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# Effects of ski piste preparation on alpine vegetation

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## Summary

**1.** Ski resorts increasingly affect alpine ecosystems through enlargement of ski pistes, machine-grading of ski piste areas and increasing use of artificial snow.

**2.** In 12 Swiss alpine ski resorts, we investigated the effects of ski piste management on vegetation structure and composition using a pairwise design of 38 plots on ski pistes and 38 adjacent plots off-piste.

**3.** Plots on ski pistes had lower species richness and productivity, and lower abundance and cover of woody plants and early flowering species, than reference plots. Plots on machine-graded pistes had higher indicator values for nutrients and light, and lower vegetation cover, productivity, species diversity and abundance of early flowering and woody plants. Time since machine-grading did not mitigate the impacts of machine-grading, even for those plots where revegetation had been attempted by sowing.

**4.** The longer artificial snow had been used on ski pistes (2–15 years), the higher the moisture and nutrient indicator values. Longer use also affected species composition by increasing the abundance of woody plants, snowbed species and late-flowering species, and decreasing wind-edge species.

**5.** *Synthesis and applications.* All types of ski piste management cause deviations from the natural structure and composition of alpine vegetation, and lead to lower plant species diversity. Machine-grading causes particularly severe and lasting impacts on alpine vegetation, which are mitigated neither by time nor by revegetation measures. The impacts of artificial snow increase with the period of time since it was first applied to ski piste vegetation. Extensive machine-grading and snow production should be avoided, especially in areas where nutrient and water input are a concern. Ski pistes should not be established in areas where the alpine vegetation has a high conservation value.

*Key-words*: artificial snow, biodiversity, functional groups, machine-grading, snow ecology, Switzerland

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## Introduction

The structure of alpine vegetation is affected by altitude, aspect and inclination. Some alpine habitats are extraordinarily rich in species, while communities in the highest and most extreme regions consist of only a few specialists (Ellenberg 1988). Furthermore, most communities are characterized by specific proportions of functional groups, such as dwarf shrubs, grasses and herbs. The communities can consist of species from special ecological groups, for example snowbed species, indicating depressions with a long-lasting snow cover and a very short vegetation period, or wind-edge species, indicating a long vegetation period and extreme winter temperatures (Körner 1999).

Alpine ecosystems are sensitive and susceptible to changes in land use and climate (Chapin & Körner 1995; Fischer & Wipf 2002; Laiolo *et al*. 2004). Perturbations of the alpine habitats and changes in snow cover characteristics, for example through skiing, are likely to have impacts on species composition, diversity and productivity of alpine vegetation, which in turn may have negative effects on ecosystem functioning and stability (Tilman 1996; Mulder, Uliassi & Doak 2001). As ski tourism is

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one of the most important economical factors in European alpine regions (Abegg *et al*. 1997; Elsasser & Messerli 2001), the area affected by ski pistes or by constructions related to tourism is still increasing.

Skiing and ski piste preparation by snow-grooming vehicles are likely to cause mechanical damage to the vegetation and the soil (Cernusca *et al*. 1990; Rixen *et al.* 2004). Furthermore, the winter preparation of ski pistes leads to a thin and compressed snow cover with decreased temperature insulation capacity. Soils and vegetation under these ski pistes may experience temperatures lower than −10 °C (Rixen, Haeberli & Stoeckli 2004), while under undisturbed snow-packs, temperatures rarely fall below 0 °C (Rixen 2002; Rixen, Stoeckli & Ammann 2003). As a result, plant species with insufficient cold hardiness and plants sensitive to mechanical stress may be damaged, resulting in shifts among functional groups and a higher proportion of unvegetated ground. In summer, piste construction measures, such as machine-grading, are carried out to remove obstacles like trees and rocks or to level rough or bumpy soil surfaces. In the process of machine-grading, the upper soil layers and the vegetation are removed or heavily damaged (Pröbstl 1990; Haeberli 1992; Bayfield 1996; Titus & Tsuyuzaki 1999; Ruth-Balaganskaya & Myllynen-Malinen 2000). Seed mixtures are often applied to accelerate revegetation, but the success of revegetation measures declines with height above sea level (a.s.l.) (Urbanska 1997).

In response to ongoing climatic changes, artificial snow production is increasingly used in most ski resorts of the world. Climate-change scenarios predict changes in seasonal snowfall patterns, with the snow season beginning later and ending earlier, and a rise in the snow line (IPCC 1996, 1998, 2001). As a consequence, the minimum altitude termed snow-secure for winter sports in the European Alps would rise from 1200 m today to 1500 m a.s.l. within the next 30 years (Abegg 1996). Winters with little snow have already been a major concern of winter sport resorts since the mid-1980s (Seilbahnen Schweiz 2001). As a strategy to minimize the dependence on natural snowfall, ski areas invest in systems for artificial snowing.

Effects of ski piste manipulation in single resorts and single effects of artificial snowing or machine-grading have been investigated in earlier studies (Urbanska 1997; Kammer 2002). In our comprehensive study, sites covered a wide range of locations, altitudes and aspects in 12 Swiss ski resorts. We investigated plots on ski pistes and adjacent control plots beside pistes. With a total of 76 vegetation records arranged in a factorial design, we addressed the following specific questions. (i) Do productivity, species richness and composition of the vegetation on ski pistes differ from the vegetation off pistes? (ii) What are the impacts of machine-grading on productivity, species richness and composition of ski piste vegetation? (iii) How does the use of artificial snow modify environmental conditions on ski pistes and how do productivity, species richness and composition of the vegetation respond? (iv) Do the effects of artificial snow differ between graded and ungraded ski pistes?

## Materials and methods

### STUDY SITES AND DESIGN

We studied the vegetation of plots on and next to ski pistes in 12 ski resorts in the Swiss Alps (see Appendix 1), ranging in altitude between 1750 and 2550 m a.s.l. and representing a wide range of vegetation types (mostly alpine grasslands on acidic or calcareous bedrock and dwarf shrub heath), time since grading and years of application of artificial snow. The study sites were chosen on machine-graded or ungraded ski pistes with either natural or artificial snow, resulting in four different ski piste types: natural snow/ungraded (ns), artificial snow/ungraded (as), natural snow/graded (nsg) and artificial snow/graded (asg). Sites were selected in consultation with the local ski piste managers to ensure that the pistes had received the same management continuously in previous years.

At each study site, we randomly chose a plot on a ski piste and an undisturbed control plot in the nearest off-piste area to allow for pairwise comparisons. The distance between piste and control plot was 15–50 m and the pair of plots did not differ significantly in altitude, inclination, aspect and management. All ski pistes were prepared by snow-grooming vehicles and were used annually by skiers from approximately mid-November/early December to Easter (mid-April). Artificial snow had been produced in all ski resorts for 2–15 years ($n$ = 21 pistes, mean 7·1 years). On 17 pistes in nine resorts, machine-grading (i.e. construction of ski pistes during which vegetation and topsoil are removed) had been carried out 4–30 years ago ($n$ = 17 pistes, mean 18·7 years). On 10 machine-graded plots, revegetation had been encouraged by sowing seed, but details of seed mixtures and sowing techniques were not available.

### VEGETATION DATA

From 1 July to 24 August 2000, we visited each site to collect vegetation records. In 4 × 4-m plots, we noted the presence of each vascular plant species and estimated its cover in seven classes according to Braun-Blanquet (Müller-Dombois & Ellenberg 1974). We assigned a cover value to each class for further calculations (0·01% to '*r*', 0·1% to '+', midpoint to other classes). To compare site conditions between plots, we calculated weighted indicator values for moisture (F), soil reaction (R), nutrients (N) and light (L) per plot according to Landolt (1977). For each plot, we also estimated the percentage area not covered by vascular plants.

To assess productivity, we randomly selected three patches of 0·2 × 0·2 m plot$^{-1}$, harvested the biomass 3 cm above ground and pooled the samples. In cases where plots had been grazed, we randomly sampled ungrazed


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areas with similar vegetation within 5 m distance from the plot. Three grazed plots with no undisturbed vegetation nearby were omitted from biomass sampling. We measured annual productivity as the total biomass excluding litter, dead biomass and woody shoots older than 1 year. The biomass was dried at 70 °C and weighed to the nearest 0·01 g.

For each plot we calculated species number and Shannon's index of diversity as $H = -\Sigma P_i \ln P_i$, where $P_i$ is the abundance class of species *i*. We calculated the abundance of four functional groups: graminoids (Poaceae, Cyperaceae, Juncaceae), woody plants, legumes and remaining forbs (including Pteridophyta), to obtain taxonomical and plant functional characteristics of the plots. According to their habitat preference in relation to snow cover and length of growing season (Ellenberg 1988; Wilmanns 1998; Delarze, Gonseth & Galland 1999), we classified 26 of 322 species as inhabiting snowbeds and 30 as inhabiting wind-edges (Wipf *et al*. 2002). Depending on their phenology, we also classified 67 species as early flowering and 94 as late-flowering, according to the flowering period indicated in Lauber & Wagner (2001). For the four functional, two ecological and two phenological groups, we calculated the proportions relative to total species number and total vegetation cover. See Appendix 2 for a list of species and their classification.

### STATISTICAL ANALYSIS

We analysed our data with hierarchical analysis of variance (ANOVA) models. Differences in the type of bedrock, aspect, slope and hours of sunshine between pairs were taken into account by the pairwise design of piste and off-piste plots. Moreover, we considered altitude as a covariate in all analyses. To mirror the study design with pairs of plots on and next to pistes, we fitted the type of plot pairs, i.e. the type of piste treatment of the piste plot in the pair. Next we fitted the factor piste, which indicated differences between plots on and next to pistes within the pairs, across all types of piste treatment. Then, we fitted the interactions of type of pair (machine-grading or years of artificial snow) and piste, which indicated whether the difference between plots on and next to the piste depended on the type of piste treatment. We considered machine-grading, which is applied only once, as a binary factor, and artificial snowing as a continuous variable (time since start of application of artificial snow) because of its potentially cumulative impacts. Three-way interactions between resort, type of plot pair and piste indicated whether effects of machine-grading and artificial snow differed between resorts. To analyse the effect of succession and revegetation measures on the vegetation of machine-graded ski pistes, we performed the same analysis on a reduced data set (pairs of graded piste and control plots) and included years since machine-grading as a continuous variable and sown as a binary factor. If necessary, dependent variables were transformed prior to analysis to reach normality. Residuals were checked visually for normal distribution. Analyses were carried out with SPSS 10·0·5 (SPSS 1999).

## Results

### IMPACTS OF SKI PISTES VS. NO PISTE

The indicator values of the vegetation composition showed an increased supply in moisture and nutrients available for plants (indicator value F, $P = 0{\cdot}098$; N, $P = 0{\cdot}003$; Tables 1 and 2 and Fig. 1) and a tendency for higher base content of the soil (R, $P = 0{\cdot}059$; Tables 1 and 2) on ski pistes. Despite the favourable environmental conditions for growth, plant productivity on ski pistes was lower than beside the pistes (Tables 1 and 3 and Fig. 2). The mean number of species per plot was 11% lower on piste plots than on off-piste plots ($P = 0{\cdot}047$; Tables 1 and 3 and Fig. 2). The pistes thus had a negative effect on the species richness in alpine grassland and dwarf shrub vegetation.

Woody plants covered 24·3% of unmanipulated control plots, but were significantly less frequent on ski pistes (10·5% cover, $P = 0{\cdot}003$; Tables 1 and 4 and Fig. 3), mainly because of their low abundance on machine-graded pistes (1·7% cover, see next section). The same pattern was found in the proportion of woody species (Tables 1 and 5 and Fig. 3). Legume species were more abundant and had higher cover on piste plots than on control plots. Both cover and species number of early flowering species were lower on piste than on control plots ($P = 0{\cdot}005$; Tables 1 and 6 and Fig. 4). Thus, the snow compaction changed the plot composition of functional and ecological groups.

### MACHINE-GRADING OF SKI PISTES

The proportion of ground not covered by vegetation was almost five times higher on graded than on ungraded piste plots ($P = 0{\cdot}008$; Tables 1 and 3 and Fig. 2) but was unaffected by revegetation measures (sowing) or time since machine-grading. Corresponding with the high proportion of ground not covered by vegetation, the light input for the plants (expressed as indicator value L) was higher on graded piste plots than on ungraded ones ($P = 0{\cdot}002$; Tables 1 and 2 and Fig. 1). Nutrient availability to the vegetation (expressed as indicator value N), which was generally increased on ski pistes, reached even higher values on graded pistes than on ungraded ones ($P = 0{\cdot}07$; Tables 1 and 2 and Fig. 1). Whereas the productivity on ungraded piste plots was similar to that of off-piste plots, it was reduced 4·6 times on graded piste plots ($P = 0{\cdot}011$; Tables 1 and 3 and Fig. 2). Machine-graded pistes that had been revegetated by sowing supported fewer species ($P = 0{\cdot}098$). The Shannon index was lower for all graded piste plots ($P = 0{\cdot}03$; Tables 1 and 3 and Fig. 2).

Machine-grading also affected the vegetation composition: woody plants, which were generally less common

**Table 1.** The effects of ski piste treatments on the parameters describing the vegetation in 12 Swiss ski resorts: Predicted means and slopes of the correlation with years of artificial snow. The *n* in parentheses refer to the biomass measurements (*n* lower because of missing values)

| | Total $n$ = 76 (73) Mean | Off-piste $n$ = 38 (36) Mean | Piste $n$ = 38 (37) Mean | Piste graded $n$ = 17 (16) Mean | Piste ungraded $n$ = 21 Mean | Correlation with years of artificial snow Slope |
|---|---|---|---|---|---|---|
| Indicator values | | | | | | |
| F* | 2·85 | 2·83 | 2·87 | 2·88 | 2·87 | 0·000 |
| R† | 2·55 | 2·50 | 2·59 | 2·61 | 2·58 | 0·007 |
| N‡ | 2·46 | 2·38 | 2·54 | 2·56 | 2·53 | 0·003 |
| L§ | 3·80 | 3·76 | 3·85 | 4·03 | 3·71 | 0·01 |
| Diversity and productivity | | | | | | |
| Species number | 36·4 | 38·5 | 34·3 | 31·7 | 36·5 | 0·30 |
| Shannon index | 3·6 | 3·8 | 3·4 | 2·8 | 3·8 | −0·02 |
| Annual productivity (g $m^{-2}$) | 158·0 | 173·1 | 143·3 | 46·9 | 216·7 | −0·25 |
| Proportion of cover (%) | | | | | | |
| Grasses | 41·4 | 38·8 | 44·0 | 38·7 | 48·4 | –0·93 |
| Forbs | 24·2 | 26·5 | 22·0 | 20·5 | 23·1 | 0·13 |
| Woody plants | 17·4 | 24·3 | 10·5 | 1·6 | 17·7 | 0·38 |
| Legumes | 5·1 | 2·9 | 7·4 | 10·6 | 4·8 | 0·15 |
| Snowbed species | 8·4 | 7·3 | 9·6 | 14·0 | 6·0 | 1·36 |
| Wind-edge species | 7·5 | 7·7 | 7·4 | 8·0 | 6·9 | −0·27 |
| Early flowering species | 35·6 | 40.8 | 30·5 | 22·9 | 36·6 | −1·26 |
| Late-flowering species | 30·5 | 28·0 | 32·9 | 34·1 | 32·0 | 0·03 |
| Bare ground | 11·8 | 7·0 | 16·1 | 28·6 | 6·0 | 0·26 |
| Proportion of species (%) | | | | | | |
| Grasses | 27·9 | 27·9 | 27·8 | 27·2 | 28·2 | −0·13 |
| Forbs | 60·2 | 59·8 | 60·6 | 63·2 | 58. 5 | 0·09 |
| Woody plants | 11·9 | 13·0 | 10·8 | 6·9 | 14·0 | −0·23 |
| Legumes | 7·8 | 6·6 | 9·1 | 10·9 | 7·6 | 0·21 |
| Early flowering species | 33·4 | 35·7 | 31·1 | 25·5 | 35·7 | −0·71 |
| Late-flowering species | 31·0 | 29·9 | 32·2 | 32·5 | 31·9 | 0·25 |

*F = 2, medium dryness; 3, medium humidity.
†R = 2, acid soils; 3, neutral or weakly alkaline soils.
‡N = 2, nutrient-poor soils; 3, medium- to nutrient-poor soils.
§L = 3, half-shaded conditions; 4, full-light conditions.

**Table 2.** ANOVA table for the indicator values of the vegetation for moisture (F), soil acidity (R), nutrient (N) and light availability (L) measured on 38 ski piste plots and 38 corresponding off-piste plots in 12 Swiss ski resorts. The type of piste treatment (machine-grading and years of artificial snowing) was fitted for pairs of piste/off-piste plots. The factor ski piste indicates the difference between piste and off-piste plots. The dependent variables were (ln($x$ + 1))-transformed prior to analysis. Three plots were excluded from biomass sampling. The sample size for productivity is therefore 73, and the degrees of freedom are indicated in parentheses. MS, mean squares; *F*, variance ratio; subscripts refer to source of variation (*)$P < 0·1$, *$P < 0·05$, **$P < 0·01$, ***$P < 0·001$

| | Skeleton analysis | | | Variance ratio | | | |
|---|---|---|---|---|---|---|---|
| Source of variation | MS | *F* | d.f. | F-value | R-value | N-value | L-value |
| Altitude | $MS_E$ | $MS_E/MS_{Rest}$ | 1 | 3·14 | 5·87(*) | 70·23** | 37·19** |
| Resort | $MS_R$ | $MS_R/MS_{Rest}$ | 11 | 3·34 | 4·87(*) | 4·43(*) | 1·83 |
| Type of plot pair | $MS_T$ | $MS_T/MS_{RT}$ | 3 | 0·16 | 0·50 | 0·25 | 0·75 |
| Piste | $MS_P$ | $MS_P/MS_{RP}$ | 1 | 3·27(*) | 4·42(*) | 14·64** | 9·46* |
| Grading × piste | $MS_{LP}$ | $MS_{LP}/MS_{RLP}$ | 1 | 0·32 | 2·68 | 4·51(*) | 24·36** |
| Duration of snowing × piste | $MS_{AP}$ | $MS_{AP}/MS_{RAP}$ | 1 | 3·68(*) | 4·80(*) | 3·26(*) | 0·13 |
| Grading × duration of snowing × piste | $MS_{LAP}$ | $MS_{LAP}/MS_{Rest}$ | 1 | 1·02 | 0·03 | 0·03 | 0·06 |
| Resort × type of plot pair | $MS_{RT}$ | $MS_{RT}/MS_{Rest}$ | 23 | 1·42 | 1·52 | 3·97(*) | 0·87 |
| Resort × piste | $MS_{RP}$ | $MS_{RP}/MS_{Rest}$ | 11 | 0·51 | 0·45 | 0·93 | 0·24 |
| Resort × grading × piste | $MS_{RLP}$ | $MS_{RLP}/MS_{Rest}$ | 7 | 0·37 | 0·44 | 1·31 | 0·18 |
| Resort × duration of snowing × piste | $MS_{RAP}$ | $MS_{RAP}/MS_{Rest}$ | 11 | 0·34 | 0·51 | 0·44 | 0·15 |
| Rest | $MS_{Rest}$ | | 4 | | | | |
| Total | | | 76 | | | | |

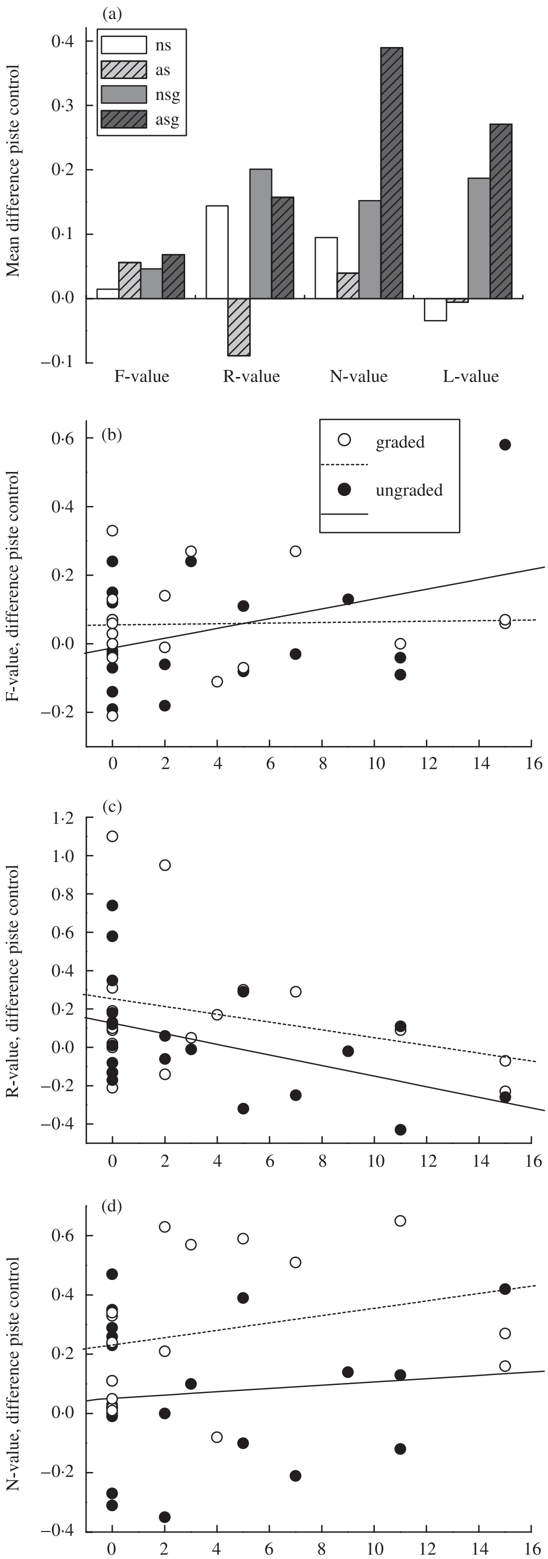


**Fig. 1.** Differences in indicator values between ski piste plots and corresponding control plots. (a) Mean differences in indicator values for the four ski piste treatments (ns, ungraded pistes with natural snow; as, ungraded pistes with artificial snow; nsg, graded pistes with natural snow; asg, graded pistes with artificial snow; F, moisture indicator value; R, reaction (soil acidity) indicator value; N, nutrient indicator value; L, light indicator value). (b–d) The relationship between the differences in (b) F (moisture), (c) R (soil acidity) and (d) N (nutrient) indicator values and the time since conversion to artificial snow.

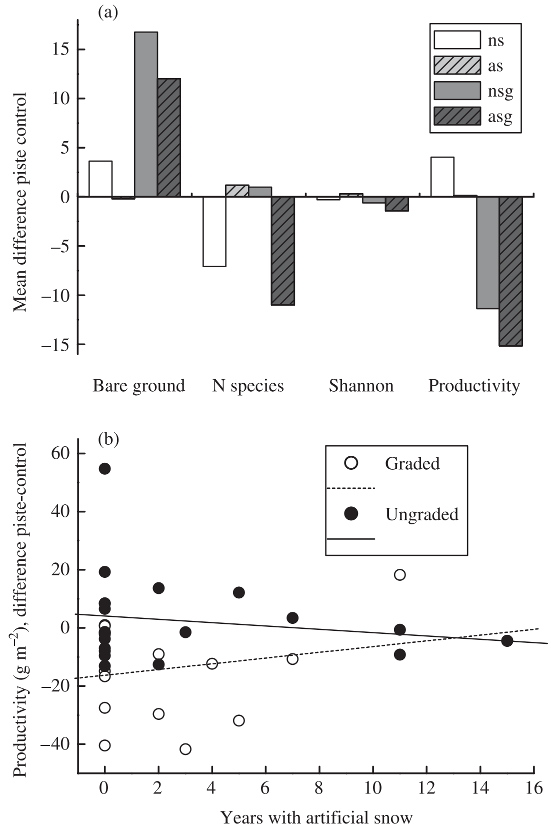


**Fig. 2.** Differences in productivity and diversity between ski piste plots and corresponding control plots. (a) Mean differences in productivity, species number, Shannon index and the proportion of open ground for the four ski piste treatments (ns, ungraded pistes with natural snow; as, ungraded pistes with artificial snow; nsg, graded pistes with natural snow; asg, graded pistes with artificial snow). (b) The relationship between the differences in annual productivity and the time since conversion to artificial snow.

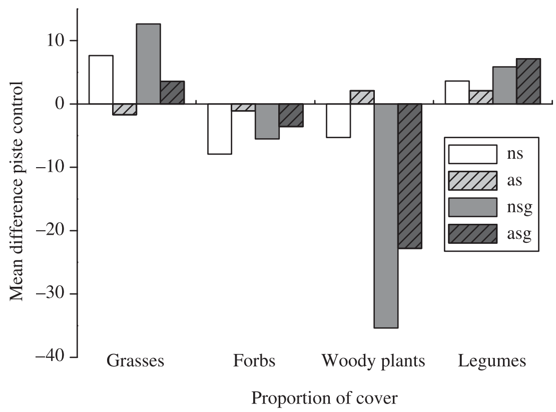


**Fig. 3.** Differences in species composition between ski piste plots and corresponding control plots. Mean differences in the percentage cover of the four functional groups for the four ski piste treatments (ns, ungraded pistes with natural snow; as, ungraded pistes with artificial snow; nsg, graded pistes with natural snow; asg, graded pistes with artificial snow).

on piste plots, were reduced by 91% on graded piste plots in comparison with ungraded ones ($P = 0{\cdot}03$; Tables 1 and 4 and Fig. 3). Whereas only 6·9% of the species on graded piste plots were woody species, they accounted

**Table 3.** ANOVA table for the proportion of bare ground, annual productivity, species number and Shannon index measured on 38 ski piste plots and 38 corresponding off-piste plots in 12 Swiss ski resorts. The type of piste treatment (machine-grading and years of artificial snowing) was fitted for pairs of piste/off-piste plots. The factor ski piste indicates the difference between piste and off-piste plots. Three plots were excluded from biomass sampling. The sample size for productivity therefore is 73, and the degrees of freedom are indicated in parentheses. (*)$P < 0.1$, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

| | Skeleton analysis | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Variance ratio | | | |
| Source of variation | MS | *F* | d.f. | Bare ground (%) | Productivity | Species | Shannon number |
| Altitude | $MS_E$ | $MS_E/MS_{Rest}$ | 1 | 254·41*** | 79·96** | 5·59(*) | 0·58 |
| Resort | $MS_R$ | $MS_R/MS_{Rest}$ | 11 | 9·53* | 2·13 | 5·06(*) | 8·00* |
| Type of plot pair | $MS_T$ | $MS_T/MS_{RT}$ | 3 | 3·18 | 4·32(*) | 1·33 | 1·62 |
| Piste | $MS_P$ | $MS_P/MS_{RP}$ | 1 | 8·81* | 9·78** | 5·02* | 4·21(*) |
| Grading × piste | $MS_{LP}$ | $MS_{LP}/MS_{RLP}$ | 1 | 13·64** | 10·71* | 0·35 | 7·27* |
| Duration of snowing × piste | $MS_{AP}$ | $MS_{AP}/MS_{RAP}$ | 1 | 0·02 | 0·01 | 0·23 | 0·26 |
| Grading × duration of snowing × piste | $MS_{LAP}$ | $MS_{LAP}/MS_{Rest}$ | 1 | 2·02 | 1·83 | 9·81* | 9·99* |
| Resort × type of plot pair | $MS_{RT}$ | $MS_{RT}/MS_{Rest}$ | 23 | 7·74* | 1·01 | 1·90 | 2·21 |
| Resort × piste | $MS_{RP}$ | $MS_{RP}/MS_{Rest}$ | 11 | 8·18* | 0·90 | 1·09 | 2·68 |
| Resort × grading × piste | $MS_{RLP}$ | $MS_{RLP}/MS_{Rest}$ | 7 | 6·05(*) | 0·93 | 1·16 | 1·85 |
| Resort × duration of snowing × piste | $MS_{RAP}$ | $MS_{RAP}/MS_{Rest}$ | 11 (9) | 2·74 | 1·60 | 0·85 | 2·27 |
| Rest | $MS_{Rest}$ | | 4 (3) | | | | |
| Total | | | 76 (73) | | | | |

**Table 4.** ANOVA table for the proportion of the four functional groups, grasses, woody plants, forbs and legumes, at the plot area measured on 38 ski piste plots and 38 corresponding off-piste plots in 12 Swiss ski resorts. The type of piste treatment (machine-grading and years of artificial snowing) was fitted for pairs of piste/off-piste plots. The factor ski piste indicates the difference between piste and off-piste plots. Three plots were excluded from biomass sampling. The sample size for productivity therefore is 73, and the degrees of freedom are indicated in parentheses. (*)$P < 0.1$, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

| | Skeleton analysis | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Variance ratio | | | |
| Source of variation | MS | *F* | d.f. | Cover grass (%) | Cover woody plants (%) | Cover forbs (%) | Cover legumes (%) |
| Altitude | $MS_E$ | $MS_E/MS_{Rest}$ | 1 | 40·49** | 0·30 | 3·28 | 0·44 |
| Resort | $MS_R$ | $MS_R/MS_{Rest}$ | 11 | 6·37* | 3·76 | 6·70* | 9·95* |
| Type of plot pair | $MS_T$ | $MS_T/MS_{RT}$ | 3 | 1·02 | 1·58 | 0·61 | 2·38 |
| Piste | $MS_P$ | $MS_P/MS_{RP}$ | 1 | 1·76 | 13·87** | 2·47 | 5·39* |
| Grading × piste | $MS_{LP}$ | $MS_{LP}/MS_{RLP}$ | 1 | 0·72 | 7·67* | 0·00 | 1·54 |
| Duration of snowing × piste | $MS_{AP}$ | $MS_{AP}/MS_{RAP}$ | 1 | 29·86*** | 9·20* | 0·69 | 0·20 |
| Grading × duration of snowing × piste | $MS_{LAP}$ | $MS_{LAP}/MS_{Rest}$ | 1 | 0·00 | 0·12 | 0·99 | 0·81 |
| Resort × type of plot pair | $MS_{RT}$ | $MS_{RT}/MS_{Rest}$ | 23 | 5·21(*) | 1·01 | 2·69 | 4·66(*) |
| Resort × piste | $MS_{RP}$ | $MS_{RP}/MS_{Rest}$ | 11 | 3·23 | 0·70 | 1·77 | 5·30(*) |
| Resort × grading × piste | $MS_{RLP}$ | $MS_{RLP}/MS_{Rest}$ | 7 | 1·53 | 1·19 | 1·02 | 2·83 |
| Resort × duration of snowing × piste | $MS_{RAP}$ | $MS_{RAP}/MS_{Rest}$ | 11 | 0·26 | 0·40 | 0·54 | 4·14(*) |
| Rest | $MS_{Rest}$ | | 4 | | | | |
| Total | | | 76 | | | | |

for 14% of the species on ungraded piste plots ($P = 0.02$; Tables 1 and 5). The reactions of forb and grass species were not uniform: in six resorts the proportion of forb species was higher on graded compared with ungraded pistes (resort × grading × piste, $P = 0.02$). The proportion of grass species depended on the time since machine-grading: compared with ungraded control plots, the proportion was higher in recently graded pistes, and lower the older the graded pistes were ($P = 0.016$). Species that flower early in the year were reduced in abundance by 28% ($P = 0.018$; Tables 1 and 6) and covered 37% less ground on graded piste plots than on ungraded ones ($P = 0.004$; Tables 1 and 6).

### ARTIFICIAL SNOW

The longer artificial snow had been applied on ski pistes, the higher the moisture and nutrient availability, and the lower the soil base content (indicator values F, N and R: $P = 0.081$, $0.099$ and $0.051$, respectively; Tables 1 and 2 and Fig. 1). However, we could not detect any effects of artificial snow on plant productivity (Fig. 2).

**Table 5.** ANOVA table for the proportion of the four functional groups, grasses, woody plants, forbs and legumes, of the total species number per plot measured on 38 ski piste plots and 38 corresponding off-piste plots in 12 Swiss ski resorts. The type of piste treatment (machine-grading and years of artificial snowing) was fitted for pairs of piste/off-piste plots. The factor ski piste indicates the difference between piste and off-piste plots. The dependent variables of were ($\ln(x + 1)$)-transformed prior to analysis. Three plots were excluded from biomass sampling. The sample size for productivity therefore is 73, and the degrees of freedom are indicated in parentheses. (*)$P < 0{\cdot}1$, *$P < 0{\cdot}05$, **$P < 0{\cdot}01$, ***$P < 0{\cdot}001$

| | Skeleton analysis | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Variance ratio | | | |
| Source of variation | MS | MS | d.f. | Grass species (%) | Woody species (%) | Forb species (%) | Legume species (%) |
| Altitude | $MS_E$ | $MS_E/MS_{Rest}$ | 1 | 2·72 | 0·08 | 22·07** | 8·59* |
| Resort | $MS_R$ | $MS_R/MS_{Rest}$ | 11 | 11·33* | 2·01 | 18·79** | 2·44 |
| Type of plot pair | $MS_T$ | $MS_T/MS_{RT}$ | 3 | 0·29 | 0·45 | 0·26 | 1·99 |
| Piste | $MS_P$ | $MS_P/MS_{RP}$ | 1 | 0·30 | 5·72 * | 0·24 | 7·31* |
| Grading × piste | $MS_{LP}$ | $MS_{LP}/MS_{RLP}$ | 1 | 1·28 | 10·18 * | 0·31 | 3·19 |
| Duration of snowing × piste | $MS_{AP}$ | $MS_{AP}/MS_{RAP}$ | 1 | 0·02 | 0·01 | 0·04 | 0·08 |
| Grading × duration of snowing × piste | $MS_{LAP}$ | $MS_{LAP}/MS_{Rest}$ | 1 | 0·04 | 0·09 | 3·22 | 0·01 |
| Resort × type of plot pair | $MS_{RT}$ | $MS_{RT}/MS_{Rest}$ | 23 | 3·03 | 2·36 | 11·63* | 1·11 |
| Resort × piste | $MS_{RP}$ | $MS_{RP}/MS_{Rest}$ | 11 | 6·93* | 0·90 | 6·21 | 0·36 |
| Resort × grading × piste | $MS_{RLP}$ | $MS_{RLP}/MS_{Rest}$ | 7 | 4·19(*) | 0·58 | 17·73** | 1·13 |
| Resort × duration of snowing × piste | $MS_{RAP}$ | $MS_{RAP}/MS_{Rest}$ | 11 | 3·44 | 0·79 | 11·84* | 0·53 |
| Rest | $MS_{Rest}$ | $MS_E/MS_{Rest}$ | 4 | | | | |
| Total | | | 76 | | | | |

**Table 6.** ANOVA table for the proportion of snowbed and wind-edge, as well as early flowering and late-flowering species, of the total vegetation cover in a plot (%) measured on 38 ski piste plots and 38 corresponding off-piste plots in 12 Swiss ski resorts. The type of piste treatment (machine-grading and years of artificial snowing) was fitted for pairs of piste/off-piste plots. The factor ski piste indicates the difference between piste and off-piste plots. Three plots were excluded from biomass sampling. The sample size for productivity therefore is 73, and the degrees of freedom are indicated in parentheses. (*)$P < 0{\cdot}1$, *$P < 0{\cdot}05$, **$P < 0{\cdot}01$, ***$P < 0{\cdot}001$

| | Skeleton analysis | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Variance ratio | | | |
| Source of variation | MS | MS | d.f. | Snowbed species (%) | Wind-edge species (%) | Early flowering (%) | Late-flowering (%) |
| Altitude | $MS_E$ | $MS_E/MS_{Rest}$ | 1 | 85·42*** | 34·45** | 51·38** | 5·29(*) |
| Resort | $MS_R$ | $MS_R/MS_{Rest}$ | 11 | 3·45 | 3·79 | 2·45 | 1·93 |
| Type of plot pair | $MS_T$ | $MS_T/MS_{RT}$ | 3 | 2·18 | 1·04 | 1·24 | 0·61 |
| Piste | $MS_P$ | $MS_P/MS_{RP}$ | 1 | 3·14 | 0·07 | 13·90** | 3·92(*) |
| Grading × piste | $MS_{LP}$ | $MS_{LP}/MS_{RLP}$ | 1 | 0·29 | 0·01 | 17·93** | 2·12 |
| Duration of snowing × piste | $MS_{AP}$ | $MS_{AP}/MS_{RAP}$ | 1 | 13·19** | 6·68* | 5·68* | 0·09 |
| Grading × duration of snowing × piste | $MS_{LAP}$ | $MS_{LAP}/MS_{Rest}$ | 1 | 0·43 | 0·84 | 7·35(*) | 1·21 |
| Resort × type of plot pair | $MS_{RT}$ | $MS_{RT}/MS_{Rest}$ | 23 | 4·09(*) | 0·83 | 2·87 | 2·13 |
| Resort × piste | $MS_{RP}$ | $MS_{RP}/MS_{Rest}$ | 11 | 0·79 | 0·22 | 1·68 | 0·74 |
| Resort × grading × piste | $MS_{RLP}$ | $MS_{RLP}/MS_{Rest}$ | 7 | 2·77 | 2·28 | 0·86 | 0·72 |
| Resort × duration of snowing × piste | $MS_{RAP}$ | $MS_{RAP}/MS_{Rest}$ | 11 | 1·56 | 0·55 | 1·20 | 1·74 |
| Rest | $MS_{Rest}$ | $MS_E/MS_{Rest}$ | 4 | | | | |
| Total | | | 76 | | | | |

The impact of artificial snow on diversity was ambiguous. While the use of artificial snow had negative effects on species number and Shannon index on graded pistes, the opposite was found for ungraded pistes (three-way interaction between piste, grading and duration of snowing, $P = 0{\cdot}034$; Tables 1 and 3).

The application of artificial snow affected the relative proportion of plant functional groups. The longer artificial snow had been used, the more it had reduced the negative effect of the ski piste treatment on the cover of woody plants per plot ($P = 0{\cdot}011$; Tables 1 and 4). However, the proportion of a plot covered by grass species declined the longer a ski piste had been treated with artificial snow ($P < 0{\cdot}001$; Tables 1 and 4). The effect of artificial snow on the species proportion of forbs and the cover of legumes was not uniform but differed between ski resorts (three-way interaction resort × artificial snow × ski piste, $P = 0{\cdot}014$ and $P < 0{\cdot}083$, respectively; Tables 5 and 6). The longer artificial snow had been applied to a ski piste, the higher the cover of

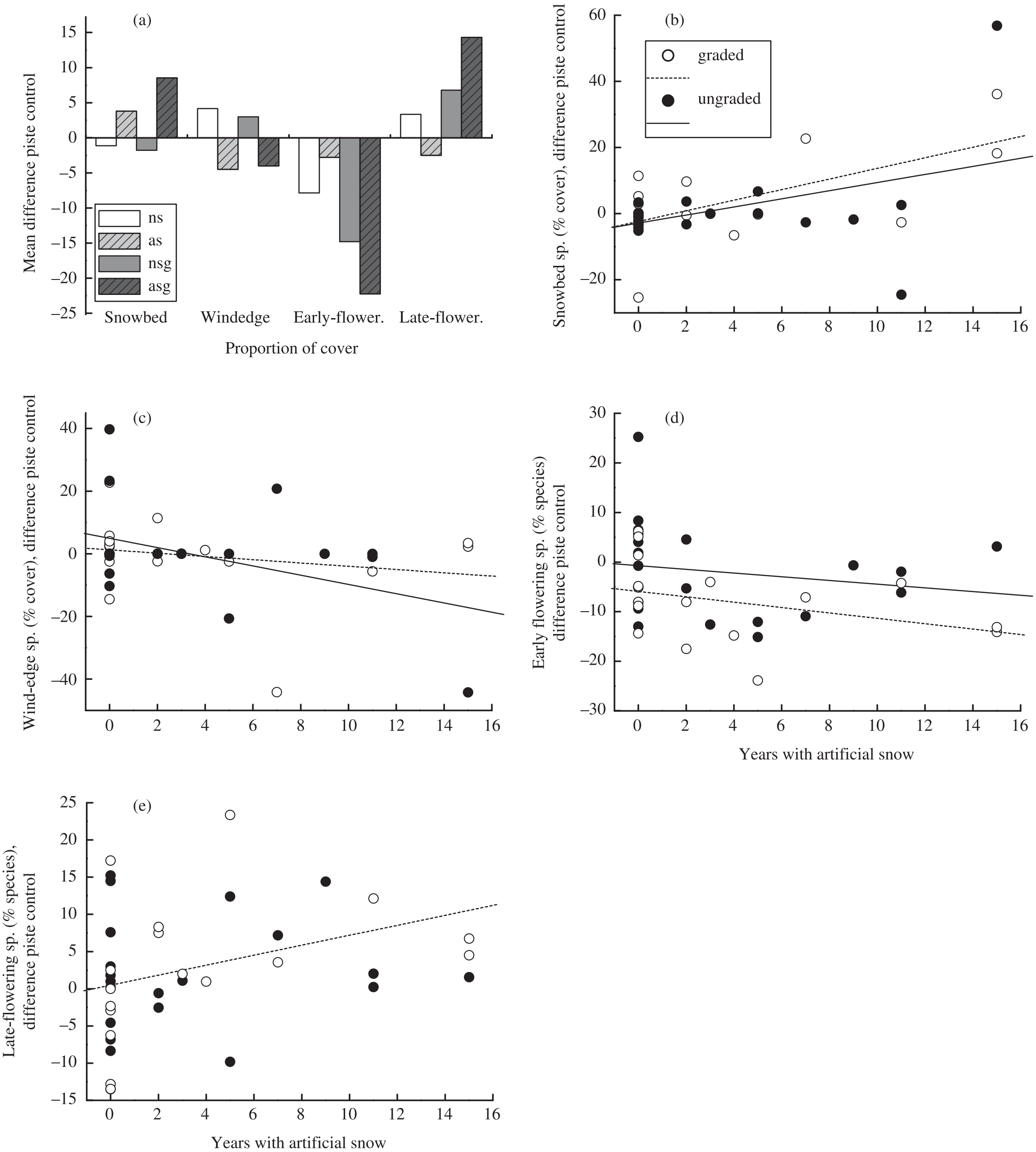


**Fig. 4.** Differences in ecological groups between ski piste plots and corresponding control plots. (a) Mean differences in the proportion of plot covered by ecological groups for the four ski piste treatments (ns, ungraded pistes with natural snow; as, ungraded pistes with artificial snow; nsg, graded pistes with natural snow; asg, graded pistes with artificial snow). (b–e) The relationship between the differences in (b) percentage cover of snowbed species, (c) percentage cover of wind-edge species, (d) proportion of early flowering species and (e) proportion of late-flowering species and the time since conversion to artificial snow.

snowbed species ($P = 0{\cdot}004$; Tables 1 and 6 and Fig. 4). Wind-edge species showed the opposite reaction. They covered less ground the longer a ski piste had been treated with artificial snow ($P = 0{\cdot}024$; Tables 1 and 6 and Fig. 4). The longer artificial snow had been applied, the lower the cover of early flowering plants on piste plots ($P = 0{\cdot}036$; Tables 1 and 6 and Fig. 4). On the other hand, the relative number of late-flowering species tended to increase the longer artificial snow had been used ($P < 0{\cdot}096$; Tables 1 and 6 and Fig. 4). Overall, the potentially snow-sensitive groups were affected most by the production of artificial snow.

## Discussion

### IMPACTS OF SKI PISTES VS. NO PISTE

The changes in indicator values for soil nutrients, moisture and reaction (base content) under ski pistes may be considered beneficial for plant growth (in terms of enhancing growth). However, other non-beneficial factors, including disturbance, seem to prevail because overall productivity and species richness on ski pistes are decreased. The negative effects may be the direct result of disturbance of the vegetation via snow compaction under skiing and via mechanical abrasion. Although some types of disturbance can increase biodiversity by suppressing dominant species in productive environments (Connell 1979; Vujnovic, Wein & Dale 2002), abiotic stress reduces productivity and dominance in alpine habitats and therefore reverses any positive effects of disturbance on plant diversity (Kammer & Möhl 2002).

The changes in the cover of woody plants on the ski pistes may also be explained by mechanical disturbance. Woody plants (mainly dwarf shrubs of the *Ericaceae*) are particularly sensitive to mechanical injuries because of their size, longevity and vulnerability of their hibernation buds (Körner 1999).

In contrast to woody plants, legumes were more abundant on pistes than next to pistes, perhaps because of decreased competition from shrubs. Legumes may have been responsible for the increased nutrient indicator values on piste plots as a consequence of their ability to fix nitrogen. The reduced abundance of early flowering species on pistes in our study was most probably the result of a narrowed temporal niche for those species. In field surveys, the flowering time of early seasonal species was postponed after soil frosts on pistes with natural snow (Baiderin 1981; Köck *et al*. 1989). A delay in flowering often decreases fecundity and, consequently, can negatively affect the abundance of early flowering species (Kudo 1993; Stanton & Galen 1997).

### IMPACTS OF MACHINE-GRADING

Vegetation responses were highly pronounced on graded pistes, most probably because machine-grading of ski pistes is a drastic measure where soil and plants are removed in summer during active plant growth. There was a strong compositional shift from woody plants to grasses or forbs, the extent of which depended partly on the resort and partly on the successional stage of the ski piste. The increased indicator values for nutrients and light may be the result of the disturbance itself (through mobilized nutrients and opened vegetation cover), or of characteristics of the following pioneer species, which often grow with high light and nutrient levels (Grime & Jarvis 1975; Grime 1977). Graded ski pistes with high proportions of bare ground are particularly prone to increased surface runoff and erosion during heavy rain (Löhmannsröben & Cernusca 1987). Revegetation processes at high altitudes are slow, even if revegetation measures such as sowing and planting are applied (Bayfield, Urquart & Rothery 1984; Urbanska 1995; Titus & Tsuyuzaki 1999; Fattorini 2001). In our study, the proportion of vegetation cover on graded pistes was negatively correlated with altitude, but positively affected by neither sowing nor time since machine-grading. This indicates how difficult it is to achieve revegetation at high altitudes. Machine-grading therefore is a particularly damaging management activity, the consequences of which are more severe and long lasting at higher altitudes.

### IMPACTS OF ARTIFICIAL SNOW

Application of artificial snow increased the moisture indicator values of the vegetation on piste plots. Artificially snowed pistes contained twice as much snow mass as normal pistes at our study sites in the winter of 1999–2000 (Stoeckli & Rixen 2000). Because water for artificial snow making is taken from lakes, rivers or ground water, it usually contains minerals and other chemical compounds (Kammer & Hegg 1990; Kammer 2002), and thus provides a nutrient input during spring melting for about 4 weeks in late spring. Accordingly, the vegetation on piste plots with artificial snow had an increased nutrient indicator value. Adding artificial snow to the ski pistes appeared to mitigate the mechanical disturbance of skiing because woody species became more abundant the longer artificial snow had been applied. Artificial snow is usually produced at the beginning of the winter and lasts beyond the end of the skiing season in spring.

The increase in snowbed and late-flowering species, and the decrease in wind-edge and early flowering species, on pistes with artificial snow probably reflect the shortened growth period resulting from a delay in snowmelt of 2–3 weeks (Newesely 1997; Stoeckli & Rixen 2000). Similar to the effects on normal pistes with their compacted natural snow, the narrowed temporal niche in spring presumably conferred a competitive advantage to the snowbed and late-flowering species over wind-edge and early flowering species (Cernusca *et al*. 1990; Newesely 1997; Rixen *et al*. 2001).

Plant diversity reacted differently to artificial snow on the graded and ungraded pistes. The increase in diversity on the ungraded pistes might be because of the decreased mechanical disturbance. The decrease in diversity on the graded pistes, on the other hand, might be a consequence of a decelerated revegetation process because of the shortened growing period. These effects can be enhanced if ice layers in the artificial snow cover decrease gas permeability (Newesely, Cernusca & Bodner 1994).

Whether the impact of artificial snow on alpine vegetation is considered positive or negative depends on the current state of the vegetation and the environmental objectives of a specific ski resort. If mechanical disturbance through snow-grooming vehicles or ski edges is a major problem, the increased protection afforded by artificial snow can be considered beneficial. However, in the case of endangered habitats poor in nutrients, like oligotrophic fens or nutrient-poor grasslands, the additional nutrients input by the melt water of artificial snow is clearly a negative impact.

We have shown that ski pistes in general, and machine-grading and artificial snow production in particular, cause deviations from natural plant species composition and decrease plant species richness. Machine-grading constitutes the most drastic vegetation disturbance on ski pistes. It should be avoided wherever possible, as it causes lasting damage that cannot be overcome even by revegetation measures, particularly at higher altitudes. Impacts of ski pistes in general, and of artificial snowing in particular, appear comparatively moderate, but are by no means negligible. With the ongoing intensification of ski resorts, the use of artificial snow will become more prevalent and the vegetation will change over an increasing area. Moreover, impacts of artificial snowing are cumulative and will become even more pronounced in the long term. In summary, mountain regions with a high proportion of areas with extensive outdoor recreation activities, like the European Alps, are facing continuous change of their traditional unique environment and vegetation. Therefore, we recommend that environmental goals in ski resort management should be established and respected. In particular, we recommend carefully recording the vegetation in a specific area before any intensification of use as ski piste, and complete avoidance of areas with vegetation of particularly high conservation value. Moreover, we recommend that large-scale machine-grading should be avoided, and that long-term snow production should be banned in areas where any increase in the supply of nutrients and water is a concern. Overall, the establishment of ski pistes should not be allowed in areas where any changes in vegetation composition or any decrease in plant species richness cannot be tolerated.

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## Supplementary material

The following material is available from http://www.blackwellpublishing.com/products/journals/suppmat/JPE/JPE1011/JPE1011sm.htm.

**Appendix 1.** List of study sites

**Appendix 2.** List of species

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