determine plant biomass at 0.25 m intervals along the transect, 5 cm vertical intervals.
- Point intercepts will be noted at 0.25 m intervals along the transects, giving a total of 200 samples. To record the first intercept among the following: live plant matter, dead plant matter, litter, bare soil, and rock.
- General survey will be made of species composition at the site, noting occurrence of exotic species and the nature and extent of groomer damage, plant form, etc. Groomer damage factors to be assessed include:
  - Erosion in areas damaged by groomer tracks.
  - Plants stripped from roots and soil.
  - Broken plants.
  - Cut marks on stems/foliage (from skis)
  - Tracks—crimps in soil.
  - Soil lifted by groomer tracks.
- Photopoints will be established where appropriate to monitor impacts at transect sites and other areas to enable relocation of transect with or without snowpack present.

Cushionfield and wetland vegetation

- Fixed line 10 m long transects will be established and information collected using a 5-pin frame at 25 cm intervals (giving a total of 200 points per community). The first intercept among the following will be recorded: plant species, dead plant material, litter, bare soil, or rock. Since the vegetation is normally not multi-layered, these data will enable calculations to be made of percentage cover of species and ground cover.
- General survey of species present at site and of groomer damage.
- Photopoints where appropriate to monitor impacts at transect site and other areas to enable relocation of transect with or without snowpack present.

TABLE 1. POSSIBLE MONITORING SITES AT CORONET PEAK SKI FIELD (SEE FIG. 1 FOR LOCATIONS)

DEGREE OF IMPACT	SKI RUNS WITH TUSSOCK GRASSLAND SITES
Frequently groomed (~every night) & heavily skied (500+/hr)	• Million Dollar • Shirt Front
Infrequently groomed (between 1–2 times/week) & moderately-heavily skied (100/hr)	• Walkabout • True left of Shirt Front
Not groomed & lightly skied (10–15/hr)	• Between Walkabout & Greengates
Not groomed & rarely skied (few people/season) (Control)	• South facing hillside of 1600 m peak, immediately NE of Coronet Peak summit (1651 m)

4.1.4 Sample sites

Coronet Peak

The vegetation at Coronet Peak is dominated by narrow leaved snow tussock (*Chionochloa rigida*), *Dracophyllum uniflorum*, false spaniard (*Celmisia lyallii*), and other native herbs. Some ski runs have been extensively modified involving earthworks to even out the terrain followed by over-sowing with exotic species. However, the areas of interest to this study are those slopes which are groomed, but are still dominated by native plant species (Appendix 2). Possible transect sites are listed in Table 1 and shown in Fig. 1.

Recommendation: Establish transects on slopes with little or no major modifications and with varying frequency of grooming. At least three transects at each site. Place each series of transects at 10 m intervals across the ski run.

The Remarkables

The main areas of concern here are impacts of on-going ski field developments on fragile alpine wetland communities (Appendix 2). The preliminary field visit identified five wetland areas between 1620 and 1770 m altitude. Three of these are identified on Fig. 2. They can be categorised according to their level of grooming and ski use, as outlined in Table 2.

Another area of concern to DoC staff at Queenstown is Doolans Basin (currently in pastoral lease), where a cat skiing operation has been proposed. The vegetation is cushionfield, wetland, grading into tussock grassland at lower altitudes. The site has not been visited but a series of fixed relocatable transects could be established on each of the plant communities where the cat skiing is to take place.

Recommendation: That transects be established in each of these wetlands, with the western extent of the Top Alta chairlift on Left Branch of Rastus Burn wetland and the transects in Doolans Basin acting as controls.

Treble Cone

At Treble Cone the issue of most concern is the impact of grooming on alpine cushionfields which retain little snow and are susceptible to damage. However, because tussock grassland is the prevailing vegetation on the slopes comprising

TABLE 2: POSSIBLE MONITORING SITES AT THE REMARKABLES SKI FIELD

DEGREE OF IMPACT	SKI RUNS WITH WETLAND SITES
Frequently groomed (~every night) & heavily skied (1000/hr)	• Alta Green wetland beneath Alta chairlift • Easy Out/Gotham City wetland
Infrequently groomed (between 1-2 times/week) & moderately heavily skied (100-400/hr)	• Water Race wetland—SW end (400/hr) • Mid Station of Shadow chairlift—S end (100/hr) • Top Shadow chairlift wetland (50-100/hr)
No grooming, moderately skied (20-100/hr)	• Water Race wetland—NE end (100/hr) • Mid station of Shadow chairlift—N end (20-30/hr) • Eastern extent of Top Alta chairlift wetland (Rastus Burn) (20/hr) • Homeward Bound (40/hr)
Infrequently/not skied, no grooming (Control)	• Western extent of Top Alta chairlift wetland, extending over creek. • Doolans Basin (cat skiing) (~5/day)

the ski field, grooming impacts on this community should also be assessed (Appendix 2).

The choice of location of transects is made difficult by the changing development history of the ski field, with much of it having been groomed at some time or during some part of a ski season. This reduces the choice of control sites (i.e., those that have not been groomed, or have been groomed only infrequently).

The preliminary field visit, however, identified a number of possible sample sites on both alpine cushionfield vegetation and snow tussock communities. They can be categorised according to their level of grooming and ski use, as outlined in Table 3.

However, in low snow years the lower mountain may have a minimal snowpack, but still be groomed and skied on. In recent years, the snowpack on these ski runs has been augmented by snow-making, thereby complicating the assessment of snow grooming impacts in these areas.

On the Upper Main Face, some ski runs have been terrain modified, with tussocks being replanted in some areas. The impact of snow grooming on such areas could be investigated using transects established on Easy Street plateau near top of Skite (terrain modified, groomed and skied) (Fig. 3), the area to true left of this site (sometimes groomed and skied), with control (no grooming, little skiing) at Saddle plateau, below bottom of Saddle T-bar station. These sites are not essential.

Recommendations:

- Establish monitoring sites comprising transects (preferably 4 per treatment) on areas of similar slope, aspect, etc., to measure relevant vegetation and soil parameters in representative areas of cushionfields and tussock.
- The transects established on ski runs with tussock grassland communities should be placed at 10 m intervals across the ski run, at each sample site.

The proposed transects at the three ski fields should be set up as early as possible after the snow has melted to ensure early flowering plants are

Figure 1. Suggested sites for transects at Coronet Peak: (a) near Million Dollar run west of Greengates (frequently groomed); (b) between Walkabout and Greengates (infrequently groomed); (c) northeast of Coronet Peak (ungroomed). Map based on NZMS 260 Series F41.

Figure 2. Suggested sites in the Remarkables ski fields for transects: (a) Alta Green (groomed regularly, and skied heavily); (b) Easy out/Gotham City wetland (groomed infrequently); (c) wetland on left branch of Rastus Burn (not groomed); (d) Mid-station Shadow chairlift (not groomed and moderately skied). Map based on NZMS 260 Series F41.

Figure 3. Suggested transect sites at Treble Cone: (a) Saddle area with tussock grassland sites (some areas groomed, others not); (b) Saddle area with cushion fields (some areas groomed, others not); and (c) Upper Main Face alpine cushionfields (some areas infrequently groomed, others not). Map based on NZMS 260 Series F40.

TABLE 3: POSSIBLE MONITORING SITES AT TREBLE CONE SKI FIELD

DEGREE OF IMPACT	SKI RUNS WITH TUSSOCK GRASSLAND SITES	SKI RUNS WITH ALPINE CUSHIONFIELDS
Frequently groomed (~every night) & heavily skied	• *Saddle Area*: Saddle run to Saddle chairlift base (~500/hr)	• *Saddle Area*: Between top of Saddle T Bar and High Street (~500/hr)
Infrequently groomed (between 1–2 times/week) & moderately-heavily skied	• *Lower Main Face*: Rollercoaster • *Lower Main Face*: Mid Wave (snowmaking too) (100/hr)	• *Upper Main Face*: Below track to true right of top T2 (i.e., top of Rollercoaster) (250/hr) • *Upper Main Face*: Old traverse from top T2 to Matuki Face (groomed 1/week)
Not groomed; moderately skied	• *Upper Main Face*: Powderbowl (250/hr) • *Saddle Area:*To side of Saddle run to Saddle chair base	• *Upper Main Face*: Below track to true right of top T2 (i.e., adjacent to T2, further downhill)
Not groomed; infrequently/not skied. (Control)	• *Saddle Area:* Further out to side of Saddle run to Saddle chair base • Towers Ridge sites (away from ski field and cat skiing) (<5/day)	• *Upper Main Face*: Above track at top of T2, eg. near tower 12 of new chairlift. • Towers Ridge sites (away from ski field area and cat skiing) (<5/day)

monitored. The transects should be re-visited in the main growing season (e.g., late January/early February) and again towards the end of the season (e.g., early March). This would ensure that all phenological and vegetative growth changes through the snow-free period are properly documented. During the ensuing winter selected transects should be checked for snow depths and density at regular intervals.

A similar monitoring programme is proposed for the following year. During the winter, it is suggested that trials involving pre-determined numbers of snow groomer passes over snow of known thickness be conducted, in collaboration with the ski companies. This would enable the identification of appropriate snow depths for groomers to operate on while ensuring minimum disturbance to vegetation and soil.

5. Acknowledgements

We wish to thank Neil Simpson, ex-DoC at Queenstown, and Dawn Palmer, DoC Queenstown Office for their advice and assistance in the field. Duncan Smith (Coronet Peak Ski Field) and Peter Thompson (Treble Cone Ski Field) provided information on grooming trails and frequency of use. David Price, Honours Graduate in the Department of Geography, University of Canterbury assisted in the preparation of the annotated bibliography. We also thank Trish Faulkner, Landcare Research Librarian, for her help in locating references for this report.

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Appendix 1

ANNOTATED BIBLIOGRAPHY

The list below represents a compilation of the important references discovered during a comprehensive bibliographic search conducted by the authors and staff in the Landcare Library at Lincoln. Some of the references were also located through a computer-based search undertaken by a student assistant at the University of Canterbury. Where possible each reference was read and a summary of the main findings was prepared. Not all references were able to be located, but they have been retained in the bibliography. The references come from a wide variety of sources (e.g., the scientific literature, internal reports, student theses), covering a range of recreational activities in low temperature environments, including snowmobiling, downhill skiing, summer trampling, and snow grooming. The information contained in these references forms the basis for the bibliographic review presented in the main body of the text.

Arkwright, S.R. 1984. The Turoa skifield development and impact. M.Sc. Thesis, Department of Geography, University of Canterbury.

Principal impacts to vegetation caused by skiing are loss of ground cover, changes in species composition, and lower reproduction rates. A vegetation monitoring programme was established in 1978 and the results indicate no significant reduction in vegetation cover between 1978 and 1980. In fact, the loss along the transects could have been the result of natural fluctuations in vegetation cover or possibly due to inadequacies in the monitoring programme. Since the programme included several areas of high winter usage, it can be concluded that the normal operation of the ski field has not resulted in substantial reductions in vegetative cover, nor were there any significant changes in species composition. There may, however, be some longer-term variations in species composition.

Baiderin, V.V. 1980. Experimental modelling of ecological consequences of winter recreations. *Soviet Journal of Ecology* 11(3): 140–146.

Found the degree of disturbance of thermal under-snow conditions of soil from skiing is directly proportional to the degree of compaction.
Snow compaction:

- *does not affect time of snow thaw;*
- *increases snow density (e.g. 0.22–0.23 g cm^{-3} for undisturbed snow compared with 0.52 g cm^{-3} for compacted snow);*
- *increases snow heat conductivity so atmospheric heat is transferred to soil sooner;*
- *decreases soil temperature;*
- *increases depth of frozen soil (e.g., freezing depth was 15 cm for undisturbed soil compared with a maximum of 108 cm under compacted snow);*
- *increases time for soil to thaw;*
- *soil under compacted snow thaws mostly on the surface, while soil under undisturbed snow thaws uniformly on surface and from bottom. Former leads to overwetting and thinning of thawed surface layer;*
- *early spring perennials and ephemerals late to bloom due to poor under-snow conditions;*
- *leads to vegetation change associated on ski runs. Summer and autumn flowering species have preferential distribution on ski slopes.*

Baiderin, V.V. 1983. Winter recreation and subnival plant development. *Soviet Journal of Ecology* 13(5): 287–291.

Snow compaction and redistribution of snowpack by skiers can result in soil erosion and vegetational changes due to disruption of winter subnival development of plants. Snow compaction:
- *increases snow density;*
- *causes a 5- to 7-fold lowering in soil temperature;*
- *causes a 7- to 11-fold increase in frost penetration;*
- *causes a change in plant phenorhythm and restructuring of plant communities.*

Distinguished three categories of plants on the ski slopes: suppressed, flourishing, and indifferent. Early spring plants were most frequently in the suppressed category; all autumn varieties were in the flourishing and indifferent categories (due to phenology of species).

Bayfield, N.G. 1971. Some effects of walking and skiing on vegetation at Cairngorm. In Duffy, E., Watt, A.S. (Eds), The scientific management of animal and plant communities for conservation. 11th Symposium of the British Ecological Society, University of East Anglia, Norwich, England.

Outlines field experiments to assess extent of trampling-induced disturbance and damage associated with winter and summer traffic, using photographic and tramplemeter observations and simulated snow trampling experiments. Found that:
- *impact transmitted through snow fell rapidly with increasing depth;*
- *a few cms depth of snow had an appreciable cushioning effect;*
- *dense snow (0.58 g ml^{-1}) had a more absorptive effect than light snow (0.09 g ml^{-1})*
- *when ski runs were covered in snow, considerable protection was given to vegetation beneath;*
- *where large snow-free patches or hummocks/ridges of uncovered ground appeared due to snow melt or wind erosion they were very susceptible to skier damage;*
- *snow compaction by skiers and groomers conserved snow since compacted snow melted more slowly than loose snow. Increase in size of late snow-lie due to compaction might have contributed to vegetation damage;*
- *ground surface topography exerts considerable modifying influence on the relationship between skier traffic and damage.*

Bayfield, N.G. 1979. Recovery of four montane heath communities on Cairngorm, Scotland, from disturbance by trampling. *Biological Conservation* 15: 165–179.

Summer foot trampling of vegetation experiment:
- *damage increased with level of trampling but some species showed delayed damage; substantial die-back occurred during following winter;*
- *most species recovered very slowly;*
- *observation over substantial period is necessary to assess responses of slow growing mountain vegetation to disturbance by trampling.*

Bayfield, N.G. 1980. Replacement of vegetation on disturbed ground near ski lifts in Cairngorm Mountains, Scotland. *Journal of Biogeography* 7: 249–260.

Discusses revegetation and regeneration of disturbed areas associated with ski lifts.
- *Native heather successful at lower altitudes.*
- *Bryophytes successful at all altitudes—up to 50% after 8 yrs.*
- *Most colonisers were also present in surrounding areas except roadsides where on-going disturbance favoured ruderals.*

Cole, D.N., Bayfield, N.G. 1993. Recreational trampling of vegetation: standard experimental procedures. *Biological Conservation* 63: 209–215.

- *A standard protocol for controlled trampling experiments is suggested. Procedure provided information immediately and after 1 yr.*
- *Changes in vegetation cover, vegetation height, bare ground cover and cover of individual species can be assessed.*

Cole, D.N. 1995. Experimental trampling of vegetation. II. Predictors of resistance and resilience. *Journal of Applied Ecology* 32: 215–224.

Experimental trampling experiments.
- *Plant morphology explained more of the variation in response to trampling than altitude, over-storey, canopy cover, or total ground-cover.*
- *Resistance was a function of vegetation stature, erectness and whether plants were graminoids, forbs, or shrubs. Caespitose/matted graminoids were more resistant than erect forbs.*
- *Resilience was a function of plant type, but hamaephytes (perennating buds located above ground surface) were less resilient than other plants.*
- *Tolerance (ability of plant to withstand cycle of disturbance and recovery)—Caespitose, matted, rosetted hemicryptophytes, and geophytes were more tolerant than Chamaephytes.*

Cole D.N., Trull, S.J. 1992. Quantifying vegetation response to recreational disturbance in North Cascades, Washington. *Northwest Science* 66(4): 229–236.

Trampling experiment, measuring immediate and post-1 year responses, of different vegetation types and intensities of trampling.
- *Sedge meadow was 25 times more resistant to trampling damage than subalpine forb meadow.*
- *Recovery during following year was greatest in forb meadow; lowest where dominated by woody species.*
- *Resilience to trampling depended on aerial arrangement of shoots, location and toughness of perennating tissues and by growth rate of regenerating tissues.*

Emers, M., Jorgenson, J.C., Raynolds, M.K. 1995. Response of arctic tundra plant communities to winter vehicle disturbance. *Canadian Journal of Botany* 73*:* 905–917

Non-vascular plants and evergreen shrubs were reduced by disturbance. Graminoids were less affected by disturbance. Where higher initial levels of disturbance there was:
- *surface compression at moist sites, with replacement of shrubs and mosses by hydrophytic sedges;*
- *persistence of bare patches in drier sites and replacement of prostrate shrubs with grasses;*
- *impacts last 8 years;*
- *wetter vegetation types usually were more severely impacted due to less resistance of substrate, but recovered faster due to greater nutrient fluxes in hydric soils and the presence of vegetatively reproducing species that competed more easily in relatively high nutrient areas;*
- *drier areas were less prone to damage, but took longer to recover due to their dependence on seeds as source of colonists—low moisture and nutrient regimes offered poorer conditions for seedling establishment.*

Felix, N.A., Raynolds, M.K. 1989a. The effects of winter seismic trails on tundra vegetation in NE Alaska, USA. *Arctic and Alpine Research* 21(2): 188–202.

- *Effects on seven major vegetation types assessed for 2–3 years after disturbance.*
- *Plant cover was reduced by up to 87% in the first summer following disturbance.*
- *Order of sensitivity was: evergreen shrubs > willows > tussock sedge > lichens.*
- *Little recovery was noted in 2nd and 3rd summers after disturbance.*
- *Moist graminoid/barren complex and tussock tundra were sensitive to winter vehicle damage as windblown snow cover often left hummocks and tussocks exposed. Small patches of bare soil commonly occurred where hummocks or tussocks had been scraped by vehicles.*

Felix, N.A., Raynolds, M.K. 1989b. The role of snow cover in limiting surface disturbance caused by winter seismic exploration. *Arctic* 42(1): 62–68.

Degree of vegetation disturbance was related to snow depth. In tussock tundra plots with snow depths over 25 cm there was significantly less disturbance than those with snow >25 cm deep. The relationship between snow cover and disturbance was less clear in moist sedge-shrub tundra.

Felix, N.A., Raynolds, M.K., Jorgenson, J.C. DuBois, K.E. 1992. Resistance and resilience of tundra plant communities to disturbance by winter seismic vehicles. *Arctic and Alpine Research* 24(1): 69–77.

Vehicle traffic over snow-covered tundra can cause long-term changes to plant communities which generally show less resistance within 4–5 years. The emphasis of management should be to minimise high levels of disturbance in all vegetation types (but especially moist sedge-shrubs) by avoiding areas of low snow cover, using light-weight vehicles in dispersed traffic patterns, and minimising sharp turns and steep grades.

Forbes, B.C. 1992. Tundra disturbance studies. I: long term effects of vehicles on species richness and biomass. *Environmental Conservation* 19(1): 48–58.

Summer use:

- *vascular and cryptogamic species richness are consistently reduced under a variety of low intensity disturbance regimes in different vegetation types;*
- *total vascular biomass was reduced in 88% of all stands;*
- *reductions were most severe among woody species. Where biomass of monocotyledons was increased, increases were more than offset by losses among dicotyledons;*
- *in mesic low-arctic meadows there were significant biomass increases among graminoids made up for losses among dicotyledons after less than 8 growing seasons;*
- *dicotyledon seedling re-establishment was virtually lacking on multi-pass tracks.*

Foreman, C.L., Ryerson, D.K., Walejko, R.N., Pendleton, J.W. 1976. Effect of snowmobile traffic on Bluegrass (*Poa pratensis*). *Journal of Environmental Quality* 5(2): 129–130.

Following snowmobiling:

- *no reduction in bluegrass stands occurred;*
- *slower early spring growth and vigour was apparent in snowmobile track areas compared with non-trail areas, but by early summer no visual differences were noted between tracked and non-tracked areas in stand, height, or colour of vegetation;*
- *soil bulk density measurements showed no soil compaction due to snowmobiling;*
- *soil surface temperature was 2–3°C lower under heavily travelled tracked areas than non-tracked areas.*

Gersper P.L., Challinor, J.L. 1975. Vehicle perturbation effects upon a tundra soil-plant system: I. Effects on morphological and physical environmental properties of the soils. *Soil Science Society of America Proceedings* 39: 737–746.

Summer use (i.e., no snow cover)
After six years:

- *soils had higher bulk densities and temperatures, accelerated and deeper thaw, and lower moisture percentages than undisturbed soil;*
- *soil morphology was little altered except for direct physical alteration of surface organic horizons and a slight increase in mottling of mineral horizons in all but the wetter portions of the track;*
- *thawed wet surfaces were most altered;*

Gersper P.L., Challinor, J.L. 1975. Vehicle perturbation effects upon a tundra soil-plant system: II. Effects on the chemical regime. *Soil Science Society of America Proceedings* 39: 689–695.

Summer use (i.e., no snow cover)
Six years after perturbation, soils within track scars had:

- *lower redox potential;*
- *lower amounts of exchangeable acidity;*
- *higher levels of exchangeable bases (Ca, Mg, K, Na);*
- *higher soil pH and base saturation;*
- *higher soluble nutrient (Ca, Mg, K, Na, NH^4-N) levels in soils solutions;*
- *higher soil solution pH;*
- *enriched nutrient environment which increased productivity;*
- *changed floristic composition;*
- *intensity of soil alteration and changes in soil/plant chemical regime was related to differences in natural drainage; scarring was worst where natural drainage was poor;*
- *slight amount of disturbance may be beneficial in terms of productivity and nutrient content of vegetation.*

Grabherr, G. 1982. The impact of trampling by tourists on a high altitude grassland in the Tyrolean Alps, Austria. *Vegetatio* 48: 209–217.

Even under light trampling the frequncy of sensitive species decreased. The most sensitive species were fruiticose lichens, followed by mosses, some forbs, and broadleaved glasses. Carix curvula *and* Ligusticum mutellina *(the dominant species) were tolerant to trampling. Trampling also increased soil bulk density, but had no influence on soil water content. Concluded that the results contradict the commonly held view that ecosystems with low diversity are much more sensitive than those with high diversity. However, if the resistant sedges were destroyed, the rate of recovery was very low, e.g., the rate of spread of the rhyzome system of* Carex curvula *was only 8 mm in 10 years. The fragility of the sedges reflected low regeneration rather than low tolerance.*

Grabherr, G. 1985. Damage to vegetation by recreation in the Austrian and German Alps. Pp. 100–111 in Bayfield, N.G., Barrow, G.C. (Eds): The ecological impacts of outdoor recreation on mountain areas in Europe and North America. *Recreational Ecology Research Group Report No.9*, 1985. (Available from Shirley Wright, Department of Horticulture, Wye College, Wye, Ashford, Kent, U.K.)

Ski run preparation leads to a consolidation of snow cover, resulting in an artificial thawing-out pattern, so that the time at which vegetation becomes snow free differs from that under natural conditions (Tischendorf 1975). This causes changes in plant growth and species composition.

Central Alps *2200–2300 m:*

Damage to vegetation is caused by smoothing out of ski piste terrain and by slicing- off action of ski edges and walkers' boots. Underlying bedrock can be exposed. ***Snow groomers can produce similar results.*** *Growth and reproduction of plants were not favoured by these processes. Repeated disturbance prevented re-establishment by seed production, a problem exacerbated by an almost total absence of annual species in alpine vegetation.*

Bavarian Alps*. this investigation of the effects of intensive skiing on vegetation of natural and artificial pastures found that:*

- *plant cover on ski pistes declined with increasing altitude;*
- *64% reduction in phaerograms in plant communities;*
- *few species (12%) from original vegetation cover re-colonised disturbed areas. Above 1400 m there were alpine ruderals;*
- *species diversity was lowest for those areas where ski piste surfaces had been levelled off;*
- *rain experiments indicated that the amount of runoff decreased exponentially with increasing root mass;*
- *soil loss was 10 times greater on piste surface than on semi-natural grasslands;*
- *most resistant plant communities were high alpine grasslands; dwarf shrub heaths were far more sensitive; mire vegetation was even more so.*

Compared with problems raised by ski piste construction, the vegetational disturbances by ski edges or heavy trampling by walkers were very minor. However, locally their intensity may increase to such a degree that genuine vegetation destruction does occur.

Greller, A.M., Goldstein, M., Marcus, L. 1974. Snowmobile impact on three alpine tundra plant communities. *Environmental Conservation* 1(2): 101–110.

Studied impacts of snowmobile traffic along fixed routes on alpine tundra (cushion-plants, rock, bare ground, and meadow vegetation). Snow-free for much of winter (wind blown); covered in snow in spring when wind velocities are lower.

- *Species ground cover measured.*
- *Where snow was lacking, soil scraped by treads, lichens removed; leaves of taller plants and prominent rigid cushion plants damaged.*
- *Breakage of stems and crushing of leaves, even with some snow cover.*
- *In open tussock land individual Kobresia tussocks were hard, leading to differential damage which should seriously retard succession.*
- *In uniform closed Kobresia meadows there is less damage.*
- *Those plants with buds well protected at or below soil surface and with little woodiness were least affected by snowmobiles.*
- *Recommended that traffic be restricted to snow-covered areas.*

Hamilton, E.H. 1981. The alpine vegetation of Marmot Basin, Jasper National Park, Alberta, and the impact of ski activities upon it. M.Sc. Thesis, University of Alberta, Edmonton, Alberta, 170 p. (available in the Landcare Library, Canterbury Agricultural and Science Centre, Lincoln)

Studied effects of skiing and snow grooming on the alpine ecosystem. Noted:

- *increased snow density;*
- *alteration of snowmelt patterns on skied and groomed areas.*

In most cases snow compaction resulted from snow densities that were still within the range of those normally found in alpine snowpacks. Thus it is unlikely that changes arising from increased snow packing would have a substantial effect on the underlying vegetation. Delayed snow melt from snow compaction can shorten the growing season and can cause the retention of cold meltwater later in the summer than normally would be the case. This leads to lower soil temperatures in the early summer, and favours the appearance of those species adapted to late snowmelt conditions.

Also assessed the type severity and extent of damage caused by shearing to plant communities.

- *Rock tundra (fellfield) communities suffered most damage.*
- *Heath tundra (cushionfield) communities were less frequently damaged.*
- *Severity and extent of damage are strongly related to winter snow cover, depth and terrain type. Exposed convex slopes with shallow snow cover are most at-risk.*
- *Woody species (e.g.,* Salix*) received only moderately frequent shearing. They will recover quickly if the underground rhizomes are left intact.*
- *Meadow tundra communities (wetlands) suffered little damage, mainly because they usually occur in areas that have a deep snow cover and are therefore protected from shearing. These areas are more likely to be affected by summer recreational activities.*

Hammitt, W.E., Cole, D.N. 1987. *Wildland Recreation: Ecology and Management*. Wiley, New York. 341 p.

The effects of snowmobiles on soil temperature regimes can be very pronounced. Compaction of snow reduces the snow's insulating qualities. Wanek (1971) found the 0-horizon under snowmobile trails to be 11°C cooler than under undisturbed snow. The A-horizon under compacted snow froze approximately one month earlier and thawed 2–3 weeks later in the spring. This shortened the growing season which can be detrimental to the life-cycle of flowering plants in the alpine tundra ecosystem. In addition, perennial herbs which have large underground storage organs often perish due to intracellular ice crystals causing cytolysis. Colder temperatures under snowmobile trails were also thought to be the cause for a 100-fold reduction in soil bacteria and a 2- to 10-fold reduction in soil fungi.

Heath, R. [date unknown]. The environmental consequences of the off-road vehicle: with profiles of the industry and the enthusiast. Source unknown.

Studies by Wanek (1971, 1974) showed that snow compaction removed the insulative layer over the soil, which prevented heat loss. One pass by a snowmobile, for example, doubled the snow density (equivalent to 50 passes by snowshoer); heat transfer was increased 4-fold.

Compacted snow took longer to melt and soil temperatures under it took several weeks to equalise in spring. This impacts on soil microbes which act on litter; bacterial activity took an additional 2 weeks to start up.

Snowmobiles have a direct and substantial impact on vegetation. Impact varies with snowcover, severity of winter, type of plant, and the environment. Some plants benefit from snowmobile effect through increased productivity and number.

- *Snow compaction can kill plants directly, rendering them susceptible to disease through colder temperatures.*
- *Retarded snowmelt means that seeds germinate late, possibly retarding the plant's life cycle.*
- *Herbs with large underground storage organs (e.g., rhizomes) were worst impacted.*
- *Impact was worst in first season—plants appeared to recover in subsequent seasons.*
- *Soil thaw takes an extra 2 weeks in bogs due to induced deeper frost penetration.*

Ives, J.D. 1974. Small-scale examples (1) The impact of motor vehicles on the tundra environments. Chpt. 17 in Ives, J.D., Barry, R.G. (Eds), Arctic and Alpine Environments, Harper and Row, New York.

Summarises historical use of mountainlands, and discusses increased usage of all-terrain vehicles, and management implications.

Hogan (1972), for example, found that snowmobiles in Mohawk valley delayed snowmelt by up to 1 week on north-facing slopes—may serve to protect steep roadways from peak runoff and subsequently increase infiltration into soil through increased water storage.

Johnson, P.N. 1989. Pisa Range: vegetation monitoring on Waiorau run proposed covenant and ski field area. Botany Division, DSIR, unpublished report, 9 p.

Outlines proposed monitoring methods to establish possible impacts of ski area, to contribute towards management of protected area, especially in relation to grazing.
Methods:
- *line transects in tussock grasslands for Scott height frequency measurements (100 points at 50 cm intervals, at 5cm vertical intervals;*
- *low vegetation: line transects, using point intercepts at 10 cm intervals, or presence/absence in 10 x 10 cm quadrats at 50 cm intervals;*
- *photo points.*

Monitoring never done.

Kattelmann, R. 1985a. Snow management at ski areas: hydrological effects. In: Watershed Management in the Eighties. Proceedings of the symposium sponsored by the committee on watershed management of the irrigation and drainage division of the American Society of Civil Engineers in conjunction with the ASCE Convention in Denver, Colorado.

***Slope grooming**:*
Investigated influences of snow grooming on: snow accumulation; timing and quantity of snowmelt; metamorphism of snow and development of snowpack, and properties relating to liquid water movement and retention in the snowpack. Snow grooming mechanically altered snow grains and redistributed them. The layered structure of the snowpack was changed as were the surface characteristics. Snow density and hardness were increased as snow metamorphism was artificially accelerated. Mechanical disturbance broke off the small points of new snow crystals, breaking weak existing bonds between them, and bringing the snow grains into much closer contact than occurred naturally. Compaction had perhaps greatest influence on snowmelt and runoff of all snow management practices at ski areas, even though it necessarily did not produce the greatest localised effect. The magnitude of compaction influence was due to its widespread nature, with open ski runs being compacted over the entire area.

Study in Sierra Nevada indicated that more snow water equivalent accumulated on a ski run than on comparable, uncompacted slopes. The additional water appeared to result from a combination of snow drifting into depression caused by compaction and downslope erosion of snow from grooming and skiing. Thus it was more due to a change in the distribution of the snowpack than an addition to total water equivalent in watershed. The additional snow stayed on ski runs several days longer than on similar natural slopes and could add to late season soil moisture and streamflow.
Ski run sections that were well shaded and had accumulated 'extra' snow from wind redistribution had snow late into spring or summer and added to late season flow.
Snow permeability was lower in compacted snow than uncompacted snow.

Kattelmann, R. 1985b. Snow compaction effects on night-time freezing. *Proceedings of the Western Snow Conference 54:* 168–171.

Artificial compaction was used to improve recreational skiing. Compaction increased density and hardness on snow with a variety of consequences:
- *snowmelt runoff from compacted areas occurred in a shorter part of each day than runoff from uncompacted areas;*
- *densification of compacted snow caused growth of larger crystals at expense of smaller ones, and reduction of porosity;*
- *mechanical disturbance brought crystals and grains into much closer contact than would occur naturally;*
- *compaction increased heatflow through snow by increasing thermal conductivity (thermal conductivity increases proportionally with the square of snow density);*
- *snow and soil temperatures were colder under compacted compared with uncompacted snow.*

Keane, P.A., Wild, A.E.R., Rogers, J.H. 1980. Soil conservation on the ski slopes. *Journal of the Soil Conservation Service of NSW* 36(1): 6–15.

Outlines Australian experience in minimising soil erosion in ski field development and maintenance.

- *Erosion damage due mainly to use of tracked or rubber tyred vehicles on ski slopes and over poorly located tracks.*
- *Tracked vehicles pulverise ground surface by loosening and uprooting ground cover and exposing surface soil.*
- *Rubber-tyred vehicles damaged and killed plants after 1–2 passes, leaving bare soils;*
- *multiple tracking occurred often especially in bogs and creeks;*
- *exposed bare soil is easily eroded by water and wind aided by frost heave during frequent freeze-thaw cycles.*

Keddy, P.A., Spavold, A.J., Keddy, C.J. 1979. Snowmobile impact on old field and marsh vegetation in Nova Scotia, Canada - an experimental study. *Environmental Management* 3(5): 409–415.

The first snowmobile pass caused the greatest increase in snow compaction—roughly 75% of that observed after five sequential passes. Compaction can affect the soil surface microstructure which determines the suitability of a site for seed germination.

Kevan, P.G., Forbes, B.C., Kevan, S.M., Behan-Pelletier, V. 1995. Vehicle tracks on high Arctic tundra: their effects on the soil, vegetation, and soil arthropods. *Journal of Applied Ecology* 32: 655–667.

Summer only (i.e., no snow cover)
Discusses impacts of summer used tracks (≥13 years old) and intensity of use (single to multiple passages) on vegetation, soil chemistry, soil arthropods, and soil thaw characteristics. Found:

- *small increases in depth of thaw beneath tracks;*
- *carbon and to a lesser extent K and P depleted, probably directly reflecting the reduction in vegetation and biological activity of soil;*
- *slight increases in* NO_3*, and* NH_4 *possibly due to decomposition and lack of N uptake, but Ca, Mg, and total N unaffected;*
- *multiple passages caused a significant reduction in vegetation cover;*
- *soil arthropod abundance significantly reduced on tracks, but diversity was not;*
- *soil moisture and over-ground water flow not affected, except in sedge meadows where passage resulted in channelling of water, leading to gully erosion in areas subjected to multiple passages.*

Larcher, W. 1985. Winter stress in high mountains. Pp. 11–19 in Turner H, Tranquillini, W. (Eds), Establishment and tending of subalpine forest: research and management,. Proceedings of the 3rd IUFRO workshop 1984. Eidg. Anst. Forstl. Versuchswes., Ber. 270 (1985).

High mountain plants are exposed to numerous constraints during winter: persistent low temperatures, frequent freeze-thaw cycles, soil frost, strong irradiation, desiccating and mechanical effects of wind, snow pressure and prolonged snow cover, fungus attack, pollution and, in winter sport regions, snowpack compaction through skiing. Overview is given on climatic stress factors in high mountains and stress effects discussed as possible limiting factors for winter survival. Winter desiccation and effects of prolonged snow cover are the greatest winter hazards for mountain plants; low temperatures are less harmful since high mountain plants in dormant state are adapted to their habitat with a resistance adequate for surviving winter stress.
Snowbed bryophytes make use of low light intensities at low temperture in spite of small chlorophyll concentrations. No experimental studies have been undertaken with vascular plants in order to estimate quantitatively process of starvation during prolonged snow

cover. Such investigations would increase understandings of winter injuries to vegetation on ski slopes in dependence on snow accumulation techniques. Plants buried below snow for long periods lose their frost resistance and can easily be damaged by low temperatures after being released.

Larson, H.F. 1971. Impact on vegetation in a northern Michigan test area. Pp. 160–163 in Chubb, M. (Ed.), Proceedings of the 1971 snowmobile and off-road vehicle research symposium*, Michigan State University Department of Parks and Recreation Resources Technical Report No.8*, Michigan State University, East Lansing.

Leeson, B.F., Isrealson, C. 1982. Initial environmental evaluation for the Lake Louise ski area in Banff National Park, Alberta. Parks Canada, Alberta. 190 p.

Liddle, M. 1975. A selective review of the ecological effects of human trampling on natural ecosystems. *Biological Conservation* 7: 17–33.

Comparison of different trapping methods of subnival invertebrates to evaluate impact of snow compaction due to snowmobile traffic. No results given.

Maysk, W.J. 1973. The snowmobile: a recreational technology in Banff National Park. Environmental impact and decision making, University of Calgary, Calgary, Alberta.

Snow compaction increased thermal conductivity 12 times. Lower soil temperatures resulted in the roots of perennial plants freezing, and their subsequent destruction by dessication and frost heave. Temperatures beneath snowmobile tracks fell to freezing point 6 weeks earlier than under undisturbed snow. Decreases in air porosity, air permeability, and gas exchange with the underlying soil have a detrimental effect on soil bacterial activity which is important in nutrient cycles and humus formation. Soil bacteria were reduced by a factor of 100 by snowmobile compaction

McCorkell, J. 1977. Winter sports development and environmental modification in Scotland. Unpublished Ph.D thesis, University of Glasgow.

McGregor, G.R. 1990. Snowpack structure and avalanching, Craigieburn Range, NewZealand. *NZ J. Geology and Geophysics* 33: 405–417.

Weather systems affecting NZ are maritime in origin, so would expect role of snowpack in avalanching to be similar to areas in maritime snow climates, e.g., Pacific NW, USA, or Cairngorms, Scotland. However, in NZ snowpack structure development processes and avalanche types, representative of both maritime and inland-continental snow climates, may be important for snow avalanching.

Meurk, C.D. 1982. Alpine phytoecology of the rainshadow mountains of Otago and Southland. Unpublished Ph.D thesis, University of Otago.

As part of a regional survey of alpine vegetation in Otago and Southland a series of transects were established in and around Coronet Peak, The Remarkables, and Treble Cone ski fields in the late 1970s. Selected key transects could be relocated and resurveyed to establish long-term changes in vegetation patterns in response to ski field activities, including snow grooming (Meurk pers comm.).

Meyer, E. 1993. The impact of summer and winter tourism on the fauna of alpine soils in western Austria (Oetztal Alps, Ratikon). *Revue Suisse de Zoologie* 100(3): 519–527.

Paper in German, Abstract in English.
Damage to high-alpine vegetation as a result of summer trampling is usually spatially and temporally restricted, so that regeneration of both plants and soil is possible. Disturbances due to shearing effect of skis on hillslopes are more serious, since damage is repeated year after year on same site, leading to complete destruction of upper soil layer. Overheating, desiccation and erosion during summer impair edaphic conditions still further. On bare spots in subalpine meadow, earthworm abundance was reduced by 85%, biomass by 94%. Compaction of snow cover by snowmobiles for ski runs reduces abundance of whole soil fauna by 70%. Preparation of ski slopes by bulldozers completely destroys vegetation, top soil and soil fauna. Succession in raw soils at high altitudes proceeds extremely slowly, so functioning soils system is lost for years.

Mosimann, T. 1985. Geo-ecological impacts of ski piste construction in the Swiss Alps. *Applied Geography* 5: 29–37.

Terrain modification during piste construction is shown to encourage soil erosion, especially in long, concave, linear hollows, on high-angle slopes, shallow or poorly drained soils and on long pistes. Erosion inhibits regeneration of the vegetation, especially above 2200 m a.s.l. Below 1600 m a.s.l. natural and/or artificial revegetation is generally more successful.
Implications for management:
- *terrain modification should only be allowed where climatic conditions permit rapid regeneration of vegetation. Upper limit in Central Alps is 2200 m;*
- *terrain modification should only be allowed where there is small risk of soil erosion (high risk areas are unlikely to regenerate);*
- *small-scale terrain modification should also be avoided where soil/site conditions are such that restabilisation is unlikely, e.g., in association with bedrock, clay-loam soils, morainic debris, shallow regolith covers, deep humus/peaty soils, wet/poorly drained sites;*
- *no terrain modifications should take place where slopes are greater than 25°;*
- *it is safe to modify low-angle slopes with light-textured soils (high silt/low clay contents) and deep regolith, or soils with well-mixed humus horizons;*
- *depressions should be filled rather than scalped protrusions.*

Nakamura, T. 1984. Human impacts on vegetation and soil of skiing area. I: A case study in Teine skiing area, Hokkaido, Japan. *Journal of Japanese Society of Grassland Science* 29: 331–340.

In Japanese
Identifies vegetation units on ski area. Not very useful.

Neugirg, B. 1986. Investigations into the effects of ski pistes on alpine pasture vegetation at Jenner, Upper Bavaria. *Zeitschrift fur vegetaionstechnik im Landschafts und Sportstattenbau* 9(2): 46–54.

CAB abstract. In German.
Possible effects of skiing on vegetation, soils, hydrology and microclimate of alpine ecosystems are outlined. Vegetation on ski pistes were compared with that on closely comparable adjacent plots. Most plots supported native vegetation. Differences were ascribed to causes other than use as pistes and arose from spread of low shrubs and associated species. Ground cover high except where sites been levelled, so had number of species reduced.

Neumann, P.W., Merriam, H.G. 1972. Ecological effects of snowmobiles. *The Canadian Field-Naturalist* 86: 207–212.

Snowmobile passage caused:

- *snow compaction resulting in 4-fold increases in thermal conductivity of snow at depth, and a 9-fold increase at the surface;*
- *reduced temperature gradients within the snow, which could impact on organisms inhabiting subnival environments through increased metabolic requirements;*
- *changes in snow pore space and crystal structure resulting in reduced water holding capacity of snow (70% near surface; 40% midway down). Structural changes in snow after longer periods of saturation reduced these differences to 52% and 23% respectively. Results in reduced ability of snow to slow runoff and to moderate effects of thawing in spring;*
- *increased snow density and changes in thermal conductivity resulted in slower snowmelt. Impacts on bacterial decomposers and litter decomposition may be significantly affected.*
- *direct damage to vegetation especially rigid woody stems.*

Newesly, C., Cernusca, A., Bodner, M. 1994. Origin and effects of oxygen deficiency on differently prepared ski slopes. *Vehandlungen - Gesellschaft fur Okologie* 23: 277–282.

(GEOBASE abstract only; paper in German).
Making a wet snow-cover during ski slope preparation implies the pressing of free water in the pores of snow in lower layers, which are still very cold, thus causing the formation of compact layers of ice at the soil surface. This ice layer inhibits a supply of oxygen into the soil.
Investigations of a number of plant species characteristic for vegetation of ski slopes, showed that the combination of oxygen deficiency and low temperatures caused by ski slope preparation can seriously damage plants.

Pesant, A.R. 1987. Snowmobiling impact on soil properties and winter cereal crops. *Canadian Field Naturalist* 101: 22–32.

Snow density under tracks was 1.7 times that of the control, and transmitted heat from the soil at 5 times the rate of undisturbed snow. Under tracks, temperatures decreased sharply and frost penetration reached depths of as much as 60 cm. Thermal conductivity of compacted snow was 2.5 times greater with a density 58% higher than that of untreated snow.

Pignatti, S. 1993. Impact of tourism on the mountain landscape of central Italy. *Landscape and Urban Planning* 24: 49–53.

Mountain landscape of Apennines, Italy has been severely affected by tourism. Conducted floral survey under skilifts—strong decline in floral diversity. Where there had been heavy traffic, number of species reduced by 50% and those species resistant to trampling expanded and became dominant.

Price, M.F. 1985. Impacts of recreational activities on alpine vegetation in Western North America. *Mountain Research and Development* 5: 263–277.

Damage to vegetation was most severe on convex slopes with thin snow cover. It resulted from skiers and from grooming. Direct damage, e.g., broken or sheared off vegetation, was readily obvious but indirect damage may occur over large areas and over a longer time period. The major cause of indirect damage was from structural damage in the snowpack resulting from compaction. Snow densities increased below skied areas and ice layering was more common. This in turn meant that snow melt was retarded, but tended to be more rapid when it occurred, compared with non-compacted areas. With time it is *probable that the retarded snow melt will cause the composition of plant communities to change, because of changes in length of growing season and soil moisture distribution and increased soil erosion by wind, needle ice, and water.*

Racine, C.H., Ahlstrand, G.M. 1991. Thaw response of tussock shrub tundra to experimental all-terrain vehicle disturbances in South-central Alaska. *Arctic* 33(1): 31–37.

Vehicle-induced subsurface thaw response in tussock-tundra area was measured in relation to increasing traffic (1, 10, 50 and 150 passes) applied by different types of lightweight (100–450kg) all-terrain vehicles compared with heavier (1200 kg) Weasel in early June, early September, weekly intervals for 10 weeks from mid-June to early September, and late July of two successive years.

Early in thaw season when thaw depths are 10–20 cm, ATVs produced more subsurface thaw than Weasels.

- *In September, Weasel produced more thaw than ATVs.*
- *Traffic intensity affected thaw response in spring more than fall.*
- *Thaw response was greater when traffic was regular through season, rather than once at start or end of season.*

Reynolds, P.C. 1982. Some effects of oil and gas exploration activities on tundra vegetation in Northern Alaska. Pp. 403–417 in Rand, P.J. (Ed.): Land and water issues related to energy development. Proceedings of the 4th annual meeting of the International Society of Petroleum Industry, Denver, Colorado. Ann Arbor, Michigan: Ann Arbor Science.

Impacts of winter cross-country oil exploration related travel on vegetation were monitored. A dry upland meadow was moderately affected by tractor trains, but recovered in 16 months from effects of low ground pressure seismic vehicles, but significant effects were still present along tractor trail after 28 months.

- *In sedge tussock tundra 40% vegetation was killed by single pass of low pressure seismic vehicle. Portions of sedge tussocks were brown, possibly killed by freezing when vehicles compressed the insulating snow layer covering the plants. A few tussocks had been crushed and broken by low-ground pressure vehicles.*
- *Single passes with low pressure vehicles with wide flexible tracks or large tyres did little damage even to the most sensitive vegetation types if ground was frozen or snow covered.*
- *Trails of tractors can kill or damage large percentage of vegetation especially sedge tussocks or riparian willows. These trails will be visible for several years.*
- *There was >50% reduction in plant cover on vehicle trails even when at least 15 cm of snow present. Low snow conditions resulted in slower recovery of vegetation.*

Rickard, W.E., Brown, J. 1974. Effects of vehicles on arctic tundra. *Environmental Conservation* 1(1): 55–62.

Discusses impacts of off-road vehicles on arctic tundra. Degrees of impact arranged in order of increasing severity of surface disturbance:

- *destruction of plant cover and breakage/compaction of surface organic mat;*
- *initiates erosion and an increase in thaw-depth. Peat compaction results in increased heat transfer into and out of underlying soil;*
- *removal of peat layer causes subsidence of frozen ground as it thaws and erosion of slopes.*

Rogers, G., Kimberley, M. 1990. Turoa ski field, Tongariro National Park. Vegetation monitoring programme. Prepared for the Dept of Conservation by the Forest and Wildland Ecosystems Division of the Forest Research Institute, Rotorua.

Outlines methods and results of vegetation monitoring programme established in 1978 to detect changes as a result of skifield management.

Methods:

- *% cover in 7 vegetation and bare ground categories was assessed from vertical colour transparencies of fixed-area quadrats photographed above permanently located pegs on each of 7 transects. Cover was assessed from 100 random points positioned on slide projection screen. Results were compared with the five surveys since 1978.*

Results:

- *Earthwork disturbance is causing sedimentation of wetland area. Vegetation change is occurring as tussocks are favoured over herbs and low-growing sedges where there is improved soil drainage due to sedimentation. Overall viability of wetland not threatened.*
- *Gravelfield and stonefield. High impact by tracked vehicles and skiers resulting in significant decline in total vegetation cover since 1982. Construction activity is degrading sensitive herb and prostrate shrub communities in central lift area.*
- *Where there was skier impact only, no clear evidence that skiing is degrading sparse herb and prostrate shrub vegetation of gravelfields and stonefields.*

Recommendations:

- *Restrict snow groomer use to periods of snowcover. Sparse alpine vegetation in high impact areas should not degrade significantly.*
- *Continue monitoring to determine effects of, e.g., increased patronage, rock grooming, snow redistribution by grooming, snow making.*

Schrind, W.D. 1971. Modification of the subnival microclimate by snowmobiles. Pp. 251–257 in Haugen, A.O. (Ed.): Proceedings, Symposium on snow and ice in relation to wildlife and recreation, Iowa State University Press.

Discusses the biological consequences of compaction from snowmobiles and the effects of mechanical compaction by snowmobiles upon the subnivean environment. Found both density and temperature to be affected by snowmobile compaction. Snowmobiling reduced the insulative quality of snow cover by decreasing depth and thermal conductivity. These were the major causative factors in the destruction of mild climates beneath the snowpack.

Sherman, H.D., Neslin, D.S. 1990. Wetlands. *Ski Area Management* 29(6): 58–59, 80–81, 83.

CAB Abstract only
General article which recognises importance of wetlands for ecological reasons, and impact that ski field activities have on them. Discusses legal regulations to be aware of.

Sterrett, K.F. 1976. The arctic environment and the arctic surface effect vehicle program. CRREL report 76-1. US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755. 33 p.

Summarises advances in understanding of the environmental damage in the Arctic which have come about since the inception of the ARPA Arctic Surface Effect Vehicle Program in 1970.
Impacts where there is no snow cover:

- *depends on vegetative morphology, anatomical features, and species composition;*
- *mosses less resistant to skirt abrasion than sedges or grasses;*
- *impacts more pronounced in wet areas than dry;*
- *micro relief is most significant characteristic influencing degree of degradation.*

Tsuyuzaki, S. 1994. Environmental deterioration from ski resort construction in Japan. *Environmental Conservation* 21(2): 121–125.

Ski slope establishment leads to clear-cutting of well developed forests, scraping off soil, seeding ground-surface. Revegetation not always successful, leaving bare patches.
Not very useful.

Walker, D.A., Cate, D, Brown, J., Racine, C. 1987. Disturbance and recovery of arctic Alaskan tundra terrain. A review of recent investigations. CRREL Report 87-11. 76-1. US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755, p 70.

Summary of over a decade of CRREL managed research regarding disturbance and recovery in northern Alaska. This work comes at a time of major transition in the focus of N. Alaskan research from single impact studies to analysis of cumulative impacts. It summarises studies of anthropogenic disturbances and discusses immediate need for new methods to approach problems of re-vegetation, restoration and cumulative impacts of terrain underlain by permafrost. Impacts discussed include balded trails, off-road vehicle trails, winter trails, ice roads, gravel pads and roads, borrow pits, roadside impoundments, etc.

Winter trails and snow and ice roads:

- *less impact on vegetation than summer use;*
- *can cause severe disturbances where snow plowing is necessary or where frozen tussocks are easily knocked over due to insufficient snow cover;*
- *frequency of passage affects snow structure; depth hoar destroyed after 2 passes; multiple passes compressed snow which then recrystallised;*
- *vegetation becomes compressed (crushed and broken at rims);*
- *after spring, no change in thaw depth;*
- *results in decreased flowering, biomass and productivity; vegetation especially intertussock species being crushed or broken.*

Wanek, W.J. 1971. Snowmobile impacts on vegetation, temperatures, and soil microbes. Pp. 116–129 in Chubb, M (Ed.), Proceedings of the 1971 snowmobile and off-road vehicle research symposium*, Michigan State University Department of Parks and Recreation Resources Technical Report No.8*, Michigan State University, East Lansing.

Referenced and discussed in Hamilton (1981).

Wanek, W.J. 1974. A continuing study of the ecological impacts of snowmobiling in northern Minnesota. Final report for 1973–74, Center for Environmental Studies, Bemidji State College, Bemidji, Minn. 54 p.

Referenced and discussed in Hamilton (1981).

Wardle, K., Wardle R. 1992. The impact of a snow groomer on the vegetation and ground cover of Broken River Ski basin. Dept of Conservation unpublished report.

Impact of snow groomer on Chionochloa rigida/pallens *tussock grassland ski basin in 1991 ski season was assessed. Vegetation transects were established and for 50 x 50 cm quadrats, the following were recorded:*

- *estimates of % cover of rock, bare ground, litter, live and dead vegetation;*
- *species present. Cover classes, and frequency of occurrence;*
- *tussock biomass estimated using height pole measurements at 1 m intervals;*
- *photographs to provide visual record of ground cover and composition;*

Results of monitoring indicated no significant impact to existing vegetation cover of Broken River Ski basin.

Heavy snow season in 1991 resulted in deep snow pack with excellent coverage over vegetation. Therefore little damage was likely. In low snow years it is recommended that groomer should not be used on shallow snowpack.

***Authors' note:** huge avalanche in 1992 season wiped out several of the monitoring sites. Need to be re-established and measured soon.*

Watson, A. 1980. Conflict in the Cairngorms - policies for protection. *Geographical Magazine* 52(6): 434.

General review of problems in the Cairngorms; non-specific.

Watson, A. 1985. Soil erosion and vegetation damage near ski lifts at Cairngorm, Scotland. *Biological Conservation* 33: 363–381.

Trampling from summer activities increased because of lifts operating all year.

Watson, A., Watson R.D. 1983. The Lecht ski development: The impact on soils and vegetation and recommendations for its amelioration. Unpublished report, July 1983, 4 p.

Housed in Landcare library at Lincoln.

Watson, A., Bayfield, N., Moyes, S.M. 1970. Research on human pressures on Scottish tundra, soil and animals. Paper No. 27 in Fuller, W.A., Kevan, P.G. (Eds): Productivity and conservation in northern circumpolar lands. New Series 16: 256–266.

Construction of ski lifts and roads has been followed by soil erosion, vegetation damage and a threat to wild animals in sensitive arctic-alpine zone of Scotland. Snow is important in determining types of plant communities. Highest ground is similar to the stony fellfield of high arctic. Winter temperatures are much higher in Scottish mountains (like New Zealand?) than in arctic or subarctic areas. Thaws sometimes occur in mid-winter on highest summits and there are frequent alterations of freeze-thaw at intermediate altitudes. Winters are sometimes long and severe and snowfalls heavy. Very windy, exposing ridges and filling hollows.
No permafrost, but solifluction present—stone stripes, raised hummock tundra, stone polygons, frost heaving. Ground frequently freezes to 20 cm depth, plus frequent crossing of freezing threshold creates big problems that compare in severity to those associated with permafrost, e.g., passage of vehicles/skiers over thawed soil surface leads to stripping off of vegetation and soil at the surface.

Willard, B.E., Marr, J.W. 1970. Effect of human activities on alpine tundra ecosystems in Rocky Mountain National Park, Colorado. *Biological Conservation* 2: 257–265.

Wood, T.F. 1987. Methods for assessing relative risk of damage to soils and vegetation arising from winter sports development in the Scottish highlands. *Journal of Environmental Management* 25: 253–270.

Need for environmental impact assessments to relate environmental characteristics of vegetation communities to likely levels of disturbance from winter recreation. Procedure outlined has five stages:

1. *Species frequency and environmental data obtained for 300 stands distributed over eight sample sites.*
2. *The 300 stands were reduced to 35 vegetation associations on the basis of their species attributes using polythetic agglomerative cluster analysis (MCAT algorithm).*
3. *Associations assigned to eight parent groups on basis of species. Ordinated and separated by discriminant analysis and ANOVA using environmental variables (i.e., topographic exposure, altitude, slope areas with steeper slopes, snow depth, humus depth, soil moisture content).*
4. *ARisk index@ constructed using selected environmental characteristics of associations and parent groups that are important in determining environmental impact of winter disturbance.*
5. *Parent groups mapped for area under consideration for ski filed and patterns of relative risk discussed as input to environmental management.*

Appendix 2

SITE VISITS

The following observations are based on diary notes made during field visits to the the main ski areas on DoC Recreational Reserve land in west Otago: Coronet Peak, The Remarkables, and Treble Cone. The former two sites were visited with Neil Simpson on 21/12/95 and Treble Cone with Dawn Palmer on 31/1/96.

Coronet Peak

Areas visited

Rocky Gully T-bar, Eighth Basin/Easy Rider: Area of undeveloped but groomed vegetation consisting of dead squashed large *Dracophyllum uniflorum, Celmisia lyallii,* and decapitated *Chionochloa rigida* (Fig.A1). Some *Dracophyllum* bushes appear to have regenerated with a lower ground-hugging form.

The area on the true right bank of the creek coming down to the base of the Rocky Gully T-bar is ungroomed and could serve as a suitable control site for transects in this area.

Parts of this ski run were modified and replanted approximately 8 years ago with exotic grasses (*Agrostis capillaris*) and clover (*Trifolium ripens*). However, native plants have been established in these areas (*Poa colensoi, Rytidosperma pumilum, Epilobium* spp., *Aceana* spp. and other native herbs).

Junction of Eighth Basin and learners' area: Looking up-slope, groomed areas are characterised by squashed and dead *Dracophyllum* and damaged tussocks (Fig. A2). This is a possible transect area.

Gullies above Aeroplane and Lunch Rocks show signs of damage on steep areas where skiers have side-slipped down-slope, shaving tussocks and *Dracophyllum* bushes. Wetlands show no evidence of damage presumably because they remain protected by a deep snow cover through much of the winter.

Knoll near double chair top base: Much groomer damage, e.g., dead *Dracophyllum* bushes.

Suggested transect areas:

- On true left and right banks of creek flowing down to bottom of Rocky Gully T-bar.
- In vicinity of Gilligans Island/Easy Rider, close to junction with learners' area.
- Million Dollar (groomed regularly) versus Walkabout (infrequently groomed) versus the ungroomed area between Walkabout and Greengates. These three sites have the same aspect and slope, and would be suitable for a comparative study.

The Remarkables

General comments

DoC Queenstown staff believe that there will be considerable pressure to proceed with further development at the Remarkables. They also expressed concern that the alpine vegetation associated with this field is likely to be more vulnerable to impacts than at Coronet, in part because of the greater extent of cushionfields and wetlands.

Some modification of hillslopes has been undertaken on this field with a subsequent tussock re-planting programme which has been reasonably successful.

Main wetland areas at-risk

1. Alta Green wetland beneath Alta Chair near base.
   Always groomed; high ski traffic. In relatively good condition despite being dissected by a 4WD track.
2. Easy Out/Gotham City wetland (Fig. A3).
   Located on the true left bank of the right branch of Rastus Burn, this is a large comparatively flat wetland adjacent the chairlift station. There is some evidence of groomer damage (Fig. A4).
3. Water Race wetland.
   This is a gently-sloping wetland, the western part of which is groomed as part of Water Race ski run. The eastern part closer to the ridge is not groomed and is a potential transect site (Fig. A5).
4. Left branch of Rastus Burn wetland (Fig. A6).
   This is rarely skied as traffic from the top of Alta Chair goes below it. This could be a good site for a control.
5. Mid Station Shadow Chairlift wetland
   A stream flows close to Mid Station and is banked by wetlands. Close to the chairlift the wetland is groomed, but to the north it is ungroomed.

Treble Cone

General observations

The Treble Cone landscape has been extensively modified by the removal of tussocks, the introduction of exotics, and major earthworks. Areas that are not groomed tend to be in gullies where there is ample snow. These areas are thus not directly comparable with more exposed groomed areas.

An added complication is that areas that were once frequently skied and thus groomed may not be so today. This shifting pattern of development appears to have lead to extensive but comparatively light disturbance across much of the ski field, with few areas that have escaped being groomed. Consequently it is difficult to find suitable ungroomed (control) sites.

Areas considered to be most at-risk from damage by snow groomers are knobs and steeper slopes across the entire field, and lower ski runs such as Mid Wave and Rollercoaster which have thinner snowpacks.

Cushionfields

The main areas of concern for grooming impacts are cushionfields occupying wind-swept knolls which retain little snow and hence are susceptible to both groomer and skier damage. Unskied cushionfields tend to have a high lichen component and fewer dead cushions (Fig. A7) compared with skied and groomed cushionfields (Fig. A8).

Possible transect sites:

Cushionfield

Unskied cushionfield area beside Tower 12 of new chairlift versus groomed (or skied) cushionfield to true right of T2 below track versus skied only area (to true left of T2 where skiers once traversed across to the Matuki Face from the top of T2).

Tussock Grassland

1. Upper Mountain
   a) Saddle Valley: The Saddle Valley area is a new development in relatively undisturbed snow tussock, and therefore offers the possibility of establishing transects in an area with a known history. However, this is a mid-to-high elevation area with substantial snowfall and impacts may be difficult to detect.

      Transect adjacent to track near chairlift where grooming will occur versus transect away from track where skiing and grooming will be infrequent (Fig. A9).

   b) Main Face: Rollercoaster (groomed and skied, but not modified) versus Powder Bowl (skied only). Should be possible to establish sites here with altitude, aspect, and gradient.

      Easy Street, gentle slope near junction to Skite (re-planted tussocks, frequently groomed and skied) versus Saddle, gentle slope just below Saddle T-bar shed (ungroomed, infrequently skied) versus true left of Easy Street, gentle slope (sometimes groomed and skied).

2. Lower Mountain

   The lower mountain in low snow years is less frequently skied but can still suffer substantial damage by skiers and from grooming where the snow cover is thin or non-existent.

   Mid Wave (groomed and skied but not modified) versus the area adjacent to Mid Wave that is not groomed would be a potential transect site.

Cat skiing

Snow groomers are also used to carry skiers up to the ridge and skirt around the ski field boundary along Tim's Table where the skiers are dropped off. The machines are normally turned at the top of the ridge where the snow can be thin and patchy. Local DoC staff are concerned at the extent of damage this area may suffer during the turning process. The area was not visited but should be kept in mind as a potential site for establishing transects.

FIGURE A1. NARROW LEAVED SNOW TUSSOCK ON EASY RIDER SKI RUN AT CORONET PEAK DAMAGED BY SNOW GROOMING AND SKI TRAFFIC.

FIGURE A2. A GROOMED SECTION OF EIGHT BASIN SKI RUN SHOWING SQUASHED AND FLATTENED SNOW TUSSOCK, AND DEAD *DRACOPHYLLUM* BUSHES.

FIGURE A3. LOWER END OF GOTHAM CITY/EASY OUT WETLAND.

FIGURE A4. SNOW GROOMER TRACKER DAMAGE ON GOTHAM CITY/EASY OUT WETLAND.

FIGURE A5. VIEW OF 'WATER RACE' WETLAND. AREA TO RIGHT OF MIDDLE FOREGROUND IS A POTENTIAL CONTROL SITE.

FIGURE A6. WETLAND AT TOP OF ALTA CHAIRLIFT (LEFT BRANCH OF RASTUS BURN). THE AREA TO THE TRUE RIGHT IS INFREQUENTLY SKIED, AND NOT GROOMED, AND COULD ACT AS A CONTROL.

FIGURE A7. CUSHIONFIELD IN AN UNGROOMED AND UNSKIED AREA NEAR TOWER 12 T-2, TREBLE CONE.

FIGURE A8. CUSHIONFIELD AT TOP OF ROLLER COASTER SKI RUN SHOWING DAMAGE FROM GROOMING (BARE GROUND, BROKEN WOODY STEMS, AND DEAD VEGETATION).

FIGURE A9. VIEW OF NEW SKI AREA (SADDLE BASIN) AT TREBLE CONE. THE TRACK IN THE MIDDLE FOREGROUND AND AREAS ON EITHER SIDE OF IT WILL BE GROOMED AND SUBJECT TO HEAVY SKIING WHEREAS AREAS TO THE LEFT WILL BE RELATIVELY UNDISTURBED. THESE COULD BE LOCATIONS FOR 'DISTURBED' AND 'CONTROL' TRANSECTS.